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COMPUTERISATION AND WAGE DISPERSION: AN ANALYTICAL REINTERPRETATION*

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The rich countries have recently seen a dramatic rise in income inequality, all the more surprising because the long-term trend had been toward equality. This paper examines one of the leading explanations; computerisation in the workplace. I offer a theory of computers' impact on white-collar work which goes far toward explaining the timing, form, and locus of recent labour market changes. The theory looks at the bureaucratic and organisational applications of computers that have been first, largest, and most influential. They have two effects on firms' demand for labour at different skill levels.

The distribution of wages and earnings has been spreading out in the rich countries for about a quarter of a century.[1] The wages and earnings of the well-off have been rising much more rapidly than those of low and middle income workers. An impressive body of empirical studies shows that the proximate cause has been a shift in the demand for labour.[2] Employers' demand has shifted from low- and middle-wage occupations and skills toward highly-rewarded jobs and tasks, those requiring exceptional talent, training, autonomy, or management ability. Supply has been inelastic in the relevant run, so that the demand shift has played out as changes in relative wages (or rates of unemployment in some countries). The distribution has spread out broadly, with high wages rising relative to median wages, which in turn rose relative to low wages. Underneath this general spread lie some specific trends. The premium paid for cognitive skills, as measured by educational attainment, has risen. The premia for other skills have increased as well. The total effect has been large; the gap between wages at the 75th percentile of the distribution and the 25th has increased by nearly 50 percentage points.[3]

Pinpointing the causes of the labour demand shift has proved difficult. Quantitative assessment of other explanations shows that skill biased technical change (SBΔT) must be an important part of the story.[4] Since the largest

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[1] See Karoly (1992), Gottschalk (1997), Gottschalk and Smeeding (1997), and Murphy *et al.* (1998) and the sources they cite. Outcomes have varied across countries, driven by differences in supply, demand, and labour market institutions, as well as by such broader forces as income policy and growth.

[2] See Autor *et al.* (1997) for a summary of the evidence and a supply-demand framework.

[3] Murphy and Welch (1993) show percentiles of the wage distribution of prime-age males; some are reproduced in Fig. 1, below.

[4] Such forces as changing conditions of domestic and international competition, immigration, the changing role of unions, the emergence of 'star systems' in many professions, etc. while obviously relevant, are too small to provide the entire explanation. See Krugman and Lawrence (1993), Borgas and Ramey (1994), Borjas *et al.* (1992), DiNardo *et al.* (1996) and Frank (1992).

technological event of the relevant period is a massive investment in information and communications technology (ICT), many observers have looked to the workplace impacts of computers and other ICT. Autor *et al.* (1997) (AKK), for example, convincingly show that the spread out in wage distributions is largest in the most ICT-intensive industries, primarily in services. A series of papers by Krueger (1993) and others links individual wages to the computerisation of work. These empirical investigations lack a theory of how technology affects labour demand in the firm, however, treating SBΔT as a residual – as we so often treat technical progress.

The purpose of this paper is to offer a new theory of workplace computerisation, specific enough to support positive, predictive, and policy analysis. The theory has three main ideas. First, I focus on computer use in white-collar bureaucracies. ICT has brought a great deal of technical change to that understudied part of production. It affects much of modern employment. Second, I examine substitution of machine decisionmaking for human decisionmaking in low- and medium-skilled white-collar work. ICT has not been substitutable for high levels of human cognitive skill nor for 'people skills' in organisations. This *limited substitution* is at the heart of the SBΔT embodied in ICT. Third, the strategic use of ICT has raised the demand for highly skilled workers. The mechanism does not work through managers and professionals literally using a computer. Instead, ICT changes the organisation of bureaucratic production at the firm, industry, and even multi-industry level. This leads to an *organisational complementarity* between ICT and highly skilled workers.

In putting this theory forward I am attempting to save the general idea that ICT has had a great deal to do with wage dispersion from the failure of a specific story of how it might have done so. Reich (1993) and others see wage premia for 'symbolic analysts' or 'knowledge workers' who use computers, especially PCs. Enough attention has now been focused on this story that it has become a standard. It is a theory of *complementarity between computers and the human capital of computer users.* I think this story is largely false. The complementarity between ICT and highly skilled workers – of which there is plenty – arises more at the level of the firm than the worker.[5]

Section 1 of this paper reviews empirical evidence about the size, locus, and timing of the labour demand shift, seeking stylised facts to explain. Section 2 looks at the literature on the applications of computers, both the large 'how to' literature on the uses of computing and the smaller analytical literature on the demand for computers. While neither of these literatures has been about labour demand, both have been about changes to the organisation and industrial engineering of bureaucracies, useful precursors. Section 3 examines the implications of organisational computing for labour demand, trying to explain the timing, form, and locus of the SBΔT. Finally, I finish with thoughts

[5] Accordingly, the powerful evidence that the specification story is false, such as that provided by DiNardo and Pischke (1997), is not evidence against computer-based SBΔT. Howell (1994) and others are incorrect when they write of a 'skills myth'.

on the future direction of ICT-based skill biased technical change, suggesting continued or even accelerated demand shifts toward the skilled.

1. The Labour Demand Shifts to Be Explained

Empirical studies have shown that large unexplained changes in the demand for a variety of skills are part of changes in relative wages. In this section, I first look at the size of this change, then summarise the findings of two empirical literatures. Each literature attempts to make the concept of 'skill' operational in different ways. This richness leads to several distinct labour-demand findings which a theory of skill biased technical change should explain. To that end, I look for a definition of 'skill' which can be linked reasonably directly to tasks and jobs in the firm.[6]

Taken together, supply, demand, and institutions have led to a general spread out across the entire range of workers' wages. For both men and women, blacks and whites, the nth percentile of the wage distribution is increasing faster over time than the mth if $m < n$. Real wages and salaries in the upper parts of the income distribution are rising rapidly and they are rising more rapidly than other wages and salaries.[7] The wages of highly paid workers have been rising rapidly in real terms, not just relative to less skilled workers. Whether the real wages of less-compensated people have been falling is more difficult to determine.[8]

The spread out in wage distributions is large. Fig. 1, reproduced from Murphy and Welch (1993), shows the interquartile range of men's wages over two and a half decades. Note the dramatic shift of the median man's wages up relative to the bottom quartile, and in turn of the upper quartile relative to the median. The important consequences of this trend, which cuts across all the rich countries, (though taking different forms as labour market institutions vary) are for the distribution of income. This paper, however, is about the labour-demand causes of the trend, not its consequences.

A wide variety of studies have examined individual worker wage equations.[9] Based on large data sets, such as the U.S. CPS, these studies predict wages with both observables – education and experience – and unobservables – the residual in the wage equation. The observables are interpreted as proxies for skills; changes in their coefficients over time are interpreted as changes in the

[6] The most convincing work about labour demand looks at quantity demanded or payroll expenditures as the dependent variable. Much of this work has used very simple skill classifications: production vs. nonproduction workers, or college-educated vs. less. The literatures summarised here have a richer definition of skill.

[7] In the United States, the only counter-trend has been that the average wages of different ethnicities and of men and women have been moving closer together.

[8] Gottschalk (1997) reports, in his Fig. 2, that the bottom 80% (!) of the distribution of men's wages fell in real terms from 1973 to 1994. A revised CPI, along the lines suggested by the Boskin Commission, would reduce this proportion dramatically.

[9] Surveyed in AKK (1997) and in Gottschalk (1997). I rely on Juhn *et al.* (1993), Bound and Johnson (1992) and Murphy and Welch (1993) and especially AKK (1997) for much of what follows.

