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The rise and fall of the factory system: technology, firms, and households since the industrial revolution

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Abstract

The factory system, which arose with the British Industrial Revolution, was responsible for bringing about the separation of the location of consumption (the household) and that of production (the plant or office). This separation has had large effects on economic welfare. The reasons behind the emergence of the factory system are analyzed here, and a new interpretation is proposed, based on the need to divide up the growing knowledge base of production in an age of technological advances. The possibilities and implications of telecommuting as a reversal of this trend are examined.

The consequences which accompanied the introduction of the modern factory are extraordinarily far-reaching... workshop industry meant the employment of the worker in a place which was separate both from the dwelling of the consumer and from his own.

Max Weber, 1920

In half a century's time, it may well seem extraordinary that millions of people once trooped from one building (their home) to

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another (their office) each morning, only to reverse the procedure each evening... Commuting wastes time and building capacity. One building – the home – often stands empty all day; another – the office – usually stands empty all night. All this may strike our grandchildren as bizarre.

Frances Cairncross, 1997

1 Introduction

What does technology *really* do to our lives and well-being? Much of the history of technological revolutions in the past two centuries is written as if the only thing that technology affected was output, productivity, and economic welfare as approximated by income. This is of course the best-understood and most widely analyzed aspect of technological progress. Yet technological progress affected other aspects of the economy that may be significant besides the quantity of output broadly defined. Among those is the optimal *scale* of the basic economic production unit and the *location* where the act of production takes place. These in turn determine whether "work" will be carried out in a specialized location and thus whether households and firms will be separate physical entities.

The stylized fact is that the Industrial Revolution of 1760-1830 witnessed the "rise of the factory." Like all historical "facts" of this kind, it is only an approximation. In reality, there were numerous precedents for large-scale enterprise and for people working in large plants even before the classical Industrial Revolution. But there can be no doubt that what the Industrial Revolution meant was the ever-growing physical separation of the unit of consumption (household) from the unit of production (plant).[1] "Factories" is a term that mixes up two economic phenomena: one is the concentration of former artisans and domestic workers under one roof, in which workers were more or less continuing what they were doing before, only away from home. These are sometimes known as "manufactories." The other involves a more radical change in production technique, with substantial investment in fixed capital combined with strict supervision and rigid discipline resulting in what became known as "mills." In practice, of course, this neat dual division

[1]Max Weber, cited above, was not the first to emphasize this aspect. Paul Mantoux opened his still classic work on the Industrial Revolution (first published in 1905) with the words "The modern factory system originated in England in the last third of the eighteenth century. From the beginning its effects were so quickly felt and gave rise to such important results that it has been aptly compared to a revolution, though it may be confidently asserted that few political revolutions have ever had such far-reaching consequences" (1961, p. 25).

did not hold, and most of the new plants were blends of the "ideal" types, with the relative importance of the "manufactories" declining over time.

The purpose of this paper is to argue that this phenomenon was largely driven by technology, which determined *both* the relative costs and the benefits of moving people as opposed to moving information. These costs overlap only in small part with the "transactions costs" postulated to explain the existence of firms by Coase and Oliver Williamson. Moreover, because I am interested here primarily in the *location* where the work is carried out, the modern distinction between firm and plant should be kept firmly in mind. In the standard theory of the firm, firms are substitutes for contracts, they reduce uncertainty and opportunistic behavior, and set incentives to elicit efficient responses from agents. Firms can hire workers or transact with suppliers in a long-term, repeated relationship, or on a one-shot basis. This theory, however, does not fully specify the actual location of production. The key to the understanding of the geography of the firm is the costs of moving goods, people, and information. In a recent paper, Lamoureaux, Raff, and Temin (2000) note that information and transportation costs determine the location and organization of economic activity but worry that these costs all decline monotonically over time, yet the organization of business shows anything but a unidirectional trend. Part of the answer, as they correctly point out, is the emergence of new techniques of coordination. My argument here is that whether workers work at home or in a central location depends on the relative costs and benefits of moving people or moving information and on the changes in the composition of output and capital-labor ratios that may change labor demand in activities requiring workers to be actually present on the shopfloor or in the office. While transportation costs and information costs may have *both* fallen, a change in their ratio may affect the location of production in a complex manner. Furthermore, the *benefits* of concentration may be moving in a different direction as the result of changes in technology and product-mix.

Large *firms* were quite widespread before the Industrial Revolution, but almost all of their employment was domestic labor (cottage industry), much of it on a putting-out basis. In this system, the "firm" (that is the merchant-entrepreneur) owned the raw materials, the goods in process and often the tools and equipment as well, and outsourced physical production to workers' homes. This may well have been more efficient in a Grossman-Hart kind of framework, in which the raw materials and the tools were strongly complementary, but capital markets underdeveloped. In that kind of world, ownership confers residual rights of control and decision, but the technology may not have required in most cases to locate the physical production in a central place.

Most workers in pre-Industrial Revolution western Europe, in any case, were independent farmers or craftsmen and the distinction between "firm," "plant," and "household" is otiose. For those who had become part of larger firms, putting-out was the answer. A condition for the putting-out system to exist was for labor to be paid a piece wage, since working at home made the monitoring of time impossible. In the stylized version, then, the factory, factory towns, and an industrial wage labor force or proletariat were all created in the closing decades of the eighteenth century and the first half of the nineteenth. The process of transition was long, drawn out, and never quite complete, but by 1914, as far as we can tell, the majority of the labor force was no longer working in their homes.

In recent years, there has been some tendency for the pendulum to start swinging back. Some telecommuting enthusiasts are predicting a return to pre-Industrial Revolution conditions, in which suitably networked households will become once again the main location in which human work will be carried out. The "death of distance" may mean that more and more production can take place from *any* location, and that hence the need for employees to be present at some central facility may become less and less required. To be sure, the demise of the industrial plant may be premature, and in any event it is not the intention of this paper to engage in prediction, much less futurism. Instead, it proposes to reexamine the causes and effects of the rise of the factory, and specifically to sort out the role of technological change in this process, to examine the beginnings of a possible reversal in recent years, and then to apply some of the insights to issues of current policy relevance.

2 The industrial revolution and the rise of the factory

Traditional industry, that is, manufacturing before the Industrial Revolution was, in François Crouzet's words (1985, p. 4) an industry without industrialists. This was surely true for the independent craftsmen who worked on their own account with the help of their family members and a few apprentices who were co-opted in the household. Workers employed by capitalists in one form or another also worked, predominantly, in their own homes. Max Weber stated it most clearly, that the distinguishing characteristic of the modern factory were "labor discipline within the shop ... combined with technical specialization and coordination and the application of nonhuman power ... The concentration of ownership of workplace, means of work, source of power and raw material in one and the same hand. This combination was only rarely met before the eighteenth century," (1961, pp. 133, 224).

As noted above, large industrial plants were not entirely unknown before the Industrial Revolution. For instance, Pollard (1968) in his classic work on the rise of Factory, mentions three large plants, all employing over 500 employees before 1750.[2] Perhaps the most "modern" of all industries was silk throwing. The silk mills in Derby built by Thomas Lombe in 1718 employed 300 workers and was located in a five-story building. After Lombe's patent expired, large mills patterned after his were built in other places as well. Equally famous was the Crowley ironworks, established in 1682 in Stourbridge in the midlands (not far from Birmingham) and which employed at its peak 800 employees. Yet Crowley's firm is the exception that proves the rule: much of the work was put out to master workmen who worked the iron in their own homes or workshops. Crowley was unusual in having set up a system of supervision, monitoring, and arbitration with his workers unlike anyone else.[3] Blast furnaces, breweries, shipyards, mines, construction and a few other industries had long been producing outside the domestic system since they could not economically operate at the scale of a household.[4] In textiles, Chapman (1974) has shown how supervised workshop production could be found before 1770 in the Devon woolen industry and in calico printing. Yet in industries such as the Yorkshire wool and the midland metal trades, centralized workshop production controlled only a few stages of output and rarely displayed the control and discipline we associate with real "factories." Wherever possible, work was outsourced to small-scale artisans working at home who at times ran cooperatives when scale economies were important.[5] Even these early factories, then, were a compromise between the domestic system and the need to produce away from home.

Notwithstanding these precursors, the Industrial Revolution brought about factories where none were before. The transition was relentless but gradual. Most firms did not switch abruptly from the domestic system to a factory system, but continued to farm out some processes to domestic workers, until mechanization and technological complexity had sufficiently expanded to make it worthwhile to bring the workers under one roof. The cotton industry provides the best example of this mixed factory system. In 1760, this industry was overwhelmingly a domestic industry. The water frame spinning machine changed all that. Richard Arkwright's works in Cromford employed about 300 workers; he also helped found the New Lanark mills in

[2]Tann (1970, p. 3) mentions a number of large works in the seventeenth century, but designates them as "exceptional cases."

[3]The insightful biography by Flinn (1962, p. 252) calls Crowley's firm "a giant in an age of pygmies" and notes that his example of successful large-scale industrial organization was not followed until a century later.

[4]One of the largest firms was the Neath colliery in Wales. Coalmines by their very nature required a presence away from home, of course, but even there coalminers were often employed with their families and paid a piece wage. In a sense, then, many coal mine employees could be regarded as subcontractors.

[5]Thus in the woolen industry of West Yorkshire, the finishing stages of the woolen output required a powered mill and was carried out in cooperatives. Berg, 1994, p. 128.

Scotland, which employed a workforce of 1600 in 1815 (most of whom were indoor). Such huge firms were unusual, perhaps, but by 1800, there were in Britain around 900 cotton-spinning factories, of which a third were "mills" employing over 50 workers and the rest small sheds and workshops, with a handful of workers - though even those by that time were larger than households. The mule, especially after it was coupled to steam power, changed the distribution of firms quickly: at first, in the early 1790s we observe something like a lognormal in which the majority of cotton were still small firms employing at most 10 workers, with a few Arkwright-type mills of 300-400 workers. By the early 1830s, when reasonable statistics rather than guesswork and pronouncements of contemporaries become the basis of our estimates, the average Manchester mill had about 400 workers. The very large and very small firms made room for medium sized ones, between 150-400 workers. The domestic spinner had by that time long disappeared.

Some of the other branches of the cotton industry – some of which had already been in large workshops before – were also quick to move into factories: carding, calico printing, and bleaching were all absorbed quickly into factories. Weaving, however, was a different matter. Although many inventors experimented with a variety of mechanical looms, the power loom did not make its effective entry on the scene until the 1820s. Until then, the handloom weaver, operating from his own home, not only was not threatened by the factory, but actually prospered. With the rapid spread of powerlooms after the 1820s, home weaving rapidly disappeared. Many of the former handloom weavers simply joined the factories they could not beat.

