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The Needham Puzzle: Why the Industrial Revolution Did Not Originate in China*

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I. Introduction

One of the most intriguing issues for students of Chinese history and comparative economic history is, Why did the Industrial Revolution not occur in China in the fourteenth century? At that time, almost every element that economists and historians usually considered to be a major contributing factor to the Industrial Revolution in late eighteenth-century England also existed in China.

Chinese civilization, like the civilizations of Mesopotamia, Egypt, and India, originated from agriculture. The first unified empire, Qin, was formed in 221 B.C. By 300 B.C., Chinese society had developed into a form that had many characteristics of a market economy, with most land privately owned, a high degree of social division of labor, fairly free movement of labor, and well-functioning factor and product markets.[1]

This comparatively developed "market economy" probably created important attitudes toward profit and contributed to the swift diffusion of the best technology. In the Han dynasty (206 B.C.–A.D. 220), the iron-tipped plow, moldboard, and seed drill were widely used in the northern part of China, where the main crops were millet and wheat. The most significant improvements in Chinese agriculture came with the population shift from the north to the rice-growing areas south of the Yangtze River that started at the beginning of the ninth century, and especially after the introduction of a new variety known as "Champa rice" from Indochina at the beginning of the eleventh century.[2] This variety, characterized by better drought resistance and faster ripening, enabled farmers to extend the agricultural frontier from the lowlands, deltas, basins, and river valleys to the better-watered hill areas, and allowed production of two and even three crops a year.[3] The change from dryland crops to wetland rice led to a spurt of innova-

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tions in farm implements, including an improved plow that required less draft power, a share plow that could turn over sod to form a furrow, and the deep-tooth harrow.[4] Many of the elements of Arthur Young's scientific (conservation) agriculture, which led to the agricultural revolution in England in the eighteenth century, had become standard practice in China before the thirteenth century.[5] By the thirteenth century China probably had the most sophisticated agriculture and Chinese fields probably produced the highest yields in the world.

China's premodern achievements in science and technology were even more remarkable. Gunpowder, the magnetic compass, and paper and printing, which Francis Bacon considered as the three most important inventions facilitating the West's transformation from the Dark Ages to the modern world, were invented in China. Evidence documented in the monumental works of Joseph Needham and his collaborators shows that, except in the past 2 or 3 centuries, China had a considerable lead over the Western world in most of the major areas of science and technology.[6]

It is no surprise that, based on this "advanced" technology, Chinese industry was highly developed. The total output of iron was estimated to have reached 150,000 tons in the late eleventh century. On a per capita basis, this was five to six times the European output.[7] Equally impressive was the advancement in the textile industry. In the thirteenth century, a water-powered reeling machine was adapted for the spinning of hemp thread, which was as advanced as anything in Europe until about 1700.[8]

High agricultural productivity and advanced industry facilitated the early development of commerce and urbanization. Peasants were linked to rural market fairs, which in turn were integrated in a national commerce network by canals, rivers, and roads. In addition to staples like rice, many local products, such as particular types of paper and cloth, became known and available nationwide.[9] Many cities flourished in the thirteenth century, astonishing even that sophisticated Venetian, Marco Polo. According to him, "Su-chou is so large that it measures about forty miles in circumference. It has so many inhabitants that one could not reckon their number"; and Hang-chou "without doubt the finest and most splendid city in the world, . . . anyone seeing such a multitude would believe it a stark impossibility that food could be found to fill so many mouths."[10] In short, China by the fourteenth century was probably the most cosmopolitan, technologically advanced and economically powerful civilization in the world. Compared to China, "the West . . . was essentially agrarian and . . . was poorer and underdeveloped."[11]

In retrospect, China had a brilliant start and remained creative for several thousand years of premodern history. Many historians agree that by the fourteenth century China had achieved a burst of technological and economic progress, and that it had reached the threshold level for a full-fledged scientific and industrial revolution.[12] However, despite its early advances in science, technology, and institutions, China did not take the next step. Therefore, when progress in the West accelerated after the seventeenth century, China began to lag farther and farther behind. Needham put this paradox in the form of two challenging questions: first, why had China been so far in advance of other civilizations; and second, why isn't China now ahead of the rest of the world?[13] The goal of this article is to bring several relevant factors together that may provide a partial explanation to this puzzle.

Several hypotheses have been proposed by prominent scholars. These explanations can be classified into two categories: those based on failures of demand for technology and those based on failures of supply of technology. Section II reviews the existing demand-failure hypotheses. It is followed in Section III by a hypothesis of my own, which is essentially a supply-failure hypothesis. Section IV explores the factors inhibiting the development of modern science and technology in China and reviews other existing supply-failure hypotheses. A summary and some concluding remarks are in Section V.

II. The High-Level Equilibrium Trap

The most widely accepted hypothesis for China's later stagnation has been the "high-level equilibrium trap," first proposed by Mark Elvin and further expounded by Anthony Tang, Kang Chao, and other writers.[14] After reviewing China's many astonishing technological and institutional achievements before the fourteenth century, Elvin first refutes with convincing examples and evidence several conventional hypotheses, such as inadequate capital, restricted markets, political hazards, and lack of entrepreneurship in China, as explanations for the stagnation of China's technical creativity.[15] He then argues that the prime cause was unfavorable man-to-land ratio. Elvin's hypothesis, with Tang's and Chao's modifications, can be presented in a nutshell, as follows.[16]

China's early acquisition of "modern" institutions, such as family farming, fee-simple ownership, and the market system, provided effective incentives for technological innovation and diffusion. Therefore, the advancement of science and technology was initially much more rapid in China than in Europe. However, the Chinese family's obsession with male heirs to extend the family lineage encouraged early marriage and high fertility despite deteriorating economic conditions, resulting in a rapid expansion of population. The possibility for continued expansion of the amount of cultivated land was limited. At the end China stood at a position "where the level of living was subsistence and where the population was so large in relation to resources and the technological potentials were so fully exploited that any further advances in output would have required increases in population and consumption that would have out-stripped the resulting rise in food supply.''[17] The rising man-to-land ratio implied that labor became increasingly cheap and resources and capital increasingly expensive. Therefore, the demand for labor-saving technology also declined. Moreover, the rising man-to-land ratio also implied a diminishing surplus per capita. As a result, China did not have a surplus to be tapped for sustained industrialization. Even though China had already approached the threshold of industrial revolution in the fourteenth century, ''by that time population had grown to the point where there was no longer any need for labor-saving devices.''[18] On the contrary, Europe enjoyed a favorable man-to-land ratio and a legacy of unexploited, traditional economic and technological possibilities, because of its hereditary feudal system. Although its scientific and technological development lagged behind China's in premodern ages, by the time sufficient knowledge was accumulated to the threshold of an industrial revolution, ''a strong need to save labor was still acutely felt,''[19] and a large agricultural surplus was available to serve ''as the principal means of financing industrialization.''[20]

Although the above hypothesis is interesting, there are several reasons for abandoning this model as a valid explanation of China's failure to launch a full-fledged industrial revolution in the fourteenth century. I will first examine the implications of the man-to-land ratio for technological innovation and then will discuss the issue of ''depletion of agricultural surplus.''