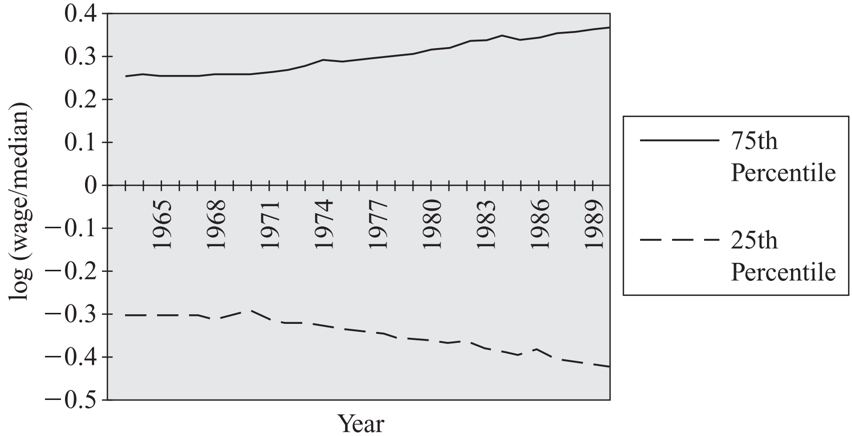

Fig. 1. *Interquartile Range of the Distribution of Men's Wages*

prices of those skills; increasing spread in the distribution of the residual is interpreted as an increase in the price of an unobserved skill. Some of these studies have used sophisticated analysis to decompose changes in skill prices into those caused by shifts in skill supply and skill demand.

Juhn *et al.* (1993), for example, plot the prices of the skills proxied by education, experience, and the residual. While all three have risen in recent decades, they have not moved in lockstep. For example, the supply shift associated with the entry of the baby boom into the labour market raised the relative price of experience (many young people in the labour force) and lowered the relative price of educated workers (many of the young people entered with education.)[10] As labour supply and demand shifts at different skill levels and types, these relative prices move around. There is some slowing in response to the baby boom's entry into the labour market, and again in very recent years.

This literature is not completely clear on what task- and job-oriented definition of 'skill' corresponds to its proxies. Most authors appear (sensibly) convinced that the education measures are related to cognitive skills. Labour market experience might measure more general skills than does tenure with a particular firm, but in either case it is less than completely clear what the skills are. They might be knowledge, or they might be 'people skills' associated with supervising and being supervised. The residual, of course, is a Rorschach blot for multiple interpretations. For present purposes, the point is that any theory of SBΔT must explain separate biases in favour of several different skills, but that this large and well-implemented literature offers few clues as to what exactly they might be.

[10] See Murphy and Welch (1993) AKK (1997) and Bound and Johnson (1992) for a variety of skill supply/demand treatments.

Another body of empirical literature classifies skills differently, using the skill contents of different occupations. Based on sources like the dictionary of occupational titles, these studies look at the detailed skill requirements of jobs. They also examine the performance of workers in those jobs on various direct skill tests. I find the Howell and Wolff (1991) categorisation of skills quite useful: they distinguish cognitive skills, motor skills, and interactive skills (such as those involved in supervising or being supervised.)[11]

These two literatures overlap in a clear finding for any theory to explain. The demand for cognitive skills has been rising over time. This finding is essentially the same whether cognitive skills are measured by education or more directly by test scores or job requirements.

F1. *Cognitive skills.* The relative demand for more highly educated workers and others with higher levels of cognitive skills has been rising.

A second finding applies to both workers in highly paid occupations and workers in lesser-paid occupations. It applies to workers whose jobs have, and do not have, high cognitive skills content.

F2. *People skills.* The relative demand for workers with 'people skills' has been rising.

Both literatures also address the timing and the industrial composition of the demand shift. Both demand for skilled workers and supply of skilled workers are trended upward.[12] Because of the large transitory changes in labour supply associated in the 1970s, and because of the macroeconomic noise of the 1970s and early 1980s, it is quite difficult to time the highest rate of changes in demand relative to supply down to the nearest half-decade.[13] The following finding about the secular (i.e. ignoring the 1970s blip) trend appears to be solid, however:

F3. *Timing.* The relative demand for workers embodying more of these skills began to rise more quickly in the late 1960s or possibly the early 1970s. A secular excess of the growth rate of demand over supply continues to the present day.

Not all industries have been equally suitable for computerisation, especially early on. The computer-intensive industries, notably in services, have seen the demand shift earlier (Wolff, 1996) and to a larger extent (AKK, 1997) than other industries.[14,15] Accordingly, we have

[11] Howell and Wolff (1991) offer these definitions: 'cognitive skills – the level of cognitive (analytical reasoning) and diagnostic (synthetic reasoning) skills required; interactive skills – the relative authority, autonomy, and degree of responsibility (for people and things) required on the job; and motor skills – the various physical and manipulative requirements of work.' p. 488.

[12] This is particularly well-documented in terms of cognitive skills. See Goldin and Katz (1996) for historical evidence focused on the entire 20th century.

[13] See Karoly (1996) for an attempt to get a better answer on timing.

[14] Although the portion of high skilled manufacturing workers increased from the 1970's to the 1980's, 'the large acceleration in within sector skill-upgrading occurs from the 1960's to the 1970's outside of manufacturing.' AKK (1997).

[15] This finding comes from research looking at labour demand behaviour. Far less of the shift in relative wages comes from composition effects associated with the shift of aggregate output toward and the computer-intensive sectors. This is as you would expect if there is a labour market that cuts across industries.

F4. *Industry.* The demand shift for skills is more marked in the more computer intensive industries.

F5. *Size and pervasiveness.* The demand for higher-skilled workers has been rising relative to mid-skilled workers, and that for mid-skilled workers in turn relative to mid-skilled workers. These shifts are substantial.

I should perhaps introduce F0 *Basics* as a pre-finding. There is *incomplete repackaging* of labour skills. The market treats distinct bundles of skills as different commodities that are priced distinctly. Employers cannot combine a number of high school graduates into an MBA, nor can they substitute experience for school learning without limit; people skills and cognitive skills are less than perfect substitutes in demand. Workers of different types are partially but not completely substitutable in demand.

We should not forget that a wide variety of forces are at work in driving relative wages, and that the task at hand is to explain what supply shifts and other demand shifts cannot explain. I will simply assume that the literature has done its work in holding variations in supply fixed, so that technology shocks of some kind must explain the facts cited here. Computerisation is not the only force affecting labour demand; consider immigration, the de-unionisation of the work force and other institutional changes, globalisation of some industries, domestic changes in the conditions of competition in other industries, ongoing non-electronic technical progress, and the emergence of 'star systems' in many professions.[16] I am going to assume that these forces are too small to explain the stylised facts, but not go overboard with that interpretation. Certainly, much of the changes in demand for blue collar workers is related to the forces just listed, and star systems (reinforced by communications technology) are likely more important for the very well compensated than the forces I just listed.

If the labour market consists of a complex set of linked markets for close but not perfect substitutes, a logical explanation of the relative wages could take any of several forms. A simple explanation could come from rising real capital/labour ratios, driven by general technical change, and dramatic increase in the demand for a few skill types.[17] Such changes would then ripple through the general equilibrium of all labour markets, producing all the relative wage movements we see. At the other extreme, one could ask a technology-based theory to work at the level of specific jobs and specific groups of workers. I take an intermediate approach, building a technology-based theory that talks about the content and skill requirements of jobs in bureaucracies, but asking it to do no more than reasonably directly explain F1–F5. That necessarily involves a broad-brush and general equilibrium view of the labour market, relative to the technological analysis. This seems worthwhile in order to be clear about the implications of an important technological shift in labour demand on its own terms, but connecting it to aggregate implications.

