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Transferring Technical Knowledge And Innovating In Europe, C.1200-C.1800[1]

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Abstract

The role of technology in the transition from premodern to modern economies in late eighteenth- and nineteenth-century Europe is among the major questions in economic history, but it is still poorly understood. A plausible explanation of premodern European technological development must account for why Europe industrialised in advance of the great Asian civilisations, despite still being a comparative backwater in the twelfth century. What appears to set Western Europe apart is not that technological progress occurred at a faster rate than elsewhere, but that progress was more persistent and uninterrupted. The technical knowledge of premodern craftsmen and engineers was largely experience-based; thus, virtually all premodern technical knowledge was, and had to be, transferred in the flesh. However, the implications for premodern economic history of the basic cognitive limitations to how technical knowledge can be expressed, processed, and transmitted have yet to be examined in any detail. This paper asks how premodern European societies were able to generate incremental technical innovation under three headings: How was premodern technical knowledge *stored* to avoid loss? How were tacit, visual, verbal, and written means of transmission used *heuristically*? How was *established and new knowledge* transmitted?

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1. Introduction

The role of technology in the transition from premodern, ‘Malthusian’ to modern economies in late eighteenth- and nineteenth-century Europe is among the major questions in economic history, but it is still poorly understood. In particular, the view that technological change before *c*.1800 was close to zero due to poorly specified property rights to knowledge and per

Dutch Republic and finally to Britain during the seventeenth and eighteenth (Davids 1995). Each new regional leader added the innovations of its predecessors to its local technical stock and recombined them in support of further technological advances. Leadership was temporary, falling prey over time to technological sclerosis, declining marginal returns, and rent seeking by producers and elites.[2]

Last, the technical knowledge of pre-modern craftsmen and engineers was largely experience-based (Reber 1993). Thus, virtually all pre-modern technical knowledge - which I define simply as knowledge of how, de0056f8echnhmarn incremental technical innovation under three headings: How was pre-modern te

European craft guilds from the late eleventh century to the early nineteenth (Epstein 1998).

Apprenticeship training was costly, for two reasons. First, skills and expertise take time and effort to acquire. Expertise depends on two main processes: heuristic search of problem spaces, and the recognition of cues that access relevant knowledge and suggest heuristics for the next step. Experts store thousands of 'chunks' of information in memory, accessible when they recognize relevant cues. Experts use these recognition processes to achieve unusual feats of memory, reorganize knowledge into complex hierarchical systems, and develop complex networks of causally related information. The knowledge of less skilled individuals, in contrast, is encoded using everyday concepts that make the retrieval of even their limited knowledge difficult and unreliable. It consequently takes about 10 years of focused training to acquire top-level expertise in activities as diverse as chess, dog training, wine tasting, playing and composing music, sports, and, possibly, language acquisition (Ericsson, Krampe and Tesch-Römer 1993). There is no reason to believe that the length of training would be any different in areas of more practical expertise - a fact plausibly reflected in the lengthy technical apprenticeships of pre-modern Europe.

Secondly, apprenticeship was costly because most craft knowledge was implicit or hard to codify.[4] Consequently, craft statutes and labour laws never specified the content of the training regime. Crafts were not learned prescriptively, because training was in the master craftsman's head and hands; instead, craftsmen and women tested the quality of training by examining its outcome. The acquisition of technical expertise was sanctioned through a mastership. Starting in the late thirteenth century and

[4] The salience of implicit knowledge and experience provided an inbuilt advantage to employing family members, who had been socialised early into the craft and generated higher levels of trust, particularly in the most technically advanced industries like mining and metal-working, ship- and high quality edifice building, and clock and instrument

with increasing frequency from the late fourteenth, many candidates to mastership had to demonstrate their skills by producing a masterpiece (Cahn 1979). The masterpiece combined a physical embodiment of collective knowledge and individual creativity and virtuosity (‘genius’). It was a demonstration of skill and of self-confidence that the proposed product could be constructed and would work; and it established the expert as someone who had assimilated tradition so well that he could adapt, modify and transcend it. Expertise also made it easier to formulate non-verbal practices and heuristics explicitly, as Salviati, on the first day of Galileo’s *Discourses*, famously remarks: ‘The constant activi 85.08 610.34044 Tm(sp1m(ty)Tj13.02