The central assumption implicit in the above hypothesis is that of a bounded potential of agriculture in premodern ages. However, given the land, labor, and social institutions, the potential of agriculture, whether in modern or premodern ages, is a function of technology. If the development of technology is not inhibited, an ''equilibrium trap'' due to the adverse man-to-land ratio is not present. Therefore, the crucial issue is whether the lack of inventive creativity is a result of the rising man-to-land ratio.

It is true that up to the twelfth century, there was a steady flow of labor-saving innovations in plows and other farm implements, and that after that few labor-saving implements were invented, as shown by Chao.[21] However, changes in the orientation of invention were not due to the worsening of man-to-land ratio, as Chao claimed. As figure 1 shows, China's population increased until about 1200, declined until approximately 1400, and recovered to the 1200 level at approximately 1500. It reached a new peak at about 1600, collapsed again by about 1650, and thereafter has grown continuously. Due to the decline in population, the estimated per capita acreage at the end of the fourteenth century was actually about 50% higher than that at the end of the eleventh century and was even about 10% higher than that at the

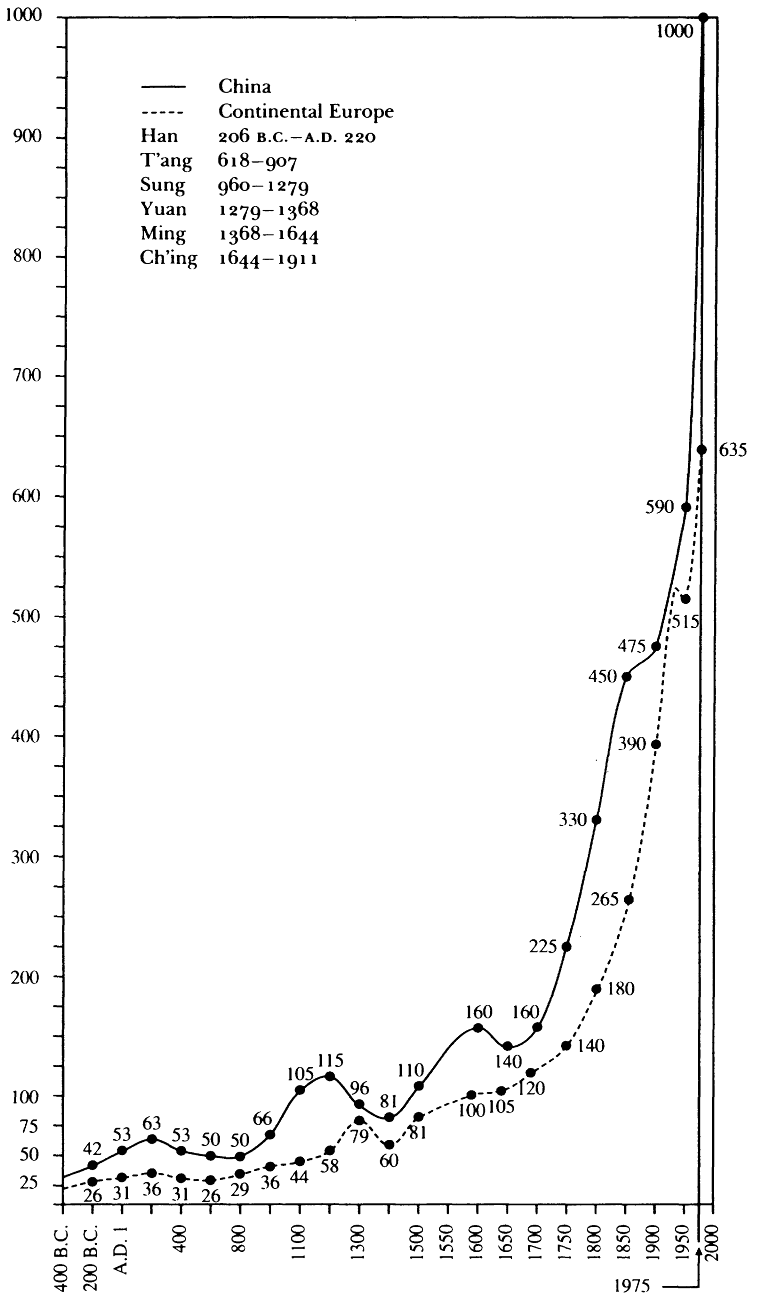

FIG. 1.—Population in China (in millions; A. Feuerwerker, "Chinese Economic History in Comparative Perspective," in *Heritage of China,* ed. Paul S. Ropp [Berkeley and Los Angeles: University of California Press, 1990], p. 227).

TABLE 1

PER CAPITA ACREAGE OF CULTIVATED LAND, A.D. 2–1887

Cultivated Land		Population		
Year	Amount (Million Mu)	Year	Number (Million)	Per Capita Acreage (Mu)
2	571	2	59	9.67
105	535	105	53	10.09
146	507	146	47	10.78
976	255	961	32	7.96
1072	666	1109	121	5.50
1393	522	1391	60	8.70
1581	793	1592	200	3.96
1662	570	1657	72	7.92
1784	886	1776	268	3.30
1812	943	1800	295	3.19
1887	1,154	1848	426	2.70

SOURCE.—Kang Chao, *Man and Land in Chinese History: An Economic Analysis* (Stanford, Calif.: Stanford University Press, 1986), p. 89.

end of the tenth century (see table 1). The per capita acreage in the mid-seventeeth century was also higher than that at the end of the eleventh century. If the man-to-land ratio were the valid explanation for the burst of labor-saving innovations up to the twelfth century, then that rate should have been even higher in the fourteenth and fifteenth centuries and again in the mid-seventeenth century.

Moreover, even if we take the man-to-land ratio in the early twentieth century as the point of discussion, the claim that there was "no need for labor-saving devices" is tenuous. Because of widespread double-cropping, labor shortages have always existed during the peak season when farmers have to simultaneously reap the first crop and prepare the land and sow or transplant the second crop. According to John Buck's survey in the 1920s, there was on average only one and a half months free of field labor for the whole of China. Most of this period was accounted for by winter unemployment in the dryland farming areas of northern China. In the irrigated parts of southern China there were hardly any periods during the year in which farm households were not fully occupied in agricultural activities.[22] Therefore, the relatively low rate of labor-saving inventions after the twelfth century cannot be explained by the fact that the population had grown to the point where there was no longer any need for labor-saving devices, as the hypothesis claimed.[23]

The other reason, implied in the above hypothesis and emphasized by Elvin and Tang, for why the demand for technology might have been dampened is an "inadequate" agricultural surplus arising from the adverse man-to-land ratio. However, this explanation has several problems. First, from the preceding discussion of demographic dynamics and per capita acreage, we can conclude that, given the technological level and social institutions, the surplus per capita in the fourteenth and fifteenth centuries should have been higher than that in the twelfth century, especially after the period of peace ushered in by the founding of the Ming dynasty in 1368. What we find, however, is a deceleration of labor-saving innovations.