[16] See sources in fn. 4.

[17] See Gordon (1990) for careful work on the size of the real capital stock taking into account technology and quality improvements in capital goods. Gordon concludes that K/Q and K/L have been rising.

2. Computers' Impact on Work: Technology and Timing

Computers' impact on work is to be found not in bits and bytes but instead in the application of computers in workplaces. This section examines the history of that application with two goals. One is to see whether the timing, size, and location within the economy of computerisation are consistent with the stylised facts. The other is to review the important analytical themes about applications of computing. While developed for very different purposes, notably advising businesspeople about applications, these have useful implications for labour demand. I divide uses of computing into three main categories – organisational computing, such as corporate accounting systems or transactions processing systems, scientific and technical computing in factories and labouratories, and individual productivity computing, such as word-processing or computer-aided design.[18] The labour-demand impact of the three different kinds of use is distinct. It is the organisational computing which is most likely to have had substantial labour market implications.

2.1. *Organisational Computing Diffuses by Value and Complexity*

Computers have become more powerful and less costly over time. Falling costs have permitted diffusion to less valuable applications. Rising power has let applications grow more complex. Organisational computing was the first, and still among the highest-value, applications types.[19] Its labour market impact reflects that.

Computers began to be used extensively in business when computer power cost several orders of magnitude more than it does now, in the late 1950s and early 1960s. These systems were based on mainframes. Accordingly, early commercial applications were in areas with large impact on using firms' costs, revenues, or service quality. Fig. 2 shows the breakdown of applications in 1969, based on an IDC survey of about 2000 large computer users.[20] One strand of the diffusion of organisational computing began in the sectors where the product itself is very nearly pure information, such as financial services. Another strand began in the information-intensive functional areas of many different kinds of companies, such as accounting, payroll, or inventory control. Looking at the listed applications, we see that their 'user' is not a person but a department, typically a white-collar bureaucracy.

The labour-demand impact of these systems is, at least prospectively, on all the workers in the bureaucracy responsible for the business task. How early and how large might that impact have been? A simple calculation is how many

[18] This division follows industry practice more than scholarly practice. As Cortada (1996) points out, we know far more about the history of computer supply than about applications.

[19] Economists somehow forgot this in the course of the 'productivity paradox' debate. Yet there is little doubt that computerisation in the 1950s and 1960s had very large social returns. See, e.g. Bresnahan (1986) for quantification.

[20] The calculations based on the IDC report were made by Phister (1979). See p. 455. I have aggregated some categories (for example, various banking and accounting ones) to make the diagram clearer, and have left a plethora of infrequent applications in the 'all other' category.

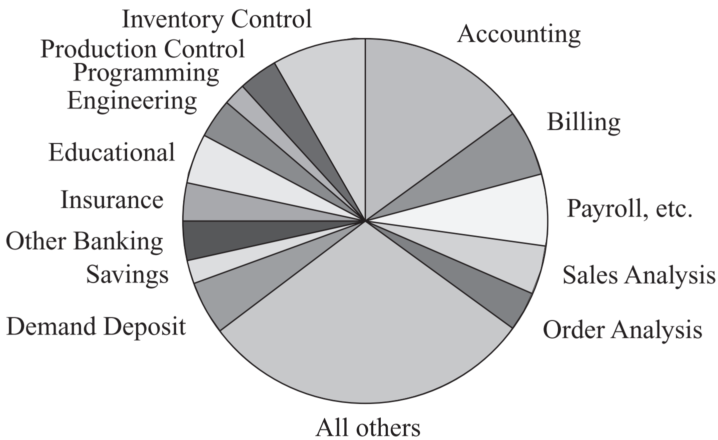

Fig. 2. *Distribution of Computer Time Among Applications, 1969*

people work in a building that has a mainframe computer in it. Data on computer usage by industry and establishment size[21] and data on employment by industry/establishment size class from social security records permit such a calculation.[22] By 1967, 21% of (covered) workers, and by 1971, 32%, worked in a computerised establishment. Clearly, this is not an accurate measure of the number of people whose jobs have been impacted by computers, but it suggests that an early labour market impact of substantial magnitude is possible.[23]

Within organisational computing, diffusion of computing power moved forward on several margins. The number of mainframe computers grew rapidly from the mid 1950s to about 1973. Most large sites had a computer by then. After that, the *count* slowed, with a total of between 60 and 70 thousand in place through the 1970s and 1980s.[24] The *total amount and value of mainframe computer power* continued to grow.[25] The number, kind, and complexity of organisational applications continued to grow – within the same sites –

[21] For 1967, I use a report of the location of 28,034 mainframe computers by industry and by establishment size from an IDC report called EDP/IR.

[22] From *Statistical Abstract of the United States, 1969*, Table No. 689. Reporting Units and Employment under Social Security, by Employment Size, By Industry: 1967. I exclude the agricultural (low computer user) and government (high) sectors since my data source is social security. The larger employment size classes are aggregated so that the two data sources conform.

[23] The calculation overcounts workers whose functions have not yet been computerised, and undercounts workers outside the establishment whose functions have been computerised. In the late 1960s and early 1970s, the overcount error almost certainly dominates. But the dramatic increase in the use of terminals connected to host computers in the 1970s means that there was a rapid growth in the undercounted portion. The fraction of the workforce whose work was computerised was rising more rapidly than the figures I report in text suggest, i.e., more rapidly than 50% in four years.

[24] In the 1980s, organisational computing came to be based on more than mainframes after the invention and spread of commercial minicomputers. In the 1990s, networks of smaller computers began to be used.

[25] The figures are based on the IDC *EDP Industry Report*. The valuation of the installed base follows industry convention in valuing models still in the marketplace at current new-computer prices.

particularly as fundamental software and networking technologies such as database management systems and communications controllers spread in the 1970s and 1980s. Workers outside the computerised site – for example, reservations clerks working at a distant terminal – came more and more to be connected to computers. The same kinds of applications spread later to smaller sites. At first, the costs of mainframes meant this spread came by time-sharing, service bureaus (e.g., ADP for payroll) or remote computing at a corporate site. After 1978, smaller sites might use commercial minicomputers or even PCs for organisational applications. Networked computing, host-based and on proprietary (largely IBM) networking protocols in the 1970s and 1980s, then on open systems in the 1990s has permitted more and more extension organisational applications. The diffusion of organisational applications thus began in the 1950s, accelerated in the 1960s and 1970s, and continues to the present day.

ICT organises, routinises and regularises the bureaucratic production process. Indeed, computer business systems *form* the modern production process for many service industries (and for the service functions of other industries.). Computerisation of any particular process tends to come in stages (Barras, 1990). The first is 'mere automation' using ICT-based systems for existing tasks. The later stages involve changing the nature of the firm's output. Where stage one might have been automated cheque processing in a bank, the existence of a machine-readable database on chequing accounts would lead to stage two, with new services like a sorted chequing account statement. Barras argues that this is systematic throughout the service sectors of the economy, and I would add that it is also systematic in bureaucracies elsewhere.

Computers and computer networks are general-purpose technologies. Advances in them permit using firms to invent new services, improve the quality of existing services, and so on. Firms do not simply install computers that automatically run effective business systems. Instead, to gain from computers' capabilities, using firms must invent new ways of organising work, new job definitions, and new management structures. Improved customer service and new and improved services are low-tech, mundane invention. In this learning-by-using co-invention lies not only much of the growth in demand for organisational computing over the years but also much of the work of managers and professionals in computer-using bureaucracies.[26]

One of the things that was really surprising to me, in studying the organisational use of computing in the early 1990s, was that the Barras model was still descriptively accurate.[27] Use of networked computing in organisations or to link buying and selling organisations set off new cycles of automation and learning-by-using. As a result, I take the implications of that view for labour demand to be timeless (with exceptions to be noted later.) We have been

[26] There as elsewhere, I have tended to write 'computers' as a shorthand for 'information and communications technology'. It is merely a shorthand. The work of Bar and Borrus (1992) shows that much the same analysis applies to business use of communications.