machines, building ships and edifices, digging mines, making clocks and watches and so on were necessarily common or accessible knowledge (not least because technicians could not keep reinventing the wheel [Hollister Short 1995]), direct evidence of on-site sharing is much thinner than for sharing via migrants, which generated disputes and demands that left written traces. Most of the evidence that does exist is associated with large building sites, one of the pre-modern era's hi-tech industries. For example, the master builder or cleric Villard de Honnecourt stated in his book of drawings (c.1215-20) that he settled points with other masters *inter se disputando* - the technical expression for formal debate that had long been standard in the university schools - to underline the fact that his art too rested on firm intellectual principles that could be applied in systematic argumentation. In 1459, master and journeyman masons involved in building major churches across Central Europe met at Regensburg and stipulated that no-one should be taught for money - with the implication that information should be freely shared (Black 1984: 9). Similarly, the habit of competitive bids for artistic and building projects, well established by the late fourteenth century in Italy and common elsewhere by the sixteenth, assumed that applicants possessed a common core of technical competencies, which patrons could only assess indirectly. Public displays by engineers - which their peers would understand, even if laypeople could not - are recorded from the late fourteenth century, when Giovanni de' Dondi of Padua put his astronomical escapement clock on public show; in the sixteenth century, craftsmen from Augsburg and Nuremberg made rival displays of technical 72a2c16.25333 318.860 0 0 13.02 85.08397 341.30061 Tm(44m43.

records of large religious and secular building sites, which gave rise to complex technical challenges and attracted skilled workers and engineers from across Europe. Cathedral building in particular demonstrates both the considerable degree of structural innovation that did take place, and its inherent limitations.

The complexity of Gothic cathedrals made it common practice, already in the twelfth century when the first new cathedrals were struck, to call on outside experts to consult on major structural issues. This fact stimulated experimentation - in the use of buttresses, the width of aisle and the height of nave, the height of pier-buttresses and pitch of the roof - that persisted after 1500 when the Gothic style went out of fashion. One measure of such experimentation is the slenderness ratio, that is, the ratio between height and width of the main supporting piers - the higher the ratio, the 'lighter' the final structure. The ratio for the cathedral of Chartres, finished in 1194, was 4.4; thirty years later, at Amiens and Beauvais, the ratio had doubled; by c.1350, at the cathedral of Palma, the master-builders achieved a remarkable ratio of 13.8 (Mark 1978).

As cathedrals grew in height, however, builders faced increasing structural problems. The lower nave, clerestory and roof were subject to increased outer thrust and wind forces, and the foundations were subject to increased vertical pressure and settlement. Since builders lacked a workable theory of s collapsed’. On other occasions, like the

3.1 Predictability, Codification and Innovation

A less charitable view of such flexibility might suggest extreme empiricism and the absence of the ability to predict. For example, the solutions to *structural* concerns in cathedral building I described were, inevitably, strongly related to the cathedral's *dimensions*, such as the ratio of height to width of the nave, and the height and angle of the clerestory and the roof. Gothic dimensions were based on geometrical criteria, which, in northwest Europe, seem to have been largely derived from simple manipulations of the square. Although the rules or algorithms were never fully formulated, they gave rise to specific engineering problems and, thus, to quite specific technical solutions.

Jean Mignot, a master-builder from northern France, insisted on applying his own geometrical design principles to the cathedral's buttresses. ‘He argued passionately that only high flying buttresses - a rigorous solution based on *scientia*, that is, on geometrical proportion - could yield a stable structure: "mere craft [*ars*] without rigorous knowledge [*scientia*] is useless"’ (Grafton 2000: 268; von Simson 1998). The Lombard masons rebutted that *scientia* without *ars*, without the practical knowledge gained from experience, was equally useless. But the discussion was not, in fact, concerned with either theory or practice taken individually, but rather with the practical links between the two. For Jean Mignot, form (based on *scientia*) defined structure (built through *ars*) - and there was only one legitimate form, derived from the geometrical permutations of the square he was trained in. The disagreement arose because the Milanese preferred another form, derived from a different, albeit equally ‘scientific’, geometrical procedure. However, they lacked the well-trained, skilled labour to build the related structur their local lodges' practice, their actions seem to have been essentially reactive.