Second, even if we take the twentieth century as a reference point for discussion, the claim that the high man-to-land ratio had depleted the agricultural surplus as a source for capital formation cannot be supported empirically. According to Carl Riskin's estimates, 31.2% of China's net domestic product was available for "nonessential" consumption in 1933.[24] Such estimates certainly depend on how "essential consumption" and "essential government expenditures" are defined. Riskin's findings indicate that the income flow in 1933 could provide for a rate of investment above 11% of national income, cited by W. W. Rostow and other economists as a threshold level for sustained economic development.[25] Moreover, the average rate of national income used for capital accumulation during the first 5-year plan period (1953–57) under the socialist government was 24.2%.[26] At that time, agricultural technology was still essentially traditional.[27]

From the above discussions, I find that the fact that the Industrial Revolution failed to occur in China in the fourteenth century cannot be attributed to a lack of demand for new technology, as asserted by the "high-level equilibrium trap" hypothesis.

III. Population, Science, and Invention

Given a set of inputs, a technological innovation must bring with it an increase in output. So long as humans' material desires are not satiated, the demand for new, better, and more cost-effective technologies is always present, though changes in the relative scarcity of labor and land in an economy may alter the patterns of invention. If technological change fails to take place, the problem does not stem from a lack of demand but from a failure on the supply side.[28] To address the Needham puzzle, we thus need to turn our attention to the supply side of technology.

Britain's Industrial Revolution in the eighteenth century is often identified with the mechanization of the textile industry, the exploitation of iron and coal, and Watt's invention of an atmospheric steam engine. However, what really distinguished the Industrial Revolution from other epochs of innovation bursts in human history, such as the one in the eighth- to twelfth-century China, was its sustained high and accelerating rates of technological innovation. The problem of China's failure to initiate an industrial revolution in the fourteenth century, therefore, is not simply a question of why China did not take a further step to improve its water-powered hemp-spinning machine. Rather, the question is why the speed of technological innovation did not accelerate after the fourteenth century, despite China's high rate of technological innovation in the pre-fourteenth-century period.

The key to this question may lie in the different ways in which new technology is discovered or invented. The hypothesis I propose as a likely explanation to the Needham puzzle is as follows: in premodern times, technological invention basically stems from experience, whereas in modern times, it mainly results from experiment cum science. China had an early lead in technology because in the experience-based technological invention process the size of population is an important determinant of the rate of invention. China fell behind the West in modern times because China did not make the shift from the experience-based process of invention to the experiment cum science–based innovation, while Europe did so through the scientific revolution in the seventeenth century.

To support the above hypothesis, I will first present a simple stochastic model of technological invention à la Robert S. Evenson and Yoav Kislev and then will use it to analyze the historical development in China and Europe.[29]

A. A Model of Technological Invention

A technology can be defined as a body of knowledge about how to combine a set of inputs for producing a certain product. The net output, measured in a value term, produced by a given technology is defined as the productivity of the technology. A better technology means one with higher productivity. The supply of technology comes from inventive activity, which can be described as "trial and error" or "hit or miss" performed by the potential inventors, including farmers, artisans, tinkers, and researchers in the fields or in the laboratories. Each trial produces a technology with a certain productivity level, which is represented as a point under an invention distribution curve (see fig. 2*A*).[30] A trial can thus be perceived as a random draw from the invention distribution. Figure 2*A* portrays the basic features of the invention distribution curve.[31] If a draw results in a technology with a higher productivity than the existing technology, a better technology is invented. The probability of inventing a better technology by a random draw can be measured by the shaded area in figure 2*A*. The adoption of a better technology to production is called technological innovation, which requires a diffusion process and time. For simplicity in describing the model, I will assume that once a better technology is invented, it is adopted by the whole economy.[32]

The mean and variance of the invention distribution function for an inventor is a function, among other things, of the inventor's stock of scientific knowledge and ingenuity, the material available for inven-

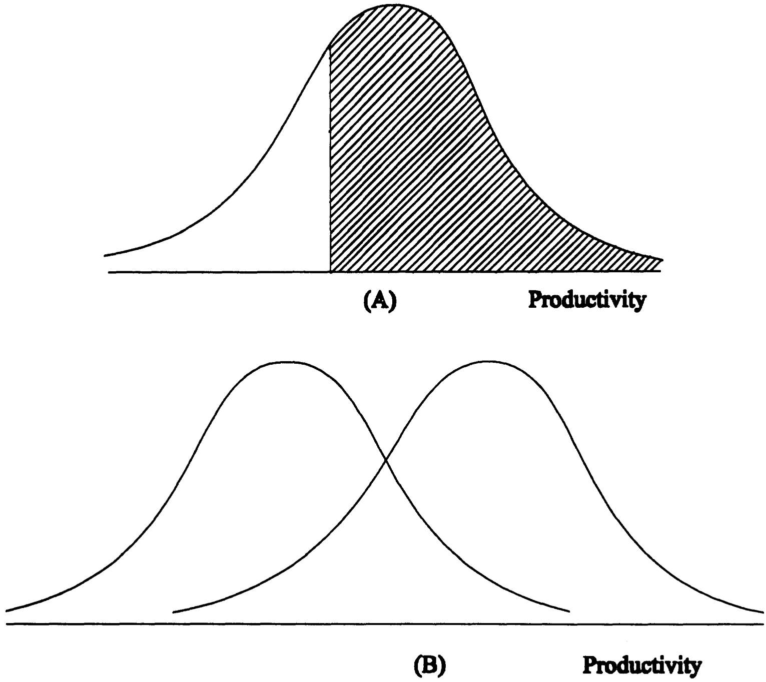

FIG. 2.—The invention distribution curve

tion, and the surrounding physical environment. An increase in an inventor's stock of scientific knowledge increases the mean of his invention distribution function, shown in figure 2*B* as a rightward shift of the distribution curve.[33] Different inventors may have different invention distribution functions because of differences in their stock of scientific knowledge. Therefore, with a given technological level in an economy, the increase of an inventor's scientific knowledge improves the probability of his inventing a better technology. It is also possible for an inventor with a low stock of scientific knowledge to make big inventions, although the probability of such events is low.

It is worth mentioning that scientific knowledge itself is a result of the trial and error of scientific research, which can be described in a similar way to the invention of technology. However, science and technology have several different characteristics. Technological knowledge is used directly for the production of outputs, while scientific knowledge is used to derive testable hypotheses about the characteristics of the physical world, which may or may not facilitate the production of technology. New technology can be discovered by a veteran farmer or an artisan as a result of casual work, while scientific progress, especially in modern times, is more likely to be made by scientists following a rigorous scientific method. This scientific method is characterized by a "mathematization" of hypotheses about nature combined with relentless experimentation.[34] Because scientific knowledge must be acquired by technological inventors before it can affect the outcome of invention, there is a time lag between progress in science and progress in technology.