[27] Cf. Bresnahan and Saloner (1996) and Bresnahan and Greenstein (1997). One would have thought that this model applied far more to the early stages of computer use than to the present.

seeing the diffusion of the same technology of organising bureaucracies (1) to smaller and smaller bureaucracies and (2) to more and more complex bureaucratic functions.

As a result, organisational computing is a very large part of computing. In the period of changing wages, organisational computing starts at almost 100% of purchases of computer systems by dollar value and falls, by the late 1980s, to just under half.[28] A more complete accounting exercise, if a harder one, would be to look at the total value of computer systems – including not only externally acquired hardware, software and networking, but also user-created software and business systems and the rest of costly coinvention. This would make organisational computing loom far larger even in the late 1980s, as organisational computing involves a great deal more 'off-budget' coinvention.[29] Finally, networking has now reversed the trend away from organisational computing toward personal computing so evident in the 1980s. Organisational computing is a very large shock to the technology of bureaucracies, which have historically had only slow and difficult progress.

2.2. *Technical Computing in Manufacturing*

ICT is a general-purpose technology that can be adapted to a wide variety of uses. Technical demanders have made qualitatively different uses of computers than we saw in organisational computing. From the late 1950s, factories, engineering departments, and scientists used minicomputers (for numerical calculations rather than data processing). In factories, minicomputers entered production processes as 'controllers' or 'instruments'. Measuring and controlling physical production processes, they acted as extensions of the engineers' toolkit. Later, numerically controlled tools became more pervasive, perhaps calling for quantitative skills on the part of line workers. While I believe these impacts are far less important than the white collar ones, I shall briefly analyse them below.

2.3. *Technical Computing for Scientists and Engineers*

The same minicomputers, and later workstations, did have an impact on the demand for scientists and engineers, by making them more useful and valuable. For example, as design and automation software improved over time, CAD/CAM applications in a wide variety of manufacturing industries became important. The individual-engineer's workstation was invented, and software evolved to increase the productivity of individual engineers. Even personal

[28] Making this calculation involves the difficult judgment call of which minicomputers are in commercial as opposed to technical use.

[29] See Bresnahan and Greenstein (1997) for evidence on this from users' behaviour in switching from mainframe-based to network-based computing systems. This study finds very large sunk costs of computer systems above and beyond the hardware and software, and shows that these are the costs of inventing new computer systems, changing workers' jobs in a complementary way, and so on.

computers were used to support individual engineers in CAD applications. In a related example, scientific laboratories in a variety of disciplines, including our own, became more and more ICT-intensive.

This is the part of ICT-based labour demand change that most closely corresponds to the story told by Reich and others. The scientists and engineers whose productivity is raised have, first and foremost, cognitive skills. And they tend to be literally sitting at a computer when a computer influences their job. The overall importance of this kind of technical progress – direct complementarity between a computer-using skilled worker and ICT – is limited by the extent of diffusion of this kind of technology. Only a small subset of the work force is scientist and engineers. And the use of individual productivity applications more broadly is very different, as we shall see.

2.4. *The PC as a Central Skill-Enhancing Technology (Not); The 1980s as the Time of ICT's Impact on the Workplace (Not)*

A number of studies have looked for complementarities between knowledge workers' or symbolic analysts' skills and ICT by examining individual workers' computer use. The argument is that computer users are doing analytical tasks, the kind of brainwork that is the future of work in the rich countries generally. These studies focus on the use of PCs as the key driver of skill-ICT complementarity.[30] A subset looks at the wages of the computer users themselves, interpreting higher wages as evidence of the complementarity. At a macro level, the tremendous increase in PC use in the 1980s seemed to coincide well with the change in relative wages. AKK, for example, report using CPS figures that the percentage of U.S. employees using a computer at work rose from 25.1% to 46.6% from 1984 to 1993.

Critics have very successfully argued that the wage relationship is not evidence for complementarity. The causality goes the other way; PCs have flowed to the high-wage jobs. This is the obvious interpretation of the result that *pencil* use at work predicts wages at least as well as computer use, reported by DiNardo and Pischke (1997) in a study of German workers. Further, the labour supply shocks of the 1970s mean that a purely PC-based theory comes too late to be the key SBΔT. Many have concluded that the ICT-based SBΔT theory is dead.

I agree with the critics that there is little complementarity between highly skilled workers and PCs, certainly not enough to affect aggregate skill demand. This by no means implies that the wider ICT theory is incorrect. The problem here is a common one in economics, one of looking at our own experience as symbolic analysts and the technologies we use ourselves rather than turning to the technological history.

The facts of PC use at work, reflected in surveys such as that reflected in

[30] Krueger (1993), AKK (1997), Reich (1993) and DiNardo and Pischke (1997) share this interpretation. Some work, for example that of Levy and Murnane (1996) has an interpretation nearer mine.

Fig. 3, do not encourage the 'symbolic analyst' interpretation.[31] First, by far the most important use of PCs is for word processing; it comes to about a quarter of PC use. While word processing raises the productivity of secretaries and typists, this seems a very implausible source of wage dispersion and certainly not what was meant 'knowledge workers' or 'symbolic analysts'. (Managers, professionals and technical workers who now do their own typing with easy-to-use PCs are likely somewhat more productive than before, but this is another very unpromising source of widening wage dispersion.[32]) Much the same problem arises as with word processing. The typical spreadsheet user is a midlevel clerk or accountant. As with word processing, individual productivity is enhanced, but not in a Reichian way.

A minority of PCs run some software that is promising for the Reichian hypothesis. Some of the uses are associated with high-skill and high-productivity applications in the upper half of the income distribution. The major examples are computer-aided-design (CAD) and related programs for design engineers, architects, and the like, desk-top-publishing (DTP) for marketing and communications experts, databases for analysis of company databases, project management and presentation and graphics programs for salespeople. Several of these categories are clumped under 'graphics' in Fig. 3, so the total amount of such usage appears to be on the order of 20% of uses. If we look at the value of shipments in the PC applications software market, we get a similar story.[33]

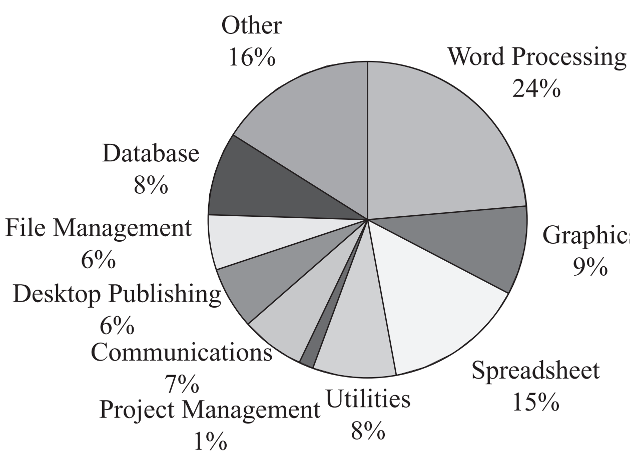

Fig. 3. *PC (DOS) Applications 1992*

[31] Computer Intelligence Infocorp surveyed a large sample of business computer users at home. The figure shows DOS users. Windows users are quite similar, and Mac users vary primarily in using more graphics applications and fewer database applications.