In textiles other than cotton, the factories marched on equally inexorably. In
worsteds, (combed wool), spinning was mechanized early and followed the trajectory of cotton toward a rapid transition to factories; combing itself, however, proved difficult to mechanize and was left to domestic or small-scale producers until the mid nineteenth century even when its output was spun in factories. Once again, we see a "mixed" system in which some stages of the production is carried out domestically whereas others are concentrated in factories. Wool lagged even further behind since spinning of carded wool proved difficult to mechanize. In flax-spinning, large scale factories emerged with the wet-spinning process invented in France and adopted in Britain in about 1825.[6] Handlooms in linen persisted until deep into the second half of the nineteenth century. On the whole, the transition from domestic manufacture to factory was the most dramatic in textiles, but even there it took over a century to complete.

[6]John Marshall of Leeds was the leading flax-spinner in Britain and his large mill was world famous. The building was designed by an architect who based it on the single-story temple of Karnak in upper Egypt.

In other industries, the transition was less spectacular because some large-scale establishments already existed by 1760, or because for one reason or another domestic manufacturing could continue to linger on. This was especially the case in iron. The few large ironworks around 1750 notwithstanding, this was still largely a small-scale industry, with much of the work carried out in little forges adjacent to the homes of blacksmiths and nailers. Cort's great invention of puddling and rolling changed the face of the industry and in rapid time eliminated small producers from the refinement process. Some of the new ironworks grew to unprecedented proportions, such as the Cyfarthfa ironworks in Wales which employed 1500 men in 1810 and 5,000 in 1830, and the Dowlais works which were of comparable size. At the same time in the hardware and engineering trades, small firms predominated (Berg, 1994b). Large factories were rare in the metal trades of Sheffield and Birmingham such as cutleries, toymakers, armorers, nailers, bucklemakers and others, where much of the production was located in small workshops and houses, interspersed with a few larger establishments.

It is sometimes felt that the rise of the factory in which workers were concentrated under one roof, and subjected to discipline and supervision was not all that much of a break with the past. The discontinuity of the Industrial Revolution has been at times overstated. It was not the beginning of "capitalist" production - the putting-out system could be quite hierarchical and tightly controlled. Moreover, pre-Industrial Revolution manufacturing produced quite a number of organizational forms that could accommodate a variety of technical needs. For instance, it could and did practice a division of labor at a fairly high level.[7] Yet the Industrial Revolution marked the beginning of the process in which the household would eventually lose its role as the prevalent locus of production. For that to be true, it did not matter all that much whether people worked in workshops of 20 or 400 employees. The welfare and other economic implications of the change were far reaching.

2.1 *Some implications*

The rise of the modern business plant as a locational unit has given rise to enormous social changes first fully identified and described by Marx. He developed the notion of "alienation," and stressed the enormous historical significance of the emergence of an industrial proletariat, the need to form a docile and malleable labor force, and the significance of people spending much of their life interacting with strangers, subjecting themselves to the

[7]Furthermore, (Berg, 1994b) has argued that decentralized organization forms lent themselves well to innovation and that small firms that practiced "flexible specialization" were a viable alternative to the factory.

hardships of the shopfloor and the coercion of the factory clock.[8] Many modern writers echo Marx's views.[9]

The full welfare implications for the household of the rise of the factory go beyond the social phenomena Marx was interested in. They include a social cost in terms of commuting. Little is known about the frequency and average distance of commuting in the early factory days, although there are some striking examples.[10] Before urban mass transit, the only way to commute was walking, which limited the commuting distance, and led many factory masters to supply living quarters in so-called factory villages. These, however, were rare in urban areas. Technologically-driven changes in the number of hours spent commuting reduced overall economic welfare in ways not wholly captured in national income statistics since some commuting crowds out leisure. Insofar that the time costs of commuting were compensated for in higher wages, these welfare costs were borne by others, but society as a whole still had to pay the cost. Changes in commuting does not "distort" the measurement of GNP as such, but any replacement of leisure by commuting time will change welfare without changing the measured aggregates. This distortion is probably small before 1850, and relative to the growth of incomes, probably not all that large after either.[11] However, if there were a *sudden* change in commuting time, it could have significant implications for economic welfare.

A related but different welfare reduction due to the rise of the factory is the collapse of the leisure-income choice to something close to a single point. Part-time employees were rare and absenteeism was usually a cause for fines or dismissal. Under the old regime, domestic workers could choose essentially any point on the leisure-income trade-off; this freedom of choice was much reduced once workers had to submit to the factory regime. Even a combination of higher wage with lower leisure, it can readily be shown, could

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[8]It might have seemed a good idea to hire factory labor in family units just as some of the pre-Industrial Revolution industries had done, and some authors have in fact argued that this was quite common (Smelser, 1959), but others have shown that this involved only a small portion of the labor force (Landes, 1986, p. 610, n. 60).

[9]Pollard (1968, p. 195) cites Ashton's aconic comment that "there was no strong desire on the part of the workers to congregate in large establishments" as "an understatement to the point of travesty."

[10]The distances cited in *Parliamentary Papers* 1831-32 are quite striking: There are repeated mentions of workers living one full hour walking away (pp. 5, 19, 95, 98, 350, 365). The source makes it not easy to conclude how typical this was, but in any case, the time-cost of the commute represented a social cost that was rare before the Industrial Revolution.

[11]The same point is made by Nordhaus and Tobin (1973, p. 521), one of the few attempts to adjust the National Income accounts to the many ambiguities that modernization throw in its path.

be welfare-reducing if it became an "all or nothing" choice.[12] This decline was compounded by the relentless erosion of the undeniable opportunities towards *joint production* of income and household services within the home, especially as far as childcare was concerned. The loss of this opportunity for domestic multitasking will further increase the upward bias in the income statistics as a measure of welfare.

Beyond that, of course, were the nonpecuniary characteristics of the factory relative to the home. Although there was a great deal of variation in actual factory conditions, and the "dark, Satanic mills" and large coalmines did not employ a majority of the workers, it remains true that in terms of the physical environment, the shift to noisy, unpleasant, and dangerous locations that many new mills surely were, reduced workers' well-being. If factory work and life in industrial towns and villages became more onerous, risky, or disagreeable, rising real wages would have the interpretation of a compensating differential.[13] The evidence for a significant nation-wide increase in real wages, however, has been called into question (Feinstein, 1998).

For the economist, this represents something of a dilemma, since in the absence of coercion, it is not logical that workers would voluntarily agree to work in factories if it reduced their utility. In fact, of course, many workers were paid a factory or coalmine premium as a compensating differential, providing workers with benefits such as housing, schooling for their children, and even milch cows (Chapman, 1967, pp. 159-60). Insofar that this was inadequate, however, factory owners, especially in the countryside, relied on pauper children and orphans "borrowed" from workhouses.[14] Beyond that, however, the economic logic of the Industrial Revolution implied that workers might end up working in factories even if it made them worse off. The reason is that the opportunity cost of many of these potential factory employees was set by what they could earn in cottage industry. This alternative declined rapidly and by 1850 was, in most cases, no longer available. The

[12]In practice, workers of course could exercise more freedom of choice than the grim all-or-nothing regimes suggest. The frequent complaints about absenteeism, especially on "St. Monday," suggest that the conditioning of workers took generations. All the same, the evidence suggests that by the early nineteenth century, the practice of taking Mondays off was in decline (Voth, 1998).

[13]This effect has been measured in an ingenious paper by Brown (1990), who concludes (pp. 612-613) that despite rising real wages "there was virtually no improvement in living standard until at least the 1840s and perhaps the entire first half of the nineteenth century."

[14]Some of the transactions between Poor Law authorities and mill owners resembled nothing as much as slave trade; e.g., the purchase of seventy children from the parish of Clerkenwell by Samuel Oldknow in 1796 (Mantoux, 1928, p. 411). Recruiting agents were often sent to scour the surrounding countryside in search of workhouse labor, and some of these children were brought in from the other end of the country, which indicates that for some industrialists pauper apprentices were indeed a cheap and satisfactory but hardly voluntary form of labor.

factories, by relentlessly driving down the price of manufactured goods, reduced these earnings and thus forced workers (or their offspring) to abandon their cottages and seek work in the mills or emigrate.[15]

The separation of worker from household means that human capital formation follows different rules: before the emergence of the factory, the only agent who has any interest in training and human capital formation beside the agent herself was her parent.[16] After the formation of factories we increasingly observe employers taking an active interest in the education and training of their labor force. There was an obvious complementarity between the fixed capital in the plant and the human capital necessary to operate it. This was recently pointed out in an important paper by Galor and Moav (2000). There is evidence suggesting that worker training initiated by the capitalist class became increasingly important with the Industrial Revolution. The skills that were in abundant supply around 1750 were largely the skills of the blacksmith, not those of the mathematical instrument maker. The machines required levels of precision work that were scarce, even in Britain.[17]

Much of this education, however, was not technical in nature but social and moral. Workers who had always spent their working days in a domestic setting, had to be taught to follow orders, to respect the space and property rights of others, be punctual, docile, and sober. The early industrial capitalists spent a great deal of effort and time in the social conditioning of their labor force, especially in Sunday schools which were designed to inculcate middle class values and attitudes, so as to make the workers more susceptible to the incentives that the factory needed and to "train the lower classes in the habits of industry and piety" (Mitch, 1998, p. 245). At the same time, we observe a growing distinction between "firm-specific" human capital (with the factories training workers in the skills needed for the core competencies

[15]This assumes only that labor productivity in a factory setting is higher than in a domestic setting. For a formal demonstration of this general equilibrium model of the Industrial Revolution see Mokyr (1976).

[16]The skills required in the large-scale putting out industry were usually low and had few complementarities with other workers; the more skilled craftsmen were by and large independent.

[17]James Watt, often impatient with his workmen, complained that Soho people have no accuracy and that he never could leave the firm without some gross inaccuracy or blundering (Pollard, 1968, p. 206). It is less clear to which extent the new cotton industry required training: some elite spinners surely possessed skills that had to be acquired over long periods, but they tend to be exceptional (Mitch, 1998, p. 261). By utilizing the existing institutions of seven year apprenticeships – a medieval legacy – Britain's craftsmen bred their own, and supplied the needs of a growing modern sector. Factories also practiced "migration," the rotation of workers from job to job. This system of accumulating human capital probably did not work as fast and efficiently as the factory masters would have liked, but surely worked better than in any other country at the time.

of that firm) and "general" human capital such as literacy and middle class values of diligence and docility that the worker could take anywhere. For that reason, we see factory masters often subsidizing schools, but almost always students' families were expected to pay part of the cost. Factory masters signed up their workers for long contracts or indentures ranging from 5-12 years Chapman (1967, p. 173).

