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Transferring Technical Knowledge and Innovating in Europe, c.1200-1800

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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 pervasive rent seeking by guilds is hard to square with the fact that the surge of technological innovation in the eighteenth century occurred within institutional frameworks not too dissimilar to those of 1300 (North 1981; Mokyr 2002).

A plausible explanation of pre-modern European technological development must account for three established facts about why Europe industrialised first, despite still being a technological backwater around 1150 by comparison with the great Asian civilisations. First, the technological revolution of eighteenth- and early nineteenth century Europe was the outcome of a process of small-scale incremental innovation that stretched back at least to the high Middle Ages. The most striking feature by comparison with other coeval societies, however, is not so much that technological progress in pre-modern Europe occurred at a faster rate than elsewhere, but that progress was persistent and uninterrupted. By contrast, technological development in the great Asian civilizations of India and China experienced comparatively short periods of efflorescence, lasting a few centuries at a time, which were regularly followed by long phases of near-stagnation.

Second, the geographical location of technological leadership in pre-modern Europe shifted over time. Between the eleventh and the nineteenth centuries, Europe's technological frontier shifted increasingly north-west: from the east-central Mediterranean to northern Italy during the thirteenth and fourteenth centuries, to southern Germany and Bohemia in the late fifteenth, to the southern Low Countries in the sixteenth, to the

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 to make things, and get them right - was, and had to be, transferred in the flesh. The shifts in regional technical leadership I just described could therefore only occur if technicians could take their knowledge elsewhere. This was arguably more easily done in Europe than elsewhere, because European technicians were not members of ascriptive (kin-, religion- or locality-based) communities, and because they benefited from competitive bidding for technical expertise across a fragmented political and economic system.[3]

The implications for pre-modern 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 pre-modern European societies were able to generate

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[2] One might speculate that in pre-modern Asia one does not seem to observe a similar process of slow, incremental technological diffusion and recombination under changing social, economic and institutional conditions. Instead, technological leadership seems to have persisted in the same regions (south-eastern China, western India) over very long stretches of time - significantly raising the probability of generalised technical sclerosis.

[3] Although ascriptive forms of membership were not insuperable hurdles to mobility in China (the barriers were higher in India), China may have lacked the kind of economic pull factors that underped technicians' mobility in Europe, because their most technologically advanced industries were concentrated in and around workshops under imperial control; China also lacked the kind of non-ascriptive institutional support, such as craft guilds, that lowered the costs of absorbing technical information from immigrant technicians . Consequently, the average cost of technical transfer was probably lower in pre-modern Europe by comparison with other societies.

incremental technical innovation under three headings: How was pre-modern 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? I focus mainly on the period before 1700, in order to emphasize the similarities with better-known eighteenth-century conditions. Section 2 discusses the nature of experiential knowledge and its intergenerational transfer. Section 3 addresses knowledge transfer between peers, including technical codification and heuristics. Section 4 discusses technological transfer across space. Section 5 concludes.

2. Acquiring Experiential Knowledge

In discussing the experiential knowledge of pre-modern technicians (craftsmen and engineers), I take as premise the fact that intelligent behaviours, long associated with the overt and conscious domain of cognitive functioning, are better understood as the result of both implicit and explicit capacities. Thus, experiential knowledge includes implicit or tacit knowledge; non-propositional and non-linear knowledge, including imagery, which has both implicit and explicit components; and explicit, propositional knowledge, which is linear and verbal or mathematical. Implicit knowledge equates to knowledge that is acquired largely independently of conscious attempts to learn, and largely in the absence of explicit knowledge about what was acquired. Implicit knowledge relies on rule finding and abstraction, and is the basis for the acquisition of skills. Thus, the distinction between implicit and explicit knowledge is hazy, and they form part of a continuum; but the implicit component is consistently greater than the explicit. Also on this definition, the boundaries between experiential knowledge in the crafts and in the sciences are far fuzzier than assumed by standard claims that craft practice and experimentation is ‘non-scientific’ because it lacks an underlying conceptual or propositional framework.