[32] More generally, Lindbeck and Snower (1996) have suggested that computers can permit workers to multitask, raising inequality by permitting assignment of the tasks to a few high-productivity workers. This may be important in blue-collar environments, but seems, like the word processing example, unpromising for the vast majority of work situations.

[33] See, for example, the report from the Software Publishers Association, reprinted on pp. 354–5 of the 1994–5 *Computer Industry Almanac*.

The individual wage equation with a regressor for computer use is simply a flawed way of measuring the labour market impact of computers.[34] PC use includes too many low-status jobs to be much of an indicator for skill complementarity. It also misses all the highly skilled managers who do not literally use computers (perhaps getting a computer-based report from a subordinate) but whose skills are highly complemented by the computerisation of the organisation. I conclude that the pencils evidence is simply not relevant to the labour demand debate. Neither is the PC evidence before it.

PCs qua PCs are not all that important a technology for labour demand. Their low prices and small scale mean that they can be deployed in uses that have modest impact on either the firm's bottom line or its labour demand. More generally, ICT has been growing cheaper and cheaper, and one margin on which it is deployed is, well, marginal. Cheaper and better ICT also permits co-invention of more and more complex uses. It is here that the impact can be found. PCs in networks, when the networks are used in complex organisational and interorganisational tasks, do have the prospect of labour market impact.

2.5. *Timing and Industry*

Already this section has shown that there are aspects of organisational computing related to the labour demand stylised facts. It is clear that we can get F5 *Timing* and F6 *Industry* right. The section has also focussed attention on organisational computing (and off PC and technical computing). I now turn to labour market implications.

3. Organisational Computing's Impact on the Labour Market

My theory of ICT's role in changing labour demand has two distinct parts. Both are limited to organisational computing. One part concerns the more or less direct substitution of computer decisionmaking (and other computer actions) for people in the operational side of bureaucracies. It is limited in scope; hence the label *limited substitutability*. The other part concerns the changing structure of organisations once the production process is computerised and the changing cognitive demands on managers. This corresponds to *organisational complementarity*.

3.1. *Limited Substitution of Computer for Human Decisionmaking*

Technical change that raises the demand for highly skilled labour *relative* to that of less-skilled labour is a candidate SBΔT (Griliches, 1969). Computer

[34] Some studies use the fraction of workers using computers in a firm or industry as an indicator of ICT intensity. This is better, but growing less useful over time. For example, the CPS 'computer use at work' question in 1984 overwhelmingly measures use of terminals, not PCs. That is good, as the fraction of workers using terminals is a good trace of organisational computing. By the late 1990s, however, the questions have come to measure use of the nearly ubiquitous PC.

business systems, from the 1960s, have involved the regularisation and routinisation of white-collar tasks. Simple, repetitive tasks are far more amenable to regularisation and routinisation than more complex and idiosyncratic ones. The result has been the systematic substitution of computer decisionmaking for human decisionmaking in clerical and related work. Decisions that were once reached by humans in a paper- and people-based system are now reached by software. The scope of this substitution has been limited. Simple decisions, closely related to individual transactions or other operational actions, have been amenable to computerisation. Such decisions have been regularised, routinised, and standardised, and the knowledge about how to reach such decisions has moved from the heads of clerks to the computer system. Much routine white-collar work has been industrialised, so the same kinds of technical change processes that have long been lowering demand for blue collar workers in factories now lower demand for modestly-skilled white collar workers in bureaucracies. Computers are good at repetitive tasks, and bureaucracies are full of repetitive tasks that might be automated. This limited substitution story is the first part of computer SBΔT – computers have been substituted first and foremost for the kinds of human capital whose relative wage is falling. This is strikingly obvious but has been equally strikingly absent from the discussion.

One impact on middle- and lower-paid white-collar workers flowed very directly from automation. Clerks of all types (record clerks such as billing clerks, auditing clerks, etc., information clerks such as check-in, reservations, etc.), and related administrative support personnel have some of their tasks taken over by the computer. Where a human clerk would, before, have completely handled a file or a transaction, now that task is split between humans and computer. This is a direct substitution of capital for labour.

3.1.1. *An example*

We can see this in a clear and simple example, telephone operators. (The clarity and simplicity of the example makes it not fully representative, because operators are far less embedded into a complex interacting production process than many other low-wage and low-status workers in bureaucracies.) Fig. 4 shows U.S. employment of telephone operators for 1960, 1970, and (almost) annually thereafter. Telephone usage is trending strongly upward in this period, driving the demand for operators upward. But automation – telephone switches are computers – leads to substitution out of workers of this type. If you think of an operator's job fifty years ago and now, you get some of the flavour of computer-based automation. Then, the operator 'did' the production of call routing in a physical sense. This called for manipulation and a modest amount of cognitive skill. Computers are good at those things. The complexity of the task assigned to the computer rather than the human operator began with very basic calculations on telephone numbers and grew into more and more complex tasks. Not all of the decisionmaking part of an operator's job was trivial but most of it has proved routine enough, that, after

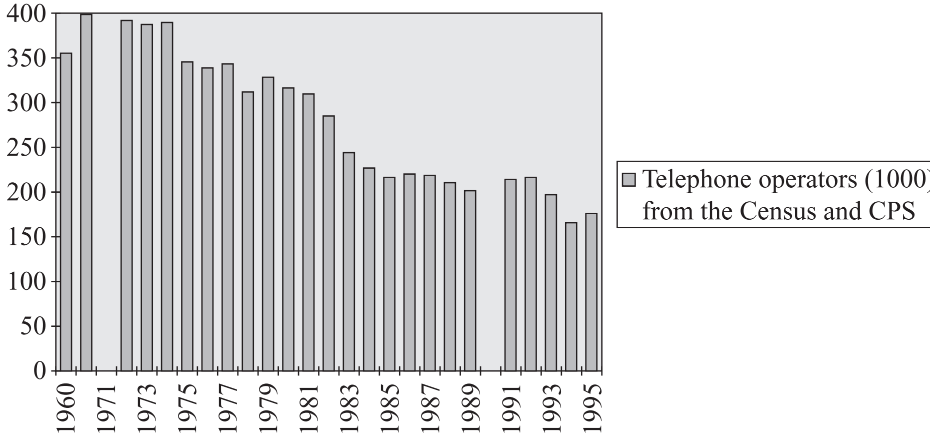

Fig. 4. *Telephone operators (1,000) from the Census and CPS*

considerable software development effort, that computers do it. This permitted more and more production with fewer operators, and also changed the skills needed.[35]

The example serves also to show shifts in the content of jobs as they are computerised. Now, the operator serves primarily as the voice of the computer. The human worker has been turned into a part of a computer system, only doing those tasks that are not economic for the computer to do. Accordingly, the desirable skills are less cognitive ones, more conversational ones.[36]

Here as well, as in most business systems, employers have found ways to use the human/computer blend to provide a higher quality product. Only about 1 out of 4 works in a telephone company, the rest 'operate' PBXs in large organisations, often those like hotels and hospitals with transient populations. Such organisations often wish to control not only the routing of telephone calls but also their emotional overtones.

Finally, telephone operator automation has also introduced an extremely effective monitoring technology, so this job is no longer suitable for those who like to chat on the phone.[37]

[35] Cf. the online *Occupational Outlook Handbook*, http://stats.bls.gov/oco/ocos154.htm. 'Technological innovations have changed the responsibilities of central office operators.' The Bureau of Labor Statistics goes on to write about the elimination of the need for manual switching, the automatic capture of billing information such as length of call, the extension of computer switching to more and more complex calls such as international, collect calls, or changed numbers, and so on. From the base of a simple 'thinking' task, i.e. switching a call, the computer extended its reach well into the human job.