The transition from household to plant involved a more subtle issue of the changing nature of competition. In a classical world, in which firms produce and households consume, firms compete with each other in a Schumpeterian sense. Those who choose techniques that are inefficient in some fashion lose market share and profits and eventually shrink and disappear. This kind of Darwinian mechanism does not work very well for households. Households that employ bad techniques may have lower utility, but only in extreme cases will these bad techniques lead to their elimination in a Darwinian sense and to a survival and proliferation of more efficient techniques. An inefficient owner/manager of a large competitive firm will see his firm go under or his assets bought out and labor hired away by another. No mechanism bringing about such efficacy comes to mind when independent households are concerned.[18] Household-firms competed in various markets, but mechanisms that eliminated efficiency differences between them worked only poorly. Social learning and emulation may have led to changes in technical choices if households had a chance to observe each other very well and compare notes as happened in craft guilds. The more efficient and industrious producers enjoyed higher incomes, but they could neither grow nor rapidly expand their numbers.[19] Inefficient or lazy household-firms may not have "died" unless their inefficiency reached truly disastrous dimensions. Moreover, even if households observed differences in outcomes (in terms of higher income) between themselves and others, they could not easily distinguish between differences in the techniques chosen and pure rents (that is income variations due to differences in endowments that they cannot change). Putting all workers under one roof allowed an immediate comparison between workers of different productivities and its remediation by instruction and the creation of better incentives. Factory masters, knowing that they may go under if they do not choose the right techniques, will whip workers (sometimes almost literally) into using the most efficient techniques.

[18]In a putting-out set-up, the entrepreneurs who owned the capital and marketed the final product would prefer to employ more efficient workers if there was a substantial cost in terms of capital utilization and product quality due to lower technical ability by bad workers, and if they were unable to recognize such workers and vary their piece rates accordingly.

[19]One "Darwinian" mechanism that would work to some extent here is that very successful and able craftsmen would attract more apprentices than their competitors, and thus transmit superior skills that in the long-run would drive out inferior ones.

In the real world of economic history, things were never that extreme. Urban artisans obviously did "pool" their knowledge and compared techniques in use.[20] In the early stages of the Industrial Revolution there was a considerable variety among the practices used by early factories and the shaking out of the inefficient was an imperfect process. All the same, the rise of the factory represented a growing stringency of the competitive environment in which workers operated, and thus increased allocative efficiency and speeded up the adoption of new best-practice techniques.

3 Explanations

Why did the factory arise when it did? There are *three* main explanations in the current literature for the unprecedented phenomenon we now call the Rise of the Factory.[21] One relies on purely technical and physical economies of scale and scope, that might have caused the minimum efficient size of firms to become larger than the household. A second is in terms of the modern microeconomics of the firm: transactions costs were higher in decentralized households and the new technology changed monitoring costs and incentives to self-monitor. A third argument is that by concentrating all workers under one roof and placing them under supervision, actual labor effort is enhanced. Below, I will briefly survey each of these explanations and then propose a fourth one.[22]

3.1 *Fixed costs and scale economies*

The most obvious candidate for the cause of a shift in plant size is that the new technologies changed the optimal scale of the producing unit and introduced increasing returns where once there were constant returns. Some equipment, for purely physical reasons, could not be made equally efficiently in small models that fit into the living rooms of workers' cottages and thus required large plants: iron puddling furnaces and rollers, steam and water engines, silk-throwing mills, chemical and gas works all required relatively large production units. Heating, lighting, power supply, security, equipment maintenance, storage facilities, and inventory control, were all activities in

[20]Recent research (Epstein, 1998) suggests that the enhancement and transmission of human capital was—at least in the early stages—the main purpose of urban craft guilds. But with the growing migration of manufacturing to the countryside in the centuries before the Industrial Revolution, craft guilds lost much of this function, and more commonly acted as a barrier to innovation.

[21]It might be noted here that this question was first asked in very explicit form by Charles Babbage (1835) in a chapter entitled "On the causes and consequences of large factories."

[22]Some of what follows below is adapted from Mokyr (1998.)

which scale economies were obviously the result of technical considerations. In others they were economic such as marketing and finance. But many of these advantages were at the level of the firm, not the plant. To a large extent they had been resolved by the pre-Industrial Revolution putting-out firms. What made the difference in terms of the locus of production in this view is mechanization.[23]

Machinery and other technological changes meant that fixed costs at the level of the plant went up. As soon as fixed costs become important, the employer has an interest in supervising the workers because shirking and volatility in labor supply reduce the utilization rate of the fixed capital.[24] By the force of this argument, the rise of the factory was a wholly technological event. Of course, "fixed costs" were heterogeneous: if the main attraction was a heated, lighted room, in which relatively inexpensive equipment could be placed, raw materials and parts be supplied, and some instruction given, the most likely outcome would be set-ups in which workers rented equipment and worked on their own account and chose their own hours, as still could be seen throughout Britain in the nineteenth century. If, on the other hand, the raw materials and the equipment were valuable and complex, factory discipline (in terms of the hours worked, the effort put in, and their allocation over different tasks) would increasingly be the norm.

Information costs and incentives. And yet, this cannot be the whole story. If it were, we would see a tighter correlation between mechanization and the transition to "manufactories." Berg (1980), Cohen (1981), and Szostak (1989, 1991), among many others, have maintained that technological change and mechanization were not necessary for the establishment of centralized

[23]Long ago, Usher wrote that "machinery made the factory a successful and general form of organization. ... Its introduction ultimately forced the workman to accept the discipline of the factory" (Usher, 1920, p. 350). Landes (1986, p. 606) has restated this argument in unambiguous terms: "What made the factory successful in Britain was not the wish but the muscle: the machine and the engines. We did not have factories until these were available." Even Maxine Berg, who has argued forcefully for the viability of small-scale production until the 1830s and beyond, concludes that the transition to the factory system "proceeded at a much faster pace where it was combined with rapid power-using technological innovation" (1994, p. 207).

[24]This insight is hardly indebted to modern theory: Karl Marx, in a famour passage, cites an industrialist telling Nassau Senior that "if a labourer lays down his spade, he renders useless, for that period, a capital worth 18 pence. When one of our people leaves the mill, he renders useless a capital that has cost £100,000." Marx (1967, Vol. I, pp. 405-06). William Smith, a Glasgow cotton spinner, noted that "when a mantua maker [a typical domestic industry, employing at most 2-3 workers] chooses to rise from her seat and take the fresh air, her seam goes a little back, that is all; there are no other hands waiting on her ... but in cotton mills all the machinery is going on which they must attend to ... when there are a great number of people congregated together, there is a necessity for the rules of discipline being a little more severe ... because the profits of the master depend upon the attention of those employed" *Parliamentary Papers*, 1831-32, p. 239.

workshops, which in fact preceded the great inventions of the last third of the eighteenth century.[25] One explanation proposed by Oliver Williamson (1980), suggests that factories, by saving on transactions costs, were simply more efficient than cottage industries (whether putting-out or independent producers), and thus their rise was inexorable. Such a simplistic approach cannot possibly do justice to the historical reality (S.R.H. Jones, 1982, 1987; Szostak, 1989). After all, the domestic system survived for many centuries, and its demise was drawn out over a very long period. Cottage industry practiced fairly fine and sophisticated division of labor, and the proximity of cottages to each other make any reliance on physical transaction costs a weak reed. Industry studies (e.g. Jones, 1987) confirm the importance of mechanization and technology as a primum movens in the emergence of factories, although they rarely specify through which mechanisms machinery brought about the factory, and do not explain the emergence of centralized workshops without any technological breakthroughs.

Some answers must come from the economics of information and especially principal-agent problems. Paying workers a piece rate - uniformly practiced in putting-out industries - solves this problem if the employer can assess the quality and quantity of the final product and if there are no cross effects between workers' productivities (so that the effort of one worker does not affect the output of another). The significance of piece wages should be realized from the following table:

Table 1:
Combinations of Organizational Set-up and Location

	Domestic Location	Factory Setting
Independent Contractors	Artisans, small shopkeepers	"Manufactories," (workers renting space and equipment)
Piece Wage	"Putting-out" cottage industries	Batch production
Time Wage	Unknown in nineteenth century, cannot be monitored	Standard model, under continuous flow or strong interdependencies

[25]Berg (1994, p. 196-97), Hudson (1992, p. 28), and Szostak (1989, p. 345) point to industry after industry that established centralized workshops employing practically the same techniques as cottage industries: wool, pottery, metal trades, even handloom weaving and framework knitting. Clark (1994, p. 155) shows how certain industries—including pin making—practiced a fine division of labor in central workshops but did little to enforce discipline and punctuality. Rosenberg and Birdzell (1986, p. 186) feel that "the spirit of the times was centralizing management before any mechanical changes of a revolutionary character had been devised." Had the steam engine and semi-automatic machinery never been invented, "more and more control would have devolved upon the factory master".

The critical point is that it was not possible for capitalists to pay their workers a time wage when they worked at home, because it was impossible to monitor their input. This meant that for all practical purposes employers who wanted to pay time wages had to move them to factories (where they still had the option to pay some of the workers piece wages as well). But why would they want to?

In a classic paper, Lazear (1986) has analyzed the conditions conducive to choosing between a time and a piece wage. In addition to the standard problem of monitoring costs, Lazear points out that paying a piece wage has a sorting function and if workers are very heterogeneous in their ability, it makes - for a given output-monitoring cost - more sense to pay them a piece wage. In this sorting context, firms with large fixed costs or physical capital will pay a mixed wage, with the output-independent (time-dependent) component higher, the higher the costs of physical capital. Lazear also points out that while piece wages introduce direct proportionality between effort and payment, time wages could be and were made contingent on some minimum of effort supplied. It might be added that by paying slightly higher wages than the workers' opportunity costs while threatening dismissal if efforts fell below some level, time wages could be made compatible with optimal levels of effort.

Measuring *net* productivity in a piece-wage putting-out world ran into two further difficulties. One was that workers had an incentive to increase their earnings by cutting corners on quality and finish and make verification for the employer difficult. This is a classic problem of asymmetric information: the worker knows where he can "cheat," making it costly for most employers to monitor the quantity and quality of output, but for the simplest processes. Lazear notes that paying a time rate not only allows the employer to monitor quality through controlling what happens at the shopfloor, but he can persuade the worker that for the same level of wage and effort, she can trade-off quantity for quality to attain the combination the firm desires.