Experiential knowledge is a good, and its exchange and diffusion demand that those who have it take deliberate action to share it through face-to-face communication. These operations are costly to implement, and have relied historically on different institutional solutions. Analytically, it is useful to break down the question how technical knowledge was transferred into the issues of inter-generational transmission and transmission between skilled peers.

The first stage in acquiring technical knowledge was through a long-term relationship of pupilage based on formal or informal sanction, in other words through apprenticeship, which is the most widespread arrangement for transmitting technical knowledge outside the family devised by human societies. In pre-modern Europe, craft guilds played a dominant (though not unique) role in overcoming training externalities in human capital formation. Since future human capital cannot act as collateral, resource poor but potentially able workers may be incapable of bearing the costs of their investment in skills, leading to a socially suboptimal supply of skilled workers. Pre-modern apprenticeship allowed trainees to exchange subsidized training for below-market wages after training was concluded. However, firms would have still supplied suboptimal amounts of training if the trainee could quit before contract expiry. Craft guilds supervised job performance, work conditions, and quality of instruction; enforced contracts through compulsory membership, statutory penalties, and blackballing; and protected apprentices against poor training in craft specific skills within oligopsonistic labour markets. In the absence of compulsory schooling, supra-local legislation, and efficient bureaucracies, formal or informal craft associations were best suited to enforce apprenticeship contracts and rules outside the family. This fact explains the extraordinary longevity of

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 activity which you Venetians display in your famous arsenal suggests to the studious mind a large field for investigation … for … all types of instruments and machines are constantly being constructed by many artisans, among whom there must be some who, partly by inherited experience and partly by their own observations, have become highly expert and clever in explanation’ (Galilei 1638: 1-2). Expertise, in other words, was also a precondition for the ability to teach, and teaching apprentices helped solve the conundrum of making tacit technical knowledge, public.

3. Collective Knowledge And Technical Heuristics

Apprenticeship contributed substantially to the collective or ‘distributed’ nature of pre-modern technical knowledge, which was an essential feature of technological progress. However, the inter-generational transmission of knowledge contributed less to innovation than knowledge sharing between skilled peers.

Technical knowledge sharing between peers occurred on site and through migration. Although practices in making, repairing and running

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making. For similar reasons, highly specialised craft knowledge and techniques was transmitted through craft lineages; see e.g. Brown, 1979.

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 prowess. And, in a letter to Mersenne dated 7 December 1642, Descartes describes the ingénieur Etienne de Villebressieu as 'a very curious man who knew many of those little chemical secrets which are exchanged between members of the craft'.

However, the strongest evidence of on-site knowledge sharing is indirect. Once again, some of the most systematic evidence occurs in the 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 structural force before the nineteenth century, they had no means of predicting the structural effects of increased scale. The most frequent solution was to build in modules and to build slowly, observing the evidence of stress over time and making repairs and innovations as needed. The flying buttress was a crucial structural innovation introduced along these lines; 'all flying buttresses in the great northern [French] churches prior to the second half of the twelfth century seem … to have been added as casual expedients only after weaknesses had become apparent or … the vaults had already pushed the walls aside and collapsed'. On other occasions, like the building of Brunelleschi's Florentine dome, 'new structural ideas were deliberately tried out on a smaller scale' (Mainstone 1968: 305).