[36] 'Telephone operators should be pleasant, courteous, and patient. A clear, pleasing voice and good hearing are important. In addition to being a good listener, prospective operators should have good reading, spelling, and arithmetic skills.' *ibid.*

[37] 'The job of a telephone operator requires little physical exertion; during peak calling periods, however, the pace at the switchboard may be hectic. Telephone companies continually strive to increase operator efficiency, and this can create a tense work environment. An operator's work generally is quite repetitive and, in telephone companies, is closely supervised. Computerised pacing and monitoring by supervisors, combined with the rapid pace, may cause stress.' *ibid.*

Much of this change is representative of what computers do to labour demand in the operational side of white-collar work. Decisionmaking tasks shift from the worker to the system. So does control, and in a routinised and systematised environment, monitoring. Fewer workers are needed per unit of output. The remaining workers need more people skills, and less cognitive ones – the substitution is limited in terms of which human skills can be automated. Jobs are redefined in a way that changes workers' tasks and thus skill requirements.

Telephone switching is nicely isolated from the rest of the organisation and thus provides an unrepresentatively 'clean' example. That is why I picked it. There are, however, some further impacts on labour demand that arise in more complex situations.

3.2. *Limited Substitution II: Organisational Change in Bureaucratic Operations*

Most ICT-based bureaucratic production is deeply embedded in complex bureaucratic processes. Automation involves complex shifts in the definitions of several jobs and in their skill requirements. These changes can be idiosyncratic to the particular firm or industry, but a few powerful central tendencies arise. One cluster of technical change is in the parts of bureaucracies that transact or account. Here the important technologies from the perspective of the labour market are large computers, database management systems, communications controllers, and the like.[38] That software performs individual transactions – collecting a bill, for example – in an organised and structured way. This permits rationalisation of the operational side of bureaucracies.

Once industrialised, white-collar work can be separated into 'front office' and 'back office' components. The back office is an industrialised data-handling shop that turns business information into machine-readable data. The front office interacts with customers or others outside the organisation.

3.2.1. *Back office and data processing*

In the back office, the job of data-entry clerk was created and employment in this category grew rapidly in the early days of computerisation, only to reverse later on. The data entry clerk is responsible for accurate transmission of data into machine-readable form, but is more efficient when *not* thinking about the content of the information. These are low skill jobs. Why did the demand for data entry not lead to a reverse skill bias in ICT-based technical change?

Data entry workers, like other 'data workers', are *industrialised white-collar workers*. Once a production process has been routinised and regularised, it is subject to the same kind of labour-saving technical change as a factory floor. Keypunch machines yielded to data-entry screens with error correction software. Human data entry yielded to OCR. More importantly, low skill work can

[38] These sotfware categories are less familiar than PC software categories, but are of enormous impact. One cannot run a transactions-processing system without a communication controller, and they are priced accordingly.

be avoided by organisational improvements. As more and more business records were computerised, there began to be duplicative data entry. Fundamental technical advances such as the relational DBMS (and the corresponding changes in record keeping practices) permit economising on data entry by removing this duplication. As white-collar work became computerised, it became cheaper to capture data from normal operations 'for free' rather than have data workers. Even customers – think of a bank customer using an ATM – became 'free' data entry clerks. (This particular trend away from data workers can only accelerate.) As more and more transactions between different firms are automated, the need for buyer and seller to separately enter data declines. Such technologies as electronic data interchange (EDI) and electronic fund transfer (EFT) allowed data worker cost savings. Thus, while the demand for business data processing has grown dramatically, its industrialisation has permitted substantial labour-saving technical progress.

3.2.2. *Front office; the moving limited substitution boundary*

Front offices undergo a technological change process with ICT that substitutes effectively for human cognitive skills but only poorly for interactive and people skills. It is the operational part of 'learning by using' in the co-invention of ICT applications that is critical here. Computer systems do not do quite what was hoped of them when first introduced, or more typically they are introduced in the hope that a valuable use will be found for them.[39]

We can learn a good deal about *front office* human/computer substitution by thinking about learning by using in transactions processing. At the beginning, applications lacked the commonsense of clerks, for example sending bills for $0.00. Only slowly did software systems improve. Over time, the foolish errors disappeared. A computer needs to be told not to send a bill for $0.00, whereas (many) clerks could be relied upon to do this without explicit instruction. Managers learned how literal-minded computers are relative to humans – a piece of generally useful knowledge. Managers also learned the rules that the clerks had been applying implicitly – a piece of knowledge often specific to a firm or market. This learning means that even human common sense, where it can be represented by rules, becomes embedded in software. After some iteration of this learning-by-using, business computer systems could perform basic accounting and transactions tasks in a far more careful and complete way than humans had, cheaper and faster. And computers' disadvantages, such as lack of commonsense, were overcome. Software tools advance to permit more and more complex 'business rules' to be embedded in computer systems. Accordingly, more and more complex transactional/operational tasks have been able to migrate from human to computer decisionmaking.

The impact on the labour market is that much of the routine decisionmak-

[39] This is most clearly understood for the English-speaking countries, especially the United Kingdom. See Barras (1990). Friedman (1989) offers a very interesting history of learning by using.

ing formerly undertaken by clerical workers passed to the computer.[40] Much of the knowledge needed to make decisions came to be represented in databases and programs.[41] This is the generalisation of the computer-operator story told above. Human social skill demand rises in the operational side of bureaucracies, while human cognitive skill demand falls.

There are two very different understandings of what this meant for front-office workers, and not much empirical research to tell them apart.[42] Either view means a large change in the demand for skills, though each view has a different set of implications. One view sees this as a 'deskilling' of clerical work. The computer tells the worker what to do. The human worker is just the eyes and voice of the computer. The other view of the computerisation of the routine part of clerical work is that it frees the human front office worker to make higher level decisions based on the information offered by the computer. A order-entry clerk may stop simply being an order-taker, and may instead suggest something else that the customer might like to buy. More generally, the clerk may be a problem-solver. This increase in clerical people's sales roles calls for an increase in people skills and calls for an increase in autonomy. It is clear from the anecdotal evidence that some of both kinds of change occurred in the middles of bureaucracies over the last three decades. As the examples we have examined here suggest, ICT-based production changes work as both an intensive and an extensive SBΔT (Johnson, 1997). Passing to the aggregate labour market implications therefore involves aggregating over several lines of causation, which I do through the notion of limited substitution.

3.2.3. *Limited substitution*

Limited substitution involves two very different lines of causation, through complete replacement of low-wage white-collar workers and through changing the definition of workers' tasks. To get to the aggregate, we must add a third line of causation, the output-expansion effect. ICT-based bureaucracies embody cheaper and better technology. Depending on the relevant output market elasticities, they could grow or shrink, with corresponding implications for aggregate labour demand. Further, the story of both back office and front office suggests the extent and organisational boundary of limited substitution has been shifting over time.

One aggregate measure is what Wolff (1996) calls 'data workers'. These

[40] I use the word 'decisionmaking' advisedly. It is of no concern to us here whether computers have what a cognitive scientist would recognise as either intelligence or common sense. It simply means that they could make some decisions, once they were regularised and routinised, that had once been made by humans. All we care about here is substitution.

[41] Zuboff (1988) provides a very interesting analysis of the process.

