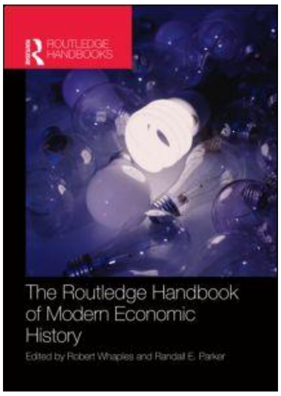

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ECONOMIC HISTORY OF TECHNOLOGICAL CHANGE

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Introduction

Consumers gain insights into the social value of technological innovations every time a computer crashes or the power goes off. Economists likewise agree that technological change promotes productivity gains and overall economic growth. Theoretical models variously treat inventive activity and innovation as exogenous, evolutionary, induced by economic or scientific factors, or path dependent. Economic analysis is predominantly static, whereas technological change is inherently dynamic, so it is not surprising that economic theory can illuminate, but fail to explain, the sources of advances in technology. Economic historians possess a comparative advantage in the realm of empirical analyses of changes over time, which allows them to make valuable contributions to understanding the role of technology in economic development. Accordingly, the interaction between "standard" economics and history has become more frequent and apparent in recent research.

The first modern industrial societies appeared in Western Europe and North America in the eighteenth and nineteenth centuries. The central research question is simple to pose: Why that time and those places? The answer is complex, but inextricably linked to the economic history of technological change. In the tradition of Montesquieu, an increasing number of investigators maintain that the present distribution of technical advances and global income was determined by endowments and events in the distant past. Location, climate, and the disease environment of some 13,000 years ago triggered a recursive system that altered the course of civilization, leading to economic prosperity in the West, and stagnation or decline elsewhere (Diamond 1997). According to this perspective, institutions are endogenous, for history and geography influence their choice, and the consequences of initial conditions tend to persist over the very long run.

Engerman and Sokoloff (2011) show that factor endowments shaped institutions, technology, and socioeconomic outcomes in the New World. The local climate, soils, and natural resources predisposed colonies in Latin America and the Caribbean to extractive political and socio-economic systems that perpetuated the rent-seeking of entrenched and unproductive elites. Markets were narrow, human capital investments limited to a select few, and the potential for innovation and economic growth quickly exhausted. By way of contrast, the endowments of the colonies in North America favored open-access institutions and greater equality, which encouraged market expansion, flexibility, education for the masses, and inventive activity. As such, the cumulative effect of past meta-economic endowments may well explain global inequality in the allocation of technology and income today. However, the question of whether geography has a direct or indirect effect on institutions that promote technology is still open, especially given "the reversal of fortunes" experienced in many jurisdictions (Acemoglu and Robinson 2012).

The first Industrial Revolution

The analysis of specific events, and the British Industrial Revolution in particular, provides another approach to the central issue of explaining technological change and growth paths. The term "industrial revolution" reflects earlier claims that Britain experienced a discrete structural transformation from an agrarian society to a modern economy marked by pervasive technical advances, and rapid rates of productivity and growth. Estimates of British total factor productivity during the early industrial period have since been revised downward, suggesting a less dramatic scenario, in which Britain may have been merely "precocious" rather than pre-eminent compared with such competitors as France and Holland (Crafts and Harley 1992). The industrial r/evolution itself clearly owed to the transformation of technologies in certain sectors, primarily textiles, iron and steel, and energy. Early British economic growth was unbalanced, with technological and productivity advances largely restricted to these highly capital-intensive industries, but little consensus exists about the explanation for such technical progress. The answers range from broad general factors such as politics, religion, and culture through to exquisitely precise estimates of wages and prices in firms and industries. Given the popular emphasis on mechanization and manufacturing, it is worth emphasizing that productivity gains and technical developments in agriculture provided the prerequisites for shifts into industry (Federico 2008).