The encounter of different technical and design traditions could, however, also generate cognitively new procedures. In sixteenth-century Spain, where tension between Gothic and Italian Renaissance building traditions was particularly lively, the master builder Rodrigo Gil de Hontañon attempted to systematize the design process by creating a sequence of codified procedures to be followed in large church-building projects. Gil's algorithms, drafted around 1540, had three objectives. They aimed to combine Gothic and Classical proportion-based design methods, and to prove their basic identity. They also tried to establish an independent 'science' of structural design. Finally, they attempted to establish new collective heuristics for on-site builders to work with. In pursuing this effort to synthesize and codify two seemingly incompatible aesthetic and building traditions, Gil was led to experiment with Gothic practices o because success could only be ascertained after the ship was actually launched. The heuristic tools of ship- and edifice building were nonetheless remarkably similar. Like masonry builders, shipbuilders achieved structural stability through a shared, mnemonically rich ‘geometric discipline’ that legitimized experience gained from building similar structures, and a ‘wider tacit or intuitive understanding of the conditions of static equilibrium’ based on two components, ‘spatial and muscular’ (Mainstone 1998).

Venetian shipwrights, for example, based their dimensions on a module that was normally the beam of the proposed galley; this was multiplied in a fixed proportion to give the deck-length, and a fraction of this in turn gave the length of the keel. In addition, the Venetian, or Mediterranean system of module building, was carvel-built. Between the late fifteenth and the early sixteenth century North Atlantic ships, which were previously clinker-built, began to be built according to the Mediterranean system. As the technology migrated, first to Portugal and Spain, thereafter to England and the Hanse area, it changed from its purely tacit and demonstrative form, which employed no graphical support, to a system that relied increasingly on graphical design.

The Venet

hydrostatic and hydr

Rheims cathedral in the mid-thirteenth century, and which seem at first glance to offer remarkably detailed building directions. In fact, many of these pl machines. Although the degree of sophistication of machine representations grew markedly over the period between the early thirteenth-century sketches by Villard de Honnecourt and his colleagues, the fourteenth century designs by Guido da Vigevano, the fifteenth century drawings by Brunelleschi, Francesco di Giorgio Martini and Leonardo, and the sixteenth-century representations of mining machinery in Georgius Agricola's *De re metallica*, they were all in one way or another 'false plans', inasmuch as they left size, proportions and many essential details, undefined (Lefèvre 2003).

The first systematic, measured plans of machines are, as we saw, those of English ships. Yet, as with architectural drawings, the development of graphic design in shipping may have been more a strategic element in the cultural and functional separation between designers and builders, than a genuine cognitive advance in the making of pre-modern ships. Certainly, the analogy raises the question - which cannot be addressed here - of the cognitive significance of graphic design for technological progress. One may simply note, that although the introduction of planning design undoubtedly allowed greater flexibility in designing form, be it the form of buildings or the form of a ship, it is not self-evident that design effected a clear improvement for innovation in structure**.**

From the late Middle Ages technicians were more likely to use 3-dimensional models in wood, clay, and gypsum to convey information about machines (including buildings), and to test their performance. Like drawn plans, 3-dimensional models have two di century later the use of models for building purposes was mentioned as a matter of established practise in architectural treatises by Leon Battista Alberti, Antonio Averlino, and Francesco di Giorgio Martini – with Martini making the cognitive aspects of model-building explicit: "Whereas it is difficult to demonstrate everything through drawings, nor is it at all possible to express many things in words, … so it is necessary to make a model of nearly every object" (Martini 1967: 1, 142). Soon after 1500, the usage of building models spread to southern Germany and France, with the English following about a century later.

Far less is known about the related practice of making scaled-down models of working machines. The earliest reference to a mechanical model is found in a late fifteenth century description of a new wire-drawing machine invented in late fourteenth century Nuremberg (Blake-Coleman 1992). A few years later, in May 1402, the master masons at Milan cathedral were asked to inspect sketches submitted in a contest to find the best mechanical device for sawing stone blocks "without manpower"; the most promising design was then to be realised in the form of a wooden model in reduced size, suggesting a well-established combination of sketch-based and 3-dimensional mechanical planning, experimentation, and demonstration of expertise (Popplow 2002).

