How the world of work is changing: a review of the evidence

Maarten Goos

International Labour Office
Geneva

Bureau international du Travail
Genève

Oficina Internacional del Trabajo
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Written by: Maarten Goos

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Maarten Goos[1]

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Abstract

This paper presents an overview of some of the recent literature about the long-run changes in labour market outcomes in advanced economies. It shows that the First and Second Industrial Revolutions, with inventions in the second half of the 19th century that had a lasting impact up to 1980, resulted in skill upgrading and decreasing overall wage inequality. To the contrary, the Computer Revolution that started in the 1980s is no longer unambiguously skill-upgrading but characterized by an underlying process of job polarization and an increase in upper-tail and overall wage inequality. However, the paper concludes by providing arguments in favour of optimism about future computerization as long as our labour markets are able to provide the necessary worker skills to support such changes.

JEL Classifications: J23, J24, N10
Keywords: Technological progress, Skills, Employment Structure, Wage Inequality

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1 Introduction

Labour markets are constantly changing. These changes, which have important consequences for individual workers, are reflected in compositional changes in employment and changes in wage inequality, and help shape labour market institutions. As such, understanding them is important for academics and policymakers alike. This paper therefore provides an overview of changes in employment and wage structures, starting with the birth of modern economies, through the First and Second Industrial Revolutions, to the ongoing Computer Revolution. Drawing on a recent literature, it outlines the content of these different episodes of development and highlights how each have had different impacts on labour markets, depending on how they interacted with the existing job structure, skill supply, product demand and the organization of production.

Section 2 of the paper first provides a brief general background to the First and Second Industrial Revolutions which took place in today's advanced economies between 1820 and 1900, with follow-up inventions up to 1980. The invention of, among other things, steam power, electricity, the automobile, modern chemistry and the telephone in the 19th century caused a sea change in manufacturing and led to a rise in services. In manufacturing, large plants replaced small artisanal workshops. On the new factory floors, economies of scale came from capital deepening and workers operating purpose-built machinery. Because machine operators required some but not much training, the gains from specialization provided many unskilled farm labourers with opportunities to move into better-paid medium-skilled blue-collar jobs. Together with an increase in medium-skilled and skilled white-collar employment in manufacturing and services, this led to skill-upgrading in the overall economy. Moreover, this skill upgrading was characterized by an expansion of the education system to such an extent that the increase in the supply of skills outpaced its increase in demand due to industrialization. Hence, skills were relatively abundant, thus reducing the skill premium and overall wage inequality. In this way, the First and Second Industrial Revolutions resulted in economic growth, skill-upgrading, mass education and lower overall wage inequality.

Section 3 of the paper then explains how the Computer Revolution, which began in advanced economies in the 1980s, is different. Although there still is a net skill-upgrading, computerization is also leading to job polarization with rising employment shares for skilled and unskilled jobs at the expense of medium-skilled employment. The reason for this is that computers can codify and perform more efficiently routine tasks mainly done by medium-skilled workers, such as machine operators and office clerks. But the tasks done by unskilled workers, such as waiters or cleaners, and skilled workers, such as managers and computer programmers, are non-routine in nature and therefore not easily codified and performed by computers. At the same time, growth in educational attainment rates has faltered in many advanced economies since 1980, reducing growth in skill supplies, thereby increasing the skill premium and upper-tail and overall wage inequality. In short, the impact of the Computer Revolution is different from that of previous episodes of development. Underlying skill-upgrading there is job polarization and upper-tail and overall wage inequality is rising not falling. To get a better understanding of these aggregate changes, Section 3 goes on to document the impact of computerization by outlining its impact on the firm's organizational design and human resource practices. It points to the importance of system-wide complementarities and the need for computerization to allow high performance work practices, such as setting up problem solving teams, job rotation, information sharing and intensive training. Section 3 also discusses, among other things, the importance of a task-based approach to labour markets and firms, and the existence of wage polarization. It also briefly documents recent employment changes in developing economies.

Section 4 of the paper then draws from our understanding of past and present labour market developments to think briefly about the future. It conjectures about the future pace of computerization to argue that, on balance, the relative demand for skilled workers will continue to increase in the future. To the extent that this increase will be met by continued investment in education and on-the-job training, there can be further skill-upgrading and economic growth without increasing, and possibly even decreasing, upper-tail and overall wage inequality, as was the case in advanced economies before 1980. Moreover, the section argues why job polarization does not justify fears of a digital invasion but calls for optimism about future computerization as long as labour markets are able to provide the necessary skills to support such changes.

2 The past (1820-1980)

This section discusses the impact of the First and Second Industrial Revolutions on labour markets. Section 2.1 gives some general background to the First Industrial Revolution that took place between 1820 and 1870 in today's advanced economies. Section 2.2 does the same for the Second Industrial Revolution between 1870 and 1900, with follow-up inventions up to 1980. Section 2.3 then discusses empirical evidence of the impacts of the First and Second Industrial Revolutions on the structure of employment. For manufacturing, it shows the shift away from the smaller artisanal shop to the larger factory. For the aggregate economy, there was skill-upgrading because of a shift away from unskilled farm labourers to medium-skilled blue-collar workers such as machine operators and medium-skilled and skilled white-collar employment in manufacturing and services. Finally, Section 2.4 looks at changes in relative wages that, together with changes in relative employment, are informative about shifts in the relative demand for and supply of differently skilled workers. It is shown that the skill premium and overall wage inequality decreased because the increase in the demand for skills due to industrialization was met by an even stronger increase in the supply of skilled workers due to the rapid expansion of the education system.

2.1 The First Industrial Revolution (1820-1870)

Before the start of the First Industrial Revolution, most people were employed either in agriculture as farmers or in a town or city as members of a guild. Guilds were organizations formed by craftsmen based on their trades, mainly textile and wood industries, each of which controlled the "arts" or "mysteries" of their crafts. Master artisans enjoyed a higher social status because of their level of expertise and because they owned small shops in which they employed and trained apprentices. The early stages of a craft worker's career mainly consisted of applying the finishing touches to an almost final good. The training needed to progress to the status of craftsman or even master mostly involved learning how to use a simple set of tools as dictated by the guild. Guilds also imposed entry restrictions, making it difficult for those lacking the capital or approval to gain access to the profession even as apprentices. In many cities, guilds united to protect their common interest, thus shaping institutions (Laing 2011). As such, work defined a person's role in society, and there was little social mobility. Wars were rationalized by a mercantilist philosophy that motivated colonial expansion and barriers to trade.

The First Industrial Revolution put an end to the political economy of mercantilism and marked an important turning point towards a free-market philosophy. Its transition gained momentum between 1820 and 1870 with the widespread adoption of steam-powered boats, ships and railways, the large scale manufacture of machine tools and the increasing use of steam-powered factories. Individual tasks began to be carried out by special-purpose machinery instead of by human or animal effort alone. Unskilled agricultural labourers moved to the factory floor to become better-paid medium-skilled machine operators. Moreover, the factory floor also demanded skilled workers such as supervisors to organize and monitor machine operators, and engineers and mechanics to develop, build and implement new machinery (Katz and Margo 2013). In short, the First Industrial Revolution increased the living standards of many workers even in poor households. Together with the rapid increase in agricultural output due to the invention of soil fertilizers, industrialization made it possible for societies to grow and escape their Malthusian poverty trap for the first time in history.

However, despite the large societal gains from the First Industrial Revolution, life expectancy in the advancing economies was still only 45 years in 1870. Indeed, living and working conditions still needed much improvement. Houses were dark and smoky and did not have any electricity. The enclosed iron stove had only recently been invented and much cooking was still done in the open hearth. Only the proximity of the stove or hearth was warm and bedrooms were unheated. There was no running water or indoor plumbing such that water for laundry, cooking, and indoor chamber pots had to be carried in, and wastewater carried out. Coal or wood had to be carried in and ashes had to be collected and carried out. Many workers still had to work long hours while barely earning a decent living, opportunities for education were very limited, and child labour was common. Although railroads began connecting cities, steam power was not practical within them so inner-city traffic still relied on horses (Gordon 2012).

2.2 The Second Industrial Revolution (1870-1980)

The key inventions of the Second Industrial Revolution took place between 1870 and 1900 and can be grouped into five categories: (1) electricity and all its spin-offs; (2) the internal combustion engine and the automobile; (3) running water, indoor plumbing, and central heating; (4) rearranging molecules, including everything to do with petroleum, chemicals, plastics, and pharmaceuticals; and (5) the range of communication and entertainment devices including the telephone, the phonograph, popular photography, radio and motion pictures. Widespread adoption of these inventions as well as additional "follow-up" inventions continued and are believed to have had a lasting impact as late as the 1970s (Gordon 2012).

Running water replaced carrying water and waste; oil and gas replaced coal and wood; electric hand tools became common by 1920; and household appliances began to proliferate with the first washers and refrigerators being introduced in the 1920s. Reading was easier with electric light, and pollution was reduced as natural gas began to be used instead of wood or coal. Communication and entertainment blossomed with the telegraph, telephone, phonograph, recorded music and, by 1920, the first commercial radio station. Television was introduced in 1929 and the first TV stations began broadcasting in 1936. Antibiotics became commercially available in 1932. In terms of transportation, the horse-drawn tram was replaced by the electric tram and the motorbus within a few years, and underground railway systems appeared in large cities. But probably none of the transportation inventions of the period 1870-1900 was more important than the automobile. Prior to its invention, workers necessarily had to live close to their jobs. The arrival of the automobile meant the decentralization of business and residential patterns leading to a suburban real estate boom, the rise of out-of-city centre department stores, supermarkets, and mail-order catalogues. The automobile was a remedy for rural isolation, led to improved roads and thus medical assistance, and expanded recreational opportunities. Other modes of transportation continued to develop. Barely two decades after the Wright Brothers' first flight in 1903, the first commercial airline flight took place in 1926. By 1958, travellers were winging their way at 550 miles an hour in a Boeing 707 (Gordon 2012).

As a result of these inventions, the labour market had been utterly changed by 1970. The transition from agriculture and the artisanal shop to the factory that had started in the First Industrial Revolution accelerated. In factories, the introduction of electricity enabled further gains from task specialization by introducing "continuous processing" and "mass production" methods (Katz and Margo 2013). As early as 1799, Eli Whitney had introduced an assembly line to produce muskets. The key innovation underlying Whitney's system was to assemble each musket in stages using dedicated machinery that could be operated by workers with minimal training. This resulted in a more uniform product that met precise tolerance standards. Over the course of the 19th century, this assembly-line method rapidly spread into other industries. A famous example is the introduction of Henry Ford's automated car assembly line in the late 19th century. In 1913, Ford took the idea one step further by introducing moving assembly methods to manufacture the Ford Model T automobile. Partially assembled automobile chassis were continuously moved along a conveyor belt from one production stage to the next – hence the name "continuous processing" – until their assembly was complete. The accompanying increase in productivity made it possible to reduce costs and thereby the price of automobiles, leading to an increase in demand for them and mass production. Consequently, Ford's automated assembly line was rapidly adopted by other industries (Laing 2011). A similar profound change in production methods would not occur until the 1950s and 1960s, when firms gradually began replacing the specialized equipment used in assembly-line production with more flexible robotic equipment for "flexible" or "lean" technologies, an issue that we will return to below.

During the Second Industrial Revolution, further specialization and capital deepening continued to increase productivity and therefore the demand for medium-skilled machine operators in iron, steel and metal processing industries, manufacture of bricks and glass products, as well as in mining and construction. At the same time the demand for skilled workers in manufacturing, such as supervisors, electrical engineers and chemists, continued to rise (Katz and Margo 2013). Besides increasing economies of scale from the division of labour on the factory floor, there were gains from trade following expanded market access as a result of the improvements in transport and communication. This need for market expansion led to the rapid growth of a service sector and an increased demand for non-production workers of different skill levels. There was an increase in employment of unskilled service workers in recreation, culture and personal services, but also of medium-skilled and skilled white-collar workers such as office clerks and salespersons in wholesale and retail and business services such as finance and real estate (Gordon 2012).

The Second Industrial Revolution had an important impact not only on employment, but also on wages and wage inequality. Initially, the skill premium, the earnings of skilled or educated workers relative to less-skilled or less-educated workers, increased because the supply of skilled workers was relatively limited. Consequently, from the second half of the 19th century to the early 20th century, wage inequality increased. However, the relative scarcity of skilled workers was gradually squeezed out by the expansion of the high school and college system, beginning from the early 20th century in the US, with Europe lagging a few decades behind, which decreased the skill premium and overall wage inequality between 1915 and 1980 (Goldin and Katz 2008).

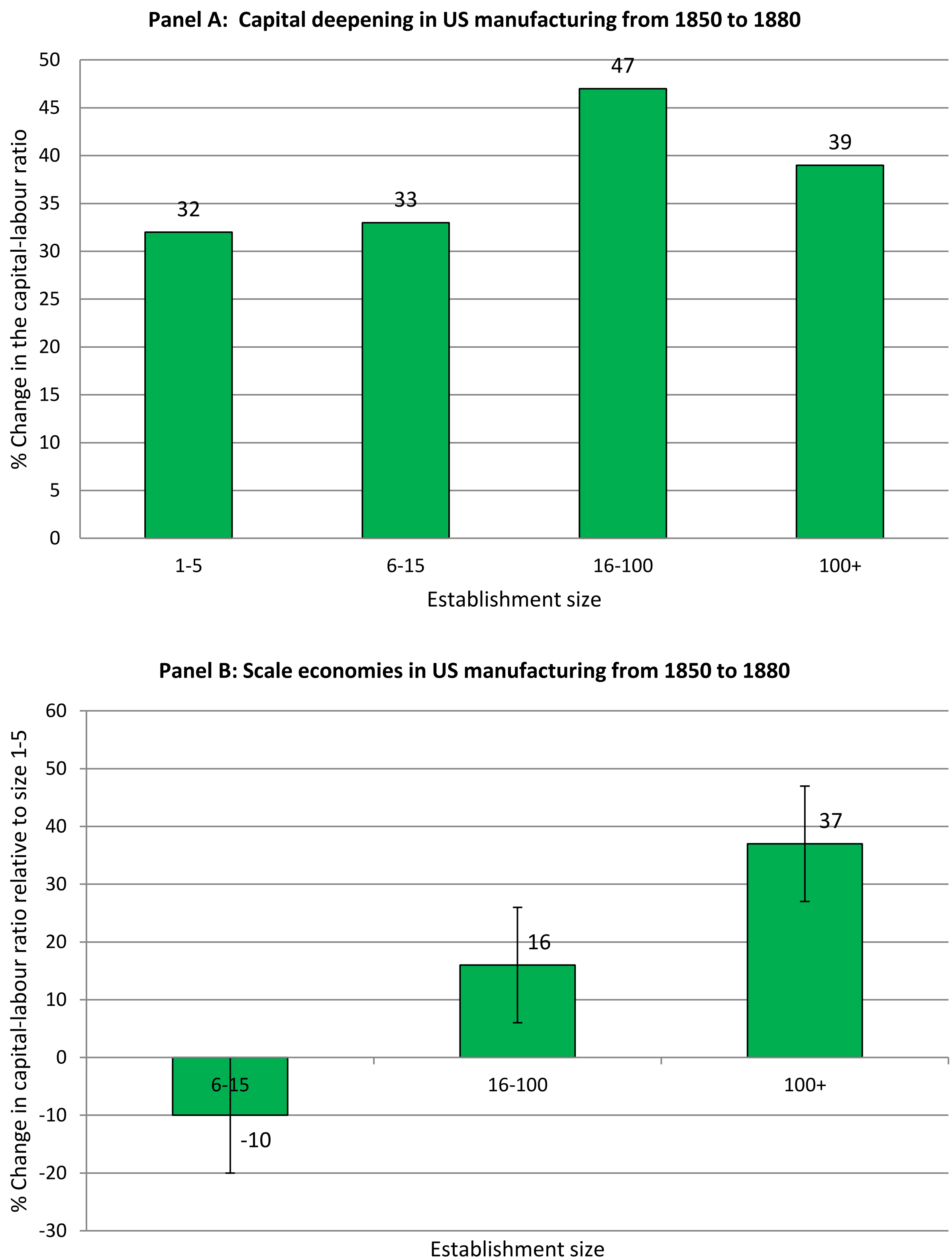
2.3 Evidence of changes in the job structure before 1980

This section provides empirical evidence in support of the relative employment impacts of the First and Second Industrial Revolutions. The summarized data are taken from Katz and Margo (2013) for the US, but their findings seem similar to those for other industrializing economies. In their paper, Katz and Margo (2013) document the transition in manufacturing from the artisanal shop to larger manufacturing plants between 1850 and 1880, and how the First and Second Industrial Revolutions led to skill-upgrading in the overall economy from 1850 to 1980. First the period 1850-1880 is discussed, then the period 1920-1980.