The other was that when the employer owned the capital – as was increasingly but by no means uniformly the case in the putting-out system – he needed to supervise the worker's handling his property. Embezzlement of raw materials (which usually belonged to the capitalist) was a widespread complaint (Styles, 1983).[26] The problem of embezzlement, like quality control, was one of asymmetric information; measuring the precise quantities of yarn supplied to a weaver and comparing those with the final output was

[26]See Berg (1994b, p. 226). Social control gradually invaded the domestic economy during the years of the Industrial Revolution. A series of acts passed between 1777 and 1790 permitted employers to enter the workers' premises to inspect their operations, ostensibly to curb embezzlement. Unwin (1924, p. 35) concludes that by this time "there was not much left of the independence of the small master, except the choice of hours."

itself costly, and had to be assessed against normal losses of raw material during the process of production and quality defects in it, which the employer did not observe directly.[27] When the equipment became more expensive and sophisticated, such as the early jennies that were still small enough to fit in a worker's home, employers wanted to be able to monitor how the worker handled the machines. Even when a piece wage was possible, then, it became increasingly attractive for employers to monitor input as well as output.[28]

Behind the question "will a piece wage be paid" is of course the classic Alchian and Demsetz (1972) "team production" problem: if individual contributions to output cannot be disentangled, supervision and monitoring is necessary just to make sure that the workers have the right incentives and do no shirk.[29] In factories there was the option of paying workers a time rate, which would be necessary if the marginal product of labor was hard to assess or beyond the worker's control. These time rates could then be supplemented by various incentive schemes that extracted maximum effort from workers and made him allocate effort correctly between tasks (including maintain the equipment). Yet this does not, by itself, explain the rise of the factory: why does "team production" become important after 1780 and not a century earlier? The answer must be, in large part, that the new technology required more team production.[30] In part this was due to the introduction of

[27]Introducing factories did, of course, not eliminate embezzlement altogether but made it possible for employers to set-up safeguards against it. Robert Owen (1857, 1920, pp. 79, 111) noted that when he started to work at the Lanark mills in Scotland "theft was very general and carried on to an enormous and ruinous extent. To make sufficient profits I adopted checks of various kinds to render theft impracticable ... [and] devised a plan by which losses would be at once discovered."

[28]This problem will be recognized immediately as a standard multi-task principal agent problem analyzed by Holmstrom and Milgrom (1991) who note that a problem for the firm is to allocate efforts and time of workers between their various duties. If it is difficult to measure the performance of an agent in one activity, it makes less sense to produce strong incentives for workers in another. Thus, the harder it was to monitor the way the employee treated the equipment and unfinished products he was given, the less the incentive to pay him a piece wage.

[29]A formalization of the Alchian and Demsetz problem was presented in Holmstrom (1982) who pointed out that what creates the need for a "monitor" is the fact that unobservable actions by workers lead to non-zero marginal products.

[30]Alchian and Demsetz themselves (p. 784) point out that technological development will expand the role of the firm, and add, with some historical license, that "with the development of efficient central sources of power it became economical to perform weaving in proximity to the power source and to engage in team production" and point out that with the invention of steam, the sharing of power sources made team production more important. They confuse "firm" with "plant" (a putting-out merchant was clearly a "firm") and get the history of weaving wrong (factory weaving did not come into being with central power sources as much as with the solving of the complex mechanical problems of making a functional power loom in the 1820s), yet their intuition about the rise of the factory is quite correct.

continuous flow production as in the case of the large cotton spinning mills and the Portsmouth blockmaking factory, and in part because of a finer and more closely integrated division of labor.[31] Under continuous flow, the speed of the entire production process was set by the plant manager and the interest in supervision and control of individual workers became obvious, because in its absence the speed of production became equal to the speed of the slowest worker.[32] Above all, the new technology required larger amounts of fixed capital, and the joint use by many workers of the same equipment makes the measurement of marginal contributions more difficult. The movement to factories was reinforced by consumer demand. Szostak (1991) points to the growing desire by consumers in an integrated market to purchase a product of standardized quality. Input monitoring became important, he argues, when consumers insisted on products of easily verifiable quality. Workers had to conform to lower tolerance limits on the various dimensions of the final product. This means that the employers had to worry about the variance of the final products not just because a higher variance made the measurement of mean quality more costly, but because the variance entered independently as a quality attribute.[33]

Labor effort. Marglin (1974) revived a Marxist tradition by arguing, essentially, that factories emerged when workers were placed under one roof in order to make them work longer hours than they would have if left at home. Since the piece wage was less than the marginal revenue product, he maintained, the more time workers put in, the higher the capitalist profit. This view is little more than a standard left-wing account according to which factories enabled employers to exercise more control over their workers and to squeeze more profits out of them. In this interpretation, then, technological progress is *not* the *primum movens.* Discipline and supervision in large factories in this view were not the means to adapt to a new techno-

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[31]The famous Portsmouth blockmaking machines, devised by Maudslay together with Marc Brunel around 1801 to produce wooden gears and pulleys for the British Navy, were automatic and in their close coordination and fine division of labor, resembled a modern mass-production process in which a labor force of ten workers produced a larger and far more homogeneous output than the traditional technique that had employed more than ten times as many (Cooper, 1984).

[32]Chapman, (1974, p. 470) has maintained that continuous flow was already typical of the early Arkwright-type factories, but the cotton-spinning industry may have been atypical. Batch production was still the rule in the vast majority of early factories and continuous flow processes became more widespread only after 1870.

[33]Langlois (1995) has argued that as manufacturers produced for larger and larger markets and produced a more and more standardized product, their fixed costs started involving specialized tools designed just for that such as jigs and dies that make screws and other standardized parts. In other words, larger markets and standardized output made it worthwhile to make Allyn Young's famous hammer (which, as he noted, would be wasteful to make to hit a single nail).

logical environment, but constituted the road to increased output and profits. Technological progress was a by-product of the intensification of social control. Interestingly enough, after it had been effectively demolished (see especially Landes, 1986), this argument was rejuvenated by Clark (1994). In a clever but ultimately inconclusive argument, Clark turns Marglin's view on its head and maintains that factory discipline was introduced to elicit more effort from workers lacking in self-control, so that they would "force themselves" to work harder and earn higher wages.[34] It might be added that Clark's argument only works when there is considerable fixed capital involved (since that allows the capitalist to spread his capital costs over more output when workers work harder, thus enabling him to pay them more) and insofar that the increase in fixed costs in manufacturing was due to new machinery - thus technologically determined - Clark's story too, boils down to a technological interpretation.[35]

The division of knowledge. Adam Smith famously believed that specialization and the division of labor leads to economic progress through three separate processes: the growing familiarity of a worker with the process he is assigned to; his ability to produce improvements on it once he is thoroughly familiar with it; and the savings of time involved in moving from one task to another. The idea of the division of labor proposed by Smith was further picked up by Charles Babbage who noted that specialization was not only useful for the reasons laid out by Smith, but also because workers had different inherent skill endowments and it would be wasteful for employees to carry out tasks for which they were overqualified. An optimal matching of tasks to (exogenous) ability was a key to efficiency (Babbage, 1835, pp. 175-76; Rosenberg, 1994, pp. 28-29).[36]

Whatever the case may be, the division of labor in and of itself does

[34]In his paper, Clark foreshadowed some recent theoretical work by David Laibson (1997) and others following a suggestion by Thomas Schelling (1992), which has reintroduced the issue of self-control and individual time-consistent behavior in dynamic models to economists. These preferences do, indeed show why rational agents would voluntarily restrict their choices. Much of that work has been directed at issues of saving, but there seems no reason why this idea cannot be extended to labor supply.

[35]A different interpretation of the need to discipline can be formulated in terms of a Grossman-Hart view of the firm. In a normal situation, employees own no assets and yet have to be made to perform efficiently. Because it is far from obvious that early nineteenth century workers could be made to respond to financial incentives, an element of coercion in the form of harsh discipline (especially for child labor) seems a substitute for an efficient incentive structure.

[36]A somewhat different and original explanation of the division of labor is implied by Holmstrom and Milgrom (1991) who point out that in a multi-task principal agent problem it may be optimal for an entrepreneur to make his workers specialize to make sure that they allocate their time and effort between tasks optimally rather than overallocate them to easy-to-monitor assignments.

not explain the emergence of factories. The domestic system lent itself well to a division of labor, including – when necessary – the establishment of larger workshops away from homes where some stages (such as wool finishing) could be carried out when the optimum scale made domestic production unpractical. The costs involved in moving intermediate products from worker to worker were not insubstantial, but they have to be weighed against the considerable costs of putting all workers under one roof. This ratio shifted increasingly in favor of the factory system in the second half of the nineteenth century, when continuous flow processes were introduced into more and more manufacturing processes.

Even together, then, Smith and Babbage did not wholly explain the phenomenon of specialization. The reason why firms needed increasingly internal specialization is because as time advanced, there was more and more knowledge that was necessary to operate the best-practice techniques in use. On the eve of the Industrial Revolution, it is worth recalling, modern chemistry did not exist, physics was mostly confined to cosmology and optics, and most of engineering, metallurgy, and farming (to say nothing of medicine) were closer to arts than to science. The vast majority of artisans and domestic manufacturers (not to mention farmers) practiced their trades without worrying too much about why the things they did actually worked.

It would thus be far-fetched to attribute the Industrial Revolution to "scientific progress." But it seems that economic historians have underestimated the intellectual roots of the Industrial Revolution. In a recent paper (Mokyr, 2000), I have tried to explore these roots. In brief, I argue that each technique has an epistemic base in natural knowledge, which is the minimum that has to be known about the underlying natural phenomena for such a technique to be conceived and designed. It is important to point out that there is a big difference between the epistemic basis necessary to generate a new technique and that necessary to operate one. The latter is sometimes referred to in the literature as the "core competence" of the firm. In the decades that followed the initial introduction of a new technique, it became possible in many industries to create user friendly techniques requiring little knowledge to operate, even if they required a considerable knowledge to be invented. In the limit we could devise an economy in which technology is designed by geniuses and operated by idiots, as Gavin Wright once remarked. In the early stages of the Industrial Revolution, this was probably rare: machinery was custom-made and not made of interchangeable parts, demanding in-house expertise for operation, repairs, preventive maintenance, and so on.