An inventor's ingenuity affects his invention distribution function. That is, the better an inventor's ingenuity, the greater the likelihood of his inventing a better technology. However, the distribution of innate ingenuity is assumed here to be the same across nations and times. Change in the available materials can also change the mean, and probably also the variance, of the invention distribution function. One salient example is the progress from the Stone Age to the Bronze Age, and then to the Iron Age. Taking the example of plows, the productivity of an iron plow is in general higher than that of a bronze plow, which in turn is higher than that of a stone plow.

The model used here assumes that the source of invention is trial and error. It is important for our discussion to distinguish two types of trial and error: one is experience based and the other is experiment based. Experience-based trial and error refers to spontaneous activity that a peasant, artisan, or tinker performs in the course of production. Experiment-based trial and error refers to deliberate, intense activity of an inventor for the explicit purpose of inventing new technology. New technology obtained from experience is virtually free, while that obtained through experiment is costly. However, in a single production period an artisan or farmer can have only one trial, while an inventor can perform many trials by experiment. Since experience-based invention involves no cost and is a spontaneous result of production, cost-return calculations are not involved in experience-based invention. On the other hand, economic considerations are a key factor in determining the undertaking of experiment-based invention.[35]

It is possible to extend the above model in several directions. However, it is sufficient to suggest a new perspective on the Needham puzzle by the several implications that can be drawn from this simple model: (1) The likelihood of inventing a better technology is a positive function of the number of trials. (2) The probability of inventing a better technology is a negative function of the highest productivity of previous draws from the invention distribution—the level of existing technology. (3) Increases in the stock of scientific knowledge and improvements in the quality of available materials raise an inventor's likelihood of finding a better technology.

B. Technological Change in Premodern and Modern Times

Technological innovation, by definition, is an improvement in productivity. What distinguishes technological innovation in the modern age from that in premodern ages is the higher rate of innovation in the modern age, which is a consequence of the shift in the method of technological invention. Although in some cases systematic experimental methods were used in premodern times, as, for example, in the discovery of magnetic declination in China,[36] it is an accepted view that technological invention was predominately derived from experience. Inventions were made by artisans or farmers as minor modifications of existing technology as a result of experience obtained from the production process.[37] The experimental method became the predominant way of finding new knowledge only after the scientific revolution in the seventeenth century. The use of science to guide experiments came even later.

The first hypothesis from the above model predicts that, when experience is the major source of technological invention, the size of population in an economy is an important factor in determining the rate of invention and the level of technology in that economy. A larger population implies more farmers, more artisans, more tinkers, and so on and, therefore, more trial and error. Moreover, given the assumption that the level and distribution of the innate ingenuity tends to be the same statistically for large and small populations, a larger population thus implies that there would be a larger pool of gifted people in that economy. From the model described in Section *A*, we can conclude that in premodern times a large population contributed positively, in a probabilistic sense, to the level of technology and the rate of technological invention, ceteris paribus.[38] This may explain why the great civilizations of antiquity were located in Mesopotamia, Egypt, and India, where fertile river valleys were favorable for agriculture and could support a large population.

Chinese civilization originated on the Loess Plateau in northwestern China, later than the great river civilizations. During the Former and Later Han dynasties (206 B.C.–A.D. 220) China's population was concentrated on the North China Plain and to the west of the gorges of the Yellow River. The principal grain was millet, but wheat, barley, and rice were also grown. During the fourth and fifth centuries A.D., Chinese settlers began to migrate in large numbers into the Yangtze River valley. Initially the method of farming was very crude, mainly slash-and-burn. As more people moved south, farming became settled, and wetland rice cultivation began to dominate. The pattern of Chinese agriculture that was practiced up to modern times essentially was established by the Song dynasty (960–1279).

Figure 1 shows that China had about twice the population of Europe until about 1300.[39] The aforementioned invention model predicts that, with experience as the principal source of technological invention, China had a higher probability than Europe of discovering new technology. In the eighth to twelfth century, the burst of inventions in

China probably was due partly to the increase in population and partly to the shift of population from the north to the south.[40] Accompanying this shift was the transition from dryland crops to wetland rice, which with suitable technology brought a much higher yield than dryland crops.[41] However, with the original dryland farming technology, the yield of rice was still much lower than its potential. This shift in crops amounted to a rightward shift of the invention distribution function arising from the change in material available to inventors. Therefore, there was a burst in technology related to rice farming, including new tools, new crop rotations, and hundreds of types of new seed. The many other technological innovations in this period, such as water transportation, which Elvin ably documented in his celebrated book, also could be explained by the same line of reasoning.

Conventional wisdom has often argued that China's achievements in ancient times were due to its early acquisition of "modern" socioeconomic institutions, including the unified nation-state, family farms, free labor migration, and so forth, which should have facilitated a more rapid diffusion of technology once invented.[42] However, to the extent that technological inventions in premodern ages were fundamentally experience based and independent of economic calculations, the impact of socioeconomic institutions on technological invention was at most indirect, based on the possibility that fast diffusion of better technology might have allowed the economy to sustain a larger population than it would have otherwise.

After a decline of population during the twelfth to fourteenth centuries, China's population started to grow exponentially, except during the short period from 1600 to 1650. From the first hypothesis in the invention model, a larger population implies that there is more trial and error and, therefore, more invention. However, the second hypothesis predicts that, given an invention distribution curve, the marginal returns to the probability of invention from a larger population will eventually diminish. The post-fourteenth-century experience in China seems to support the implication of the second hypothesis. After the burst of technological invention from the eighth to twelfth centuries, the technological level moves to the right end of the experience-based invention distribution curve. Invention was still possible and actually continued to appear, but the probability of big breakthroughs became smaller and smaller. Most inventions took the form of minor modifications. Technological change could not recover to a higher rate until there was a rightward shift in the invention distribution curve, made possible by applying Galilean-Newtonian physics, Mendelian genetics, and contemporary biological, chemical, plant, animal, and soil sciences.[43]

During the period of experience-based technological invention, Europe was at a comparative disadvantage due to its smaller population—a smaller population means a smaller number of trials. However, this disadvantage was countered by the shift to experiment-based technological invention and the closer integration of science and technology arising from the scientific revolution in the seventeenth century. Of course, as mentioned above, the experimental method had been used to invent technology even in ancient times. However, the popularization of the experiment as a vehicle for inventing new technology was a phenomenon that emerged only after the scientific revolution.[44] The experimental method removes the constraints of population size on technological invention. The number of trials that an inventor can perform in a laboratory within a year may be as many as thousands of farmers or artisans could perform in their lifetimes. However, if only experimental methods had been applied, the result would have been a single burst of technological inventions, as in the eighth to twelfth centuries in China. Soon thereafter, Europe would have faced the gradual exhaustion of invention potential and a slowdown in the rate of innovation, as China did after the fourteenth century. Therefore, more important than the popularization of the experimental method is the continuous shift to the right of the invention distribution function by the increasing integration of science with technology.