Achieving expertise, as we saw, bespeaks an ability to display flexibility with the rules. Major changes to plans were made as the need for them arose, in response to changes in the commission or to structural problems. Thus, when Brunelleschi did not provide workers with a 3-dimensional model for the Florentine Spedale degli Innocenti, the masons and carvers deviated from his design. Originally conceived as a block (*cuadro*) on its shelf in majestic isolation from other buildings, the design of Philip II's palace of the Escorial was gradually extended to include various outbuildings. Twenty years after the start of the building works, 'the artisans were still unsure whether the sanctuary was to be rectangular or apsidal, and [the master mason Herrera] was asked for drawings to clarify the question.' In 1577 'grave doubts arose about the stability of the dome support where the stones were showing fractures. It is reported that public fears caused Herrera reluctantly to reduce the height of the dome's pedestal by 11 ft., and to eliminate the niches, which reduced the mass of the pillars' (Kubler 1982: 82, 98). At about the same time, Venetian architects and masons refused to approve a single plan for the construction of the Rialto Bridge, which was therefore built in stages, with each stage receiving a different plan (Calabi and Morachiello 2000). A century later, Christopher Wren 'adapted the design [of St. Paul's Cathedral] as defects occurred, or his widening experience suggested improvements'. Although as a natural philosopher he developed a wrong theory of arches, as a practical engineer employing little or no calculation he was highly successful, because he employed the heuristics of practical building and engineering (Hamilton 1998).

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.

Although the development in Gothic building of heuristic 'rules of thumb' or algorithms provided reasonably safe and economical solutions, while reducing computation and design time, it also tended to establish a conceptual identity between building structure and form (Mainstone 1968). This made it hard to transfer the structural theory developed in one Gothic building lodge or lodges in one region to somewhere that had a different ideal form. An instance of the conceptual and technical problems that could ensue occurred at the building site of the new cathedral at Milan at the turn of the fifteenth century. The difficulties arose because Milan at the time was an architectural backwater, and local building skills were inadequate. From the start, therefore, the Milanese asked experts from Central Italy - then architecturally and technically more advanced, yet still peripheral to the Gothic powerhouses further north - to advise them on the form and structure of the new church. Importantly, the plan drawings were based on simple manipulations of the triangle - with the result that the nave and roof of the cathedral were both lower and broader than in the Gothic heartland over the Alps.

Structural problems soon arose, however, so the Milanese brought in North European experts to advise them - with explosive effects. In 1400, 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 structure and were forced back onto their own local judgment and experience.

The problem of combining, or synthesizing, different empirical traditions that did not clearly distinguish between building structure and form could be addressed in different ways. One way was to codify existing traditions. In the late fifteenth and early sixteenth centuries, several German master masons (Matthäus Roriczer, Lorenz Lechler, and others) drafted detailed notebooks or handbooks that reproduced the square-based configurations of form. The reasons for doing this are not entirely clear, but one relevant factor was probably the increased circulation of masters, journeymen and trainees between Central European building lodges, which must have given rise to confusion and conflict over which lodge tradition would prevail. Although we do not know if the German master masons were trying to synthesise different lodge traditions or if they were simply codifying 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 on classical arches, and to 'apply new arithmetic procedures to Gothic rib vaults' (Sanabria 1998).

An assessment of craft and engineering heuristics must distinguish between well structured problems, in which situations, operators, and goals tests are all sharply defined, and little specific domain knowledge is needed; and ill structured problems, which require extensive experiential knowledge to be solved effectively through a combination of inductive and deductive processes. Designing buildings, for example, is a poorly structured task. The tests of success are complex and ill defined, and are often elaborated during the solution process. The solution requires flexibility that will often manifest itself as a lack of precision, a 'good-enough' and make-do approach that mathematically grounded theoreticians find disconcerting. Pre-modern ship-building appears superficially more structured than edifice building, but in other ways it was similarly open-ended: critically, it could not proceed, like building, by testing individual modules as they were built, 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 Venetians had written up their shipbuilding schema already in the fifteenth century, followed by the Portuguese in the mid-to-late sixteenth, but these drawings were purely descriptive and were not used for planning purposes. Proportional design for future planning seems to have been introduced by the Englishman Mathew Baker in the 1580s, spreading from the 1630s together with 3-dimensional modelling and becoming the norm in England after the Civil War. The French, spurred by Colbert’s build-up of the navy, introduced design slightly later but with more sophisticated geometrical methods and tools. These innovations appear to have had two practical implications. On the one hand, planning design may have introduced greater building flexibility. It did not entirely break the link between structure and form, because designers still lacked adequate hydrostatic and hydrodynamic theories; modelling new ships on the basis of experimental drawings was therefore very risky. In the English case, moreover, only part of the hull was designed; the rest was still derived geometrically in the dockyard. Yet even with these limitations, scaled design did offer a more effective way than the algorithm-based Mediterranean system of keeping track of experimentation in the absence of material constraints (McGee 2003).