On the eve of the British Industrial Revolution, China and Japan were more similar to than different from Western Europe, in terms of such important demographic, economic, and institutional factors as life expectancy, efficient goods and labor markets, effective legal systems, and respect for property rights (Pomeranz 2000). East Asian historians point out that early Chinese technologies were sophisticated and frequently far in advance of pre-industrial European achievements (Bray 1994). Thus, the "Great Divergence" that ultimately produced stagnation in Asia and industrial progress in Europe likely owed not to systematic, but to somewhat serendipitous, factors. Europeans (and Britain in particular) were able to benefit from accessible and relatively cheap energy supplies and from the resource endowments in their colonies in the New World. Allen (2009) concurs that ready access to coal facilitated the adoption of technologies that were developed to save on the relatively high costs of British labor inputs. The price of labor was also high in other locations such as Holland, but they lacked the deposits of coal that were necessary to power the industrial process.

Cultural features, broadly defined, have often been cited to explain the timing and location of the Industrial Revolution. These include religion and the role of nonconformists in technological innovation, rationalist–scientific approaches to nature, an educational approach that fosters skills among the general population, and the degree of political stability. The link between war and technology has a long scholarly tradition, and the economic concept of "creative destruction" originated with Werner Sombart's (1913) classic thesis that wars have a positive impact on industrialization and technological change. In this tradition, Rosenthal and Wong (2011) speculate that international political economy in Western Europe was more conducive to inventiveness and industrialization. In particular, the tendency for warfare and political fragmentation in Europe produced an unintended benefit: it created greater incentives for urbanization, invention, and industrial progress, compared with the centralization and political stability of imperial China. Warfare influenced the concentration of manufacturing within cities, which changed relative prices and biased European technical change toward capital-intensive technologies.

Some attribute industrialization and advances in technology to such norms as thrift, honesty, and the capacity to work hard (Landes 1999; Clark 2008). Similarly, according to Mokyr (1990, 2002, 2010), technological change and industrialization cannot be explained by standard economic variables. England benefited from the ideas and ideals of the rational scientific revolution dating from the seventeenth century that culminated in an age of "Industrial Enlightenment" (see also Jacob 1997). In the eighteenth century, exogenous discoveries about nature, changes in artisanal knowledge, and the rationalization of information combined to generate new inventions and productivity advances. Technical elites had access to scientific principles, and there was widespread diffusion of information about natural phenomena that could be manipulated to enhance economic welfare. Social agendas, appropriate institutions, and relative prices could to some extent influence incremental extensions in the set of useful knowledge, but technological ascendance owed primarily to the *dea ex machina*. Crafts (1995) contends that major technological change in Britain was idiosyncratic or random.

These theories imply that economic progress is a function of knowledge inputs whose supply is inelastic or unresponsive to economic incentives. Walt Rostow (1960) and Nathan Rosenberg (1974) contended that science and specialized knowledge comprise preconditions for economic and social progress. However, biographical information and patent records for "great inventors" credited with significantly expanding the frontiers of technology do not support the view that familiarity with formal science and engineering education played a significant role in the creation of technological innovations during early British industrialization (Khan 2010). Scientists and trained engineers were not well represented among the great British inventors until very late in the nineteenth century. Scientific endeavors of the day owed to skittish dons or aristocratic amateurs, whose efforts were directed to impractical pursuits and general principles in astronomy, magnetism, mathematics, botany, and chemistry, rather than to useful knowledge. Those great inventors who did have scientific training tended to produce innovations that were broadly distributed across sectors, rather than contributing to the key industries that were associated with productivity gains in the Industrial Revolution. England's economic advantage did not depend on advances in science or formal investments in specialized human capital. Instead, the economically valuable innovations of the eighteenth and early nineteenth centuries were largely produced by workers who benefited from apprenticeships and on-the-job learning. As such, industrialization may have owed more to a pre-industrial institution, the craft guild, which had long facilitated the acquisition of skills and technical diffusion (Epstein 1998).