By the early 1500s scaled-down models were being used both in engineering competitions and for applications for technical patents. Models were commonest until the mid-sixteenth century in the two most advanced industrial regions of the time, north-central Italy and southern Germany, but thereafter they began to be used also in Spain and France. In the early decades of the sixteenth century a Nuremberg craftsman made a "nice wooden design for the king of England, about one *Ellen* long, in which one water wheel drove mechanisms for grinding, sharpening, polishing and fulling", but this may have been an article for the king's private collection (Popplow 2002: 12); 3-dimensional models are first recorded in English ship-building in the early seventeenth century, and the English patent office made it a requirement to submit a working model of mechanical inventions only from about 1720.[5]

3.3 Experimentation

Despite the documented use of model machines from the 1300s, evidence of technical experimentation in pre-modern Europe is irregular and rarely indirect; some of it was reported previously in discussing building practices. It was exceedingly rare for inventors, tinkerers, and simple craftsmen and engineers to write in any detail about their activities (as opposed to their speculations, like Leonardo) before the eighteenth century. However, two unusual sixteenth-century texts do shed light on kinds of experimental practice that under normal circumstances left no material trace, namely machine and chemical testing.

The description by Giuseppe Ceredi, a Paduan engineer, of his invention (or rediscovery) of Archimedean water-screws for drainage and irrigation purposes contains what may be the first suggestion in print to build models at different specifications in order to optimize machine-building. Here is Ceredi's description: 'I was able to fabricate a great many models, small and large, adding, changing, and removing various things according to the condition of the material, or the grouping of many primary and secondary causes, or the variety of the mediums, or the proportions, or the force of the movers, or many other obstacles that hinder the thing sought. For it is well known by scientists [*scientiati*] that when things are put

[5] After the late 16th c. models of machines increasingly became collectors' items in Kunstkammern and articles for mechanical demonstration in the private homes of engineers and the public establishments of scientific academies and engineering institutions. Model-based testing was central to the work of eighteenth-century engineers like Christopher Polhem (1661-1751), Antoine de Parciewux (1703-68) and John Smeaton (1724-92). In the same years, in a curious inversion of their origins in craft and engineering practice, reforming technical institutions briefly adopted machine models as a means to teach apprentices craft skills without submitting them to craft-based training.

in operation, so numerous and great a heap of observations need to be kept in mind all together to hit on any new and important effect that it is almost impossible to fit them all properly together'. Having found that no uniform rules could be found concerning the optimum construction of water-screws, he ultimately determined that the best procedure would be to use a screw about 8 m. long, to raise water about 5 m. Ceredi was aware of scaling problems with machines, and proceeded accordingly. 'To put this into execution', Ceredi stated, 'and have it based firmly on experience as guided by reason, it was necessary to make a large number of models, both small and large, now with one length and height of channels and now with another, in order to be able to proportion the whole to the mover [the screw] and to its organ [the crank]."

At about the same time, the French potter Bernard Palissy described how, over ten years, he slowly mastered how to combine the quality of clay, the pot's thickness, the melting point, type, quality and colours of the because their results depended critically on a combination of material ingredients, and atmospheric and other conditions that could not be easily controlled for, and thus, easily reproduced.

In sum, evidence of technical heuristics and codification shows how pre-modern craft and engineering knowledge was shared or ‘distributed’ within industrial districts. By implication, most inventions would also have been shared (Allen 1983). However, knowledge sharing was more likely in ship- and edifice-building, mining and metalworking, and in the production of clocks and scientific instruments, which displayed strong division of labour and advanced levels of coordination and where cooperation provided clear economies of scale and scope - sectors that are also notable for having played the most technologically innovative role in the Industrial Revolution. Sharing may have been less intensive in industries like glassmaking and in some of the luxury goods sectors, where chemical processes whose scientific basis was poorly understo descriptions and plans and drawings we

construction difficult to decipher from the illustrations alone. The English architect Inigo Jones, for example, learned the design principles of the orders and the fundamental planning issues of domestic architecture on his own; since he was not trained as a mason or carpenter, however, he needed to speak with workers and architects in order to learn practical building techniques. Between 1613 and 1614 he traveled to Italy for this purpose; on meeting the architect Vincenzo Scamozzi, Jones asked him for help with the technical aspects of vaults, noting in his diary: “Friday the first of August 1614 spoake with Scamozo in this matter and he hath resolued me in this in the manner of voltes”.