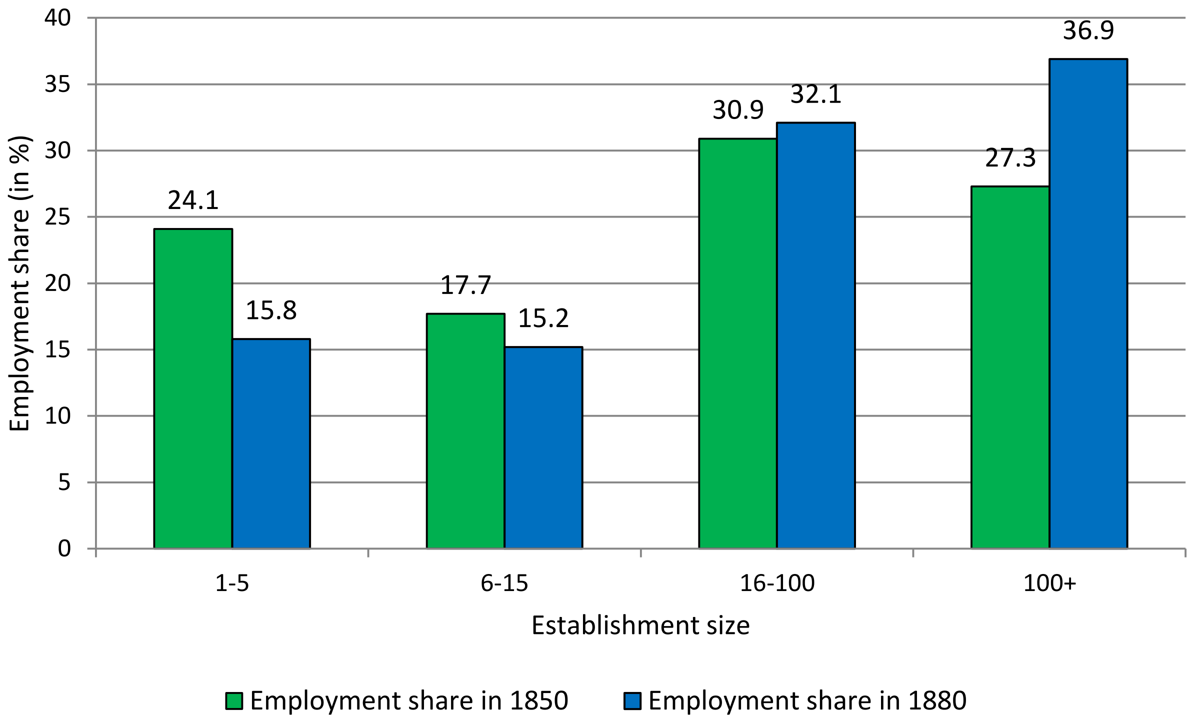
1850-1880

Firstly, Panel A of Figure 1 uses the US Census of Manufacturing from 1850 and 1880 to show the percentage change in the capital-labour ratio by the size (in terms of employment) of manufacturing plants. Because of the widespread adoption of steam-powered machinery in the second half of the 19th century, one would expect to see an increase over time in the average capital-labour ratio, a process also known as capital deepening. Panel A shows that capital deepening indeed took place between 1850 and 1880. For example, the capital-labour ratio in plants employing 1 to 5 employees increased by 32% over this period. Moreover, one would also expect there to be economies of scale from industrialization resulting in more capital deepening in larger plants. Panel B of Figure 1 therefore shows the amount of capital deepening for firms of different sizes relative to the amount of capital deepening observed in the smallest firms. The reported percentage point differences monitor, for example, the firm's location or sector, so that they capture differences in capital deepening that are most probably explained by changes in production technologies, such as the introduction of machinery and the division of labour on the factory floor. Panel B shows that, in plants employing 16 to 100 employees, the capital-labour ratio increased 16 percentage points faster than in smaller plants employing 1-5 employees. For firms with more than 100 employees, this difference stands at an even larger 37%. Finally, Panel C of Figure 1 provides further evidence in support of the view that the First and Second Industrial Revolutions changed the business landscape and organization of production. The panel shows that employment became increasingly concentrated in larger establishments, indicative of an important shift from the small artisanal shop towards the larger factory floor occurring between 1850 and 1880.

Figure 1: Capital-labour ratios in US manufacturing, 1850 and 1880



Panel C: Increase in establishment size in US manufacturing from 1850 to 1880

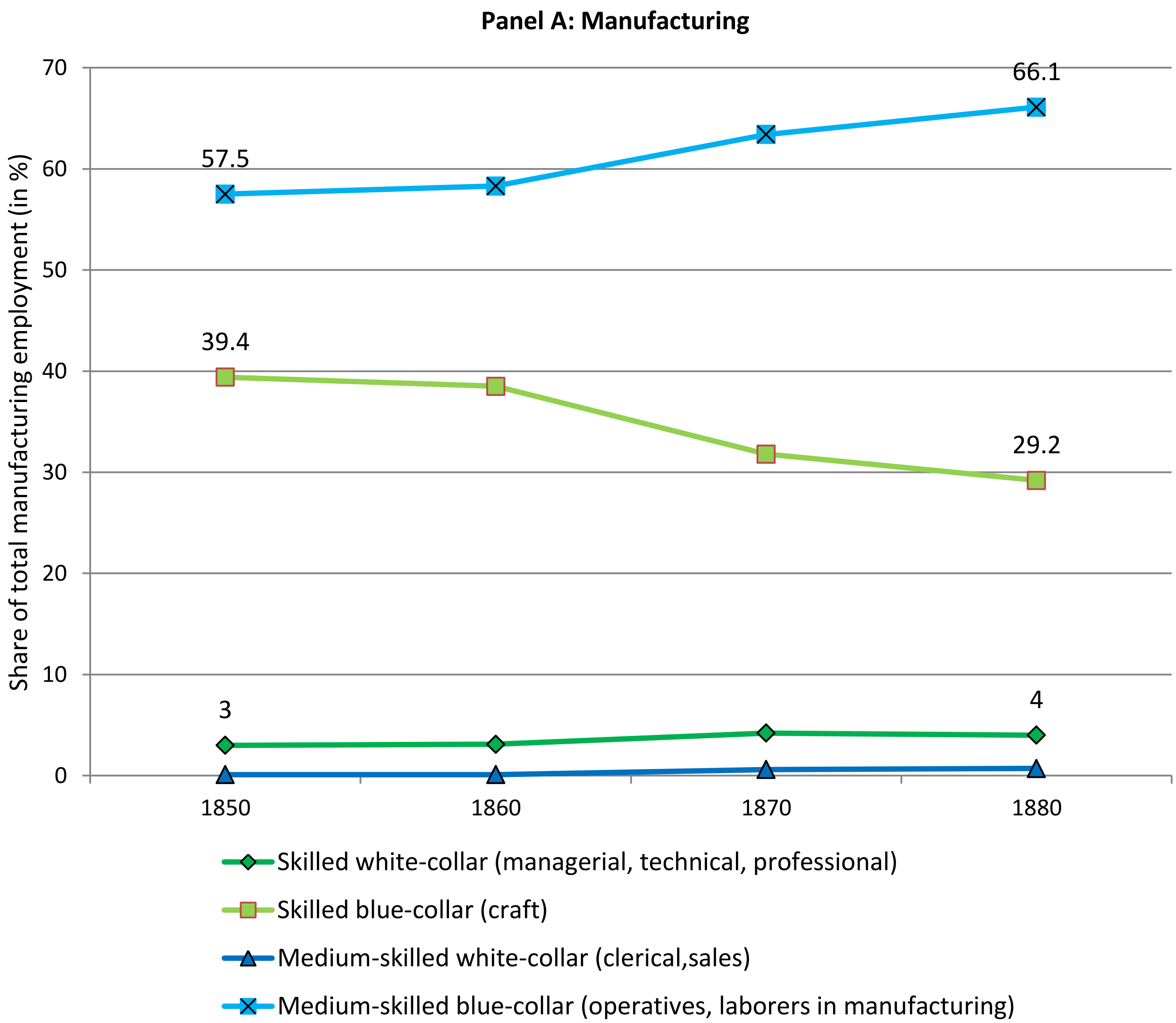


Notes: Data are taken from Table 1 in Katz and Margo (2013) who use the US Census of Manufacturing in 1850 and 1880. There are 4,905 establishments in 1850 and 7,175 in 1880 in the data. Panel A reports the logarithmic difference in the mean capital-labour ratio between 1880 and 1850 by establishment class size. Each number in Panel B is an estimated difference-in-difference coefficient of the interaction term between the size class of the establishment and a dummy variable for the year 1880, in a regression that pools all establishments in 1850 and 1880 and that further includes a dummy for the year 1880, the number of workers employed, and dummies for urban status (establishment located in a city or town of population 2,500 or larger), state and 3-digit SIC industry codes. The error bar around each estimated difference-in-difference coefficient captures a range that is twice its estimated standard error. If the range does not cross the x-axis, the estimate is significant at the 5 per cent level. Panel C shows employment shares by establishment size for 1850 and 1880.

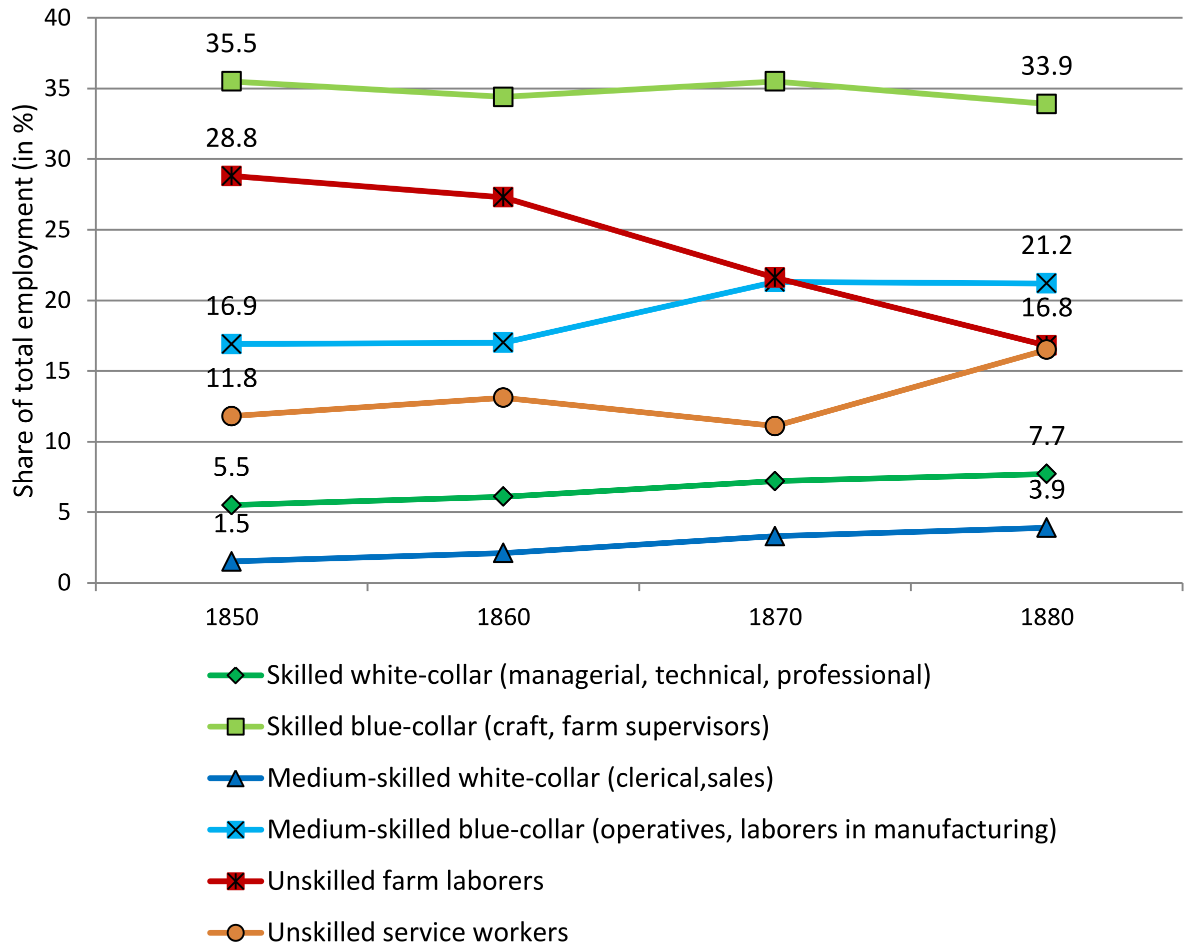
An interesting question is how capital deepening impacts the structure of manufacturing employment. This can be seen in Panel A of Figure 2, which is again taken from Katz and Margo (2013) using US Census of Population data. The figure plots a time series for the occupational composition of manufacturing employment between 1850 and 1880 for: 1) medium-skilled blue-collar workers such as machine operators and other manufacturing labourers; 2) medium-skilled white-collar workers such as clerical and sales workers in manufacturing; 3) skilled blue-collar workers, mainly craftsmen; and 4) and skilled white-collar workers such as managers, technicians and other professionals in manufacturing. Note that it is assumed that there are no unskilled workers in manufacturing. The reason for this is that even medium-skilled blue-collar machine operators, the least skilled among manufacturing workers, require some, albeit limited, training. This makes the least skilled manufacturing workers more skilled than unskilled service workers and farm labourers. These latter categories will be added later when non-manufacturing employment is included to look at employment changes for the aggregate economy. Panel A of Figure 2 shows that, of all manufacturing workers in 1850, 3% were skilled white-collar (managers, technicians and other professionals), 39.4% were skilled blue-collar (craftsmen), 0.1% were medium-skilled white-collar (clerical and sales) and 57.5% were medium-skilled blue-collar workers (machine operators and other manufacturing). By 1880, these numbers were 4.7%, 29.2%, 0.7% and 67.8% respectively. That is, the employment share of skilled white-collar but also of medium-skilled jobs increased, at the expense of skilled blue-collar jobs paying middling wages in manufacturing. These findings support the hypothesis that technological progress in the 19th century increased the relative demand for medium-skilled machine operators, clerical and sales workers compared with skilled blue-collar craftsmen. Although this suggests that there was de-skilling in manufacturing, Katz and Margo (2013) also point to the relative increase in skilled white-collar employment and suggest that a more nuanced view would be to say that manufacturing employment was "hollowing-out" rather than "de-skilling".

The hollowing-out of manufacturing employment between 1850 and 1880, however, does not mean this must also be true for the economy as a whole. In particular, we argue above that the second half of the 19th century was also characterized by the rise of a service sector. This created jobs for unskilled service workers (in recreation, culture and personal services), medium-skilled white-collar workers in services (clerical and sales occupations in services), and skilled white-collar workers in business services (finance and real estate). Moreover, in 1850 most workers were still employed in agriculture, and the expansion of large manufacturing plants and the service sector provided many with the opportunity of moving into better-paid jobs. To see this more clearly, Panel B of Figure 2 adds jobs in services and agriculture to the analysis of the manufacturing sector in Panel A. More specifically, it reworks data reported in Katz and Margo (2013) to add unskilled service workers and unskilled farm labourers as separate occupation groups; clerical and sales workers in services are added to the group of medium-skilled white-collar employment; skilled farmers are added to the group of skilled blue-collar jobs; and skilled service workers are included in the skilled white-collar category. Panel B clearly shows that, for the economy as a whole, technological progress between 1850 and 1880 led to skill-upgrading: Despite the increase in unskilled service jobs from 11.8% in 1850 to 16.5% in 1880, the share of unskilled workers as a whole fell, due to the sharp decline in unskilled farm labourers from 28.8% in 1850 to 16.8% in 1880. The share of medium-skilled blue-collar and white-collar jobs taken together increased from a total of 18.4% in 1850 to 25.1% in 1880, whereas the share of skilled workers was stable overall due to a decrease in skilled blue-collar jobs from 35.5% in 1850 to 33.9 % in 1880, offset by an increase in skilled white-collar jobs from 5.5% in 1850 to 7.7% in 1880. In other words, due to the expansion of medium-skilled jobs relative to unskilled jobs there was skill-upgrading between 1850 and 1880 for the aggregate labour market.