Whatever the case may be, the era of the Industrial Revolution witnessed a huge expansion in the knowledge base of the techniques in use. A great deal of engineering and technical knowledge had been created and was available to the progressive and energetic entrepreneurs of the post- 1815 period.

Access costs were crucial: much technical knowledge is self referential: It is knowledge about knowledge. But even if one knows that something is known, how costly is it to find out? Can such knowledge be obtained or purchased? The expansion of the epistemic base of technology meant that in an increasing number of industries efficient production required more knowledge than a single household could possess. This was realized early on: in the 1806 report to Parliament on the woolen industry, the commissioners noted that "it is obvious, that the little Master Manufacturers cannot afford, like the man who possesses considerable capital, to try the experiments which are requisite, and incur the risks, and even losses, which always occur, in inventing and perfecting new articles of manufacture, or in carrying to a state of greater perfection articles already established... The Owner of a Factory, on the contrary, being commonly possessed of a large capital and having all his workmen employed under his own immediate superintendance may make experiments, hazard speculation ... may introduce new articles and improve and perfect old ones." (*Parliamentary Papers*, 1806, p. 12).

The fixed factor here is not just resources, but the capacity of people to learn and retain. When the total amount of knowledge needed for production exceeds the normal ability of an individual to know, specialization becomes inevitable. The advantages of specialization were compounded by differences in mental endowment. In a specialized world of a division of knowledge, the smartest workers can be assigned the most complex chunks of knowledge. As long as production was simple and could be summarized in a finite number of rules of thumb, a single household could know all there was to know and effectively serve as the unit of production with all the advantages thereof. But the Industrial Revolution and the subsequent technological developments meant that after 1760 many of the production process increasingly required a level of knowledge and a set of operating procedures that went beyond the capability of the individual household.

This point was formalized and elaborated upon in a seminal paper by Becker and Murphy (1992), which suggested a new interpretation of the role of the firm. Given the limitations on what each worker can know, they maintain, the total knowledge that the firm has to possess is chopped up into manageable bites, divided amongst the workers, and their actions are then coordinated by management.[37] In addition to Smith's dictum about the

[37] A similar point is made by Pavitt and Steinmueller (1999, pp. 15-16) in the context of the knowledge *generating* activities in the firm (that is, R&D). They point out that uncertainty and much tacit knowledge require "physical and organizational proximity" that guarantees efficient coordination of the knowledge-generating and the production and marketing functions of the firm. the skills involved in this coordination are themselves tacit and hence some meetings and personal contact remains important in industries that rely on a high degree of innovation, yet this does not mean that outsourcing to individuals working normally from other locations would not be effective.

division of labor being limited by the size of the market, the division of labor is limited by the size of the knowledge set necessary to employ best-practice techniques. The point is not just that each worker knows what she needs to know to carry out her task, but that she becomes in charge of a subset of the total knowledge required so that others can ask her when needed. This means that asymmetric information is not "a problem" for the firm but an essential way for it to operate. Specialization in knowledge does not only "exacerbate the problem of asymmetric information" but it demands it (Kim, 2000). Not everyone can and should know everything. The organizational problem for the firm is to ensure that agents who possess knowledge, reveal it fully and truthfully to those who need it. Inside a plant agents knew and could trust each other, and this familiarity turned out an efficient way of sharing knowledge. Putting all workers under one roof ensured repeated interaction and personal contact provides maximal bandwidth to maximize the chances that the information be transmitted fully and reliably. As long as distance was a critical factor in information transmission, the benefits and costs of proximity have to be traded against each other.

The model predicts that when the minimum core competence is small, plants can be small and coincide with households; when it expands it will require either a sophisticated and efficient network for the distribution of knowledge or a different set-up of the unit of production. In an age in which direct contact was the main technique of sharing information, access costs are minimized within a single plant, especially when the exact description and formalization of the technical details of production were more difficult than demonstration and emulation. Factories thus served as repository units for technical knowledge and reduced access costs to this knowledge for individual workers. The model further predicts that when knowledge can be shared and trusted among people by means other than personal contact (say, through electronic communication), firms may survive, but large plants may become less necessary.

The replacement for the domestic system was the large-scale plant/firm which brought the workers under one roof, made them specialize, and coordinated the exchange of knowledge between them. In addition to unskilled laborers, such plants employed experts: engineers, mechanics, chemists, foremen, and just dexterous, clever, employees who could fix things that were broken and knew which tools was needed for each task. Often, of course, this expertise was supplied by the "master" or entrepreneur himself. James Watt worked in Boulton's plant in Soho and personally supervised the production of engines. In an age in which there were few alternatives to the exchange of information, such direct contact was inevitable if the firm was to practice a division of knowledge. Furthermore, as Babbage already pointed out, because some of those inhouse experts could service a large number of other workers, it inevitably created further economies of scale.

The Becker-Murphy framework as well as the asymmetric information framework point to centrality of the relative cost of moving knowledge relative to moving people. It was costly to move workers from their homes to the factory, but even costlier to supervise, coordinate and instruct them at home. These relative costs are only one factor in determining the location of labor, but they demonstrate the extent to which exogenous changes in information technology and transport technology affect the place where work is carried out.

Moreover, knowledge has to be transmitted not only across space but also across time. The reason is that like in all good evolutionary models, knowledge is carried by carriers who are subject to wear and tear. Unless they have an ability to pass this knowledge on to new generations, it will go extinct. The pre-industrial economy had two parallel systems to accomplish this: from parent to child, and from master to apprentice. Such a system will work well when the knowledge is relatively limited and does not change much between generations, and when there were few gains from applying the knowledge in one field to another. By 1750 these assumptions were beginning to be eroded in more and more industries, and by 1850 they had become obsolete in many industries. The plant served as a unit that transmitted this knowledge over time: new hires learned the trade "on the job" by direct contact with veteran workers, observation and emulation. Hence the practice of learning through "migration" I noted above. With the formalization and codification of much technical knowledge, this role has been eroded to some extent, but as long as tacit knowledge was a large enough component of the firm's competence, its transmission over time remained a main function of the plant (Howells, 1996).[38]

The acceleration of technological progress placed the domestic workers at a disadvantage. As new techniques were becoming available after their learning stage in the life cycle was completed, it would be far more costly for them to keep up than it would be for a large plant. The diffusion and implementation of new techniques to a group of workers in the same building was faster and cheaper than if workers stayed in their homes, since this helped to avoid duplication and above all, workers taught each other. Workers with a comparative advantage in learning (often negatively correlated with age) might pick up new techniques first and help spread them. In an industry

[38]Pollard (1968, p. 124) notes the change in managerial and organizational requirements that accompanied continuous technological change. He regards the improvements in management as "over and against" technical changes and does not fully realize the direct causal connection between the two. And yet modern research establishes exactly that: there was a strong and direct complementarity between organizational and technological change. See Geraghty (2000) for an elaboration on how organizational change enhanced the benefits of technological change and vice versa.

of household-sized, self-contained cottages, such diffusion mechanisms would be more costly.[39]

It could be argued that much of the knowledge that firms relied upon was codifiable and could be looked up in the ever-increasing stream of technical manuals, engineering textbooks, and encyclopedias that became available during this period and could be accessed or purchased from external sources (Mokyr, 2000). Moreover, interfirm flows of knowledge obviously took this form. But much of what the new technology required was uncodified or "tacit" knowledge that was hard to buy, sell, or obtain from books and periodicals.[40] Moreover, access to codified knowledge required uncodified knowledge consisting just of knowing that it existed, where to find it, and the ability to read, understand and apply it. These were all by and large tacit skills.[41] Such tacit knowledge was costly to acquire as a separate entity, and large plants could train or hire specialists who possessed it and thus were better settings for easy access than individual households.

Modern economists in the traditions of evolutionary economics and organization theorists treat the firm as a single unit that "knows things."[42] Firms have "corporate core competencies" and "organizational practices."[43] The point I want to make turns this argument on its head: the optimal size of the firm (or plant, to be accurate) is a function of the relative efficiency with which knowledge flows inside a firm relative to between firms, and the total amount of knowledge necessary to run a best-practice operation in a competitive world. For a given communications technology, the rapid growth of knowledge necessary to use the newest techniques (let alone improve them) meant that household-sized firms became impractical. All the same, the technological and informational trade-offs between different forms of organization were sufficiently multi-dimensional to allow the survival and

[39]In a putting-out context, keeping technological secrets was of course impossible and indeed some factories were set up just to keep industrial processes secret (Chapman, 1967, p. 39).

[40]The original source on codified vs. tacit knowledge is Polanyi (1962). An enlightening application of the concepts to economics is Cowan and Foray (1997) and Cowan, David and Foray (1999).

[41]This point is well-made by Cowan and Foray (1997) who point out that tacit knowledge is needed to access codified knowledge and that in many ways the two are complements, not substitutes.

[42]One of the most perceptive of these theorists, Paolo Saviotti, writes for example that "Firms scan the external environment in order to detect ... possible pieces of external knowledge which are useful for their productive purposes. When they find such useful pieces of knowledge, they have to internalize them ... the capacity of firms to learn and internalize knowledge depends on the firm's previous knowledge." (Saviotti, 1996, p. 175.) Firms have what he calls "knowledge bases" which is the collective knowledge used by the organization.

[43]Much of this very large literature is summarized ably in Pavitt and Steinmueller, 1999.

coexistence of very different forms of organization. The large prototypical Chandlerian factory was just one of these forms. Another is a cluster of much smaller firms working in close proximity exchanging knowledge through informal cooperative channels (Piore and Sabel, 1984). As Sabel and Zeitlin (1985) and Scranton (1997) have emphasized, the picture of mass production of standardized output produced by Chandler and others ignores the many industries that needed the flexibility and agility of specialized production.[44] Large factories and domestic artisans were only extreme forms of industrial organization: in many parts of Europe, such as Lyons, Sheffield, and the industrial districts of Northern Italy, complex networks are observed in which homework and factories are mixed and combined in a variety of forms.