[42] The main strands of research have been normative rather than positive and have used (interesting!) anecdotes rather than systematic investigation. One normative research literature seeks to advise business people on how to computerise organisations. Zuboff (1988) is a very interesting example. Sociology has contained two normative literatures, one arguing that computerisation is bad, the other that it is good, for office workers. See Hughes (1989) for a review of this literature.

contrast with 'knowledge workers' in that data workers are users or handlers of knowledge, not producers of it.[43] Data workers include but are not limited to clerical workers, and Wolff rightly acknowledges the difficulty in defining the boundary between knowledge workers and data workers. Fig. 5 shows data workers as fraction of total employment in the US goods and services sectors. The more data-intensive service industries use more of this type of worker. As you can see, both series rise in the early period of organisational computing, then decelerate, declining slightly in the 1980s.

The appropriate economic interpretation blends together all of the distinct stories I told. At first, computers led to more specialised data workers through retasking and the output effect. Later, reorganisations slowed the growth of the data worker category without ending the change in skill demand within low-wage white-collar work. The effect of the technology has been both to change the demand for cognitive skills and that for people skills in the bottom of bureaucracies. ICT based production involves considerable substitution of computers for human cognitive skills. This substitution is limited, suggesting a decline in the demand for cognitive skills in modest bundles. This is the beginning of a theory of F1, cognitive skill demand. Further, we learn that computers have had a large impact on the demand for certain people or interactive skills in the operations parts of bureaucracies, related to F2, *People* skill demand.

This theory also has implications for how we measure skills for the purposes of labour market analysis. There is a complex and as yet poorly understood map between the kinds of skills and tasks described in this section and broad labour market indicators such as educated vs. less educated workers, produc-

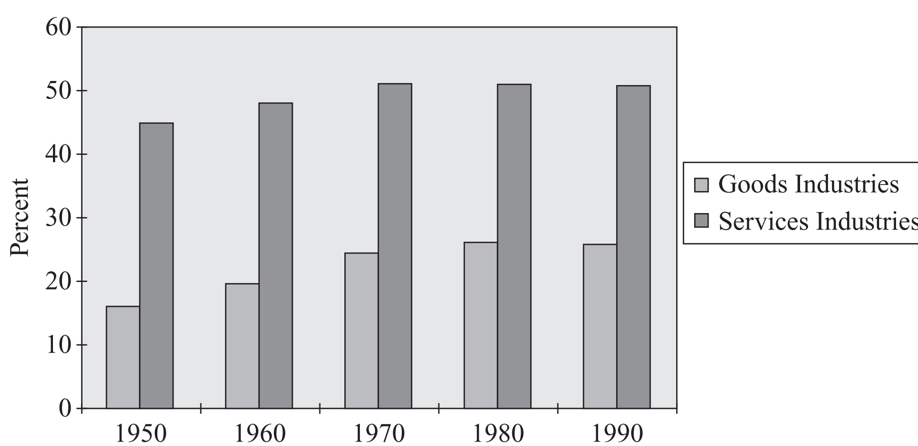

Fig. 5. *Data Workers as a Percent of Total Employment in Two Sectors* (Wolff, 1996, p. 28)

[43] Cf. p. 4 of Wolff for more on the sources and definitions. Categories also include 'goods workers', 'service workers', and so on.

tion workers vs. managers and professionals, and so on. Rather than asking what the implications of this theory are for those broad categories, we should worry about the adequacy of the categories.

3.3. *Rising Demand for High Skill Labour*

The demand for highly skilled labour has been rising rapidly. This, too, has an attractive explanation in the industrial engineering of ICT-based bureaucracies. The technical change that is inherent in the shift to ICT based production raises the return to thinking by managers and professionals and also increases people skill demand.

3.3.1. *Daily co-invention*

The analytical literature on business computer systems emphasises their complementarity with (1) changes in organisation and (2) new services. It also emphasises the cognitive difficulty of inventing new business computer systems.[44] Much of the relevant invention (or co-invention) is routine and ongoing. This leads to *organisational complementarily* between computers and skilled workers, especially managers and professionals.

Routinised bureaucratic production offers opportunities for incremental technical progress. Once a database of transactions has been built, managers and professionals co-invent improvements in products or processes. *Marketing* managers now have the opportunity to know much more about customers. Computer databases provide the underpinnings for much analytical marketing thinking. Once research has discovered what customers want, the computerised production process can be changed to deliver it. This is typically not trivial, involving the definition of new services permitted by the expanded production opportunities.

The same occurs on the *accounting and control* side of bureaucracies. The existence of large operational databases allows research on the incentive problems in an organisation. This can extend to customers and suppliers. Research can predict which customers pay slowly. Within the firm, research can show who is an effective sales person, an effective lower-level manager, etc. ICT-based production then offers the opportunity to act on these practical research results. This is not typically trivial, either, involving the setup of new incentive contracts, new forms of monitoring and reporting, and so on.

These same points apply broadly. A wide range of managerial functions now calls for more complex cognitive skills. We have seen the extension of computerised production to more and more complex kinds of transactions and the linking together of more and more data. Managers and professionals do more research as a result, and turn their results into operations more systematically. This calls for new cognitive skills, having a deep understanding of

[44] See Barras (1990), Bresnahan and Saloner (1996), Bresnahan and Greenstein (1997), Brynjolfsson (1994), and Friedman (1989).

one's own organisation and one's customers' needs.[45] This is clearly directly related to the rising demand for large bundles of cognitive skills.

3.3.2. *Scope of managerial action*

There is a relationship between the computerisation of bureaucratic operations discussed under limited substitution, above, and the demand for highly skilled labour. The effect of computerisation is to make managerial and professional actions highly influential. In a people-based organisation, the scope of influence of a new idea is limited by the need to communicate it to all the clerks. In software-based production, the same idea can be applied to *all* customers, *all* transactions, etc., by embedding it in the system. This raises the marginal product of skilled worker's ideas, even if those workers never see a computer.

This also calls for new levels of interpersonal skills in organisations. Effective design of new service products, once the desirable ones have been identified, calls for not only quantitative skills but also traditional marketing and people skills (it is not only incentives that make people be nice on the phone). The design of new incentive schemes, for real people not the radically rational ones of our theories, calls for as much EQ (emotional intelligence) as IQ.

Changes in company structure permitted by improved information flows have changed managerial skill requirements in another way. As bureaucracies grow flatter, and as the jobs in the bottom of the bureaucracies change, monitoring, supervision, and oversight change as well. Managers' skill requirements have moved correspondingly upward. This cluster of changes speaks directly to F2 People skill.

ICT-based production calls for increases in cognitive skills and people skills.[46] There is a shift in the relative demand of very capable people relative to moderately capable, which speaks to F5, pervasiveness across the range of incomes.

4. Changes in Industrial (Blue-Collar) Labour Demand?

To complete the picture of computerisation and labour demand would call for extension of the same kinds of analysis to other production processes such as those in manufacturing plants, and to other kinds of work, such as blue collar. In a statistical sense, we know much more about those industries and those kinds of work. There has been a long-term shift out of blue-collar labour. Recently, that trend has been particularly rapid in those industries with rapid

[45] Bartel and Lichtenberg (1987) suggest that high levels of cognitive skills may be particularly important in creating and adapting to change, notably in implementing new technology. The managerial side of computer-based production processes is an excellent example of this story.

[46] Interestingly, there has been an attempt, with much more limited success, to substitute computers for managers or other high-level operational personnel. This was the first view of 'artificial intelligence'. I conjecture that the limited substitution of AI for managers and professionals has to do with the growing noncognitive component of their work in organisations. Some of AI's successes – in medical diagnosis and in loan underwriting – are in very high cognitive-content tasks.

technical progress measured by computerisation and R&D (Berman *et al.* 1994), although this appears to be limited to a few industries (Berman *et al.* 1997).