Figure 2: Occupation distributions in the US labour force, 1850-1880



Panel B: Aggregate economy



Notes: Data are taken from Table 4 in Katz and Margo (2013). Panel A uses data from the first panel of Table 4 in Katz and Margo (2013). Panel B combines data from the first and second panels of Table 4 in Katz and Margo (2013) to separate out the different skill groups. Details on how the numbers reported in Table 4 in Katz and Margo (2013) are combined to obtain employment shares by skilled white/blue-collar, medium-skilled white/blue-collar and unskilled farm labourers and service workers are available on request.

1920-1980

Figure 3 shows that this process of skill-upgrading for the aggregate economy continued up to 1980. The figure uses the 1920 to 2010 US Census of Population from the Integrated Public Use Microdata Series (IPUMS) and the IPUMS 2010 American Community Survey, taken from Katz and Margo (2013). The occupational categories constructed are similar to those in Panel B of Figure 2. From 1920 to 1980, the share of unskilled workers (service workers and farm labourers taken together) fell from 16.8% in 1920 to 13.8% in 1980. The figure also shows that this decline is explained exclusively by the sharp fall in unskilled farm labourers (from 8.6% in 1920 to 0.9% in 1980) despite the rise in unskilled service jobs (from 8.2% in 1920 to 12.9% in 1980). Medium-skilled employment (blue-collar and white-collar taken together) increased from 40.4% in 1920 to 45.1% in 1980. This rise in medium-skilled jobs was driven by the steady increase in white-collar clerical and sales jobs from 13.1% in 1920 to 25.9% in 1980 (after which its share fell to 23.1% in 2010, as discussed in Section 3 below), whereas the employment of medium-skilled blue-collar jobs was about 27% in both 1920 and 1950 but declined after that to 19.2% in 1980 (and further to 12.6% in 2010, which is another trend change discussed in Section 3 below). Figure 3 also shows that the relative employment of skilled workers (blue-collar and white-collar taken together) did not change much between 1920 and 1980, but that this is the net effect of an important shift of 17.1 percentage points (34.4% in 1920 minus 13.3% in 1980) away from skilled blue-collar and an increase of 15.6 percentage points (27.9% in 1980 minus 12.3% in 1920) towards skilled white-collar jobs.

In short, the shift from artisanal shops to manufacturing plants provided many unskilled farm labourers with the opportunity to move into medium-skilled blue collar jobs such as machine operators. Together with an increase in medium-skilled and skilled white-collar employment in manufacturing and services, industrialization led to skill-upgrading in the aggregate economy.

2.4 Evidence of changes in relative wages before 1980

One way to see whether skill-upgrading is mainly because of an increase in the relative demand for skills due to industrialization, or because of an increase in the relative supply of skilled workers, is to combine relative employment with wage changes using a simple supply-demand framework. This is what this section does. First the period 1850-1915 is discussed, then the period 1915-1980.

1850-1915

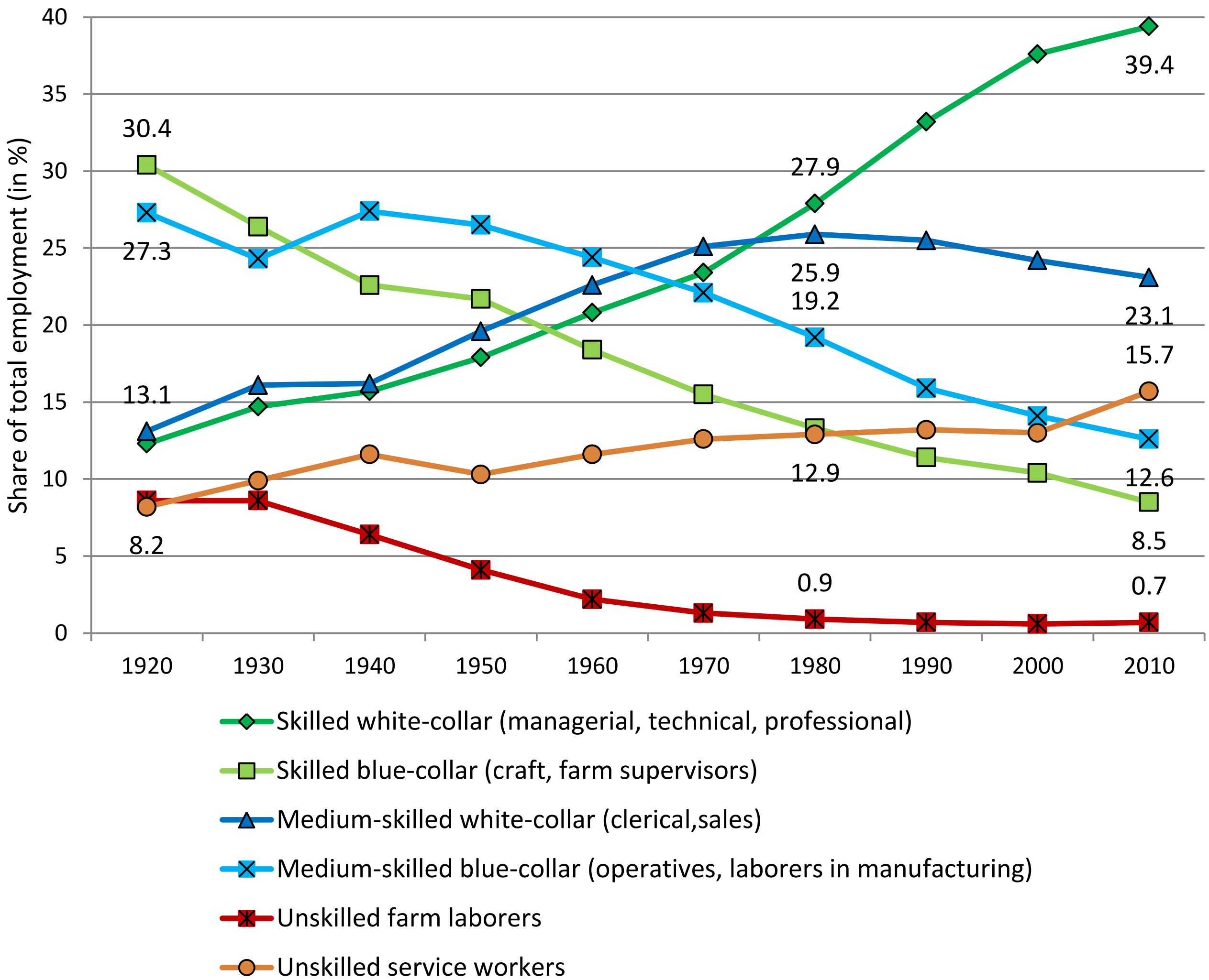
Panel B of Figure 2 shows that there was skill-upgrading in aggregate employment between 1850 and 1880. To know whether this skill-upgrading was driven mainly by an increase in the relative demand for skilled workers, due to industrialization, or by an increase in the relative supply of skilled workers, due to education, one can look at the skill premium. The assumption is simple: the skill premium increases if growth in demand for skilled workers outpaces growth in supply. Conversely, the skill premium falls if growth in the supply of skilled workers outpaces growth in demand for it. That is to say, we can use a simple supply-demand framework to get a better understanding of the drivers of skill-upgrading and changes in the skill premium or wage inequality.

One difficulty in doing this for years before 1915 is obtaining good information on wages. Some evidence is found in Katz and Margo (2013) who use the Reports of Persons and Articles Hired for army forts in the US to generate a time series of wages for unskilled workers, skilled artisans, and medium-skilled clerical workers between 1866 and 1880. Their estimates suggest that wages of clerical workers increased relative to wages of unskilled workers and skilled artisans. Together with the increase in clerical employment compared with skilled artisans and unskilled workers shown in Panel B of Figure 2, this suggests that the increase in the relative demand for clerical workers, due to industrialization, outpaced supply in the second half of the 19th century. However, the wage data analysed in Katz and Margo (2013) also have some important limitations. Firstly, the Census employment data presented in Figure 2 are more comprehensive than the wage data derived from army fort reports. For example, child and female labour were important in the civilian labour market but not at army forts. Secondly, the economic organization of forts was not the same as, for example, the typical manufacturing establishment and therefore wages paid at forts might not be good proxies for civilian labour market conditions. Better wage data are available for years after 1915, but then the forces of supply and demand probably also changed, as we discuss next.

1915-1980

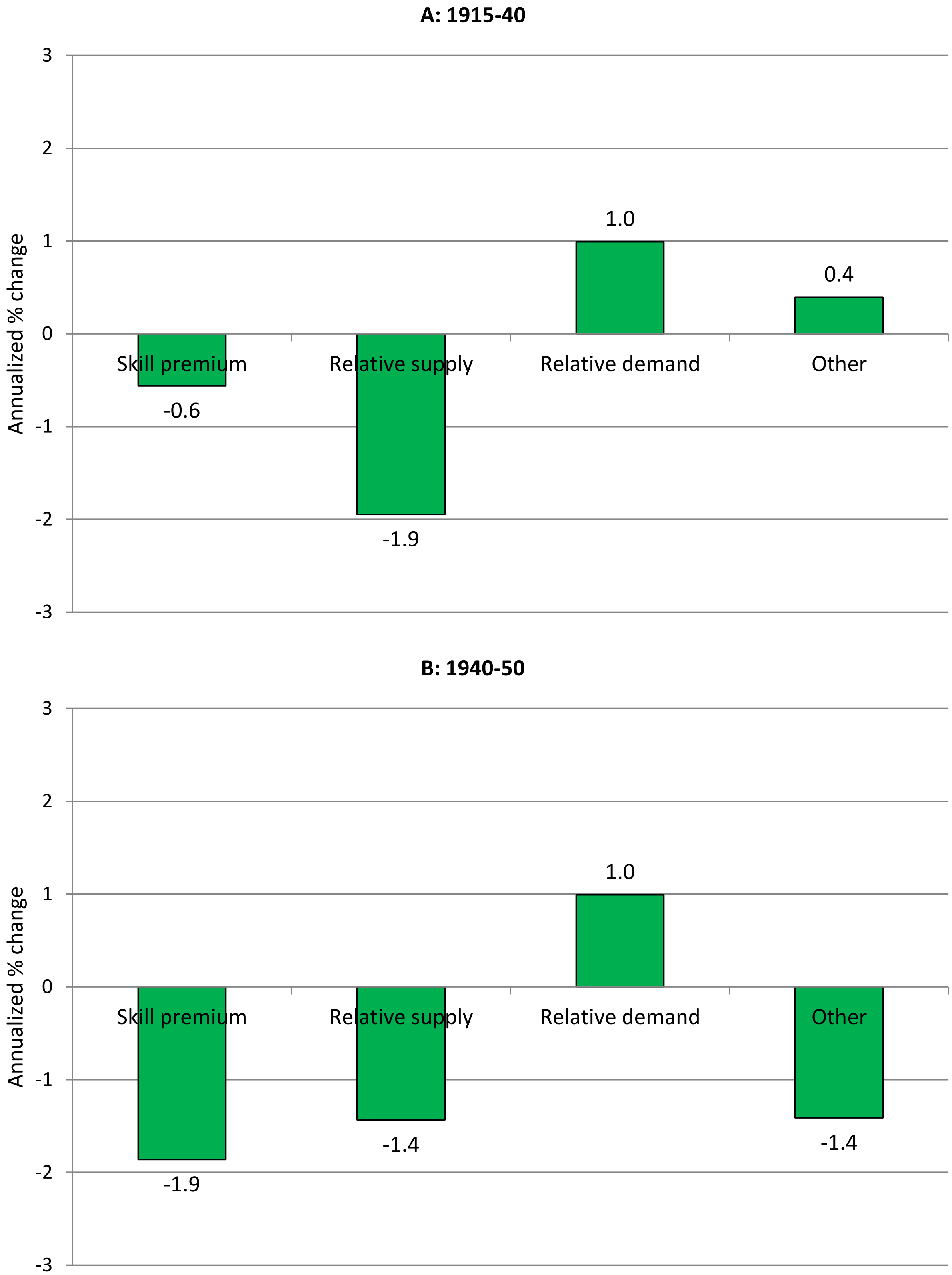
From 1915 until 1980 there was further skill-upgrading in the aggregate economy, as shown in Figure 3. However, in contrast to the years before 1915, the skill premium fell between 1915 and 1950, increased in the 1950s and 1960s, and fell again in the 1970s, at least in the US. To illustrate this, Figure 4 uses the US 1915 Iowa State Census, the IPUMS 1940 to 2000 Census, and the 1980 to 2005 CPS MORG taken from Goldin and Katz (2008). The first bar in every panel shows the annualized percentage change in the skill premium which is the ratio of the average wage of college over non-college workers. For example, between 1915 and 1940, the skill premium fell by 14% over 25 years or 0.6% annually. In the 1940s the skill premium decreased at an even faster pace of 1.9% annually, whereas in the 1950s and 1960s it increased at an annual rate of 0.8% and 0.7%, respectively. In the 1970s the skill premium fell by 0.7% per year, after which it increased rapidly at an annual rate of 1.5% in the 1980s and somewhat slower afterwards.

Figure 3: Occupation Distributions in the US labour force, 1920-2010

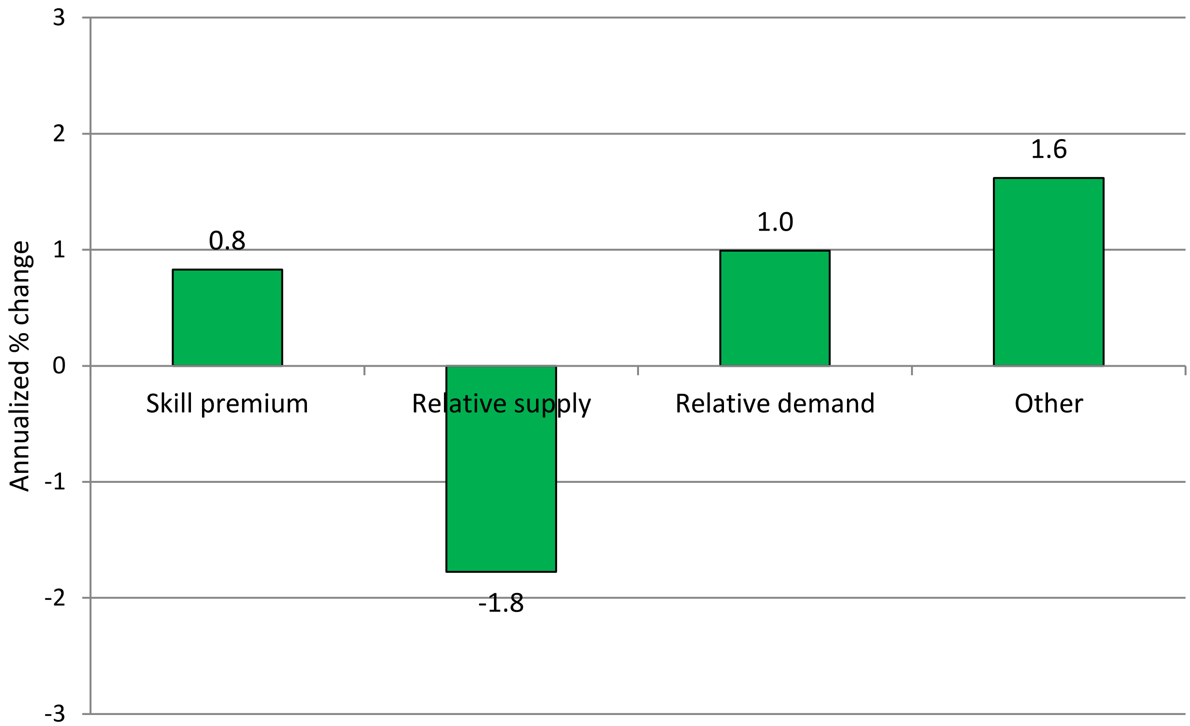


Notes: Data are taken from the first panel of Table 6 in Katz and Margo (2013). Details on how the numbers reported in the first panel of Table 6 in Katz and Margo (2013) are combined to obtain employment shares by skilled white/blue-collar, medium-skilled white/blue-collar and unskilled farm labourers and service workers are available on request.