North and Thomas (1973) emphasized the role of institutions in the British Industrial Revolution, and they attributed a large part of the credit to the patent system. Early studies of the British patent system concluded that, although its operation was somewhat flawed, patentees nevertheless made significant contributions to the Industrial Revolution (Dutton 1984; Sullivan 1989). Others are less sanguine, and point to the use of patents for speculation and advertising, to the inefficient rules and standards that led to a bias toward elites in the roster of patentees independently of their productivity, and to inventive activity outside the patent system (MacLeod 1988; Khan and Sokoloff 1998; Moser 2005; Khan 2011a). Dutton had highlighted the operation of markets in patented invention, but examination of the data reveals that trade in British patents was actually quite limited (Khan and Sokoloff 2004). This finding is unsurprising since British rules and standards established significant barriers to entrepreneurship and invention in the form of prohibitively high monetary and transactions costs, uncertain property rights, and restrictions on ownership in patent property. Such features caused nationwide lobbies of manufacturers and patentees to continually express their dissatisfaction with the patent system (Khan 2005).

The high costs of patent fees and other deficiencies of the British patent system likely encouraged some inventors to appropriate returns through alternative means, such as keeping their discoveries secret. Several groups followed the opposite strategy of sharing technical knowledge with competitors. Allen (1983) finds that British iron producers participated in "collective invention," mutually exchanging information about designs and incremental innovations that lowered costs or improved performance. Similarly, Cornish steam engineers collaborated by circulating their findings about best practice and improvements in pumps to drain mines, both informally and in publications (Nuvolari 2004). Cartels of cotton spinning firms in Japan reported information on their production costs to the Ministry of Commerce during the 1880s, and the association later published in its journal reports on wages and work schedules, machinery, and new innovations. Firms also contacted each other directly in order to find out about improvements being implemented and this culture of cooperation led to uniformly low costs and high productivity in the industry (Saxonhouse 1974).

In Europe, an extensive array of prizes was conferred on "deserving" inventors. Systematic studies of prizes include an assessment of devices on display at the Crystal Palace Exhibition of 1851, the majority of which were unpatented (Moser 2005). Brunt *et al.* (2008) conclude that prizes offered by the Royal Agricultural Society of England were effective in inducing technological innovation, although the awards seemed to be more valuable as tools of advertising and commercialization. The grants of prizes to British great inventors were primarily connected to status rather than to factors that might have enhanced productivity (Khan 2011a). The most significant variable affecting the possession of a prize was an elite or Oxbridge education, which substantially increased the odds of getting an award, despite the traditional hostility of such institutions to pragmatic or scientific pursuits. However, specialized education in science and engineering, patentee status, and employment in science or technology, had little or no impact on the probability of getting a prize. In short, in Britain both patent and prize-giving institutions exhibited a bias toward recipients from privileged backgrounds. By way of contrast, among the American great inventors, and among general inventors at annual state industrial fairs, prizes were determined by the nature of the technology rather than the identity of their recipients, although the conferral of prizes was idiosyncratic and not as market oriented as patents (Khan 2011a, 2012b). American technologies at the cutting edge tended to be patented, and few eminent inventors were associated with competitions for prizes. As such, exhibitions offered limited opportunities for the diffusion of novel inventive information, and primarily functioned as a forum for commercialization (Khan 2012b).

Technological innovation in the United States

Britain's early technological lead was soon eroded by other nations, and studies debate whether that erosion owed to indigenous efforts or to international transfers and spillovers. The British tried to prohibit the emigration of skilled artisans, machines, and technology, but were unable to prevent such transfers. As a follower country, the United States initially benefited from the importation of technology inputs and the diffusion of information from overseas (Jeremy 1981, 1991). For instance, Éleuthère Irénée du Pont, a student of the French chemist Lavoisier, immigrated to the United States. He obtained funding, technical assistance, and machinery from France, and this helped to launch the DuPont powder mill and the U.S. explosives industry early in the nineteenth century. However, the benefits from wholesale adoption tend to be limited because factor endowments and market conditions vary across countries, and spillovers decline sharply with distance (Keller 2002). In Britain, the textile industry employed the skill-intensive mule technology, whereas American endowments favored ring-spinning technology that economized on skilled inputs (Saxonhouse and Wright 1984). It is worth noting that the textile sector was hardly typical, and in many industries the prevalent technologies were readily apparent to anyone who was skilled in the art, with inventions that merely involved pragmatic incremental manipulations to suit local conditions (Burt 1991). In any event, indigenous U.S. technological capabilities soon proved superior to European efforts in many industries, and numerous examples indicate net flows in the opposite direction, from the United States to Europe. For instance, Charles Goodyear's patents in the 1840s for the vulcanization of rubber were not only copied in England, but also British inventors re-patented his discoveries in their own name. Similarly, Samuel Colt, Hiram Maxim, and other gun manufacturers and inventors transformed the technology of European warfare (Khan 2005). Wilkins (1970, 1974) highlighted the role of American multinational business enterprises, founded to exploit patents in sewing machines, elevators, shoemaking machinery, and electrical equipment, in spreading technological innovations to Europe.