On the other hand, the use of scaled design made it possible to plan ships with more complex shapes. In the Mediterranean system, a single mould was sufficient to define the whole hull shape (except for the ends). This mould was used directly at midship section and at all sections between amidships, while the end stations (about 10 percent of the ship length from the ends) were constructed on the basis of a rule of curvature or interpolant. Thus the variety of shapes was governed by the chosen midship section and by the few parameters of the longitudinal interpolant, which created section shapes that were close cousins of the midship section and did not permit much curvature. The introduction and improvement of scaled design allowed the English to introduce two interpolants, and the French to design ships with two or more (the number of interpolants defined the number of times the curve of the hull could be changed). This was a typical example of how technological latecomers could benefit from, and improve their predecessors' experience.

3.2 Drawings and Models as Heuristic Devices

Comparison between Venetian and Portuguese ship-drawings, whose sole purpose was to depict established building proportions for non-practitioners, and English and French scaled drawings, which aimed to establish new proportions for master-builders, suggests that we should not take the nature and purpose of design for granted. Consider the aesthetically stunning plans of Gothic cathedrals, the first of which depicts

Rheims cathedral in the mid-thirteenth century, and which seem at first glance to offer remarkably detailed building directions. In fact, many of these plans were presentation copies, drawn after the building was finished; others were drawn for the building commission, and thus differ substantially from the final product; none appear to have been actual working copies, used by the building lodge for practical purposes, because none were actually drawn to scale.

There were two major obstacles to the practical use of Gothic drawings for building purposes. One was the use of geometrical rules in design. This had the advantage of being easily ‘portable’, since it did not rely on fixed measurements, but the method also generated irrational numbers (such as the diagonal of a square) that could not be easily reproduced on arithmetically proportioned plans. The second obstacle to the use of drawing was, paradoxically, the rediscovery by Filippo Brunelleschi of 3-point perspective in early fifteenth-century Florence, which led his friend Leon Battista Alberti to emphasise the use of ‘illusionism in architectural rendering’. As Alberti recognised, however, the perspectival method was of no use to planners and builders. It took three generations of Italian draftsmen to find out how to draw ‘plans and elevations, not according to the perspective method but by orthogonal projection, which … permits every element to be shown at the same scale, so that the carpenter and the mason can work from it’ (Lotz/Ackermann 1977: xviii-xix). But Alberti’s technical effort had another, more desirable consequence (from his point of view), which was to replace the master mason’s traditional role as surveyor and planner with the far more prestigious figure of the architect-designer.

Plans, which avoid distortions whilst representing the spatial elements of the object so that it can be reproduced, were nonetheless practically unknown outside architecture before the seventeenth century. In particular, the pictorial or illusionistic method persisted in the drawing of 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 distinct uses: 1. to store information and to help communicate it from one person to another (e.g. designer to client, builder or supplier); 2. to help produce in the engineer and client the necessary level of confidence that the proposed structure will work and can be built (Addis 1998a). Although the use of 3-dimensional building models is attested as far back in time as Babylonian Mesopotamia, it became a more regular documented practice only in fourteenth-century Tuscany; a 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

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[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 enamel, the level and constancy of fire, and the pot's position in the kiln to make Italian-style enamel (Fayence) (Palissy 1996). Although narrated in the form and with the tropes of Reformed Christian salvation, the tale of Palissy's struggle to control for the many variables of pot-making rings true in reminding us that in chemical processes, visual and 3-dimensional models were of little use. Positive results could only be gained through an approach on the borderline between alchemical and craft practice, exemplified also, for example, by the systematic recipe books for Venetian glassmaking that survive from the early sixteenth century on. It is all very well to define the 'scientific method' as 'accurate measurement, controlled experiment, and an insistence on reproducibility'. As Palissy noted, the problem with this ideal, to which in principle he subscribed, was to know *what* to measure and experiment with - something scientists would be no better at defining for nearly three centuries thereafter. So recipes were the solution - but recipes, as opposed to machines, were hard to transfer, 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 understood gave individual craftsmen a competitive edge.