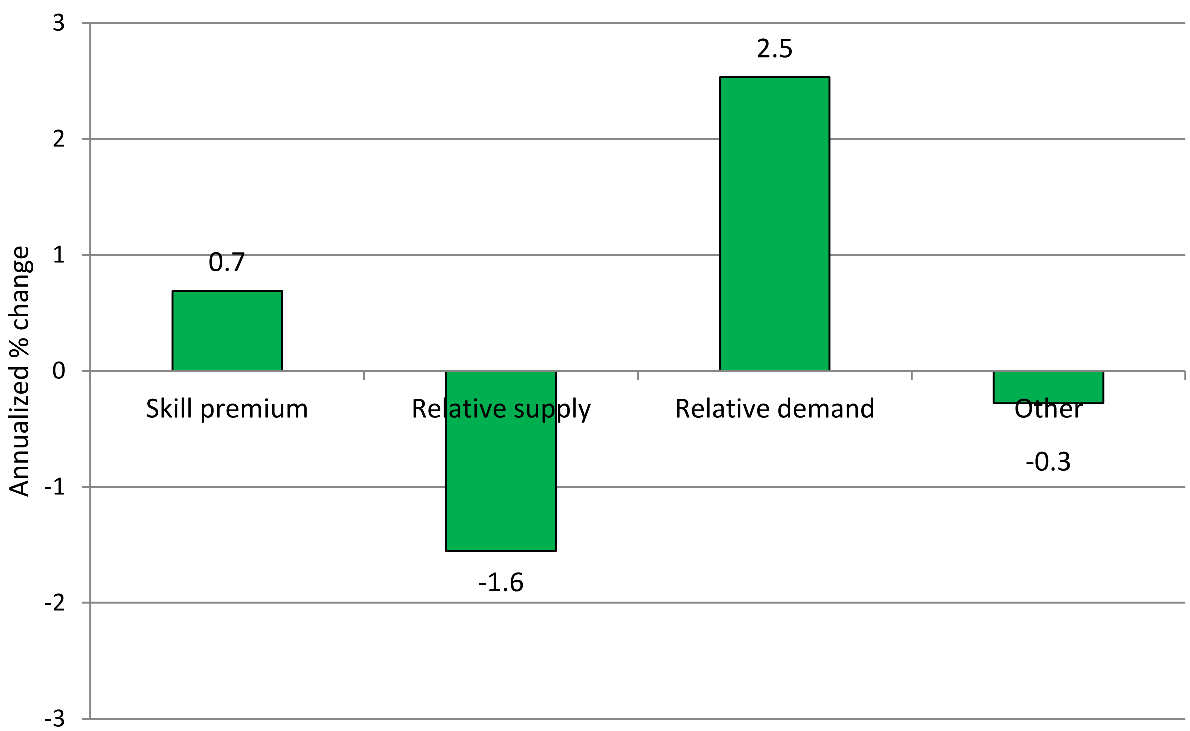
Figure 4: The US skill premium, relative supply and demand, and institutions, 1915-2005



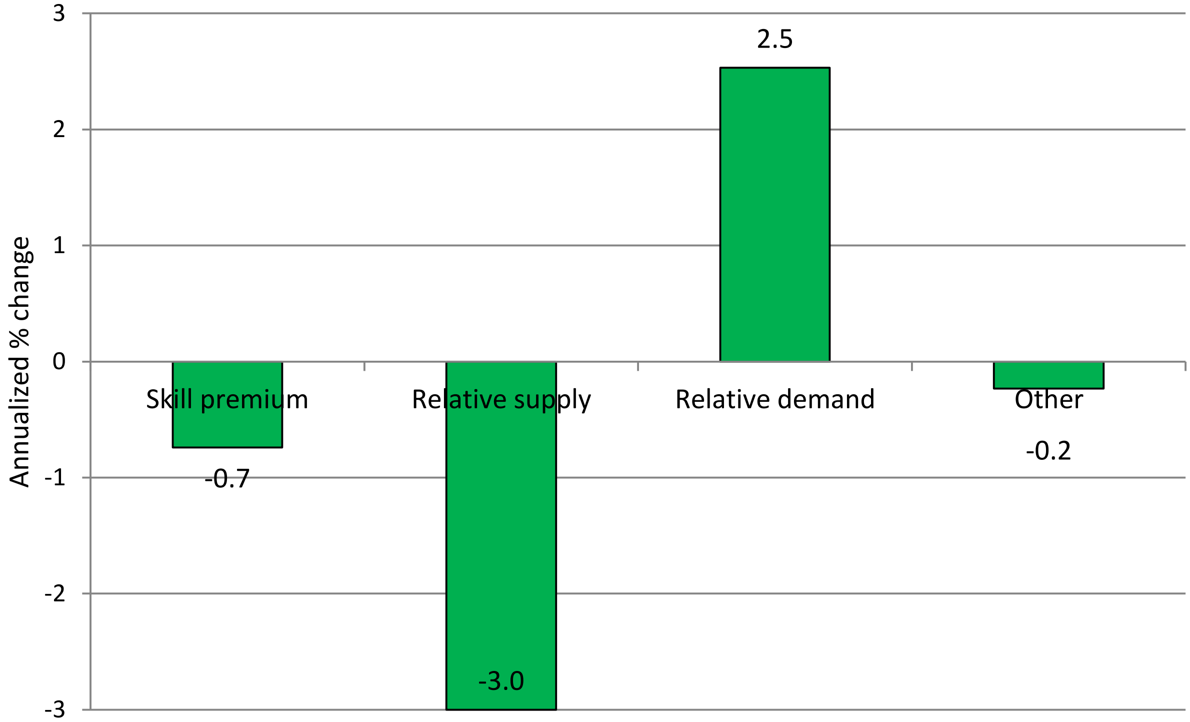
C: 1950-60



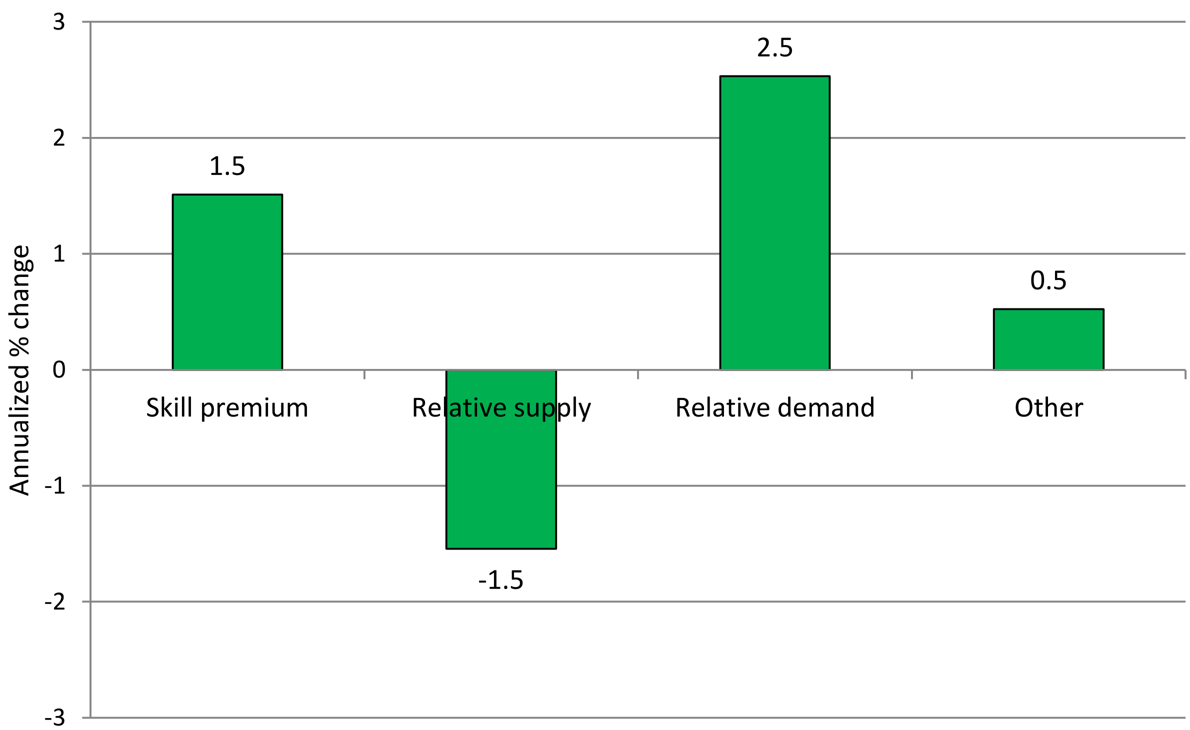
D: 1960-70

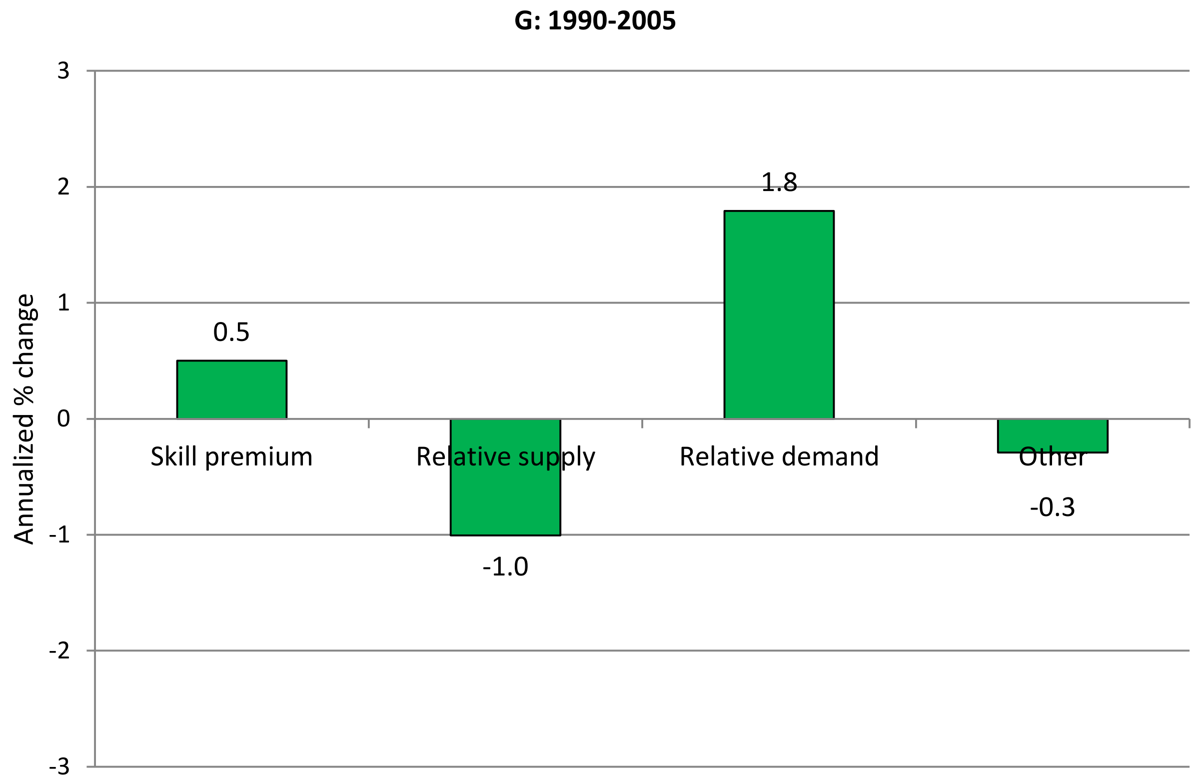


E: 1970-80



F: 1980-90





<u>Notes:</u> The data are constructed by combining information from Table 8.1 and Table 8.2 in Goldin and Katz (2008). The skill premium is taken from Table 8.1 in Goldin and Katz (2008) and is the difference in the logarithmic average wage between a worker with a college degree and a worker with a high school degree. The relative supply measures are taken from Table 8.1 in Goldin and Katz (2008) who obtained those measures directly from their underlying micro data. The relative demand measures are obtained from combining data in Table 8.1 in Goldin and Katz (2008) with point estimates reported by them in column (3) of Table 8.2. In column (3) of Table 8.2, Goldin and Katz (2008) estimate a relative supply-demand framework assuming relative supply is perfectly inelastic and relative demand follows a secular time trend that is allowed to differ in years before 1960 and after 1992. To see the magnitude of shifts in relative supply and demand in terms of quantities rather than wages, the numbers have to be multiplied by 1.64 which is the estimated elasticity of substitution between college and high school workers. For example, for the period 1915-1940 the skill premium decreased at an annualized rate of 0.6% a year. This decrease is explained by an annualized increase of 3.19% in the relative supply of college workers and this would have, all else being equal, resulted in a decrease in the college premium of 1.9% a year. Similarly, the increase in the relative demand for skilled workers at an annualized rate of 1.6% would have, all else being equal, increased the skill premium by 1% a year.

Figure 4 also shows why, on balance, the skill premium decreased between 1915 and 1980. The remaining three bars in each panel show numbers that combine estimates from a supply-demand framework reported in Goldin and

Katz (2008). The first panel shows that the annual decrease of 0.5% in the skill premium between 1915 and 1940 is driven by: a) an increase in the supply of skilled relative to unskilled workers which, all else being equal, would have decreased the skill premium by 1.9% annually; b) an increase in the demand for skilled, relative to unskilled workers, which would have increased the skill premium by 1% annually; and c) other factors which would have increased the skill premium by 0.4% annually. That is, between 1915 and 1940 the increase in the supply of skilled workers outpaced the growth in demand, thereby reducing the returns to skill and overall wage inequality in the economy.

Why did the relative supply of skilled workers increase in the US between 1915 and 1940? Goldin and Katz (2008) document succinctly the reasons why the American educational system expanded rapidly between 1915 and 1940. The first reason, they argue, is that education was publically provided and publically funded by small and fiscally independent districts, bringing free education geographically close to many children in rural constituencies. Secondly, education was under secular control and gender neutral, such that it was open to both male and female children, from all religious backgrounds. Finally, education was practical in its curriculum, diverse in many dimensions, and forgiving. In a review of Goldin and Katz (2008), Acemoglu and Autor (2012) also point to the emergence of a political system that favoured the wishes of the majority of the population and its demand for education. All these virtues resulted in the rapid expansion of America's educational system between 1915 and 1940 and held the promise of equality of opportunity and the American dream. In this, the changes in the US educational system between 1915 and 1940 were exceptional compared to, for example, Europe's more elite education system at that time. But also in Europe there was mass education in the 20th century, albeit with a lag of a few decades, and many European countries have been able to catch up (Goldin and Katz 2008).

Turning to the period 1940 to 1980, the second panel in Figure 4 shows why the skill premium further decreased by a rapid 1.9% per year during the 1940s. Just as for the years before 1940, one reason was that the increase in the relative supply of skilled workers outpaced the relative increase in demand. However, in contrast to earlier periods, the 1940s were also characterized by changes other than supply and demand which, by themselves, would have decreased the skill premium by an annualized 1.4%. To explain this, Goldin and Margo (1992) point to institutional and cyclical factors. These include the strong demand for war production workers in the first half of the 1940s and the rise of union bargaining power. Because some of these institutional and cyclical changes were only temporary, the third panel in Figure 4 shows that the skill premium bounced back in the 1950s despite the fact that growth in the relative supply of skilled workers was still outpacing demand. Finally, the fourth and fifth panels in Figure 4 show why the skill premium increased in the 1960s and decreased in the 1970s. It increased in the 1960s because the relative demand for skilled workers accelerated, whereas it decreased in the 1970s following a large increase in the relative supply of skilled workers.

To sum up, between 1915 and 1980, skill-upgrading resulted from increases in the relative demand for skills due to industrialization, but also from increases in the relative supply of skilled workers due to an expansion of the education system. From 1915 to 1960, growth in the relative supply of skilled workers outpaced the increase in demand for it, thereby decreasing the skill premium and overall wage inequality. This decrease was amplified during the so-called Great Compression of the 1940s, when institutional factors were also at play, followed by a partial reversal of their impact in the 1950s. The 1960s were characterized by stronger growth in the relative demand for skill thereby increasing the skill premium, whereas in the 1970s the skill premium fell because of exceptionally strong growth in the relative supply of educated workers. Overall, the skill-premium fell between 1915 and 1980, thereby reducing overall wage inequality.

3 The present (1980-2014)

Section 3.1 provides some general background to the Computer Revolution that started in 1980. Section 3.2 argues that, because routine tasks are codifiable and can be done more efficiently by computers, computerization necessitates a more nuanced task-based view of labour markets, the firm's organizational design and its human resource practices. Section 3.3 then focuses on the impact of computerization on aggregate changes in relative employment and the importance of high performance work practices at the firm level. It shows that with underlying skill-upgrading there is also a shift towards workers being employed in non-routine tasks, leading to job polarization in the aggregate labour market and the use of high performance work practices in firms, such as setting up problem solving teams, job rotation, information sharing and intensive training. Section 3.4 summarizes existing evidence about the impact of computerization on lower-tail, upper-tail and overall wage inequality. In contrast to the period before 1980, upper-tail and overall wage inequality is increasing mainly due to a slowdown in growth rates in educational attainment. The section also shows that upper-tail wage inequality is falling, at least in the US, due to computerization. Finally, Section 3.5 briefly looks at recent changes in relative employment in developing economies.