As in any society, science and technology in Europe initially were separate and distinct: science was viewed as philosophy, while technology was the practice of artisans. Scientists had no interest in, or inclination toward, technological affairs, and technological developments were mostly the results of the toil of unlettered artisans. It was only by the time of Galileo that "sciences concerned with utilitarian technology had found spokesmen capable of winning attention and commanding respect."[45] At the beginning, the contribution of science to technology was sporadic; in fact, whether or not science was a major contributing factor to the Industrial Revolution in the eighteenth century is still subject to debate.[46] However, at least by the mid-nineteenth century, science had already begun to play an important role in technological invention.[47] The sustained acceleration in the rate of technological innovation that is a major characteristic of modern economic growth is made possible only by the continuous rightward shift of the invention curve brought about by the continuous progress in science.[48] Needham found evidence that China began losing ground to Europe in the technological race only after the scientific revolution had occurred in Europe.[49]

IV. Why a Scientific Revolution Did Not Occur in China

Any discussion of the Needham puzzle is incomplete without an explanation of why modern science did not arise in China. As stated above, science, in essence, is a body of systematic knowledge about nature that is expanded through a mechanism similar to that of technological invention, that is, the process of trial and error. China's large population gave it a comparative advantage in developing science in premodern times. However, since the advent of the scientific revolution, scientific discoveries have been made primarily by a new and more effective method that is the combination of two elements: (*a*) mathematization of hypotheses about nature, and (*b*) using controlled experiments or replicable tests to examine the validity of hypotheses. The Chinese were not historically unreceptive to the experimental method. In fact, in ancient times, they had conducted more systematic experimentations than did the Greeks or the medieval Europeans.[50] The question, then, is why the many gifted of China's large population, with the advantages of superior early achievement, did not make the transition to the new methodology in the fourteenth, fifteenth, seventeenth, or eighteenth centuries. The key to this problem lies in various factors that inhibited the growth of modern science in China.

Considerable research, including some by Needham himself, has been done in an attempt to identify the inhibiting factors in China's politico-economic institutions. A survey of all existing hypotheses is beyond the purview of this article. I will only comment on two of them. Needham's explanation is that China had a "bureaucratic system," which arose from the need of maintaining its vast array of irrigation systems, while Europe had an "aristocratic feudalism," which was relatively more favorable to the emergence of a mercantile class. When the aristocracy decayed, it gave birth to capitalism and modern science. The bureaucratic system in China at first was favorable to the growth of science. However, it inhibited the emergence of mercantilistic values and thus "was not capable of fusing together the techniques of the higher artisanate with the methods of mathematical and logical reasoning which the scholars had worked out, so that the passage from the Vincian to the Galilean stage in the development of modern natural science was not achieved, [and was] perhaps not possible."[51]

In a similar vein, though with different emphasis, Wen-yuan Qian and others argue that it was China's imperial and ideological unification that prohibited the growth of modern science.[52] In their view, intolerance was common to all premodern societies. In Europe, however, there were competitions between church and state, between church and church, and between state and state, which made the resistance to new basic ideas less effective. Therefore, Europe's cluster of more or less independent states created favorable conditions for scientific development. China, on the other hand, was ruled by one dominant ideological system backed by absolute political power, and no genuine public dispute was allowed. As a result, despite the fact that "the Chinese people have been innovative in mechanical skills and technologies, traditional China's politico-ideological inhibitions kept Chinese people from making direct contributions to the theoretical infrastructure and methodological foundations of modern science."[53]

The above explanations improve our understanding of the issues in some ways. However, discrimination against merchants and artisans in ancient China was probably not as serious as Needham makes out. As legally defined, traditional China was at once a Confucian and a "physiocratic" state; merchants were the lowest social class within a four-class scheme. However, there was a discrepancy between legal texts and social realities. Historical data reveal that successful merchants, moneylenders, and industrialists of the Former Han period (206 B.C.–A.D. 8) were treated almost as social equals by vassal kings and marquises.[54] By the medieval period, big business and financial organizations had already appeared and flourished in China, most of them owned by members of gentry families. Therefore, young men who were not interested in books and learning but had an adventurous personality could find socially approved outlets in commerce.[55] Furthermore, during the Ming-Qing period, the discriminatory laws forbidding merchants to take civil service examinations were formally removed. After 1451, the channel for purchasing offices and even academic degrees was opened. Thus money could be directly translated into position and became one of the determinants of social status.[56]

It is also true that, as Qian argues, through the civil service examinations China was able to effectively impose a state ideology. However, Qian may have overstressed the shackling effects of ideological and political uniformity on intellectual creativity. One counterexample to Qian's assertion was the challenge of Wang Yangming (1472–1529) to traditional philosophy and social order. Wang's teaching stressed heterodox intuitive knowledge, the intrinsic equality of all men and the unity of knowledge and conduct, all in sharp contrast to the official neo-Confucian philosophy that emphasized academic conservatism and social status quo. His teaching initiated a powerful social movement and numerous followers and admirers established hundreds of private academies (*shuyuan*) to disseminate Wang's philosophy. Although the Ming court proscribed his teaching in 1537, 1579, and 1625, Wang's disciples were able to continue the movement, and they left a permanent imprint on the nation's educational system.[57] Admittedly, the political environment was not conducive to unorthodox thinking. However, if a revolutionary philosophy such as Wang Yangming's was able to emerge and take root, the effects of ideological rigidity on intellectual creativity in premodern China must not have been as inhibitive as Qian believes. Revolutionary movements often have to emerge in settings unfavorable to their existence. Copernicus, Kepler, Galileo, and other pioneers of the scientific revolution in Europe had to contend with schoolmen who upheld the dogma of the authority and omniscience of the classics and even had to risk their lives in religious courts. In fact, it may be that the pioneers of the scientific revolution in premodern China had to battle harder than their European contemporaries for social recognition and acceptance, due to such factors as pointed out by Needham, Qian, and others; however, it is also fair to say that politico-ideological authority in premodern China was not absolute and that the Chinese system did not in itself preclude the possibility for geniuses to make revolutionary breakthroughs.[58]

I agree with Needham, Qian, and others that China's failure to make the transition from premodern science to modern science probably had something to do with China's sociopolitical system. However, the key to the question is not so much that this system prohibited intellectual creativity, as they argued, but rather that the incentive structure of the system diverted the intelligentsia away from scientific endeavors, especially from the mathematization of hypotheses about nature and controlled experimentation.

In premodern times, many scientific findings were made spontaneously by geniuses with innate acumen in observing nature. Individual ingenuity is, of course, important for the progress of modern science. However, the advance of modern science from its inception has relied on the mathematical systematization of hypotheses about the external universe and on tests by controlled experiment. To be able to accomplish this, a scientist must have updated knowledge about the universe, as well as training in abstract mathematics and controlled experimental methods. This knowledge and training gives scientists a stock of acquired human capital with which to observe nature to determine what can be added to science by empirical observation and experiments. A larger population means more geniuses, and therefore, in premodern times, implied probabilistically more achievements in premodern science. However, even though there may be many geniuses in a society, without the necessary acquired human capital, the society will not be able to launch a scientific revolution. This special human capital, a necessary requirement for membership in the club of modern science, is expensive and time-consuming to acquire.