The large plant/firm in this set-up is thus a substitute for the incomplete markets in technical knowledge.[45] This is not to say that such markets did not exist at the time. Britain in the Industrial Revolution had consulting engineers, instrument makers, machine-tool producers, and a variety of independent inventors and mechanics of whom John Smeaton and Joseph Bramah were the most famous, who could be and were hired to dispense advice. Engineering and other specialized expertise, inevitably, were purchased by firms when inhouse knowledge was inadequate. The way in which the entrepreneurs of the time did this was either to hire specialists such as the consulting engineers working for Boulton and Watt for a specific task, or to subcontract out work.[46] One of the best examples of such outside professional consultants were the famous British "coal-viewers" who not only advised coal mine owners on the optimal location and structure of coal mines but also on the use of the Newcomen steam pumps employed in mines in the eighteenth century (Pollard, 1968, p. 152-53). Civil engineers was a term coined by John Smeaton, who spent much of his life "consulting" to a large number of customers in need of technical advice. At first civil engineers were mixed up with mechanical engineers, but with the proliferation of machinery and engines, independent mechanical engineers grew separate.[47] All the same,

[44]Some of these firms were quite large, others were medium and small. As late as 1923, Scranton shows, "speciality production" employed only slightly fewer workers than "routinized" (mass) production. There is no evidence in Scranton's work that much of this speciality production operated anywhere but in plants and factories that were considerably larger than households, but his work is an antidote to the view that in the late nineteenth century Chandlerian high "through-put" mass-production became the rule.

[45]The notion that the role of firms is to be above all a *locus* for specific and tacit knowledge has been proposed by many writers in the so-called neo-Schumpeterian school. For examples, see Saviotti (1996); Antonelli (1999); and Nooteboom (1999).

[46]The mechanics trained by Boulton and Watt at Soho were sought all over Britain for their expertise. Apprenticeship there was "a recommendation to any firm" and only they knew how to use the special Soho slide rule (Pollard, 1968, p. 207).

[47]The list of great mechanical engineers after 1815 includes some of the inventors that sustained the technological momentum of the Industrial Revolution: William Murdock,

such consultants were of limited use not only because they possessed general knowledge when often firm-specific knowledge was needed, but because of the issues of credibility and trust involved when hiring expertise.

For many of the tasks at hand, then, this over-the-counter knowledge was not suitable. Technical knowledge, then as now, combines the understanding of general relations and principles with local problems, specific to an industry, to a product, and to a set of routines that a firm has adopted. The more specific and local these technical routines were, and the more tacit the knowledge was, the more production had to rely on an inhouse supply of expertise. The Becker-Murphy idea of knowledge-pooling becomes increasingly applicable. Even in services, the division of knowledge became more common: physicians were attracted to hospitals where expertise could be pooled despite the relatively high codifiability of much of medical knowledge. Lawyers, architects, and teachers formed larger units in part for the same purpose, or created professional associations and cooperatives that did the same.

4 Beyond the industrial revolution

In the decades that followed the Industrial Revolution, the process that sprouted in the years after 1760 came to its full fruition. As noted earlier, the concentration of workers under one roof depends on the ratios of costs and benefits of moving information relative to that of moving people. Before 1850, these costs changed little, and the emergence of the factory as described above was due primarily to changes in the benefits due to changes in the production technology. While these changes continued at an accelerated rate during the so-called second Industrial Revolution after 1860 or so, there were some major developments in the technology of moving people and information. The age saw some breakthroughs in communication and information technology: the telegraph and later the telephone, as well as a variety of management devices that facilitated the flow of information inside the firms, such as pneumatic tubes, mimeograph machines, public address systems, and typewriters.[48] All the same the preponderance of productivity gains were in the movement of people: trains, streetcars, bicycles and

one of the inventors of gaslighting; Richard Roberts, the miraculously gifted inventor of the self-actor; Arthur Woolf, the inventor of the compound steam engine; Henry Maudslay, the first to apply mass production to the production of wooden gears and pulleys for the sailing vessels of the British navy, and the Brunels, shipbuilders and engineers.

[48]In fact, as Lamoureaux, Raff, and Temin argue, the improvements in communications before 1914 made it possible for firms to distribute their output in more remote areas and exploit economies of scale and speed by concentrating production in large plants. This essentially Chandlerian interpretation abstracts from the complex relationship between mass production and the flexible specialization of their suppliers or other firms catering to more specialized needs.

internal-combustion cars clearly reduced the costs of moving people relative to moving information.

Production technology continued to favor large units. The Chandlerian firm, as it is often thought of, came to the fore in the closing decades of the nineteenth century and technical factors were paramount in its emergence. Among these factors were the development of railroads which became not only the standard model for the next generation of large firms, but also created ever larger markets for standardized products. In many other industries associated with the second Industrial Revolution such as steel, transportation, and chemicals, small and household-sized plants were simply impossible. Moreover, the growing modularization of manufacturing, involving the mass production of products based on interchangeable parts, and the use of continuous flow production on assembly lines made the large-scale production plant, whether identical to the firm or not, inevitable in many industries.

Simple technological factors increasing minimum efficient scale, however, are not the entire story. For one thing, *some* technological advances reduced optimal size or at least flattened the cost curves considerably. The most important of these was electricity, which made power supply less bulky and allowed small, household-sized firms access to power on the same terms (disregarding quantity discounts) as their large scale competitors. But other inventions pointed in the same direction. In transportation, the growing optimal size of ships and the obvious scale economies of railroads have to be weighed against the democratization of transportation through bicycles and cars which allowed household sized producers to sell transport services.

The transition was thus more gradual and complex than mass-production enthusiasts have allowed for. Studies of firm size during the second Industrial Revolution have noted that very small-scale business still had considerable life in it until deep into the nineteenth century.[49] The statistical difficulty that mars this debate is that most industrial and population censuses did not count people working at home or in little workshops attached to it (what the French census, the exception in this case, called *isolés*). The only country that reported the number of such workers with accuracy was France. The 1906 French census estimates that in manufacturing, about 33 percent of the manufacturing labor force in France worked in isolation, which to a large extent must have been in workers' homes.[50] The German Industrial census of 1895 reported a total of 1.88 million workers who worked by themselves, out

[49]The British census of 1851 demonstrates that the household-sized firm was far from gone: of the total number of masters (129,002) who made a return, over half (66,497) employed five men or less, of which 41,732 employed nobody but themselves. The 1871 shows very similar returns. Moreover, these returns were incomplete and without question understated the number of very small and one-person firms (Musson, 1978, p. 68).

[50]A summary of the proportion of manufacturing workers by industry in France in 1906 is provided in the chart.

Industry	Home-workers (1000's)	Workers away from home	Percentage home workers
Food Processing	37.2	293	11.3
Chemicals	1.4	116.9	1.2
Rubber and paper	2.6	78.1	3.3
Printing	5.2	91.1	5.4
Textiles	162.4	686.1	19.1
Apparel making	890	441.8	66.8
Straw and baskets	13.6	19.6	41.0
Glass and pottery	3.1	153.1	2.0
Stone-cutting	12.9	24.7	34.3
Leather	122.2	155.3	44.0
Wood and Carpentry	200.5	361.6	35.7
Iron and Steel	0	73.6	0
Metalwork	93.7	552.5	14.5
Fine metals and Jewelry	4.5	23.9	15.8
Total	1,550.0	3,071.5	33.5

Source: France (1910), pp. 188-193. The computations refer to workers "travaillant isolément" and those in firms employing more than one worker, and leave out the category of *chefs d'établissement*. This tends to understate the number of homeworkers, since many of those "bosses" were small-time artisans employing apprentices or servants.

of a total "trade and industry" (*gewerbe*) employment of 10.54 million (17.8 percent) and a manufacturing employment of 7.52 million or 25 percent. [51]

Undercounting and inconsistent definitions by statistical services have led to considerable confusion on the average size of firms in the industrialized parts of Western Europe. This confusion was sorted out by Kinghorn and Nye (1996) who note that once we correct for these omissions, Germany's reputation as a nation of giant, technologically progressive plants is shown to be undeserved. Although their adjustments for these omitted firms are based on some carefully spelled-out assumptions, they are the best estimates we have. They compute that in the decade before World War I, 95 percent of all German industrial establishments still employed 1-5 workers and that these firms employed 67 percent of the work force. In the United States, the proportion of such firms was smaller (91 percent) and they employed 33

[51]These numbers reflect probably serious undercounting. More detailed data for Baden show that one worker in six worked in plants in which there was only one worker present. I am indebted to Dr. Joerg Baten of the University of Munich for making these data available.

percent of the labor force.[52] Much like what I am arguing here, Kinghorn and Nye conclude that "the size of an enterprise is a response not only to the demands of a narrowly defined production technology but also to organizational considerations." Yet such "organizational considerations," too, are clearly a function of technology, if not the production technology of the firm itself, then the technology it uses for management to communicate with workers, with outside suppliers and customers, and workers to communicate with each other.

Yet as I argued before, the changes in the cost of moving people about set the numerator of the ratio of moving people vs. moving knowledge. As a result, between 1850 and 1914, the concentration of workers in large factories, department stores, large offices, and similar "mills" continued apace.

5 A contemporary perspective

A recent heading in *USA Today* (July 5, 2000, B-1) states that "Many Companies [are] Kicking the Bricks-and-Mortar Habit" and proceeded to describe a list of firms where staffers work from their homes and meet only a few times a year. Conference calls, email, and the internet have begun to replace the water cooler and the meeting room, and the comfort of the living room is threatening the corporate cubicle.[53] Cairncross, in her sensible and informed book (1997, p. 234), declares that "the falling price of communications will affect where people work and live. The old demarcation between work and home will evaporate." The term "tele-cottages" (coined by futurist Alvin Toffler in 1980) which has cropped up in describing this phenomenon is particularly apt, because it implies the historical connection to a pre-1750 past.[54] What has happened in recent years is that the relation between distance and the cost of transmitting information has weakened. This change is not just due to one factor: the internet is only one factor in this story; the sharp decline in the cost of long-distance phones and the explosion in the use of cellular networks is another.

[52]The French census of 1906 carries out a similar exercise, and compares average firm size between different countries.

[53]Lamoureaux, Raff, and Temin (2000, p. 46) point out that the internet's impact on specific coordination mechanisms will be profound, but they focus on its role in goods markets, not the labor markets or communications that involve the exchange of technological as opposed to commercial information.

[54]The argument I am making here about f actories parallels the argument made about the future of cities. Gaspar and Glaeser (1998) and Mokhtarian (2000) point out that face-to-face communications are in many cases a *complement* to long-distance contact, and that cities may well survive modern information technology. I should add, perhaps unnecessarily, that even though the Industrial Revolution set into motion an unprecedented urbanization movement, large urban concentrations of course predate the rise of the Factory.