3.1 The Computer Revolution

The previous section discussed the First and Second Industrial Revolutions following the inventions in the 19th century of steam power; electricity; the combustion engine; running water, indoor plumbing and central heating; petroleum, chemicals, plastics and pharmaceuticals; the telephone and radio; and rail, road and air travel. Although these inventions mainly occurred in the relatively short time span between 1850 and 1915, most economic historians believe their impacts lasted up to the 1970s (Gordon 2012). The previous section also outlined the strong skill-upgrading in employment that took place between 1850 and 1915 due to an increase in both the supply of and demand for skilled rather than unskilled workers. Moreover, because growth in the relative supply of skilled workers, driven by the rapid expansion of the education system, outpaced growth in demand, the skill premium and therefore overall inequality fell between the early 20th century and 1980. Industrialization, the consequent wage increases for many workers and the compression in wage dispersion all contributed towards strong economic growth and the rise of a middle class. But this section shows that, with the arrival of the Computer Revolution, things changed significantly from the 1980s onwards.

In the latter part of the 20th century, building on ideas first implemented in the Japanese motor industry in the 1950s and 1960s, the organization of production underwent another profound change. Firms gradually began abandoning the specialized machinery used in mass assembly-line production to replace it with more flexible robotic equipment. Rather than installing vast amounts of fixed capital to mass produce the same good, new methods of "flexible" and "lean" production make it possible to quickly retool or re-program machines to produce small customized batches of different varieties designed to fit customers' needs. The modern manufacturer is a multiproduct firm characterized by flexible machinery with low set-up costs, short production runs, continuous product improvements, a focus on product quality rather than volume, low inventories, and a reliance on outside suppliers or vertical disintegration rather than vertical integration (Laing 2011).

In explaining these changes, a key role is played by the invention of robotic machinery and computers more generally, hence the name "Computer Revolution". Most observers date the beginning of the Computer Revolution to the release of the Apple II home computer in 1977 and the introduction of the IBM-PC in 1981 (Card and DiNardo 2002). This was followed by the IBM-TXT in 1982 and the IBM-AT in 1984. In 1990, Microsoft's Windows 3.1 revolutionized the desktop landscape by introducing an operating system based on a more user-friendly windows interface. The World Wide Web was introduced in 1991 and became widely accessible after the introduction of Netscape Navigator in 1994 and Google in 1998. Over the past decades, computing power has doubled every two years, a trend known as Moore's law named after Intel co-founder Gordon Moore who, as early as 1965, predicted exponential growth in the capabilities of digital electronic devices such as CPU processors and memory storage.

To get a first idea of how the Computer Revolution is changing labour market outcomes, return to Figure 3 above to look at changes in the occupational composition of employment after 1980. The figure suggests that the demand for skilled white-collar jobs such as managers, engineers and other professionals accelerated after 1980. For example, many engineers today are writing software code or designing new products from their office desks; market-oriented production has increased the need for better demand management; the introduction of high performance work practices, discussed in greater depth below, has increased the demand for human resource managers. Figure 3 also shows that the employment share of medium-skilled workers (both white- and blue-collar) increased from 40.4% in 1920 to 45.1% in 1980, but fell to 35.7% in 2010. An important part of this decline is the relative decrease in medium-skilled white-collar jobs that started around 1980. An intuitive explanation for this, and Section 3.3 discusses empirical evidence in support of it, is that computers substitute for office clerks because what they do can be codified and ultimately expressed in software language. Finally, Figure 3 also shows important trend changes in the employment share of unskilled workers after 1980. Between 1920 and 1980 the share of unskilled employment (unskilled farm labourers and service workers) fell, due to the decline in farm labourers from 8.2% in 1920 to 0.9% in 1980, despite the rise in unskilled service workers from 8.2% in 1920 to 12.9% in 1980. On the other hand, between 1980 and 2010, the share of unskilled employment (unskilled farm labourers and service workers) increased from 13.8% to 16.4% because of continued growth in unskilled service jobs from 12.9% in 1980 to 15.7% in 2010 combined with a farm labour share that bottomed out in 1980 and has remained stable at around 1% ever since. The relative growth in unskilled service employment is also intuitive as, for example, the job of a waiter in a restaurant is not easily done even by the most powerful computer. In short, labour markets in advanced economies are no longer unambiguously characterized by skill-upgrading. Although there is continued growth in the employment share of skilled white-collar jobs at the expense of medium-skilled employment, the fraction of unskilled service workers is also growing. This process, rising shares of skilled and unskilled and falling share of medium-skilled employment, is known as “job polarization”.

3.2 The task approach to labour markets and firms

This section argues that a more in-depth understanding of the impact of computer technology requires a task-based approach. This section first discusses a task-based approach to aggregate labour markets, before it turns to a task-based view of the firm’s organizational design and the importance of high performance work practices.

The task approach to labour markets

One way to better understand the labour market impacts of recent technological progress is to think more carefully about how computerization has changed the nature of automation. As was documented in Section 2, part of the gains from automation in the First and Second Industrial Revolutions came from the increased employment of medium-skilled blue-collar machine operators. However, computerization is now displacing these workers because their tasks can be codified and performed more efficiently by computers. Moreover, recent automation means that computers can substitute for many of the routine tasks done by medium-skilled white-collar workers, such as office clerks. In a nutshell, contrary to the increase in the relative demand for medium-skilled white-collar and blue-collar jobs in the First and Second Industrial Revolutions, demand for these jobs is now decreasing because of the routine nature of the tasks done and the fact that they can be codified and more efficiently performed by computers.

Whereas computers can substitute for labour in routine tasks, they have difficulty doing non-routine tasks such as managing a team or waiting tables in a restaurant. This is because whereas routine tasks are mainly done in middling jobs by medium-skilled workers, non-routine tasks are concentrated in skilled white-collar jobs and unskilled service work. So far, computers cannot easily manage teams or wait tables. This non-monotonic relationship between task-routineness and skill necessitates a "task approach" to labour markets. In a task-based framework, workers supply a pre-market set of skills, most notably their education. Based on their comparative advantage, these workers are then sorted across jobs that differ in their task demands. Crucially, computerization changes these task demands and therefore also the sorting of differently skilled workers across jobs accordingly. Most notably, Autor, Levy and Murnane (2003) were the first to analyse such a task-based framework and they argue convincingly, using data from the US, that computers have been displacing workers from routine tasks. Goos and Manning (2007) then showed that for the UK this leads to job polarization because computerization decreases the demand for medium-skilled labour relative to both skilled and unskilled labour. Some of the results in Autor, Levy and Murnane (2003) and Goos and Manning (2007) are summarized below. More recently, a number of studies have successfully used a task approach to get a better understanding of labour markets. The studies are too numerous to summarize here, but see Autor (2013) for an overview and some additional references.

Organizational design and high performance work practices

Whereas the task approach is useful to get a better understanding of the aggregate labour market, computerization is also having profound impacts on the design of organizations and human resource practices within firms. In a series of pioneering papers, Milgrom and Roberts (1990, 1995) and Holmstrom and Milgrom (1994) examine the relationship between a firm's production technology and its organizational structure. Specifically, they argue that important system-wide complementarities exist among various business activities. For example, assume a firm that initially uses mass-production methods and traditional human resource practices. Next assume that the firm wants to change from its mass-production technology to a more flexible and lean production method, perhaps by substituting flexible robotic equipment for its existing machinery. However, the productivity gains from so doing might be limited if the firm does not also change the way it organizes its workers. When the firm was using mass production methods, workers did not require much training to operate machinery. However, using a more flexible production method, workers have to be better skilled and cross-trained in order to understand why machinery operates the way it does and what are its capabilities. To this end, the firm can implement high performance work practices such as setting up problem solving teams in which non-managerial workers participate in problem solving and decision making; job rotation so that workers are trained to perform a wide variety of different tasks; better screening of job applicants who have desirable attributes such as the ability to cooperate with others; information sharing among themselves and their management; more intensive training to enhance their decision-making and problem-solving skills; incentive pay and profit sharing; and it can also provide implicit guarantees of job security to increase worker involvement (Laing 2011). In short, only by also changing its human resource management will the firm be able to successfully implement the flexible and lean production methods that the Computer Revolution allows.

The existence of system-wide complementarities also points to a potential risk that firms face when implementing new technologies. Because complementarities are often unknown, wrong investments can easily lead to failure. For example, Milgrom and Roberts (1995) discuss the failed attempt by General Motors, once a leading example of mass-production, to emulate the flexible production systems of its Japanese competitors. In the 1980s, General Motors spent vast amounts of money on robotic and other capital equipment to upgrade its assembly line. It did not, however, make equally important investments in its human resource policies, its decision systems, and other aspects of its organizational design. Consequently, in the early 1990s General Motors had assembly lines that should have been the most flexible and lean in the world but that produced only a single model, while the corporation as a whole lost money at unprecedented rates (Laing 2011). Similar evidence is provided in a series of papers that examine differences in human resource practices across similar steel plants (Ichniowski, Shaw and Prennushi 1997; Boning, Ichniowski and Shaw 2007; Bartel, Ichniowski and Shaw 2007). A common theme that emerges from these studies is that a plant's productivity positively depends on the presence of high performance work practices, but also that some plants are slow to adopt these practices because of their inherent risk of failure.

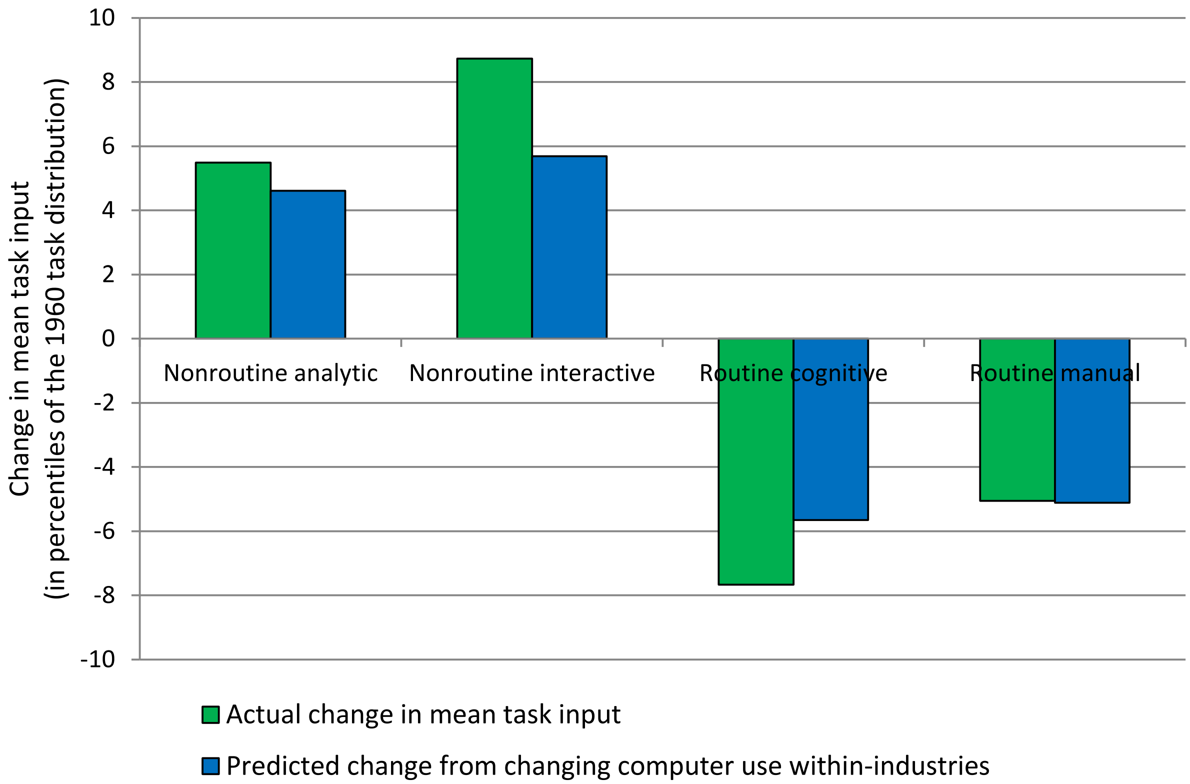
3.3 Evidence of recent changes in relative employment

This section begins by summarizing some existing evidence about the impact of computerization on the overall employment structure. It then turns to evidence about the impact of computerization on human resource practices within firms.

Recent changes in the job structure

This section summarizes some of the existing empirical evidence about the impact of computerization on the structure of employment. Figure 5 is constructed from Autor, Levy and Murnane (2003) and uses the 1977 Dictionary of Occupational Titles (DOT) to measure the task content of occupations and US CPS MORG data between 1980 and 1998 to measure employment. Figure 5 shows four different task measures: 1) non-routine analytic tasks are high in occupations that require high levels of education, and are done by skilled white-collar workers; 2) non-routine interactive tasks generally capture the degree of responsibility for direction, control and planning, and are also done by skilled white-collar workers; 3) routine cognitive tasks extend to occupations that require the precise attainment of set limits, tolerances or standards, and are done by medium-skilled white-collar workers; and 4) routine manual tasks capture the ability to manipulate small objects with fingers, rapidly or accurately, and are done by medium-skilled blue-collar workers. For each task measured in Figure 5, the first bar shows the change in its mean between 1980 and 1998. In line with our discussion in Sections 3.1 and 3.2, it is clear from the figure that there has been a shift away from both types of routine task (cognitive and manual) towards both types of non-routine task (analytic and interactive). That is, in 1998 the labour market was assigning workers to very different and more non-routine tasks than it was in 1980. However, to know whether this reallocation was mainly driven by technological progress and changing tasks demands, one would like to relate it to measures of computerization. This is done in the second bar for each task measure in Figure 5. Here, the changes in mean task inputs predicted from a regression of task changes on to changes in computer use within industries are reported. These second bars are close to the first bars in Figure 5, suggesting that computers adopted in most industries in the 1980s or 1990s indeed left workers doing less routine and more non-routine tasks. Similar shifts in task demands within industries have also been found for other countries (Michaels, Natraj and Van Reenen, 2013). To summarize, as computers have increasingly been adopted in our workspaces, they have taken over many of the routine tasks, leaving workers to perform non-routine tasks.

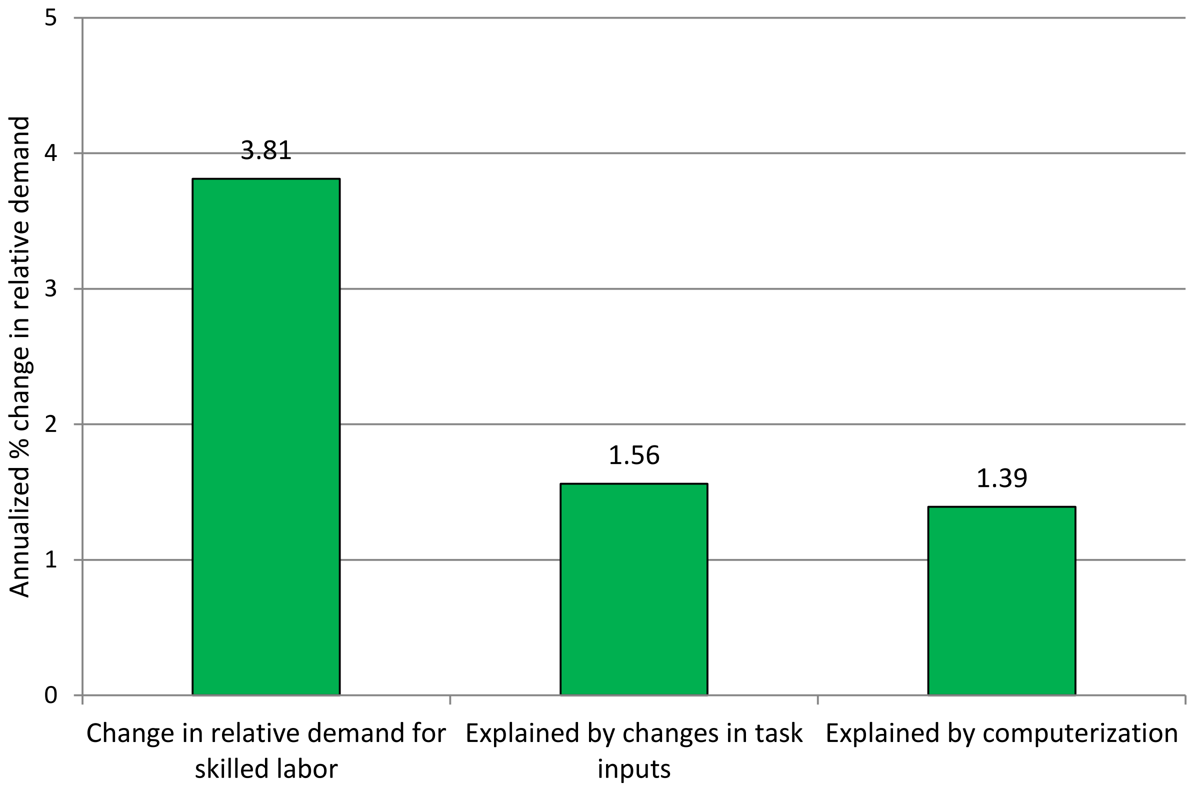
Figure 5: Changes in task inputs and computerization in the US, 1980-1998



Notes: Data are taken from Panels A and B of Table VII in Autor, Levy and Murnane (2003) but rescaled to capture 18-year changes for the period 1980 and 1998. The overall change in mean task input is expressed in percentiles of the 1960 task distribution. These 1960 task distributions are constructed by assigning a percentile to each of 1,120 industry-gender-education cells based on their rank of task intensity, constructed from the 1977 Dictionary of Occupational Titles (DOT). Therefore, the mean of each task is 50 in 1960 by construction. The mean of non-routine analytic tasks was 53.2 in 1980 and 58.7 in 1998; of non-routine interactive tasks was 53.3 in 1980 and 62.2 in 1998; of routine cognitive tasks was 51.8 in 1980 and 44.4 in 1998; and of routine manual tasks was 53.8 in 1980 and 49.2 in 1998. The predicted changes are obtained from an industry-level regression of the change in mean task input on to the change in computer use between 1984 and 1997.