Patents provide important insights into the sources of U.S. technological progress in the nineteenth century (Khan 2005). The United States created the world's first modern patent system. The primary features of the American patent institution gradually diffused across the globe as international patent laws became more harmonized (Penrose 1951). The U.S. patent system was deliberately designed to ensure widespread access, and featured low fees and an examination system where trained employees of the patent office certified that the patent granted comprised an original advance in the state of the art. The basic parameters of the system were transparent and predictable, in itself an aid to those who wished to obtain patent rights. In addition, American legislators were concerned with ensuring that information about the stock of patented knowledge was readily available and diffused rapidly. Numerous reported decisions before the early courts declared that, rather than unwarranted monopolies, patent rights were "sacred" and to be regarded as the just recompense to inventive ingenuity. The courts explicitly attempted to implement decisions that promoted economic growth and social welfare.

The nineteenth century proved to be an age of inventions patented by Americans. The growth in U.S. patents was especially dramatic from the 1840s through the 1870s, a period in which the per capita rate of patenting increased 15 times (Khan and Sokoloff 2001; Khan 2005). Extensive technology markets developed as early as the 1840s, when trade in patents boomed, attaining a volume of three to six times the number of patents issued (Khan 1995). There is ample evidence that such inventive activity was induced by factors that affected the appropriability of returns, over time and across place. The time series of patent grants was procyclical, varying with the business cycle (Sokoloff 1988). The early take-off in per capita patenting occurred when improvements in waterways led to an expansion in market demand. Although urban and metropolitan areas excelled in inventive activity, the most significant increases were associated with formerly isolated locales that were newly exposed to larger markets. Improvements in market access led to a greater proportionate response among rural residents who were new to invention. Further evidence on the identities of nineteenth-century patentees suggests that the specific design of the patent system played a substantial role in inducing relatively ordinary individuals to reorient their efforts toward exploiting market opportunities (Sokoloff and Khan 1990). These patterns characterized both incremental and significant inventions, because great inventors in the United States were even more entrepreneurial in their efforts to use the patent system to extract returns from their technological creativity (Khan and Sokoloff 2006; Khan 2005). By way of contrast, such factors as learning-by-doing and localized knowledge spillovers did not significantly influence the course of technological development (Lamoreaux and Sokoloff 2000; Sutthiphisal 2006).

The experience of women inventors offers another perspective on the role of incentives, property rights, and legal institutions in influencing technological change. Economic historians who address the relationship between women and technology have limited their attention to the impact of technical changes on women in the household or labor market (Jellison 1993; Goldin and Katz 2002). Few systematic studies examine women's contributions to inventive activity, and some authors even deny that they made worthwhile discoveries. Cardwell's history of technology devoted no more than two paragraphs to women inventors out of a total of over 500 pages, on the grounds that "female technologists of any distinction are hard to find" (1994: 506). At the other end of the spectrum are exhaustive lists of inventions that possibly might have been attributed to women (Stanley 1993).