4. Spatial Transfer Of Technical Knowledge

4.1 Texts and Patents

Thus far we have focused on how pre-modern technical knowledge was codified and shared. In order to fully answer the initial question of how pre-modern technical innovation was generated and sustained, we must also address the matter of how technical knowledge travelled.

In theory, technical knowledge could be disseminated across space in three ways: through publicly available texts, through patents, and through migrating individuals. In practice, published, 'disembodied' technical knowledge did not disseminate well, as John Harris, a lifelong student of technological transfer between eighteenth England and France, concluded: 'the craft nature of virtually all the technologies … meant that written descriptions and plans and drawings were only marginally useful' (Harris 1998: 549).

Pre-modern technical writers seldom practiced what they described, and so typically overestimated the role played by explicit, propositional knowledge in craft and engineering practice. Written manuals were incomplete and sometimes misleading; they might contain technical details not actually applied in solving the problem; and they left out crucial practising 'tricks'. Such problems were compounded by the difficulties faced by experts in describing what cues they responded to and what factors contributed to their decisions. An investigation on the training of Spanish ship pilots for the Indies defended their alleged incompetence as follows: 'even though a person is not very resolute in responding to the theory, [yet] he understands it well, and he who has experience understands it if he acts correctly, and *there are many who don't know how to propose or explain how to use an instrument, but with one in their hand use it very well'* (Sandman 2001: 276). The large tacit and non-linear component of experience-based knowledge explains why equally skilled experts in the same field disagreed on how to do their job (Ash 2000), and why not a single pre-modern innovation was transferred through print alone.

The most popular and sophisticated manuals, architectural treatises, were searched for formal motifs rather than for building techniques. The woodcuts in the most famous and extensively copied treatise, by Andrea Palladio (published 1570), were drawn in orthogonal projection and therefore may have made it possible for architects to study building proportions; however, they gave little indication of construction methods or the use of materials, for Palladio like other treatise writers assumed that architects and builders would adapt his designs to local building traditions and to the availability of materials (Trogu Rohrich 1999). Part of the popularity of Palladio's treatise arose from this inherent flexibility. By contrast, most readers would have found the technical information on 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, pre-modern patent laws did not require novelty and originality; most patent descriptions were generic and did not remotely approximate a modern blueprint; and innovations were seldom examined systematically before the eighteenth century. Although some administrations (such as Venice in the early sixteenth century), demanded a working model of patented machinery, inventors working on models were frequently unable to overcome scaling problems with full-sized machines, as noted by Giuseppe Ceredi in 1567 (Ceredi 1567: 52; Drake 1976). The problems arose particularly for large-scale mechanical inventions involved in power generation (milling, hydraulics, heating). In practice, patents were a means for towns or rulers to encourage the introduction of a new machine or process in their jurisdiction, by conceding a contingent monopoly over exploitation. Patents were also used as a means of commercial advertisement. Since patents tended to require costly lobbying and upfront fees, and placed the entire burden of proof and investment risk on the inventor'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 "experimentally," but they could not be understood or explained according to the canons of logic and natural philosophy' (Eamon 1994: 53). During the sixteenth century alchemists such as Paracelsus, Girolamo Cardano, and Andreas Libavius deliberately associated their practices with craft activities and methods in order to emphasize their empirical, non-scholastic approach. Seventeenth-century new scientists were thus offered a ready-made conceptual framework, which stressed secretiveness and unreliability, into which to slot craft practices, and which moreover drew attention to the scientists' self-declared intellectual openness.