Because routine tasks are mainly done by medium-skilled white-collar and blue-collar workers and non-routine analytic and interactive tasks by skilled white-collar workers, one would also expect the changes in task demands documented in Figure 5 to explain part of the increase in the relative demand for skilled workers shown in Figure 4. To see this, Figure 6 reports figures again taken from Autor, Levy and Murnane (2003). The first bar gives the estimated increase in the demand for skilled relative to unskilled workers between 1980 and 1998 in the US. It is an estimate obtained from a supply-demand framework just as in Figure 4, but note that demand shifts are now expressed in terms of relative quantities instead of the skill premium. For example, the shift in the relative demand for skilled workers corresponds to an annualized 3.81% increase in the ratio of college/non-college labour. This is consistent with the evidence in Figure 4 that, also after 1980, demand has continued its long-term trend in favour of high-skilled workers. Given the nature of recent technological change, one would also expect this increase in the relative demand for skills to be driven by changes in task demands and, ultimately, by computerization. To this end, the second bar in Figure 6 shows that changes in task demands within industries to a large extent explain the increase in the relative demand for skilled workers, and the third bar in Figure 6 shows that much of this is driven by computerization. In short, Figure 6 shows that a more task-based approach can go a long way towards a better understanding of recent labour market changes.

Figure 6: Task changes and shifts in the relative demand for skills in the US, 1980-1998

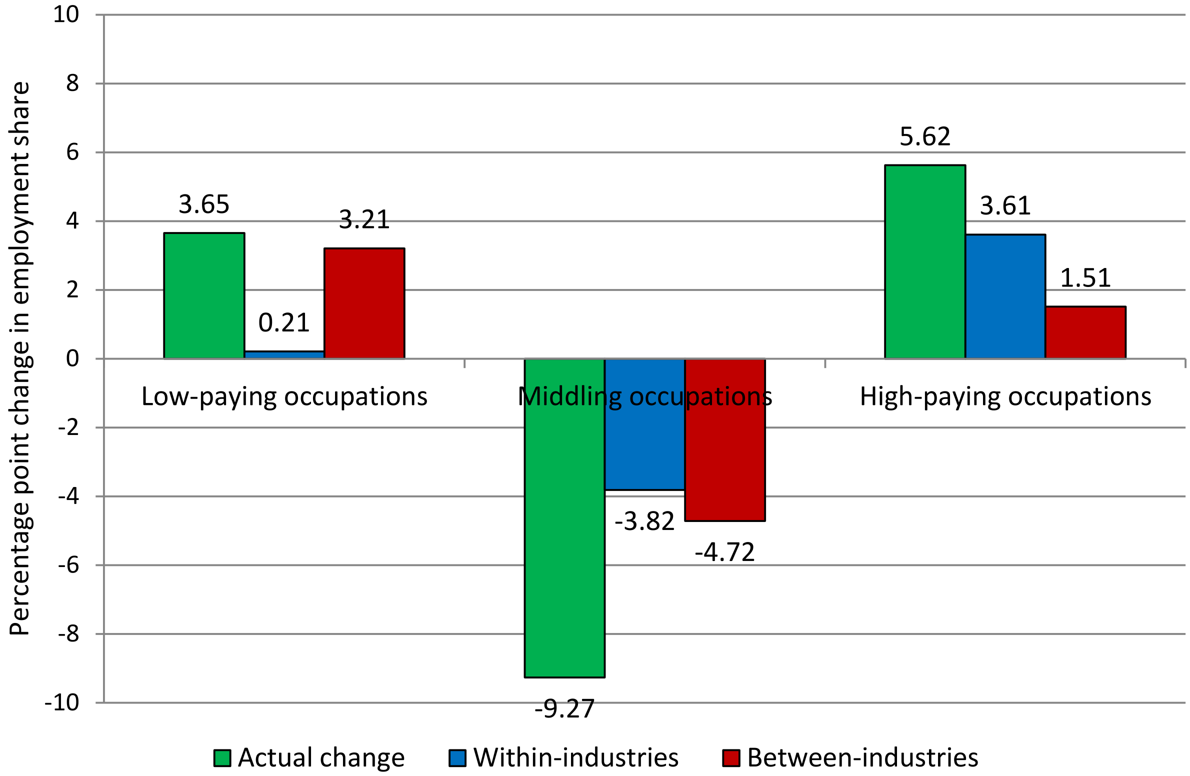


Notes: Data are taken from Panel E of Table VII in Autor, Levy and Murnane (2003). The first bar, the change in the relative demand for skilled workers, is an estimate obtained from a supply-demand framework as in Figure 4 above (although in Figure 4 shifts in relative supply and demand are expressed in relative wages not quantities) assuming an elasticity of substitution between college and non-college labour of 1.4. The second bar, the change in the relative demand for skilled workers explained by changes in task inputs, is obtained as follows: It is the impact across industries of an industry-level relationship between changes in the share of college workers and the sum of task measures where each task measure is multiplied by a fixed coefficient. These fixed coefficients are obtained by estimating a fixed-coefficients model of educational requirements in industries as a function of their task inputs in 1980 and 1984. The third bar, the change in the relative demand for skilled workers explained by computerization, does the same as the second bar but uses predicted rather than actual task changes at the industry level as in the second bar of Figure 5 above.

The analysis in Figures 5 and 6 shows how computerization has shifted labour demand away from routine medium-skilled towards non-routine skilled labour, but it does not account for the increasing employment share of unskilled service jobs, shown in Figure 3. Examples of unskilled service jobs are food service workers, security guards, janitors and gardeners, cleaners, home health aides, child care workers, hairdressers and beauticians, and leisure occupations. Many of these jobs make intensive use of non-routine manual tasks based on eye-hand-foot coordination that humans find easy but computers find difficult. Consequently, computerization is increasing the demand for unskilled service workers relative to medium-skilled workers. Although on balance there is still skill-upgrading, as the first bar in Figure 6 shows, there is also job polarization: an increasing fraction of workers is employed in either high-paying or low-paying occupations at the expense of medium-skilled employment. Goos and Manning (2007) were the first to rigorously analyse the process of job polarization for the UK and link it to the impact of computerization. Today, the process of job polarization has been documented for many advanced economies (see, for example, Autor, Katz and Kearney 2006, 2008 and Autor and Dorn 2013 for the US; Goos, Manning and Salomons 2009, 2013 for 16 European countries).

To illustrate job polarization, Figure 7 reports estimates from Goos, Manning and Salomons (2013) for 16 Western-European countries based on, among other data, the European Union Labour Force Survey. The first bar shows changes in employment shares between 1993 and 2010 for 1) low-paying non-routine manual; 2) middling routine; and 3) high-paying non-routine analytic and cognitive occupations, pooled across 16 Western-European countries. The figure shows that the share of low-paying occupations increased by 3.6 percentage points, from 21.6% in 1993 to 25.2% in 2010; the share of workers employed in middling occupations fell by 9.3 percentage points, from 47.7% in 1993 to 38.4% in 2010; and the share of employment in high-paying occupations increased by 5.6 percentage points from 31.7% in 1993 to 37.3% in 2010. Moreover, Goos, Manning and Salomons (2013) provide a task-based framework to explain this job polarization. Specifically, they use the DOT task measures from Autor, Levy and Murnane (2003) to predict job polarization both within and between industries, given by the second and third bar for each occupation group in Figure 7 respectively. Just as computer use changes within industries shown in Figures 5 and 6, the within-industry changes in Figure 7 capture the profound nature of changing task demands when adopting new production methods. For example, an important part of the overall and within-industry decrease in middling occupations is explained by the relative displacement of office clerks and machine operators from performing routine tasks in many industries. But computerization is also expected to have an impact that goes beyond the mere reallocation of capital and labour at the workplace. One such approach is that investment in new technologies is often intended to make the firm more competitive in product markets by lowering the price for its good or increasing its quality. If different industries do this to different degrees, computerization also results in changes in relative product demand. For example, it is not unrealistic to think that consumers today are buying more consumer electronics because their real prices have fallen or their quality has improved, at the expense of clothing, for example. This increase in the relative demand for consumer electronics then feeds back to the labour market by increasing the demand for highly-paid designers of consumer electronics relative to middling machine operators in textiles. The third bars in Figure 7 show that these between-industry shifts away from middling towards high-paying occupations are qualitatively important and contribute to the process of job polarization. Also note the large between-industry increase in the relative demand for low-paying occupations which mainly captures the shift in consumer demand towards personal service activities, thereby increasing the relative demand for unskilled service workers. Autor and Dorn (2013) provide similar evidence for the US of the rise in low-skill services and its contribution to job polarization. In short, although there is skill-upgrading on average, labour markets in advanced economies are also polarizing into high-skilled and low-skilled jobs due to computerization.

Figure 7: Job polarization in 16 European countries, 1993-2010



Notes: Data are taken from Table 4 in Goos, Manning and Salomons (2013). The 16 European countries are Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden and the UK. The group of low-paying occupations are the four ISCO 2-digit lowest-paid occupations according to a mean wage rank of all occupations in 1993, accounting for 21.6% of total employment in 1993; the group of middling occupations are nine ISCO 2-digit occupations, accounting for 47.5% of total employment in 1993; the group of high-paying occupations are the eight ISCO 2-digit highest-paid occupations according to a mean wage rank of all occupations in 1993, accounting for 31.7% of total employment in 1993. The split across occupations groups (4 lowest-paid, 9 middling, 8 highest-paid) is only a means to capture, in the most aggregate way possible, the impact of fundamental drivers such as computerization. The within-industry and between-industry components are obtained from a shift-share analysis that is rooted into a structural and empirically estimated task-based model of production – see Goos, Manning and Salomons (2013) for details.

That computerization leads to job polarization does not exclude other explanations. Some of these are related and therefore difficult to disentangle from technology, whereas others are more distinct from it. Some are likely to be temporary, whereas others will be longer lasting. One alternative explanation that has received some attention in the literature is the impact of globalization, defined in two separate ways. Firstly, the recent rise in offshoring could contribute to job polarization if it is mainly middling occupations that are affected by it. For example, Goos, Manning and Salomons (2013) find some evidence that offshoring is displacing medium-skilled blue-collar machine operators because firms can set up new production lines abroad and import intermediate tasks. But their data also show that offshoring cannot explain the large fall in the employment share of medium-skilled white-collar office clerks. Moreover, if vertical disintegration is part of a new organizational design with its system-wide complementarities, the decision to offshore part of the production process is most likely related to computerization on the factory floor at home. Secondly, globalization also captures the increasing openness of some large countries, like Brazil or China. For example, Autor, Dorn and Hanson (2013) argue that import competition from China alone explains one-quarter of the decline in US manufacturing between 1990 and 2007. In an accompanying paper, however, they argue that this mainly reflects a between-industry effect that does not explain the pervasiveness of job polarization across occupations within industries. Yet other explanations for job polarization exist. For example, the job polarization literature in part originates from the discussion concerning to what extent it is a cyclical phenomenon, worsening during recessions (see, for example, Wright and Dwyer 2003 and Manning 2003). Reasons for a cyclical component to job polarization could be the collapse of housing demand, export demand, or aggregate income affecting middling jobs disproportionately during recessions. If this is the case, many of the middling jobs lost are expected to return once the economy recovers. However, if job polarization is stronger during recessions because the market is forcing more firms into rethinking their organizational design, the changes made are irreversible and displaced workers do not possess the necessary skills to move into new jobs, the recovery will be jobless. Recent work in the US suggests that the latter may be the case (Jaimovich and Siu 2012).

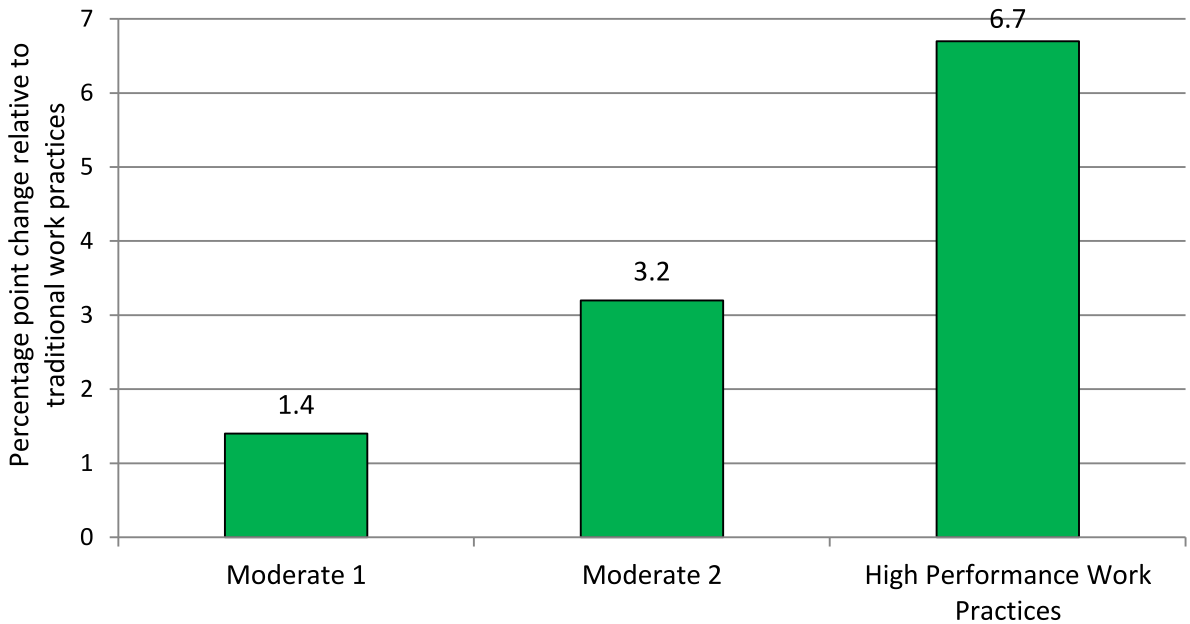
The importance of high performance work practices

At the firm level, computerization implies the introduction of flexible and lean production methods. However, these investments cannot be carried out in isolation because of the existence of system-wide complementarities in the firm's organizational design. This is perhaps most important for the successful harmonization of modern production methods with human resource practices. When using specific purpose-built machinery to mass produce, the firm does not need to think much about incentivizing its workers to elicit effort: a worker moulding metal parts on a car assembly line would slow down production the moment he starts shirking. But when using a more flexible and lean production method, individual effort is often more difficult to measure and elicit. For example, assume that team involvement to improve a product's quality or design becomes more important to the firm. How does the firm measure each worker's individual contribution to the team? If the firm can better observe team performance than individual effort, one solution to elicit effort from workers is to tie incentive pay to team performance, but this can lead to freerider problems. Indeed, exactly because adopting new technologies requires substantial changes in the way employees work, decision-making should be more decentralized to allow employees to experiment which requires further adjustment to people management. Generally, therefore, when introducing new production technologies, the firm also needs to rethink its human resource practices.