For several reasons, which are embedded in China's historical and political legacy, the gifted in ancient China had fewer incentives than their Western contemporaries to acquire the human capital required for "modern" scientific research. In the West, the states were governed by hereditary feudal aristocrats. In China, after the Qin unification in 221 B.C., the state was ruled by bureaucrats. Civil service examinations were instituted during the Sui dynasty (589–617), and after the Song dynasty (960–1275), all bureaucrats were selected through competitive civil service examinations. Government service was by far the most honorable and in every sense the most worthwhile occupation in premodern China. Therefore, traditional Chinese society considered entry into the ruling bureaucracy the final goal of upward social mobility.[59] Naturally, the gifted were attracted to these jobs, and they had ample incentives to invest their time and resources in accumulating the human capital required for passing the examinations.[60] The basic readings for the examinations, which students had to memorize by heart, were the Confucian classics, with a total of 431,286 characters.[61] That required 6 years of memorization, at the rate of 200 characters a day. After memorizing the classics, students were required to read commentaries several times the length of the original texts and to carefully scan other philosophical, historical, and literary works, which were needed as a basis for writing poems and essays in the examinations.[62] Because of the strictly defined curriculum for the examinations, most people, including most of society's geniuses, would not have had the incentive to devote time and resources before passing the examinations to the type of human capital required for scientific research. Moreover, once they passed the examinations, they would be occupied with the demands of officialdom and with official ladder climbing, and thus would for the most part still have no time or incentive for acquiring those types of human capital.[63]

In premodern times China's population was larger than that of Europe. This would indicate that China had more geniuses than Europe in premodern times. However, because of the incentive system created by the specific form of civil service examination and officialdom, fewer of the gifted in China than those in Europe were interested in acquiring the human capital essential for the scientific revolution. Therefore, despite her early lead in scientific achievement, China failed to have an indigenous scientific revolution.[64]

V. Concluding Remarks

In this article I have attempted a hypothesis for the puzzle: Why was China's science and technology so far in advance of other civilizations historically, only to fall in modern times? Many causes may have contributed to this paradoxical phenomenon. In this article I postulate a simple hypothesis with a few relevant factors that are ignored by most students of Chinese history as well as of comparative economic history. In premodern times, most technological inventions stemmed from the experiences of artisans and farmers, and scientific findings were made spontaneously by a few geniuses with innate acumen in observing nature. In modern times, technological inventions mainly result from experiment cum science. Scientific discovery is made primarily by the technique of mathematized hypotheses and models about nature tested by controlled experiment or replicable tests, which can more reliably be performed by scientists with special training. Under the premodern model of technological invention and scientific discovery, the larger the population in a society, the greater the number of experienced artisans, farmers, and geniuses in the society. Therefore, other things being equal, more advance in technology and science would be more likely to occur in a larger society. China had comparative advantages in premodern times because of its large population but fell behind the West in modern times because technological invention in China continued to rely on happenstance and experience, while Europe changed to planned experiment cum science in the scientific revolution of the seventeenth century. The reason that China failed to have a scientific revolution I have attributed here to the contents of civil service examinations and the criteria of promotion, which distracted the attention of intellectuals away from investing the human capital necessary for modern scientific research. Therefore, the probability of making a transition from primitive science to modern science was reduced.

To the extent that the above hypothesis is valid, several policy implications for economic development are in order. In premodern times the large population size in an economy is potentially an asset for economic growth, as a large population is likely to contribute to a higher rate of technological innovation and scientific discovery in that economy. Experience-based invention is still an important source of technological change in modern times, especially with respect to minor modifications of existing technology. However, if this large population is ill equipped with the acquired human capital necessary for undertaking modern scientific research and experiment, the likelihood that the economy will contribute to modern technological invention and scientific discovery is small. For a developing country in modern times, many technologies can certainly be imported from developed countries at a much lower cost than the cost of inventing them independently. However, many empirical studies have found that the success or failure of technology transfers crucially depends on the domestic ability to follow up with adaptive innovations on the imported technology, which in turn depends on domestic scientific research capacity.[65] Therefore, in modern times a large population is no longer an endowment for economic development. More important than the size of the population is education with an emphasis on modern curriculum.

Notes

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1. Kang Chao, *Man and Land in Chinese History: An Economic Analysis* (Stanford, Calif.: Stanford University Press, 1986), pp. 2–3.

2. Ping-ti Ho, "Early Ripening Rice in Chinese History," *Economic History Review* 2, ser. 9 (December 1956): 200–218.

3. It is worth mentioning that, like many modern agricultural innovations, the promotion of Champa rice was sponsored by the government. The Song emperor Chen-Zong bought a large quantity of Champa rice from the south and made it available to farmers in the Yangtze delta (Chao, p. 200).

4. Ibid., p. 224.

5. Anthony Tang, "China's Agricultural Legacy," *Economic Development and Cultural Change* 28 (October 1979): 1–22.

6. Before Joseph Needham's works on China's achievements in science and technology, few people in the West, or in China, for that matter, understood that many of the basic inventions and discoveries upon which the modern world rests came from China. Needham's research started in 1937 as a result of his befriending some Chinese students in Cambridge who had profound knowledge of the history of Chinese science. His systematic research started in 1948, and the first volume of *Science and Civilization in China* was published in 1954 by Cambridge University Press. More than 10 volumes have been published and several more volumes are under preparation.

7. E. L. Jones, *The European Miracle,* 2d ed. (Cambridge: Cambridge University Press, 1987), p. 202.

8. Mark Elvin, *The Pattern of the Chinese Past* (Stanford, Calif.: Stanford University Press, 1973), p. 195; and Jones, p. 202.

9. Elvin, p. 166.

10. Quoted in ibid., p. 177.

11. Carlo M. Cipolla, *Before the Industrial Revolution: European Society and Economy, 1000–1700,* 2d ed. (New York: Norton, 1980), p. 171.

12. Chao; Elvin; Tang (n. 5 above); Joseph Needham, *Science in Traditional China: A Comparative Perspective* (Cambridge, Mass.: Harvard University Press, 1981); and Wolfram Eberhard, "Data on the Structure of the Chinese City in the Pre-Industrial Period," *Economic Development and Cultural Change* 5 (October 1956): 253–68.

13. Joseph Needham, "Introduction," in *China: Land of Discovery and Invention,* by Robert K. G. Temple (Wellingborough: Patrick Stephens, 1986), p. 6.

14. Elvin, chap. 17; Chao; and Tang.

15. Elvin's discussion is enlightening. However, I will not repeat his arguments here, for the sake of brevity. Readers interested in these arguments may refer to Elvin, pp. 286–98.

16. Although their general views on China's unfavorable land-to-labor ratio and its implication for industrialization are similar, Elvin, Tang, and Chao have different emphases. While Elvin and Tang stress diminishing agricultural surplus and China's inability to support a sustained industrialization, Chao emphasizes the swelling labor surplus and its impact on demand for labor-saving technology. Additionally, Elvin does not explain the mechanism that led to the explosive population growth.