Pre-modern patents faced similar technical and cognitive problems. Patent law was first established at Venice in 1474 and spread rapidly either in law or in practice to the rest of Italy and northwards, first to the German principalities, then to France, Spain and the Low Countries, and subsequently to England (Frumkin 1947-49). By contrast with their modern counterparts, however, preinventor's shoulders, barriers to entry to the technology market via patents were generally high. The propensity to patent was also affected by other factors. Many product and process innovations were never patented because they were better protected as trade secrets or because they were part of the collective knowledge of a craft; for example, the makers of watches, clocks, and astronomical and other scientific instruments, most of who were organised in guilds, opposed patents that tried to privatise knowledge that was already in the craft's domain or that were perceived to restrain trade (Epstein and Prak 2005). Consequently, pre-modern patent rights seem not to have played a major role in innovation before 1800 (MacLeod 1987, 1988; Molà 2004).

The assumption that patent rights to invention were necessary for pre-modern technological innovation rests on the view that intellectual creation is non-rivalrous, and that once in the public domain, it can be copied at no additional cost. This fact may be true but is economically irrelevant, since what matters is the application of the new idea, which has learning and physical costs. In pre-modern manufacture, the costs of application arose from the largely implicit nature of technical knowledge, which created the need for one-on-one training and meant that technological innovations had to be transferred by travelling craftsmen and engineers.

4.2 Transferring Skilled Technicians

In practice, technological transfer could only be successfully achieved through human mobility. However, successful transfer faced four obstacles. The two most oft-cited, trade secrecy and guild opposition to innovation, were also the least important.

As the previous discussion of technical heuristics makes clear, most so-called craft secrets were in fact open to anyone willing to train in the relevant craft and engineering practices. For example, although 'Gothic' geometrical principles for drawing elevations - developed around Paris between mid-twelfth and mid-thirteenth centuries - were said to be the closest guarded masons' 'secret', they were actually shared by every trained mason north of the Alps. The application of Gothic principles was simply a practice that distinguished trained masons from everyone else, and there is no evidence of technical exclusivism (Shelby 1976; Fernie 1990). Similarly, the distributed character of technical knowledge - institutionalized through apprenticeship, guild practice and division of labour, and the systematic circulation of skilled labour - meant that genuine technical secrets were hard to keep, if they were deemed useful.

The belief that crafts were vowed to secrecy and exclusivism appears to have originated during the seventeenth century among the 'new scientists' and natural philosophers. Fascinated by technicians' proven empirical knowledge of the material world, empirically-oriented intellectuals between the late fifteenth (Leonardo) and the early seventeenth century (Bacon, Galileo, Descartes) wrote admiringly about craft practices and craft knowledge. But their admiration was tinged with suspicion, based on three distinct elements. First, they were unable to understand technical knowledge without extensive practice, and being unaware of the cognitive reasons for this, they found it hard to believe that illiterate or near illiterate technicians could know more about nature than they did. Thus, for example, reports of Royal Society experiments never name the technicians who actually made and maintained the instrumentation and performed the experimentation (Shapin 1988). Second, the new scientists wished to distance themselves forcefully from the long-standing tradition of alchemy, which they associated not wholly justifiably with a strong desire for secrecy and with social and technical exclusivism (Newman 1998, 1999, 2000). In this the new scientists followed the Scholastics, for whom 'knowledge of [alchemical] secrets was strictu sensu impossible: they could be experienced, and could be found out "e understood or explained according to the canons of logic and natural philosophy’ (Eamon 1994: 53). During

Individual instances of resistance to change tell us little about relations between the guilds and technological progress in general. A theory of guild innovation must identify both the *technical* and the *political* criteria that dictated the choice of technology and established a given technological path. In principle, one would expect the crafts to prefer technology that privileged skill-enhancing, capital-saving factors. Despite a lack of systematic research, evidence from patent records indicates that this was precisely the kind of innovation that prevailed in England before the mid- to late eighteenth century, when the country's guilds were still very active. Between 1660 and 1799, labor saving innovations accounted for less than 20 percent of the total, whereas innovations aimed at saving capital (especially working capital) and at quality improvements accounted for more than 60 percent. There is no reason to believe that patterns elsewhere in Europe were very different (MacLeod 1988: ch.9; Griffiths, Hunt, and O'Brien 1992: 892-95).