The third strand in the emerging theory of craft practice arose from the new scientists' concern with establishing a readily transportable method, whose principal aim was to codify the facts of the natural world into a universal language. This set them explicitly at odds with technicians, who they described as having no method at all. As we have seen, this was in fact a misrepresentation, for codification was nearly as important an activity among technicians, although its purpose differed: for technicians, codification was a means to make things that worked rather than an end in itself.

The claim that guilds systematically opposed outside innovations is equally problematic. One reason is that it is excessively generic. If it is meant to say that guilds never innovated, it is demonstrably false (Epstein 1998; Epstein 2003; Epstein and Prak 2005); a recent study of patenting in sixteenth-century Italy shows that guilds were in the forefront of testing and introducing technical innovations (Molà 2004). If, on the other hand, the claim is meant to say that guilds would at some point become technically conservative, it loses any predictive value. The argument is also methodologically naive. Although it assumes that all innovations that were refused were better than current practice, the record seldom reveals whether guild opposition was driven by rent seeking or by an objective assessment of the innovation's merits.

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 wealthier and more innovative masters were more likely to influence government policy, and under normal circumstances authorities seem to have allowed them to circumvent guild regulations. On the other hand, city councils were more willing to meet the small masters' concerns if labor saving innovations coincided with a serious economic downturn, both to ensure social and political stability and to restrain unemployed craftsmen from leaving the town. In other words, guilds were most likely to act as "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 regional leader. Britain, for example, was a one-way technological debtor up to the late seventeenth century; between 1600 and 1675 it imported from the Continent the most advanced techniques in metal smelting and forging, in the making of glass, pottery, guns and watches, scientific instruments, wool, linen and silk cloth, and in hydraulic engineering and agriculture (Hollister-Short 1976). This position of dependence began to be reversed after *c.*1675, and already by 1720, the English Parliament had become so worried about international competitors, and so confident in native technical prowess, that it passed a law banning the emigration of resident technicians.

The two main obstacles to technological transfer were, therefore, information and transport costs, which restricted labour mobility, and the absence of a local skills base that could successfully apply incoming techniques. Exogenous innovation could be absorbed only given an adequate supply of trained technicians who could make, operate and repair the new machinery: a major hurdle with transferring British coal-based technologies to non-coal based Continental economies in the eighteenth century, for example, was the incompatibility of the associated intermediate goods, parts and skills (Harris 1978). Transmission of the most up to date knowledge could therefore be excruciatingly slow. It took over a century to transfer Hollander paper beaters from the seventeenth-century Netherlands to eighteenth-century France because of a lack of good machine makers and repairers; eighteenth-century French metalworkers had no knowledge 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 accurately by trends in urbanisation, and in financial and other market integration (Bairoch, Batou and Chèvre 1988; Epstein 2001; Neal 2000; Persson 1999). The most salient example of the correlation between technological leadership and urbanisation is pre-modern England, which was transformed between 1650 and 1750 from a technological and under-urbanised semi-periphery to the most technologically innovative and urbanised country in the West. The most plausible reasons for the correlation are the standard Marshallian ones: economically successful towns attract skilled workers, whose pooling stimulates the growth of specialised intermediate goods industries; knowledge spillovers among firms increase; and reliable knowledge improves and increases with use. This model fits well with the evidence that pre-modern regional technological leadership followed commercial leadership, with a certain lag (Davids 1995).

5. Conclusions

Notwithstanding the absence of much written evidence, evidence from technical practice suggests that pre-modern non-scientific technical knowledge expressed significant degrees of abstraction, experimentation and cumulation. There is also strong evidence that pre-modern technicians codified heuristic rules in response to increasing pressure for standardization and rising mobility of skilled workers. These conclusions challenge Mokyr's recently drawn distinction between 'propositional' and 'prescriptive' knowledge (Mokyr 2002).