17. Tang, p. 7.

18. Chao, p. 227.

19. Ibid.

20. Tang, p. 19. In addition to the unfavorable man-land ratio, Elvin also viewed static markets as a factor inhibiting technical creativity in China. Although China had large, integrated national markets, e.g., for cotton cloth, Elvin argued, "It was not the size of the eighteenth-century British market

(tiny compared to that of China) but the speed of its growth that put pressure on the means of production there to improve" (p. 318). However, this argument is misleading. Before the revolution in England's cotton industry, Europe had already imported cotton cloth from Asia. However, "by hand methods Europeans could not produce cotton cloth in competition with the East. But the market was endless if cotton could be spun, woven, and printed with less labor, i.e., by machine" (R. R. Palmer and Joel Colton, *A History of the Modern World,* 6th ed. [New York: Knopf, 1984], p. 429). Therefore, as in China, the market size for the British cotton industry was initially static. The growing potential came from the cost-competitiveness of mechanized production. If there had been an industrial revolution in China's cotton industry that made costs of production lower than those of the traditional technology, the market potential in China for the "modern mechanized" firms would have been endless also. Elvin's explanation is also not consistent with the fact that during the first century of the Ming dynasty (1368–1644) and the Qing dynasty (1645–1911), the Chinese economy was booming. A similar view on the role of market expansion was advanced by Jones, although he attributed the stagnation of markets in China as well as in Turkey and India to the invasion of Manchu, Ottoman, and Mughal—all minorities from the steppes. He argued that "the economies became command hierarchies imposed on customary agricultures. These weakened investment in human and physical capital, slowing and diverting for the duration of the empires much further growth of the market" (pp. xxiv–xxv [n. 7. above]). If Jones's explanation for the slowdown in the Manchu empire (1645–1911) is valid, China should have had brisk development under the Ming empire (1368–1644), which was ruled by Han Chinese. However, the slowdown in technological development was already under way during the Ming dynasty.

21. Chao points out that among the 68 major farm implements that appeared after 221 B.C. and before modern times in China, 35 were invented between 961 and 1279, and only four were invented in 1369–1644. Among these four, two were labor using rather than labor saving in nature (p. 195).

22. John L. Buck, *Land Utilization in China* (Nanjing: Nanjing University Press, 1937).

23. The above discussion does not imply that the change in man-to-land ratio has no consequences for technological innovation in an economy. Since relative scarcities of resource endowments in an economy affect relative prices of those resources, for the purpose of cost minimization, the optimal intensities of capital, labor, and land usage embodied in a technology for performing a certain task will be different from economy to economy and from region to region within an economy. For example, when Japan imported textile machinery from Britain in the late nineteenth century, most of the innovations involving the imported textile machinery made the machinery more labor-intensive; as a result, there was a substantial decline in the capital-labor ratio between 1886–90 and 1891–95 in the firms using the British machinery (Keijiro Otsuka, Gustav Ranis, and Gary Saxonhouse, *Comparative Technology Choice in Development: The Indian and Japanese Textile Industries* [New York: St. Martin's Press, 1988], p. 21). The reason for that type of modification was that the capital intensity of British machinery was tailored to Britain's capital and labor endowments, which differed from Japan's. A similar phenomenon was also found when foreign technology was transferred to China. Robert F. Dernberger's study of China's modern sector in the early twentieth century shows that Chinese industry tended to be small and had a high labor-capital ratio. However, the unfavorable man-to-land ratio did not inhibit the demand for new technology, as "Chinese-owned factories in the modern manufacturing

sector outnumbered foreign-owned factories by more than ten to one" ("The Role of the Foreigner in China's Economic Development," in *China's Modern Economy in Historical Perspective,* ed. Dwight H. Perkins [Stanford, Calif.: Stanford University Press, 1975], p. 41). In the above examples, the new technology, even after the adjustment in labor-using innovations, was still more capital-intensive than the indigenous technology. As pointed out by W. E. G. Salter, "the entrepreneur is interested in reducing cost in total, not particular costs such as labor costs or capital costs. . . . Any advance that reduces total costs is welcome, and whether this is achieved by saving labor or capital is irrelevant" (*Productivity and Technical Change* [Cambridge: Cambridge University Press, 1960], p. 43).

24. Carl Riskin, "Surplus and Stagnation in Modern China," in Perkins, ed.

25. W. W. Rostow, *The Stages of Economic Growth* (Cambridge: Cambridge University Press, 1960).

26. State Statistical Bureau, *China Statistical Yearbook, 1988* (Beijing: Zhongguo tongji chubianshe, 1988), p. 60.

27. Dwight H. Perkins and Shahid Yusuf, *Rural Development in China* (Baltimore: Johns Hopkins University Press, 1984), chap. 4.

28. Theodore W. Schultz, *Transforming Traditional Agriculture* (New Haven, Conn.: Yale University Press, 1964).

29. Robert E. Evenson and Yoav Kislev, "A Stochastic Model of Applied Research," *Journal of Political Economy* 84 (April 1976): 265–81.

30. This assumption implicitly assumes that numerous technologies, each with a different combination of inputs, can have the same productivity level.

31. In the figure, we assume that the distribution function is standard normal. However, the arguments in this article are independent of the type of the distribution function.

32. This assumption is harmless because of the long time span in the article. A better technology will eventually prevail in an economy.

33. In the figure, we assume that the increase in the inventor's stock of scientific knowledge results in a rightward shift in the mean of distribution of the invention distribution function without changing the variance. However, the increase in the stock of scientific knowledge can also result in an increase in the variance of the distribution without changing the mean. The increase in both the mean and the variance will increase the likelihood of inventing a better technology. For a mathematic proof of the statement, see Evenson and Kislev. Of course, the mean and variance of the distribution can also be changed at the same time.

34. Joseph Needham, *The Grand Titration: Science and Society in East and West* (London: Allen & Unwin, 1969), p. 15. For further discussions on scientific discoveries, see Sec. IV of this article.

35. The Schmookler-Griliches hypothesis of market demand–induced invention and the Hicks-Hayami-Ruttan hypothesis of relative factor scarcity–induced invention are relevant only for analyzing experiment-based invention. However, for the adoption of technology, economic considerations should have been relevant since antiquity (Zvi Griliches, "Hybrid Corn: An Exploration in the Economics of Technological Change," *Econometrica* 25, no. 4 [October 1957]: 501–22; Jacob Schmookler, *Invention and Economic Growth* [Cambridge, Mass.: Harvard University Press, 1966]; John R. Hicks, *The Theory of Wages* [London: Macmillan, 1932]; Yujiro Hayami and Vernon W. Ruttan, *Agricultural Development: An International Perspective* [Baltimore: Johns Hopkins University Press, 1971]).

36. Needham, *Science in Traditional China* (n. 6 above), p. 22.

37. Cipolla (n. 11 above), A. E. Musson, ed. *Science, Technology, and Economic Growth in the Eighteenth Century* (London: Methuen, 1972), p. 58.

38. The contribution of population to invention is emphasized by William Petty, Simon Kuznets, F. Hayek, and Julian Simon. See the discussion by Julian L. Simon, *Theory of Population and Economic Growth* (New York: Blackwell, 1986), chap. 1. It should be emphasized that the above arguments are true only in a probabilistic sense. The model does not imply that a small country cannot make a major contribution to technological invention. It only implies that, when experience is the major source of technological invention, the probability of such event is smaller for a small country than for a large country.