The response to innovation by individual crafts depended primarily on political rather than market forces. There was a fundamental difference in outlook between the poorer craftsmen, who had low capital investments and drew their main source of livelihood from their skills, and who therefore (frequently in alliance with the journeymen) opposed capital-intensive and labor-saving innovations, and the wealthier artisans who looked on such changes more favourably. The decision to innovate was also affected by relations between the guild's constituencies and the state. On the one hand, the weal2145 386.8ffer704 nto99062 229.0s 40880712 49.v1l51.54094 T 888 9.09

"recession cartels" when economic circumstances took a turn for the worse, but they still required political support to enforce cartel restrictions successfully against free riders and competing guilds. Thus, Dutch guilds began to resort systematically to restrictive policies when the country entered a long phase of stagnation after the mid-seventeenth century—but only after obtaining municipal approval (de Vries and van der Woude 1997: 294, 340-41, 582; Unger 1978: ch.5).

Although most technical knowledge remained either unformulated or unrecorded, one should not confuse the absence of written texts detailing technical practice with technician's fundamental commitment to secrecy. Rather, the absence of texts is evidence that writing (including, for many purposes, drawing) was a highly ineffective mode of transmission. As Palladio's work suggests, useful or experiential knowledge - knowledge that works - is, in principle, local. This does not mean that it is necessarily secret, or that it remains in an individual's head: pre-modern technical knowledge was extensively socialized and shared. Some elements of experiential knowledge - in shipping, and to a lesser extent in building - were increasingly codified in writing. A partial result of written codification was to make local knowledge *less* local, accessible both to the emerging professional categories of designers and, in principle, to makers outside the original community of practitioners. Other experiential knowledge was embedded in objects, and objects could travel and be observed: ships could be seen, clocks could be taken apart, imported Chinese porcelain could prove that something deemed impossible, or unknown, could in fact be done.

Strong evidence as to the effectiveness of technological transfer through migration comes from the observation, discussed previously, that technological leadership moved over time from southern to northwestern Europe - from Italy (1200-1450), to the southern Rhineland and southern Netherlands (c.1450-1570), to the Dutch Republic (1570-1675) and finally to Britain after c. 1675 - largely thanks to skilled individuals trained by guilds or by other communities of specialized technicians (miners, builders, shipbuilders etc.).

Between *c.*1300 and *c.*1550, European craft guilds and polities devised institutional arrangements that sustained craft mobility and raised the *potential* rate of technological innovation. Skilled migrant workers were up mainly of apprentices and journeymen, who travelled on a seasonal basis, or made up mostly of established masters, whose migrations tended to be permanent. Organised apprentice and journeyman mobility grew out of the temporary skills shortages that followed the plague epidemics of 1348-50. By 1550, tramping was common in much of Western Europe, although it was only fully institutionalised in German-speaking central Europe and less extensively in France. In England, independent journeyman organisations were formed after the decline of London as a national training centre from the 1680s. Since the main purpose of organised tramping was to coordinate information and allocate skilled labour more efficiently across regions, formal organisations never arose in densely urbanised regions like northern Italy and the Low Countries where information costs were low (Epstein 2004; Wildasin 2000).

Apprentice and journeyman mobility helped develop and diffuse technical knowledge within areas that were institutionally, economically and culturally similar. Nascent monarchies and territorial states, by contrast, made it a point to attract new skills and technology from outside such zones. Competition for skilled workers, for example for master cathedral builders, existed already during the Middle Ages, but it increased markedly during the early Renaissance (*c*.1450-1550) in the western Mediterranean, and after the Reformation in north-central Europe, when European rulers made it policy to attract displaced craftsmen from enemy lands. The Huguenot migrations to Geneva and England and the wholesale transfer of artisan skills from Brabant to the Netherlands after the sack of

Antwerp in 1585 are just some threads in a complex web of politically driven technical diffusion (Scoville 1953). From the mid-seventeenth century, mercantilist states promoted domestic industry and engaged in industrial espionage more systematically than ever before, and attempts by guilds and political authorities to stop skilled workers from migrating were hindered by weak administrations and state competition (Harris 1992).

Each relay of the technological torch set in motion a period of rapid innovation in the new regi2dsa of high quality steelmaking that had been practised in Germany, northern Italy, Sweden and England for up to two centuries before (Rosenband 2000; Smith, 1956).

Bottlenecks to technical transfer were relaxed over time by falling information and transport costs, which can be proxied reasonably accura

However, the main *direct* source of pre-modern technical innovation was the craft guild, for three reasons. First, it enforced the rules of apprenticeship against free riding and exploitation. Second, it offered institutional, organisational and practical support to the migrant apprentices, journeymen and masters who transferred their technical knowledge from one town and region of Europe to another. Third, it supplied incentives to invention that the patent system did not by enforcing temporary property rights over54nBmbr

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