The notion that "distance is dead" is of course not to be taken literally. Even if people work at home, physical goods still have to be moved and certain services still need to be provided *in loco*, although technology will determine to what extent "virtual" activities will replace physical presence. It is far from clear that the sharp decline in communications and information-processing costs reduce or increase the economies of agglomeration. Evidence for the decline of the economies of agglomeration due to the internet and lower phone rates so far is very mixed. In a global sense, the assumption that travel and telecommunication are substitutes seems at least questionable (Mokhtarian and Salomon, 2000) and at some level they are obviously complements.[55] Moreover, travel has a high income elasticity and as new technology generates growth, the demand for travel is likely to increase. There is hence some justified skepticism whether telecommuting is the panacea for traffic congestion (Mokhtarian, 1997, 1998, 2000). As Couclelis (2000) has argued, the rapid improvements in information processing have led to a fragmentation of activity, in which work is increasingly carried out in smaller time units, interspersed with leisure activity and at times multi-tasked with it.

All the same, much work will be capable of being performed outside the rigid confines of the workplace. The interest in telecommuting and working at home is not new. Kraut (1989) describes some of its advantages and possible drawbacks before the appearance of the Internet.[56] The "factory" as a system is in retreat not only as a central location where people have physically to go to, but also as a time-organizing institution in which work begins and ends at given times and the lines between leisure and labor are firmly drawn. Instead, work is dispersed over space as well as time, allowing workers to calibrate their trade-offs more precisely. The welfare implications of homework are the mirror image of the costs of the factory system: less commuting, more flexibility in the leisure-work trade-off, and the ability to combine work with household-services production.[57] For many workers the freedom to design and control the parameters of their physical work space

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[55] As Mokhtarian and Salomon point out, the cellular phone is by construction a complement to human travel.

[56] Kraut's pessimism about the future of the option to work from home was based on his assumption that firms and organizations need to coordinate work and thus require co-presence, and that home based employment is largely to be found in occupations where the need for such coordination is low. He felt that such "routine" jobs are quite rate, and did not address the possibility that information technology might make co-presence unnecessary for a large number of other jobs. The sharp decline in communications costs and quality was not anticipated even by experts.

[57] In this respect, however, there is a profound asymmetry with the demographic conditions in the nineteenth century, when single-headed families with small children were rare.

may be equally important.[58] The direction technological progress has taken in the past twenty five years should make a partial return to household-production thus quite logical. For one thing, the *relative costs* of sending and receiving information vs. the costs of moving people have fallen sharply. The full costs of commuting (including time) have not declined. City and suburban highways are about as congested as they were two decades ago and public transportation has not improved substantially. To be sure, some improvements have made the commutes more pleasurable (e.g. better car stereos and walkmen, airconditioned cars) or more productive (through cell phones and laptop computers). Yet on the whole this entire sector has shown comparatively little technological progress. On the other hand, the ability to store, manipulate, and transmit information keeps expanding at a dazzling rate, and the connections between private homes and other homes and businesses have improved in quality and speed as dramatically as their price has plummeted. Ever faster and cheaper access to huge stores of knowledge has shown little evidence so far of diminishing returns. In some sense, a worker whose work consists largely of reading a computer monitor and interacting with it, could be located practically *anywhere*. At the same time, the large number of married women and single head-of-households in the formal labor force makes the opportunity costs of working away from home in terms of housework jointly produced with income particularly high.

A large and rapidly growing literature on telecommuting discusses the prospects of this movement taking hold and it seems a reasonable speculation that the pendulum of the "unit of production," after two centuries, is slowly swinging in the other direction. Exact numbers are hard to come by, and estimates differ from source to source. The 1990 census reported that 3.4 million workers aged 16 and above worked "only or mostly at home" (Russell, 1996). In 1997, it was estimated that the "number of telecommuters" in the US was about 11 million.[59] Recent estimates put the number of U.S. based employees who were commuting at some time in 1999 at 19.6 million, but far fewer actually telecommuted on each given day.[60] In addition, there

[58] One telecommuter reports that she has just "created the right atmosphere for herself" in her home office, with the TV on at a low volume so that it feels as if there are people in the room with her. *New York Times*, November 2, 2000, p. D-8.

[59] The estimate was based on a survey commissioned by a New York market research company FIND/SVP, cited by "Telecommute America" a website maintained by AT&T. This figure is also quoted by McCune, (1998). A recent estimate of the International Telework Association and Council reported that 16.5 million (12 percent of the labor force) now work at home at least one day a month and 9.3 million of these worked at least one full day at home. Cf.http://www.telecommute.org/twa2000/ research_results_key.shtml.

[60] Khaifa and Davidson (2000). Simulations carried out by Mokhtarian (1998) suggests that 6.1 percent of the workforce may be currently telecommuting, with 1.5 percent doing so on any given day. More recently, Mokhtarian has put the number of telecommuters at about 8 percent *not* including independent home-based businesses (Professor Patricia

are 21.4 self-employed homeworkers (Miller, 2000). The distinction between telecommuters and independent contractors is getting rather murky, and with the growth of a just-in-time labor force, separate statistical estimates of the two will become hard to interpret. For my present purposes what matters, above all, is where workers spend their time at work. Recent survey data clearly suggest that all over the industrialized world, teleworking is catching on.[61]

Just as the Industrial Revolution did not quite create factories *de novo* but turned them from a rarity into the normal way in which production was carried out, it seems clear that the movement away from "factory-settings" will eventually run into diminishing return and that the economy will remain a mixture of work at home and work away from home. Certain industries and services, from food processing to dental care, will inevitably require a *physical* presence. But the weights will change significantly, and such a transformation, much like the movement in the other direction two centuries ago, will be largely technologically-driven, depending both on the production technology itself and the information technology used to communicate with them and monitor them.

The welfare implications of the decline of the factory go beyond just computing the time-cost of commuting and concerns the way we define input and output, efficiency and productivity. The commuting costs in terms of *time alone* in the US nowadays is estimated at about 30 billion person hours at an estimated cost of $320 billion. The additional costs in terms of resources and environmental costs are at least as large. The inefficient utilization of space, pointed out by Cairncross in the quote on top of this paper is another cost. Needless to say, there is little evidence to date that any of these costs have been reduced. All we know is that in the century and a half after 1750, these costs were gradually imposed on industrializing economies. They are dwarfed, of course, in comparison with the enormous gains made in income per capita, but that is not to say that if these costs were reduced rather quickly, they should not be counted as gains.

Whether they are large or small, these costs should be included in our national income accounts, but they rarely are. The purchases of transportation services needed for getting to work are treated as consumption. Commuting time does not enter into GNP calculations but is treated as leisure (and thus

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Mokhtarian, personal communication). More definitive figures will have to await the results of the 2000 census as well as a sensible definition of what exactly is being counted.

[61]The leader in teleworking appears to be Finland with 10.8 percent of its labor force telecommuting at least once a week, followed by the Netherlands with 8.2 percent. See http://www.telecommute.org/twa2000/research_results_key.shtml. According to a recent estimate for Britain, 1.5 million workers now define themselves as "technology-dependent homeworkers," up from 1.2 million a year ago, almost 5.5 percent of the workforce. See http://www.analytica.dial.pipex.com/twstats00.

added nowhere). From a welfare point of view this is mildly absurd, and although economists have long recognized this, the treatment of these items in our national accounts remains an open issue. A considerable amount of time spent on "leisure" is nothing of the sort but is spent as an intermediary cost toward production or consumption. While national income accounting does not actually subtract these costs from output, there can be little doubt that in principle it should do so, to preserve the notion that intermediary inputs should be subtracted because aggregate output is a net measure.[62] The new-economy pessimists who fail to see much evidence of a gain in productivity should keep in mind that the numerator of all productivity measures fails to capture some of the most important effects of the new technology.[63] In short, commuting - much like shopping - is a "friction" that drives a wedge between total output as a measure of *effort* and as a measure of *welfare*. Hence, a sharp increase in telecommuting and telecottaging would have clear-cut welfare effects but would appear nowhere directly in our national accounts.

To be sure, telecommuting is still a long way off as an economy-wide phenomenon, and many of the people who can work from home do not do so all the time. Predictions on how many people will be telecommuting in the future have a very wide range and critically depend on assumptions about changes in the costs and efficacy of data transmission.[64] Changing technology will not necessarily eliminate the workplace as an institution, but will make commuting to work increasingly optional and part-time. The unbundling of "going to work" from "working" is unambiguously welfare-improving: it will separate those whose net marginal utility from going to work exceed the costs from others who commute out of necessity.[65] It could be argued

[62] Kuznets (1971, pp. 7-8) already pointed out that the changing boundary between the costs of producing income and that income itself impart an upward bias on the long-term series of national product as measures of economic well-being.

[63] This particular aspect of Information and Communications technology is often overlooked by the new-economy-skeptics such as R.J. Gordon (2000a, 2000b) who maintains that this technology is less dramatic than the great breakthroughs in steel, electricity, the telegraph, and indoor plumbing of the late nineteenth century. Yet the computerized access to large stores of useful knowledge and the ability to observe, coordinate, and monitor production activities taking place far away can restore the home as a location of work, with all the concomitant social and economic ramifications.

[64] Mokhtarian (1998) decomposes the proportion of telecommuters the intersection of those whose jobs are amenable to telecommuting, those who prefer to work at home, and who are not prevented by inertia or fear. Over time, however, these proportions cannot but go up. Not only that more and more workers will end up in the "information sector," but more and more of these jobs become sufficiently integrated with information technology to raise the proportion of jobs that can be done from home.

[65] As Cairncross (1997, p. 237) predicts, the office will become a "club" where people congregate for networking and gossip, where firms motivate workers and embue them with loyalty to the firm, much like the early capitalists, only doing so with the help of health clubs and "retreats" rather than religious and moralistic preaching.

that the factory or office provides what one might call a "tavern effect." The medieval tavern and the modern pub provided the social institution in which people who worked apart got together and interacted. Maybe the last thing an economy in which loneliness is already a national affliction, and in which people, in Robert Putnam's term are "bowling alone" is to get rid of the workplace, with its watercoolers and cafetaria to compensate for the cubicles. The simple response to that is that people in need of social interaction can still arrange to meet for lunches or conversations at places of their choice, in which they control the timing and place. Community life has not done well in America in the second half of the twentieth century, but perhaps the reason is in part that community life and the workplace are *substitutes*, competing for the same time and serving similar needs. If the workplace and the commute were to claim less time and effort, people might reinvent the social institutions we associate with life before the Industrial Revolution as well as create entirely new forms of social interaction, as witnessed by the growth of email pals and internet chatrooms.