39. In antiquity, a determinant factor of the population size in an economy was the carrying capacity of the agriculture, which depends on physical environment and technology. The physical environment in China was not particularly favorable for agriculture, compared to the fertile river valleys (Ping-ti Ho, *Huangtu yu zhongguo nongye de qiyuan* [Loess and the origin of Chinese agriculture] [Hong Kong: Chinese University Press, 1969]). However, probably due to luck, China was early in inventing the technology of row cultivation and intensive hoeing (sixth century B.C.), the iron plow (sixth century B.C.), the efficient horse harness (fourth century B.C.), the multitube seed drill (second century B.C.), and so forth (Robert K. G. Temple, *China: Land of Discovery and Invention* [Wellingborough: Patrick Stephens, 1986]). Therefore, agricultural productivity in China was relatively high compared to that in Europe at that time. This might have contributed to China's larger population.

40. In the first century A.D., more than 75% of the Chinese population was in the north; by the end of the thirteenth century, the opposite was true. Beginning with the fourteenth century, the population in the north recovered gradually to reach about 45% in the twentieth century (Elvin [n. 8 above], chap. 14).

41. The average yield of millet, wheat, and rice in the fourteenth century is estimated to be 104, 108, and 310 catties, respectively (Chao [n. 1 above], p. 215).

42. Ibid.; Elvin; Needham, *Science in Traditional China* (n. 12 above); and Tang (n. 5 above).

43. As predicted by the third hypothesis of the model, as the Chinese acquired modern methods and better materials in the form of Western-designed machinery with contact with the West in the late nineteenth century, creativity reappeared (Elvin, p. 315).

44. Peter Mathias, "Who Unbound Prometheus? Science and Technical Change, 1600–1800," in Musson, ed. (n. 37 above).

45. Cipolla (n. 11 above), p. 244.

46. Musson, ed.

47. Rondo Cameron, *A Concise Economic History of the World* (Oxford: Oxford University Press, 1989), p. 165.

48. Hicks (n. 35 above), p. 145; Simon Kuznets, *Modern Economic Growth: Rate, Structure, and Spread* (New Haven, Conn.: Yale University Press, 1966), pp. 10–11; Nathan Rosenberg and L. E. Birdzell, Jr., *How the West Grew Rich* (New York: Basic Books, 1986), p. 23.

49. Needham, *Science in Traditional China,* p. 122. That the lack of modern science limits the possibility of technological invention is acknowledged but not developed by Elvin (p. 297); Tang; and Chao (p. 227).

50. Needham, *The Grand Titration* (n. 34 above), p. 211.

51. Ibid.

52. Wen-yuan Qian, *The Great Inertia: Scientific Stagnation in Tradi-*

tional China (London: Croom Helm, 1985); Kenneth Boulding, "The Great Laws of Change," in *Evolution, Welfare, and Time in Economics,* ed. Anthony M. Tang, Fred M. Westfield, and James S. Worley (Lexington, Mass.: Lexington Books, 1976); Albert Feuerwerker, "Chinese Economic History in Comparative Perspective," in *Heritage of China: Contemporary Perspectives on Chinese Civilization,* ed. Paul S. Ropp (Berkeley and Los Angeles: University of California Press, 1990).

53. Qian, p. 91.

54. Ping-ti Ho, *The Ladder of Success in Imperial China: Aspects of Social Mobility, 1368–1911* (New York: Columbia University Press, 1962), p. 42.

55. Eberhard (n. 12 above).

56. Ho, *The Ladder of Success in Imperial China,* p. 51.

57. Ibid., pp. 198–200.

58. I want to emphasize that I do not mean to belittle the importance of cultural pluralism, political tolerance, and so on, which are emphasized by Qian and others, for the progress of modern science. However, what I am discussing here is the scientific revolution at the crucial point of its birth, which was Europe in the seventeenth century. From the historical evidence cited by William Monter, one can conclude that records of tolerance at that time were not much better in Europe than in China. It would be a fallacy here to compare the Western system after the rise of modern science with the premodern system in China.

59. Ho, *The Ladder of Success in Imperial China,* p. 92.

60. This is best reflected by a famous poem by the Song emperor Chen-Zong:

> To enrich your family, no need to buy good land:
> Books hold a thousand measures of grain.
> For an easy life, no need to build a mansion:
> In books are found houses of gold.
> Going out, be not vexed at absence of followers:
> In books, carriages and horse form a crowd.
> Marrying, be not vexed by lack of a good go-between:
> In books there are girls with faces of jade.
> A boy who wants to become a somebody
> Devotes himself to the classics, faces the window, and reads.

Quoted in Ichisada Miyazaki, *China's Examination Hell: The Civil Service Examinations of Imperial China* (New Haven, Conn.: Yale University Press, 1976), p. 17; published in Japanese in 1963 and translated into English by John Weatherhill.

61. Ibid.

62. The examinations not only enabled the emperors to select the most talented people for the civil service but also instilled a moral system, through Confucian teaching, which greatly reduced the costs of governing. Jones (n. 7 above) wondered why China was able to maintain unity despite wide regional diversity and the backwardness of premodern means of control and communication (p. 221). As suggested by Ray Huang, "The dynasty stood upon its moral character, which was its strength. Otherwise it would never be able to govern the people. The secret of administrating an enormous empire . . . was not to rely on law or power to regulate and punish but to induce the younger generation to venerate the old, the women to obey their menfolks, and the illiterate to follow the examples set by the learned" (*1587, a Year of No Significance: The Ming Dynasty in Decline* [New Haven, Conn.: Yale University Press, 1981], p. 22). These principles of loyalty and filial piety were the

essence of Confucian teaching. After the thirteenth century, a military coup was almost unheard of in China, and China proper was never for long under more than two administrations. The civil service examination and the stress on Confucian classics probably was the ingenious institutional innovation that contributed to this phenomenon.

63. The comment by Sung Ying-Hsing (Song Yingxing), author of the famous 1637 technology book *T'ien-Kung K'ai-Wu* (A volume on the creations of nature and man; Chinese technology in the seventeenth century) to his book is the best footnote to this point. He wrote: "An ambitious scholar will undoubtedly toss this book onto his desk and give it no further thought: it is a work that is in no way concerned with the art of advancement in officialdom" (trans. E-tu Zen Sun and Shiou-Chuan Sun [University Park: Pennsylvania State University Press, 1966]).

64. During Song times, mathematics and astronomy were studied in the state university (*guo zi jian*) and were required for examinations. It is a pity that in 1313 such subjects were dropped and the required readings officially limited to a set of Confucian texts. As a result, by Ming times many of the mathematical writings of the Song were lost or had become incomprehensible.

65. Gustav Ranis, "Science and Technology Policy: Lessons from Japan and the East Asian NICs," in *Science and Technology: Lessons for Development Policy,* ed. Robert E. Evenson and Gustav Ranis (Boulder, Colo.: Westview, 1990); David C. Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (Cambridge: Cambridge University Press, 1989).