I am cautious in extending the analysis of this paper into industrial technologies for a variety of reasons. Most importantly, information technology is far less central there than in service industries and in the white-collar functions of 'industrial' industries. There is less for computerisation to explain; application of science and engineering in industry has led to systematic reduction of all direct production costs, including direct (production) labour. A second reason for caution is the smaller role played by industrial technologies in modern labour demand. From a general equilibrium of the labour market perspective, the 'industrialised' countries are not – they are the formerly industrialised countries now specialised in services, including those service functions which are closely complementary to industrial production. These two reasons add up to a small likely impact of ICT on labour markets if we restrict attention to industrial processes.

There are, however, at least two points about ICT in industrial processes that are worth noting and which may have an aggregate contribution to make. The first has to do with the management of industrial processes. An important role of information technology has been in improving managerial control of inventory and capacity, much of through production planning systems. For example, a very important line of technological development in manufacturing starts with the inventory control systems of the 1950s and 1960s and continues through categories such as MRP (manufacturing resource planning) to the ERP (enterprise resource planning) systems of the present. Relatedly, improvements in computer systems have permitted more precise and quantitative analysis and forecasting of demand. The net impact of planning systems plus better demand analysis has been better matching of inputs to demand. This reduces all direct costs, notably direct labour costs, per unit of usable output.

More broadly, improvements in the control of production processes permit substitution out of the inputs involved directly in production. There is a potentially important general equilibrium point here. Much of the use of ICT in white-collar functions I covered in earlier sections is reported by practitioners to improve the quality of bureaucratic work rather than to permit economising on the size of the bureaucracy. Practitioners report two general cases, and either might be relevant here. (1) If what the bureaucracy does is control and direct production, the impact of improving it may be to economise on directly productive inputs – including production labour. (2) If what the bureaucracy does is make products or services more useful to customers, then an improvement in the technology of bureaucracies could lead to an expansion in the bureaucracy relative to the directly productive unit. Of course, this depends on the elasticity of demand for bureaucratic services, which is not one of the better-measured economic quanta.

A second point refers more directly to the use of information technology in the industrial process itself. An interesting direction to follow would be the use of first minicomputers and then computers of all kinds to measure, monitor, and control very specific production subprocesses. The human task 'if the temperature goes over 1237°, turn down the gas' is quite amenable to automation, as is the related one that finishes '... call the engineering department'. Systematic deployment of ICT in more and more complex measurement and control of those production subprocesses that involve heat or other chemical reaction is likely to have reduced demand for operatives and labourers far more than engineers. Parallel developments in making manufacturing capital more intelligent, such as computer-numerically-controlled machine tools, have parallel effects in some very different industrial processes. All of these are likely to have shifted the skill demands of the operatives and labourers. To the extent that their skills are cognitive, these improved control systems and improved tools shift demand. An open question is whether the use of these specific technologies in industrial processes is a proxy for more general technical progress there or instead measures something specific about computerisation in factories.

5. Conclusion

Information and communications technologies have been a powerful transforming force in white-collar work. Invention of ways to use computers in bureaucracies has meant the regularisation and routinisation of bureaucratic work, a process that has renewed itself steadily over 50 years. Organisational computing draws on such important technologies as database management systems and communications controllers far more than PCs.

The *organisational computing theory predicts the main stylised facts*. The resulting technical change has been skill-biased. (a) Computer decisionmaking has systematically substituted for human decisionmaking in modest cognitive skill tasks. (b) Computers in organisations have been complementary to large bundles of cognitive skills, especially where these are bundled with people skills. (c) Organisational computing has been complementary to 'people skills', and to autonomy, raising their return. The resulting shift in labour demand by skill – or by skills – has been dramatic. (d) The changes have come at the time, and in the industries, primarily services, and the functions, primarily white collar, where organisational computing has had its largest impacts. Enough people work in white-collar bureaucracies, and the impact of organisational computing has been pervasive enough, for this skill biased technical change to affect the rich economies in the aggregate.

In this paper, those predictions have been linked only to broad, qualitative observations about the general equilibrium of the labour market. The more detailed predictions also offer an agenda for systematic measurement and testing. The basis of the theory in the technology of computer-based production offers the strongest of these. We should shift way from individual computer use as a technology indicator, and from a view of the individual job as the conceptual labour-demand unit. The firm and the organisation of its workforce offer better grounds to get at the important flows of causation. More

ICT-intensive production will be characterised by specific patterns of substitution and complementarity, mediated through changes in the structure of the firm. Second, there is a disconnection between the skills whose demand is shifted by ICT and the way we categorise workers. Human capital is not a scalar concept, and our standard proxies of age, experience, tenure, gender, etc., map only imperfectly to workers' abilities. This is especially marked for noncognitive skills: we are left using the rapidly growing demand for pleasant and convincing workers to predict 'within group' wage inequality. This means simply that we have the groups wrong. We need to think carefully through the mapping between the proxies for human capital we observe and analyse and the underlying dimensions of valuable skill.

Is organisational computing not just ancient history, looking back at the earliest uses of computer technology and missing such large events as the PC revolution? On the contrary, *organisational computing is the wave of the future* more than of the past. The uses of ICT are one of the most difficult economic and technical forecasts, yet enough is now visible now to permit a bold guess. Networked computer business systems are advancing rapidly. This has already led to a renaissance of organisational computing invention. First 'client/server' computing and now 'intranets' blend PCs into organisational computing. Networked computing also permits the extension of business computer systems to wider and wider geographical scope, and to cross company boundaries – 'inter-organisational computing'. Less far along, but potentially very powerful, are business-to-consumer transaction applications using electronic commerce for improved service, mass customisation, and individualised advertising.

Will this technical progress lead to persistence of the kinds of labour market impact we have already seen or to a reversal of it? There are strong trends in favour of persistence in the near future. Organisational computing continues to affect production in much the same way, even as it uses PCs and servers instead of terminals and hosts. Potentially more importantly, inter-organisational applications involve the automation of buying and selling bureaucracies, and improvements in the technology of transacting. This has the very serious prospect of continuing to automate moderate skill white-collar work while increasing the demand for highly skilled managers and professionals. The amount of mid-skill white-collar work in buying and selling is stunning, so limited substitution will find new scope there. Inventing new inter-organisational applications and managing the organisations that can participate in them will call for extraordinary management skill and extraordinary technical skill in implementation. Organisational complementarity is not finished.

How large an effect? Persisting for how long? There you have a researchable question to which I do not know the answer and an unresearchable question.

There has been a long-term trend in technical progress reducing the labour content of industrial processes, and a resulting long-term trend away from relatively low-wage blue-collar work toward higher paid occupations. Organisational computing accelerates that trend and extends it into white-collar work.

Even more, it extends it into the growth sectors of the economy. Hence its ongoing aggregate implications.

This shift in labour demand could have led, depending the supply response, either to a movement of traditionally low wage workers into more highly rewarded activities or to increased inequality. In actuality, supply has responded slowly and inequality has increased. Some see this as an indictment of modern economies' fairness, while others fear it will lead to a new antigrowth political economy. It has led everyone to worry about the effectiveness of the schools, and to the hope that changed policies toward schools will open up the labour supply bottleneck.

I worry that our focus on schools, while warranted, is too narrow. The skill biased technical change of the present raises the return to a wide range of skills, not only cognitive ones. Interpersonal skills, knowledge of the world of work, ability to work steadily and autonomously, flexibility, and reliability are all in increased demand. It is not immediately obvious that it is a problem only in the schools if the supply curve of these has shifted left. Family, church, neighbourhood, and club all have a role to play in labour supply, and they have (at least from my parochial US perspective) declined troublingly, especially for young people in the bottom half of the income distribution. The good news here is that improvements in any of a wide variety of labour supply institutions, whether schools or not, could lead to more economic mobility and success.

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