Patent records are incomplete indices of invention, but do permit a more objective assessment of women's contributions to technological change than the plethora of case studies featured in historical accounts (Khan 2000). Although in other regards women may have been excluded from the benefits of a democratic society, the U.S. patent system offered them equal opportunities to excel. Women were motivated by potential profits, and responded to changes in the legal system that expanded their property rights and offered greater access to potential income from their investments in inventive activity (Khan 1996). Unlike their male counterparts, women inventors disproportionately resided in rural towns and frontier areas; women in these locales, without the benefit of readily available help, likely had a greater incentive to devise inventions to help in their household tasks. The study of women inventors reminds us that technological change is far broader than the realm of machines, and encompasses improvements in diet and techniques of food preparation, more efficient processes of child-rearing, and new designs in furnishing. Female patentees were applying their creative insights to the sphere in which they had the greatest experience. In the process, as the extensive archives of assignment contracts show, many became adept participants in the flourishing market in domestic inventions. Their experience suggests that the spheres of household and market were closely linked for both men and women and, like the economy at large, the household economy was the locus of both invention and innovation (Khan 2000).

The Civil War was a turning point for women inventors, and illustrates the extent to which all categories of inventors responded to market incentives (Khan 2009). During the war, per capita patenting by women increased significantly, including such inventions as war vessels and hospital equipment. Hartcup (1988) considered the First World War to be the first technological war in history, but one doubts that he took much account of the American Civil War. Both ordinary and "great inventors" dramatically changed the rate and direction of their activities toward military technologies, and toward other areas where markets were expanding, such as prosthetics for amputees and substitutes for cotton textiles. New entrants into invention tended to be rather ordinary individuals without much technical training or wealth, who responded to perceived need by filing job-related patents for improvements. Moreover, engineering or technical expertise did not yield greater numbers of military inventions. During the war, inventors with little wealth benefited from markets in invention, which allowed them to assign or sell their rights to investors, and their material circumstances after the war improved to the extent that they caught up with their peers. Thus, the market for inventions that flourished in the middle of a devastating conflict served to allocate inventive resources toward the war effort. The war proved to be a temporary setback for both technological and economic progress, and postbellum patenting soon soared to a greater and sustained level.

Effective patent and legal institutions encouraged the securitization of property rights in invention, leading to an extensive market in technology. The potential to sell off their ideas especially benefited those technologically creative inventors without the capital to go into business and directly exploit the fruits of their ingenuity (Khan and Sokoloff 2004). The accelerated increase in the extent of the market during the 1870s promoted a Smithian process of specialization and the division of labor between invention and commercialization. Patent agencies and patent attorneys throughout the country served as intermediaries who minimized transactions costs in the market exchange of patented inventions. At the same time, patentees with a comparative advantage in technological creativity increasingly specialized in inventive activity, especially after the nature of technical inputs into inventions became more complex (Lamoreaux and Sokoloff 1996, 2001). The nineteenth century primarily remained an era of independent inventors, even among professional inventors who exhibited considerable "contractual mobility;" it was not until the twentieth century that productive patentees entered into long-term arrangements with firms, often as principals rather than as employees (Lamoreaux and Sokoloff 2005).

Conventional accounts of technological change in both manufacturing and agriculture have tended to focus on the creation and diffusion of capital-intensive machinery, and on labor-saving productivity advances. Even in the antebellum period, American agriculture was certainly more mechanized than in Britain, and this was reflected in the patent records, for fewer than 5 per cent of British patents covered inventions in this sector, relative to almost one-quarter of total patents filed in the United States (Khan 2005). Standard research has focused on the introduction and diffusion of hybrid seed corn, the substitution of the tractor for horse power, and mechanical reapers for harvesting wheat and corn. More recent contributions to the economic history of agricultural technology venture beyond the plethora of machinery and tools to highlight institutional factors, and non-machine innovations embodied in crops and livestock. For instance, although continuous-processing sugar-production technologies were associated with economies of scale, a wide range of efficient mill capacities still persisted, owing in part to adjustment costs and local institutional conditions (Dye 1998). A reexamination of the diffusion of reapers credits their adoption to changes in institutions, including the growth of local markets and cooperative sharing of reaper services by small farmers (Olmstead and Rhode 1995).