Modern human resource management is diverse and depends on finding the right mix of policies that fit the firm's overall organizational design. For example, to elicit team effort, some firms use team incentive payment schemes together with a high effort culture to counteract free-riding. Examples of policies to create a high effort culture are careful employee selection, indoctrination and orientation at the time of entry, team-oriented work groups, and other opportunities for workers to meet managers. Complementary to this, firms also use subjective performance appraisals and team problem-solving initiatives to build trust among workers. A final example is an employment (but not task) security policy that is a necessity if the firm depends on workers' ideas about improving productivity that may result in the elimination of jobs (Ichniowski, Shaw and Prennushi 1997).

To illustrate this, Figure 8 examines the impact of human resource practices on the productivity of US steel plants. The data are taken from Ichniowski, Shaw and Prennushi (1997) and are based on interviews that were conducted at 26 steel finishing lines. Because the technology used is very similar across the different plants but there was substantial variation in their human resource practices, the authors can assess the impact of those human resource practices on a finishing line's productivity. To this end, four different regimes are identified based on seven human resource practices. The seven practices are 1) worker involvement in teams; 2) information sharing and regular meetings with management; 3) regular training; 4) extensive screening of new hires; 5) incentive pay; 6) employment security; and 7) job flexibility/rotation. The first regime is "Traditional Work Practices" and has none of these seven policies. The second regime is "Moderate 1" and has low levels of practices 1) and 2) but little else. The third regime is "Moderate 2" and has more of 1) and 3) and one or two other practices from 4), 5) or 6). Finally, "High Performance Work Practices" have all seven. The coefficients in Figure 8 then give the impact on a steel finishing line's uptime of Moderate 1, Moderate 2 and High Performance Work Practices relative to Traditional Work Practices. For example, in a finishing line in a plant using High Performance Work Practices, scheduled operation time is 6.7 percentage points longer than a finishing line using Traditional Work Practices. The estimates for Moderate 2 and Moderate 1 are 3.2 and 1.4 percentage points respectively, and all three point estimates in Figure 8 are statistically significant. In follow-up research, the authors also find that IT investment in flexible and lean production methods also allows the firm to adopt modern human resource practices (Boning, Ichniowski and Shaw 2007; Bartel, Ichniowski and Shaw 2007).

Figure 8: The impact of high performance work practices on productivity



Notes: Figure 8 shows OLS regression estimates taken from the fifth column of Table 4 in Ichniowski, Shaw and Prennushi (1997). The dependent variable is the percentage of scheduled operating time that a steel finishing line actually runs, or the line's "uptime" as a measure of its productivity. Uptime has a mean of 0.92 across 2,190 line-month observations. The independent variables are the four human resource practices "Traditional Work Practices", "Moderate 1", "Moderate 2" and "High Performance Work Practices" (and a number of line specific characteristics as controls). To construct these categories, the authors start from seven human resource policies: 1) Worker involvement in teams; 2) Information sharing and regular meetings with management; 3) Regular training; 4) Extensive screening of new hires; 5) Incentive pay; 6) Employment security; and 7) Job flexibility/rotation. "Traditional Work Practices" has none of these policies. "Moderate 1" has low levels of 1) and 2) but little else. "Moderate 2" has more of 1) and 3) and one or two other practices from 4), 5) or 6). "High Performance Work Practices" have all seven. The coefficients in Figure 8 give the impact on uptime of "Moderate 1", "Moderate 2" and "High Performance Work Practices" relative to "Traditional Work Practices". All three estimates are statistically significant at the 1% level.

Further evidence of the importance of human resource management practices in the context of the Computer Revolution is found by Bloom, Sadun and Van Reenen (2012). They show that the acceleration in US productivity growth after 1995 relative to Europe is primarily observed in sectors that intensively use (rather than produce) information technologies, such as wholesale and retail, and can be largely attributed to better people management practices in US firms. To exclude any misleading effects of different locations of firms in the US or Europe (e.g. differences in product market competition, regulation, skill supply, market size, etc.), the authors consider the performance of US-owned firms in the European market only. This performance is compared to the performance of domestic firms as well as non-domestically (but non-US) owned firms: US-owned firms are found to be more productive due to a better exploitation of information technologies resulting from people management practices (concerning promotions, rewards, hiring and firing) which are more complementary with these technologies. These results also hold up in a comparison of US takeovers of previously non-US owned firms in the European market: after US takeover, such firms show evidence of higher information technology productivity although no such difference was found before the takeover took place. Importantly, the complementarity between computer technology and human resource management practices is found even after controlling for the complementary between computer technology and worker skills. This indicates that the effect of the Computer Revolution on the organization of work is not driven solely by the higher skill levels required of workers for working with new technologies, but truly captures a need to manage and organize labour differently in the workplace when using these technologies.

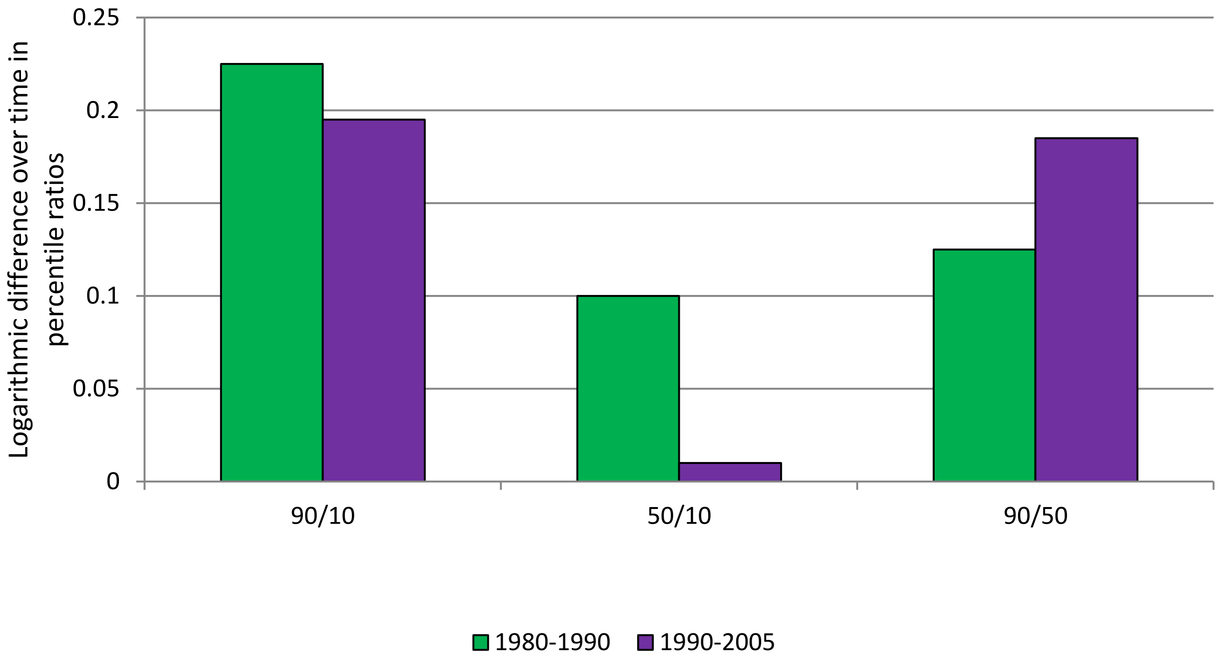
In short, computerization is having profound impacts on the structure of employment in aggregate labour markets and within firms. Since 1980, labour markets have been polarizing into "lousy" and "lovely" jobs that are non-routine task-intensive at the expense of middling employment that is routine task-intensive. That the labour market has been reallocating employment towards non-routine jobs is also evident from the recent emergence of high performance work practices, particularly those concerning human resource management. Next we turn to what has happened to relative wages after 1980.

3.4 Evidence of recent changes in relative wages

It was shown in Section 2.4 that wage inequality fell between 1915 and 1980 and Panels A to E of Figure 4 show why this was the case: the relative supply of skills due to the high school and college movements outpaced the relative demand for skilled workers due to skill-biased technological progress. However, Panels F and G of Figure 4 also show that, more recently, the skill premium increased, especially in the 1980s. As the panels suggest, much of this increase in the skill premium can be accounted for by a deceleration in the relative supply of college-educated workers, from an annualized -3% in the 1970s to -1.5% in the 1980s to -1% in the 1990s and early 2000s, combined with a continued increase in the relative demand for skills. Card and Lemieux (2001) show that there was indeed a slowdown in growth rates of educational attainment for workers born around 1955 and starting work in the mid-1970s. This slowdown made educated workers scarcer in these cohorts, thereby reducing the relative supply of skills and increasing the skill premium. Autor and Katz (1999), Goldin and Katz (2008), Autor, Katz and Kearney (2008) and Acemoglu and Autor (2011) provide similar evidence in support of the hypothesis that a slowdown in the relative supply of skilled workers, combined with continued growth in their relative demand, is an important explanation for the rise in the skill premium and therefore overall wage inequality after 1980.

However, underlying this increase in overall wage inequality is an important divergence in trends at the top and bottom of the wage distribution. This can be seen from Figure 9, which summarizes some of the evidence in Autor, Katz and Kearney (2008) based on US March CPS data for full-time and full-year male workers between 1980 and 2005. The figure shows logarithmic differences over time in the 90/10 percentile ratio to capture changes in overall wage inequality; for the 50/10 percentile ratio to capture changes in lower-tail wage inequality; and for the 90/50 percentile ratio to capture changes in upper-tail wage inequality. For each percentile ratio, the first bar looks at changes from 1980 to 1990 and the second bar at changes from 1990 to 2005. Looking at changes in overall inequality confirms what was already known from Figure 4: US overall wage inequality has increased over the past three decades. But it is interesting to look also at changes in lower-tail and upper-tail inequality separately. Lower-tail inequality increased substantially in the 1980s but not after that, whereas upper-tail inequality increased throughout the entire period. Why did the rise in lower-tail inequality stop in the 1990s? Autor, Katz and Kearney (2008) and Autor and Dorn (2013) argue that computerization, by increasing the demand for unskilled service workers relative to middling jobs, has resulted in "wage polarization": The wages of low-paid service workers have increased relative to the median. And if wage polarization dominates the countervailing compositional impact of job polarization, lower-tail wage inequality will decrease. In a nutshell, computerization and a slowdown in educational attainment growth rates have led to an increase in overall and upper-tail wage inequality since the 1980s in the US and other advanced economies (for example, see Card and Lemieux 2001 for evidence for Canada and the UK). But there is also a silver lining that computerization could be increasing the relative wages of our least skilled workers since the 1990s.

Figure 9: Changes in overall, lower-tail and upper-tail wage inequality in the US, 1980-2005



Notes: Numbers are taken from Figure 3 (left panels) in Autor, Katz and Kearney (2008) and are based on weekly wages derived from the March CPS data for full-time full-year male workers between 1980 and 2005. See Autor, Katz and Kearney (2008) for similar results when using hourly wages constructed from the MAY CPS/MORG files, women and education and experience groups.

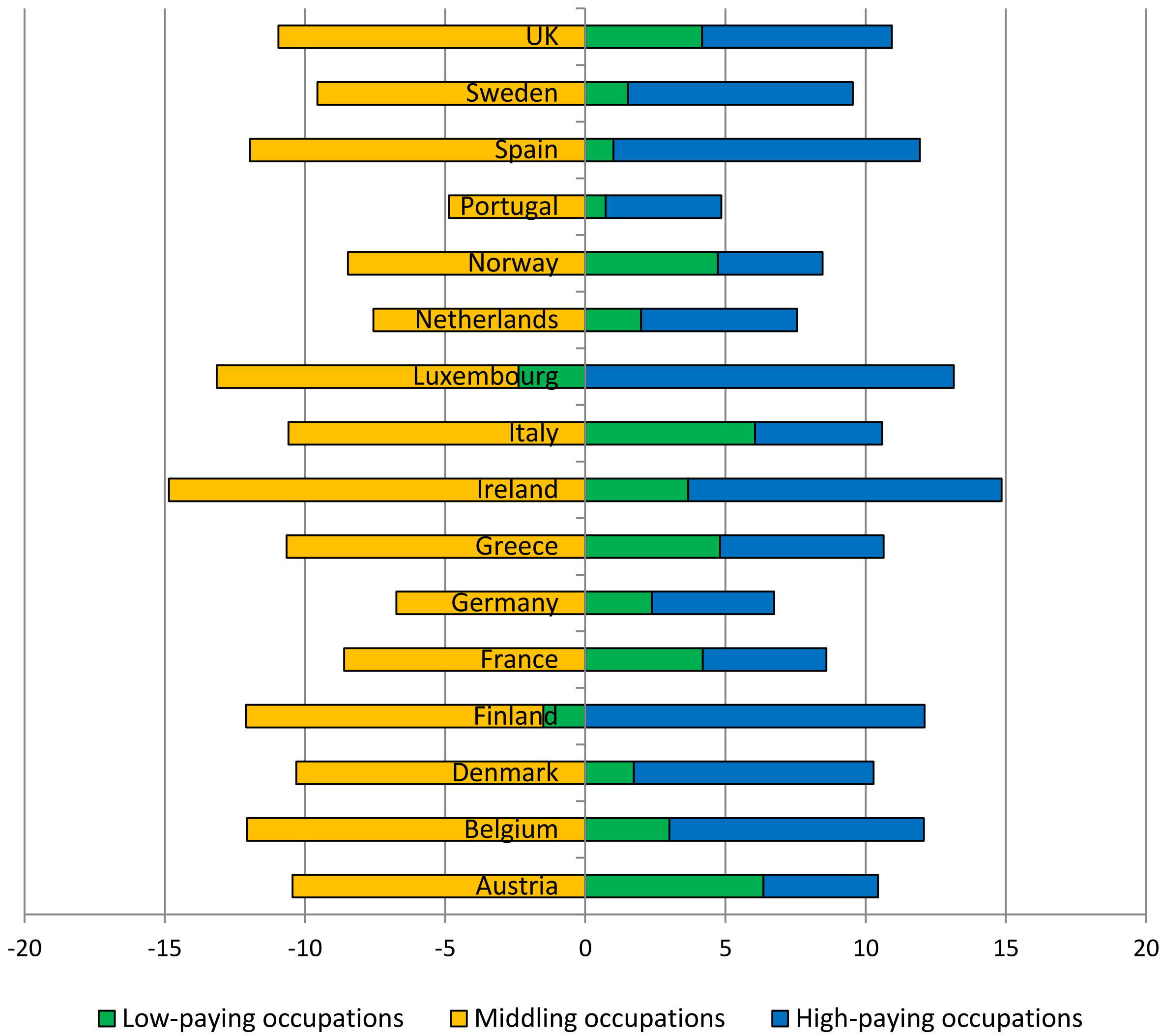
The analysis above shows that a simple supply-demand framework can go a long way towards explaining the changes in overall, lower-tail and upper-tail wage inequality after 1980. However, it does not provide a full understanding of the impact of computerization on labour markets and firms. Therefore, economists have recently started to build much richer models than the simple supply-demand framework to get a better understanding of labour market outcomes and their fundamentals. Most notably, Acemoglu and Autor (2011) build on Autor, Levy and Murnane (2003) to develop a Ricardian task-based framework to think meaningfully about how differently skilled workers sort into different tasks. Their framework allows for more than two skill levels and explicitly includes computing capital to predict changes in relative wages between unskilled, medium-skilled and skilled workers following computerization. For example, the framework developed in Acemoglu and Autor (2011) explains why it could be the case that there has been substantial job and wage polarization since the 1990s in the US. Assume a labour market that allocates unskilled, medium-skilled and skilled workers to different tasks based on workers' comparative advantages, and that computerization is captured by an increase in the spread of routine tasks that can be codified. This displaces middling workers from doing routine tasks, which leads to job polarization. Also, middling workers are reallocated to tasks for which they have lower comparative advantage, which will tend to push down their wages resulting in wage polarization. However, little is known about how exactly the labour market allocates workers to tasks. But promising research on this is starting to emerge – see, for example, Autor and Dorn (2009) or Autor and Handel (2013).

3.5 Evidence for other countries

Our analysis so far has focused on labour markets in advanced economies. The evidence suggests that in early stages of development, during the First and Second Industrial Revolutions between 1850 and 1980, there was skill-upgrading for the economy as a whole. The main reason for this skill-upgrading was the opportunity for many unskilled farm workers to move into better-paid medium-skilled blue-collar jobs as machine operators in factories. At the same time, industrialization increased the demand for medium-skilled and high-skilled white-collar workers in manufacturing and services, educated by a rapidly expanding education system. Mass production to satisfy the consumption needs of a rising middle class and compressed inequality also contributed to strong economic growth.