Pre-modern technical progress was both sustained and limited by the manner by which generic technical knowledge was codified and by 'collective invention' (Allen 1983; Epstein 2004). Pre-modern technical codification faced three important cognitive limitations, which it shared in several ways with contemporary natural philosophy. First, pre-modern technicians, like seventeenth and eighteenth century natural philosophers and their modern counterparts, faced the problem that tacit knowledge - both ostensive knowledge, and knowledge inexpressible in natural language - is ubiquitous and unavoidable; thus, written codification was, by definition, always incomplete. Second, pre-modern technicians, like natural philosophers, faced the problem that some kinds of knowledge were more easily codified and transferred - via proportions and ratios, diagrams, models and 'recipes' - than others. Thus, technical knowledge related to chemistry and metallurgy was harder to mobilize, because the character and quality of inputs was more variable, and because the final product could not be easily 'reverse engineered' to reveal its underlying manufacturing process. Lastly, pre-modern technology's empiricism made it hard for technicians to distinguish clearly between theoretical structure and form; a similar difficulty may explain the inability of most pre-modern natural philosophy to generate technologically fungible science. Technicians extrapolated experiential knowledge from empirical observation of what worked within a given set of material circumstances and practices. They produced 2^{nd} order codifications of practice, rich in information, able to capture a high degree of variance in information, but possessing limited predictive powers. Although practices and practice-based algorithms gave broad scope for technical improvements, they offered little information on how a set of rules with different premises would affect a known technical process. In other words, each set of rules came with a corresponding bundle of practices.

In principle, the weak distinction between structure and form, between rules and practice that we saw at work in cathedral and shipbuilding, raised the costs of switching from one set of rules to another. In practice, however, these constraints were less serious than those coming from restrictions to information flows, for there is no reason to believe that most pre-modern technologies, based on empirical practices and available materials, had reached their technical frontier even by 1800. The most severe restrictions to pre-modern technological reliability and innovation arose from the high information and reproduction costs related to experience-based knowledge. The principal source of diminishing returns to technical knowledge seems to have been the cost of communication between dispersed craftsmen and engineers, rather than the narrowness of the pre-modern crafts' epistemic base.

Although in principle tacit knowledge should have raised the appropriability of rent streams from invention, in practice appropriability was rather low, because the system of apprenticeship training and the use of a mobile skilled labour force made it difficult for individuals to protect technical secrets. Since patent laws and patent concessions were commonplace but ineffective, and displayed high barriers to entry, incentives for individually driven innovation were rather weak. Most technical knowledge within industrial regions or districts with integrated skilled labour markets would have been shared, but technological transfer over long distances was inherently rivalrous, because it required non-local patterns of expertise to be applied successfully.

A distinctively European technological system emerged from the late eleventh century, based on craft-based apprenticeship training, non-ascriptive membership of craft associations, and, increasingly, inter-state competition for skilled workers. These three elements defined a set of necessary and sufficient endogenous conditions for the accumulation, codification and circulation of reliable technical knowledge (Epstein 2005).

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 over members' innovations. Notably, only the first effect was the outcome of deliberate policy; the other two were unintended consequences of the club goods that the craft supplied its members.

Growing state competition and urbanization pushed down the costs of technical dissemination over time. Urbanization offered increasing opportunities for exchanging knowledge, higher average quality of labour, a greater likelihood of matching skills to demand, and stronger incentives for the codification of knowledge. Although it is not a priori clear whether high urbanisation attracted skilled migrants, or whether migration (driven by exogenous factors like war) caused high urbanisation, the evidence points to the primacy of the former, pull factors, specifically of urban commercial success. Migration by skilled workers allowed new technological leaders to shift rapidly to the technological frontier, recombine foreign with domestic knowledge, and innovate further. The acceleration of technical innovation during the eighteenth century is less likely to have been caused by an intellectually driven 'Industrial Enlightenment' than by increasingly mobile technicians who shared both propositional and prescriptive knowledge among themselves.

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