Olmstead and Rhode (2008) point out that biological innovations were pervasive in American agriculture, long before the scientific discoveries of the twentieth century. Crops were adapted to other regions, and to different soil types. New hybrid plant varieties were created, livestock selectively bred, and defenses continually devised to protect against insects, microorganisms, and animal diseases that had the potential to decimate crops and livestock. These innovations enhanced and extended the availability of arable land, while maintaining farm yields. As a result, non-mechanized technologies dramatically increased the productivity of land and labor on farms, allowing agricultural production to outpace population growth. An important part of the story relates to how institutional changes combined with and facilitated such agricultural innovations. The "dust bowl" was created because of externalities which led to an underinvestment in techniques to control the erosion of soil, a problem that was resolved by institutions for collective action that internalized the external effects (Hansen and Libecap 2004). Moreover, U.S. government agencies played a larger role in the spread of technological innovations in agriculture, introducing institutions that lowered risk and increased the return to investments in new farm technologies (Farrell and Runge 1983).

Technological achievements in the nineteenth century propelled the United States on the trajectory of productivity and economic progress that would establish it as the foremost industrial nation. However, the nature of technical progress itself was transforming toward the end of the nineteenth century. In the general population, both technology and educational inputs grew rapidly. New technologies increased the demand for skilled labor and the rates of return on human capital acquisition, and the educational system at the secondary and tertiary levels met and satisfied those needs (Goldin and Katz 2008). Specialized knowledge and science became increasingly necessary for inventive activity at the frontier. Individuals with science and engineering degrees began to dominate among the later birth cohorts of great inventors in both Britain and America (Khan 2005, 2011a). At the same time, inventive activity required larger sources of financial capital, and at times necessitated research collaborations with co-inventors trained in other disciplines. Technologically creative inventors were increasingly likely to work within corporate enterprises, which could exploit their discoveries in-house. Perhaps as a result of such factors, in the first few decades of the twentieth century there was a decline in the roster of multiple patentees and independent inventors (Lamoreaux and Sokoloff 2005). The rates of patenting that U.S. residents achieved during the second industrial revolution would not be attained again (recent increases owe to foreigners patenting in the U.S.).

Throughout American history, policy makers were aware of the trade-offs between the promotion of technological progress and the potential for monopolization (Khan 2011b). Changes in the organization of technology included the greater prominence of corporations in the creation and diffusion of inventions and innovations. The well-known industrial concentration that followed the merger movement at the turn of the century created firms with a great deal of market power. Economies of scale and scope may have engendered corporations that entrenched their positions through anticompetitive practices, but such factors also promoted technological progress through creative destruction along the lines that Schumpeter (1950) had suggested (Nicholas 2003). Although British firms have been criticized for lagging in this area, they too performed creditably by making significant investments in research and development (Edgerton and Horrocks 1994). High-technology companies such as DuPont, Eastman Kodak, and General Electric established large research laboratories that employed eminent applied scientists (Mowery 1983). Corporate research and development further benefited from spillovers in academic institutions in terms of both training and research, and the growth of pharmaceutical laboratories was associated with links to researchers in nearby universities (Furman and MacGarvie 2007). The service sector is often overlooked, but technological and organizational changes in the shift from "counting house to office" dramatically increased productivity, perhaps to a greater extent than in manufacturing, and may have accounted for U.S. competitive advantage (Broadberry and Ghosal 2002).

Conclusion

For many, it is tempting to propose that technological changes in the twenty-first century have created a new era, and that today's information technologies herald a "new economy." But convincing arguments can be made to support the claim that the truly transformative eras lie in the past. Gordon (2000) asks whether the innovations of the current information age surpass the great inventions of the second industrial revolution, and concludes that computers and the Internet do not match up to the discoveries of the late nineteenth century, which had a ratchet effect on social welfare. According to Field (2011), the 1930s comprised the most productively progressive decade of the twentieth century, because organizational and other technological advances in electrification, transportation, communications, and distribution generated high rates of total factor productivity growth and "a great leap forward." Although these perspectives are certainly valid, it is worth remembering that, since the first days of settlement, Americans have employed and enjoyed incremental improvements that satisfied the purpose of generating and diffusing information, from newspapers, through the telegraph, telephone, computers, to the Internet (Chandler and Cortada 2003). This conclusion is equally valid in other dimensions, for what stands out in any assessment of the economic history of technological change are the continuities between the past and the present.

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