In the 1980s, however, labour markets in advanced economies changed. Computerization started to codify the routine tasks done by medium-skilled blue-collar and white-collar workers, in contrast to the non-routine nature of unskilled service and skilled jobs. Together with a disappearing agricultural sector, at least in terms of employment, computerization is leading to job polarization and, possibly, a disappearing middle class. If this is true, one would expect to find evidence for job polarization in each advanced economy that has access to modern technology. To see this, note that Figure 7 presented evidence of job polarization for 16 Western-European countries pooled. But it would be interesting to see whether job polarization also occurs within each of those countries separately. Figure 10 confirms that job polarization is pervasive – the share of high-paying and low-paying occupations has increased relative to the middling occupations in each country.

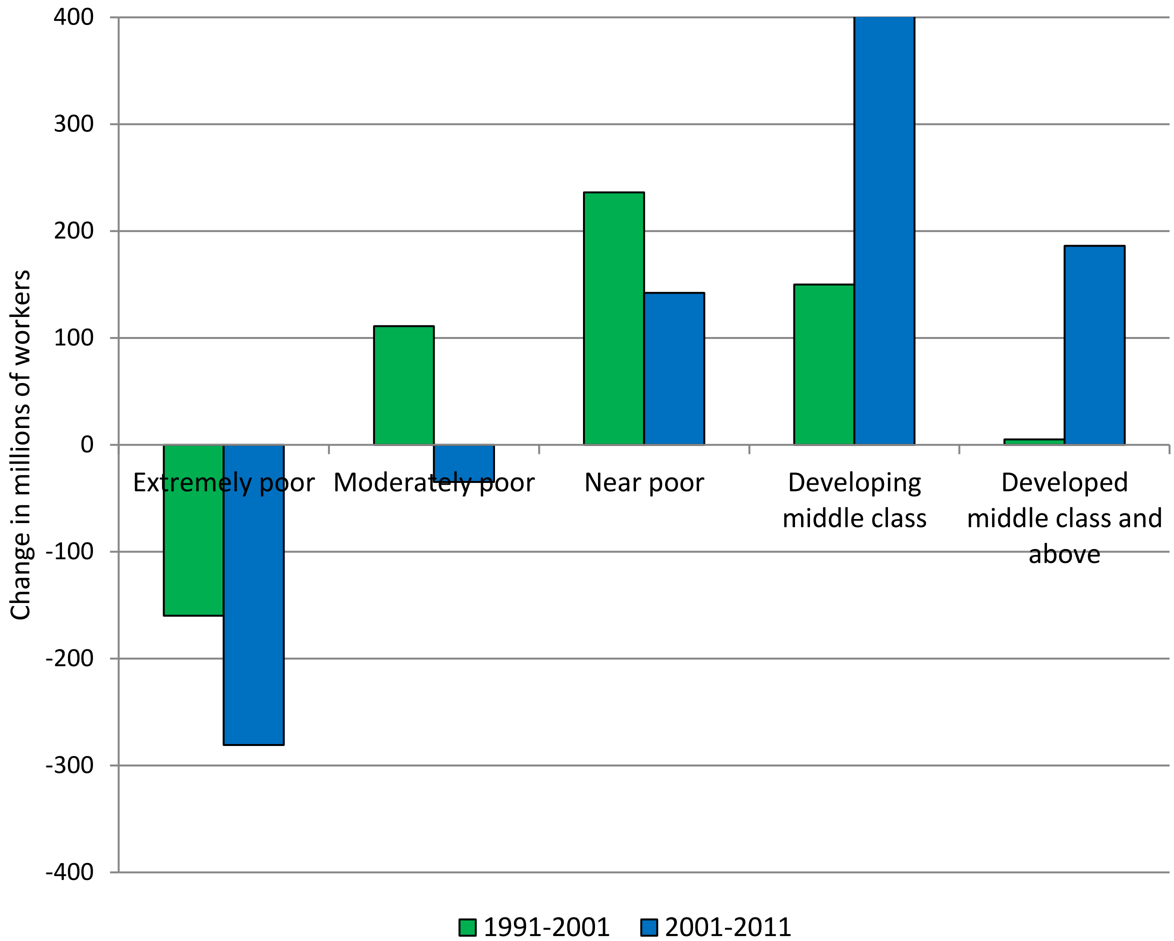
Figure 10: Percentage point changes in employment shares by occupation group and country, 1993-2010



Notes: Numbers are taken from Table 2 in Goos, Manning and Salomons (2013). See Figure 7 for further details on the data underlying this chart.

However, the process of job polarization is unlikely to be pervasive in developing economies. Instead, one may expect to see a change from unskilled jobs, mainly in agriculture, to middle class employment, mainly in manufacturing, as was the case for today's advanced economies at earlier stages of development. Unfortunately, evidence on employment dynamics by skill, sector or occupation in developing economies is scant. Perhaps most relevant is recent work by Kapsos and Bourmpoula (2013) who carefully define five economic classes of workers based on an absolute measure of per capita household income in developing countries: 1) "extreme working poor" for a household living on a per-capita income of less than $1.5 a day; 2) “moderate working poor” between $1.5 and $2; 3) “near poor workers” between $2 and $4; 4) “developing middle class workers” between $4 and $13; and 5) “developed middle class and above earning more than $13 a day. Using this definition, the authors show that middle class workers differ from the poor in that they have better access to electricity, running water and sanitation, education, healthcare and that they are more likely to be employed in industry and services than agriculture. These differences seem qualitatively similar to the differences between unskilled and medium-skilled workers in advanced economies in the late 19th century. Applying their definition of class to income data, combining it with employment estimates and inferring missing observations, the authors construct employment shares by economic class for all 142 developing countries between 1991 and 2011. Based on this data, Figure 11 replicates a figure from Kapsos and Bourmpoula (2013). The figure shows the absolute changes in millions of individuals by economic class between 1991 and 2011. Clearly there has been skill-upgrading in the developing world. Much of this is driven by the rapid development of China, especially after 2001, but the authors show that qualitatively similar changes are observed in other developing economies. In short, the changes in Figure 11 for the developing world resemble the changes in Figures 2 and 3 above for the US in the late 19th and early 20th centuries. There we argued that the fundamental drivers of skill-upgrading were the First and Second Industrial Revolutions together with a rapid expansion in the educational system, and it would be interesting to know whether the same is true for the developing world today.

Figure 11: Changes in employment by economic class in developing countries, 1991-2011



Notes: Data are taken from the left panel of Figure 8 in Kapsos and Bourmpoula (2013). The five economic classes of workers are based on an absolute measure of household per-capita income: 1) “Extreme working poor” for a household living on a per capita income of less than $1.5 a day; 2) “Moderate working poor” between $1.5 and $2; 3) “Near poor workers” between $2 and $4; 4) “Developing middle class workers” between $4 and $13; and 5) “Developed middle class and above earning more than $13 a day. There are 142 developing countries in the sample.

4 The future

Gordon (2012) cites four classic examples of bad predictions concerning technology: 1) In 1876, Western Union, the monopolist at the time for delivering wire messages in the US, wrote in an internal memo: "The telephone has too many shortcomings to be considered as a serious means of communication."; 2) In 1927, the head of Warner Brothers said: "Who the hell wants to hear people talk?"; 3) In 1943, Thomas Watson, chairman of IBM, said: "I think there is a world market for maybe five computers"; and 4) In 1981, Bill Gates said: "640kB ought to be enough for anybody", although this last prediction is believed to be an urban myth. It is clear from these examples that predicting the future is difficult, especially when it comes to technological progress. Despite these reservations, this section conjectures on the future of our labour markets by drawing from the analyses outlined in the previous sections of this paper. It briefly focusses on 1) the future pace of computerization; and 2) the need for continued investment in education and on-the-job training.

The pace of computerization

Economists are divided about how the Computer Revolution will continue to unfold. For example, Gordon (2012) points out that the economic impact of the recent Computer Revolution need not be as prosperous as that of the earlier First and Second Industrial Revolutions. He argues that the three industrial revolutions in advanced economies have been episodic, each with their one-time only inventions and their specific impacts on our economies. Therefore, the fact that the First and Second Industrial Revolutions resulted in large improvements in living standards does not imply that the same must necessarily be true for the Computer Revolution. One reason for this, Gordon (2012) argues, could be that the First and Second Industrial Revolutions had follow-up inventions that increased productivity up to the 1970s, but that this follow-up process from the Computer Revolution is already fading. However, Brynjolfsson and McAfee (2011) call on Moore's law to argue that most of the impact from computerization is still to come. To illustrate this, the authors refer to the driverless car, an achievement that seemed impossible ten years ago but not today. These diverging views highlight that the pace at which future inventions belonging to the Computer Revolution continue to be made is difficult to forecast.

Related to the discussion about the future impact of computerization is the impact of globalization, partially driven by computerization (for example, through improvements in communication and information technologies which enable the offshoring of certain parts of the production process) but perhaps partly also as an independent force due to declining man-made barriers to trade. For example, Blinder and Krueger (2013) argue that 25% of US jobs are offshorable. Autor, Dorn and Hanson (2013) find that import competition from

China alone explains one-quarter of the decline in US manufacturing between 1990 and 2007. In an accompanying paper, however, they argue that this mainly reflects an industry-specific effect that does not fully explain the changing occupational composition within manufacturing. That is, there is no reason to believe that manufacturing employment would vanish in the long-run. To illustrate this, assume that US steel plants, perhaps in response to import competition from China, introduce flexible production lines and high performance work practices to increase productivity. Although this might result in less total employment, it also implies that steel workers will specialize in non-routine tasks, like working in teams to improve uptime or getting trained to work rotation. Consequently, it is not clear *a priori* that manufacturing employment would have to vanish or even decrease, given the existence of system-wide complementarities, the sorting of skills into tasks based on comparative advantage (as modelled in Autor, Levy and Murnane 2003 and Acemoglu and Autor 2011) and occupational task-bundling (the fact that occupations are partially indivisible bundles of tasks is a point also made by Autor 2013 and analysed more formally in Autor and Handel 2013). In this respect, the impact of computerization is most likely to be very different compared to the rapid increase, starting in the late 19^{th} century, in the productivity of farm land due to soil fertilizers and farming machinery, and the consequent near disappearance of farm labourers.

In short, the effects of future technological progress on the employment and wage structures cannot be easily extrapolated. Future inventions will affect employment and wage structures differently depending on which tasks derive a comparative advantage from this new technological capital vis-à-vis human labour, as well as the distribution of these tasks across the wage structure. However, changes in skill supply as well as on institutional factors are also shown to be capable of counteracting or reinforcing the labour market effects of technological advances. In particular, strong increases in skill supplies have contributed to strong skill-upgrading in employment and less upper-tail and overall wage inequality before 1980. After 1980, however, less strong growth in relative skill supply has increased upper-tail and overall wage dispersion. In this light, the need for continued investment in education and on-the-job training is briefly discussed below.

The need for continued investment in education and on-the-job training

This section argues that continued investment in skills will: a) contribute to future economic growth; b) reduce future growth in top-income inequality; and c) protect workers against the adverse effects of job polarization.

a) On balance and for the economy as a whole, there has been skill-upgrading in advanced economies since the start of industrialization in the mid-19^{th} century. Goldin and Katz (2008) follow an extensive literature that estimates the impact of this skill-upgrading on US economic growth between 1915 and 2005. They use a simple equation that relates growth in output per worker to capital deepening, growth in educational attainment rates (measured in efficiency units to capture quantitative as well as qualitative changes) and a residual. The authors find that 14% of the growth rate in output per worker can be explained by the increase in average time at school by almost 6 years between 1915 and 2005. Although this contribution of education to economic growth differs somewhat between decades, there is little sign that its impact is fading over time. More investment in education and on-the-job training will not only improve labour market outcomes, but also contribute to economic growth more generally. Moreover, Goldin and Katz (2008) and Acemoglu and Autor (2012) argue that these numbers most likely underestimate the true impact of human capital on economic growth. For example, the equation used in Goldin and Katz (2008) does not account for the fact that higher income leads to higher savings and more investment, which leads to capital deepening. It also does not account for the fact that an educated workforce invents more or that there might exist important complementarities between a worker's education or on-the-job training and changes in task demands from computerization. Indeed, Bloom *et al* (2012) find a strong positive association across firms and industries between the intensity of college-educated employees and better human resource management practices, providing empirical evidence for such complementarities.

b) The analysis in Section 3.4 showed that overall and upper-tail inequality is rising in some advanced economies and that this, in part, can be explained by a lack of education. The analysis of historical developments in the US college wage premium has shown that wage inequality increased during periods where the supply of highly skilled labour was outpaced by demand for it: increasing investment in human capital can therefore act to attenuate a tendency for increased inequality resulting from technological progress. Furthermore, if college attainment rates rise, it might become increasingly difficult to provide the quantity and quality of education that the labour market increasingly requires. For the US, Goldin and Katz (2008) and Acemoglu and Autor (2012) point to the lack of inclusiveness of the education system and its failure to provide basic education for poor, minority and immigrant children, who are most likely to drop out of the education system at an early age. Also Europe, with its relatively exclusive and unforgiving education system, could benefit from a further increase in its high school completion rates.

c) Employment growth in advanced economies has recently been polarizing into low-paid and high-paid occupations at the expense of middling jobs. The rise in low-paid relative to middling employment, however, does not mean that less education or on-the-job training is needed or that there is a problem of "over-education". Firstly, it is unlikely that middle skills will entirely disappear due to system-wide complementarities and task bundling in jobs, as was argued above. Secondly, Autor and Handel (2009) show that there is a positive skill premium even in low-paid jobs. One explanation for this could be that firms, including those employing low-paid workers, adopt modern human resource practices and that skilled workers are better at them (Bloom *et al* 2012).

In summary, it is most likely that, on balance, the relative demand for skilled workers will continue to increase due to computerization. To the extent that there is continued investment in education and on-the-job training to match the increased demand for skills, there will be further skill-upgrading and economic growth without further increasing or even decreasing upper-tail and overall wage inequality, as was the case in advanced economies before 1980. Moreover, job polarization does not justify fears of a digital invasion for two reasons. Firstly, it is unlikely that computerization will displace medium-skilled workers entirely because of system-wide complementarities in organizational design, the complex play of selection based on comparative advantages and task-bundling in jobs. Secondly, there is evidence that computerization leads to wage polarization, thereby increasing the relative wages of the least-paid workers and reducing lower-tail wage inequality. To conclude, this section calls for optimism towards future computerization as long as our policies can provide the necessary skills to support such changes.

5 Conclusions

It is undoubtedly true that economic progress is increasing average living standards in developing and developed economies, and that an important part of this happens through adjustment in work. However, inventions are one-time only events and the impact of different episodes of technological progress on labour markets is not the same.

The First and Second Industrial Revolutions, that took place between 1820 and 1900 with follow-up inventions up to 1980, introduced steam power, electricity, the automobile, modern chemistry and the telephone, among other things. The consequent rise of manufacturing provided many unskilled farm labourers with the opportunity to move into medium-skilled blue-collar jobs. Together with an increase in the relative demand for medium-skilled and skilled white-collar employment in manufacturing and services, there was skill-upgrading. However, the skill premium, and therefore overall inequality, decreased because of mass education that led to an increase in the supply of skills that outpaced its increase in demand. In this way, the First and Second Industrial Revolutions resulted in economic growth, skill-upgrading, mass education and lower overall wage inequality.

The Computer Revolution that began in advanced economies in the 1980s is different. Underlying skill-upgrading there is also job polarization: rising employment shares for skilled and unskilled workers at the expense of medium-skilled employment. At the same time, growth in educational attainment rates has slowed in many advanced economies since 1980, reducing growth in skill supplies and increasing the skill premium and upper-tail and overall wage inequality. Within firms, computerization is characterized by the adoption of flexible and lean production methods based on robotic equipment and the existence of system-wide complementarities with, for example, high performance work practices such as setting up problem solving teams, job rotation, information sharing and intensive training.

It would seem, therefore, that computerization has not emulated the prolonged economic success of the First and Second Industrial Revolutions. However, today's marriage of computerization to human resources within the firm is much more complex than the machine-skill complementarity that characterized the period before 1980. Together with ongoing and future technological advances, this complexity implies that it will take time for firms and labour markets to fully digest and reap the benefits of the Computer Revolution and only if our labour markets can provide the necessary skills to support such progress.

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