Most scholars looking into the issue agree that there is considerable heterogeneity amongst workers, and by allowing them to sort themselves according to their preferences, aggregate welfare must increase. In addition, workers can, of course, mix: they can go to the office on odd hours, avoid rush-hour traffic and bad weather conditions, stay home to attend a domestic need, and so on. Finally, to repeat, some level of multi-tasking is feasible when working at home. Babysitting and cooking are two activities that can be thought of as compatible with simultaneous work but the advantages of such jointness should not be overstated and many employers of telecommuters demand that small children be placed in child care. A reasonable question to pose is whether the total full output of a worker watching a child is less or more than a worker away from home concentrating fully, and whether employers can adjust their payments for the reduced but still positive productivity of a mother. Switching to some kind of piece wage might resolve this, much as it did before the Industrial Revolution. An increase in *flexibility* of hours away from home is probably as important for parents and homeowners as the actual numbers (Humble et. al., 1995). An increase in the technological opportunity to telecommute will thus allow an increase in housework at little or no costs in terms of "real" output. Again, however, our convention of *not* including housework in our measures of National Income means that any such change will be welfare-improving without registering in our national income accounts.

The degree to which a post-industrial economy will return to a home-production economy, much like the way we arrived there, will be determined by technology. It seems natural that some jobs lend themselves to telecommuting and others do not (Handy and Mokhtarian, 1996). But that is conditional on the continuous progress of technology, especially on the supply of bandwidth. If current trends continue, it is likely that few jobs will be immune from radical changes in location and the geography of labor supply. This is not to say that face-to-face contact will disappear. If communications techniques can be devised which provide a "virtual meeting" of acceptable quality, location may become indeterminate. Until then, just as the emergence of the factory system in its early days produced a "mixed system" in which a single firm employed both factory workers and domestic workers, thus our economy might find such a combination attractive, perhaps through workers who work at home 3 days a week and go into the office the other two.

How do the four causal roots of the emergence of the factory discussed above perform in analyzing the impact of modern technology on the future of the workplace? Economies of scale at the plant size have not been eliminated, but due to increasing automation, robotization, and the substitution of capital for labor, fewer and fewer workers are employed in manufacturing, and the remaining are increasingly monitoring and controlling production through automated processes. Some scale effects are weakened by modern information technology: inventories can be kept at lower levels, and the advantages of mainframe computers, once the sole prerogative of large firms, have melted. While it seems unlikely that wholly robotized factories, supervised by remote monitors are in our near future, the number of workers whose physical presence on the shopfloor is required has been declining.[66] For services, a similar phenomenon becomes increasingly visible on the horizon. The twentieth century witnessed the demise of the household-sized Mom-and-Pop corner stores, to be replaced by large-scale department and specialty stores. The current trend toward e-tailing may well encounter some teething problems, but if it continues, there is little in the industry outside warehousing and shipping that cannot be outsourced to independent employees working from their homes. The same holds true for banks, law firms, insurance companies, and higher education.

[66]Pavitt and Steinmueller discuss the options of "informatizing the factory" which must eventually spell the decline of the importance of distance there as well. The use of so-called intelligent agents that control robotized operations may sharply reduce the number of workers present on the shopfloor. See "Thinking Machines," *Business Week*, Aug. 7, 2000, pp. 78-86. An example is VEC (Virtual Engineering Composites) which allows the manufacturing of molded products through internet remote control. this technology allows the production of virtually any molded product anywhere with a minimum of labor present. See "The Revolution in a Box," *Time*, July 31, 2000, p. 30. Another example is a new tire-making technology introduced by Pirelli known as MIRS (Modular Integrated Robotized System) in which 125,000 tires are produced a year by an automated system monitored and run by three white collared employees behind their computers (*Le Monde*, July 15, 2000, p. 13).

The monitoring of effort put in by workers is trickier. The new technology will require one of two things: the ability of firms to monitor a worker's productivity, or when that is not feasible to be able in some way to observe what the worker does even if she is not in the same location (say, through remote closed-circuit digital cameras). Improved information technology should make measuring output easier and thus reinstitute piece wages ("tele-piece-rates"), that is, subcontracting and payment per project. The ability of employers to monitor remote workers by electronic means may help solve other monitoring problems. Thus the employer can observe from a distance how many hours a worker has been online, which activities were carried out, and how the work has been performed. This will make it possible for employers to pay a time wage to domestic workers if necessary, removing one of the most potent reasons for factory-settings. Modern information technology is thus a large step toward reducing the information and transaction costs that made "firms" necessary in the classic Coasian formulation. In other words, the problem of a principal-agent problem requires *asymmetric* information, assuming information technology to be given. Insofar as modern information technology "symmetrizes" the distribution of knowledge inside the firm, it may make the organizational structures devised to cope with asymmetrical information less necessary.

The Marglin-Clark view of factories regards them as places where workers are controlled and disciplined so as to increase their work-effort and productivity. It seems likely that in the twenty-first century such problems of motivation will be less of a problem because the conditioning that makes workers self-motivated is provided through the education system. This will not work for all, but the firms will have to learn to sort workers into those who can be relied upon to work hard enough in a home setting.[67] What little anecdotal evidence there is points uniformly to an increase in productivity resulting from telecommuting.[68] It is hard to know what such increases reflect precisely. Some of it must be simply selection bias: the workers most likely to benefit from telecommuting should be expected to be the first to switch. Other effects may be a reduction of fatigue and tension caused by

[67] McCune (1998) argues that a home office tends to reinforce an employees tendencies: it will make a workaholic labor harder and longer and give a procrastinator ample opportunity to delay work. Some firms have recently taken a more skeptical view of telecommuting "believing that telecommunting causes resentment among office-bound colleagues and weakens corporate loyalty." See *Wall Street Journal*, Oct. 31, 2000.

[68] The estimates tend to be all over the map. At Nortel Networks, productivity increases were estimated at 10% (Strickland, 1999). Humble et. al., (1995) report a range of 10-200 percent with the mean at 30 percent which is consistent with the survey used by DuBrin and Barnard (1993). McCune (1998) reports productivity increases ranging from 4 to 25 percent. All these figures are based on small samples and suffer from poor controls and selection biases.

commutes or fewer distractions by fellow workers. More detailed information about relevant variables such as changes in absenteeism and turnover rates is unavailable. All the same, even if it turns out that productivity and related measures are not much improved by a change in location, the increase in total social welfare due to a reduction in friction costs is enough to make it significant, to say nothing of nonpecuniary aspects of work.[69]

Finally, the function of the plant or office as a unit in which knowledge is divided and shared has been widely discussed in the business literature.[70] It seems plausible that if employees mostly communicate with each other electronically anyway, there may be little point in making them drive to work and putting them in little cubicles next to each other. But things are not quite that easy. For one thing, in addition to ease of access, proximity in a plant or office created personal familiarity and thus conditions of trust and believability. There is always a role for body language, intonation, and general demeanor in human communications.[71] Even with vastly improved communications, for many purposes direct personal contact with in-house experts may still be necessary. All the same, while much of our ICT revolution was born in industrial districts such as Silicone valleys, the next stage may be the virtual industrial district, a network of workers all over the globe.

The amount of personal contact relative to long-distance communications depends on the ratio of codified to uncodified (tacit) knowledge. If the new information is increasing codified, as Cowan and Foray (1997) suggest, it may well be the case that access through impersonal connections may render much personal physical presence unnecessary. It is true, of course, that in order to access codified knowledge, we need the codebook, and the knowledge of the code itself may be largely tacit. Improved access to technological knowledge may make it advantageous to produce more widely accessible codebooks (Cowan, David, and Foray, 1999). But modern communications and search engines not only permit quick and easy access to codified information, it also makes it easier for agents to locate and hire people who possess the tacit knowledge that interprets the codified knowledge. Such people do not have to be employed by the firm, and indeed are often hired as subcontractors and consultants. Moreover, firms that need to produce something that requires access to specialized knowledge it does not possess, tend to subcontract out

[69]The Nortel survey reports that 90 percent of work-from-home employees reported "increased job satisfaction" and 73 percent "decreased stress levels" (McCune, 1998).

[70]Hudson (1998) makes this point clearly: "Telecommunications networks now link manufacturers with assembly plants, designers with factories, engineers with hardware vendors, suppliers with retailers, retailers with customers. No longer is it necessary to have all the expertise in house."

[71]In the late nineteenth and early twentieth century it was believed, similarly, that the telephone could replace face-to-face meetings and that telecommunications would reduce transit congestion (Mokhtarian, 1997).

the whole stage of the production to specialists. Such vertical disintegration, if driven to extremes, may jeopardize the entire notion of a "firm" as we understand it. To some extent, firms may be replaced by virtual "teams," assembled on an ad hoc basis for specific projects. This will require some kind of reputation-maintaining technology, which is precisely what the internet provides.

Does the introduction of modern ICT enhance the competitiveness of the economy and the diffusion of new techniques? The return to household-plants and even household-firms will not mean a return to a world of peasants and artisans with loose selection standards. Modern ICT will make it quite easy to establish and lose a reputation for expertise and reliability. Establishing standards for veracity will be one of the challenges of the world of cheap access to knowledge. In such a world, however, the image of a pre-1750 household-producer muddling on without continuously keeping up with best-practice techniques seems remote. More worrisome is how society will handle those individuals who cannot or will not stay up-to-date.

To sum up, in recent years, modern communications and information technology are weakening many of the advantages that the "factory" has had over the household. With increased female participation in the labor force and little improvement in commuting technology, the *relative* costs of factories vs. home production have gone up. It is hard to make predictions about the trend, especially given how little hard information we have about the current state of telecommuting.[72] The changeover will be slow, much like the full establishment of the factory was and for much the same reason: a major social constraint is that the babyboom generation grew up using typewriters, telephones, and cars to commute to work and will have a difficult time to fully change its lifestyle.[73] It will have to await workers who grew up in hardwired homes, and for whom the internet comes naturally to accept fully the new lifestyle implied. Technology, now as in the past, opens doors; it does not force society to walk through them. It seems, however, that on the whole the changes may mean a social improvement quite comparable in its impact on society as the rise of the factory did in the eighteenth and nineteenth centuries. The difference is that in modern age, a sorting principle will be operational: more and more of those workers that want to work at home will be able to, whereas those who prefer to work in centralized settings, or who would not be as productive at home for one reason or another, will

[72]It might be worthwhile to cite the 1806 British Committee which predicted confidently that it was their "decided opinion that the apprehensions entertained of [the Domestic System] being rooted out by the Factory system are, at present at least, wholly without foundation" (*Parliamentary Papers*, 1806, p. 10).

[73]Andrew Ure's words in 1835 (p. 15) resonate with the modern experience: It was found "nearly impossible to convert persons past the age of puberty, whether drawn from rural or from handicraft occupations, into useful factory hands."

be able to maintain the status quo. This is an option the handloom weavers, the frame knitters, and the nailmakers of the nineteenth century never had.

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