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European Central Bank, 2000.

¹³ L. E. O. Svensson, "Monetary Policy Issues for the Eurosystem," NBER Working Paper No. 7177, June 1999, and in Carnegie-Rochester Conferences Series on Public Policy, 51-1 (1999), pp. 79-136; "The First Year of the Eurosystem: Inflation Targeting or Not?" NBER Working Paper No. 7598, August 2000, and in American Economic Review: Papers and Proceedings, 90 (May

2000), pp. 95-9.

¹⁴ I have been invited to submit regular Briefing Papers for the Committee on Economic and Monetary Affairs (ECON) of the European Parliament for its hearings with ECB officials. These are available on www.princeton.edu/~svensson.

¹⁵ L. E. O. Svensson, "Does the P* Model Provide Any Rationale for Monetary Targeting?" NBER Working Paper No. 7178, June 2000, and in German

Economic Review, 1 (February 2000), pp. 69-81; S. Gerlach, and L. E. O. Svensson, "Money and Inflation in the Euro Area: A Case for Monetary Indicators?" NBER Working Paper No. 8025, December 2000; G. D. Rudebusch, and L. E. O. Svensson, "Eurosystem Monetary Targeting: Lessons from U.S. Data," NBER Working Paper No. 7179, June 1999, and in European Economic Review, 46 (2002), pp. 417-42.

Technology and Inequality

Daron Acemoglu*

Many OECD economies have experienced sharp increases in wage and income inequality over the past several decades. In the United States, for example, the college premium — the wages of college graduates relative to the wages of high school graduates — increased by over 25 percent between 1979 and 1995. Overall earnings inequality also soared: in 1971, a worker at the 90th percentile of the wage distribution earned 266 percent more than a worker at the 10th percentile. By 1995 this number had risen to 366 percent.¹ Are new technologies — in particular, computers, computer-assisted machines and robotics, and advances in communication technology — responsible for these changes? More generally, what are the implications of technical change for the labor market?

Some economists now believe that, although other factors including the decline in the real value of the minimum wage, de-unionization, and globalization have played some role, the major driving force behind the changes in the U.S. wage structure is technology. This consensus is built on

the notion of technology-skill complementarity: technical change favors more skilled (educated) workers, replaces tasks previously performed by the unskilled, and increases the demand for skills. Consequently, many commentators see a direct causal relationship between technological changes and these radical shifts in the distribution of wages taking place in the U.S. economy.²

Although the consensus is now broad, the idea that technological advances favor more skilled workers is a 20th-century phenomenon. In 19th-century Britain, skilled artisans destroyed weaving, spinning, and threshing machines during the Luddite and Captain Swing riots, in the belief that the new machines would make their skills redundant. They were right: the artisan shop was replaced by the factory and later by interchangeable parts and the assembly line. Products previously manufactured by skilled artisans came to be produced in factories by workers with relatively few skills, and many previously complex tasks were simplified, reducing the demand for skilled workers.

A major 19th-century technological advance, interchangeable parts, in fact was designed to be "skill-replacing" (un-skill-biased). Eli Whitney, a pioneer of interchangeable parts, described the objective of this technology as: "to

substitute correct and effective operations of machinery for the skill of the artist which is acquired only by long practice and experience; a species of skill which is not possessed in this country to any considerable extent."³

There are also no compelling theoretical reasons to expect technological change always and everywhere to be skill-biased. On the contrary, if replacing skilled workers is more profitable, new technologies may attempt to replace skilled workers, just as interchangeable parts did. Even the most purportedly skill-biased technological advance, the microchip, can be used in scanners to complement unskilled work just as effectively as in personal computers to complement skilled workers.

Recent research takes these issues into consideration and analyzes the origins of skill bias and the conditions under which new technologies would be more or less skill biased. In this article, I survey some of this recent research, and how it might shed light on the recent increase in inequality. I also briefly discuss the links between technology and trade, technology and changes in the organization of production, the interaction between technical change and labor market institutions, and potential reasons for cross-country differences in inequality trends.

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Technology and the Recent Changes in Wage Inequality

There is general agreement among economists that technical change in the United States and the OECD over the past 60 years, or even over the past century, has been skill-biased. That is because the past 60 years have seen a large increase in the supply of more educated workers, yet returns to education have risen. In the absence of substantial skill bias in technology, the large increase in the supply of skilled workers would have depressed the skill premium, as the economy moved along a downward-sloping relative demand curve — in other words, as skilled workers substituted for the unskilled in production and as consumers substituted goods produced using skilled workers intensively for labor-intensive goods. Because this did not happen, the relative demand for skills must have increased, most likely because of changes in technology. Of course here, “technology” needs to be construed broadly: it is not simply the techniques and machines available to firms, but also the organization of production, organization of labor markets, consumer tastes, and so on.

Many commentators in fact believe that there has been an acceleration in skill bias beginning in the 1970s or the 1980s. The most popular, but by no means the only, version of this hypothesis claims that there has been a notable acceleration in the skill bias of technology, driven by advances in information technology, or perhaps a “Third Industrial Revolution.” A variety of studies document how the introduction of many modern technologies often is associated with an increase in the employment of and demand for more skilled workers.⁴ But probably the most powerful argument in favor of an acceleration in skill bias is that returns to schooling rose over the past 30 years despite the unusually rapid increase in the supply of educated workers. As a result of the entry of the large and well-educated baby-boom cohort starting in the late 1960s, and because of the Vietnam-era draft laws and increasing government sup-

port for higher education, the educational attainment of the U.S. labor force increased sharply starting in the early 1970s. Consequently, the relative supply of skills increased more rapidly on average in the three decades following 1970 than in the previous three decades. Without an acceleration in skill bias, we would expect a slower increase in the returns to education in the post-1970 era. In contrast, the U.S. skill premium increased rapidly during the past three decades, while it was approximately constant in the pre-1970 era. Furthermore, during this time period the U.S. labor market also experienced a sharp increase in within-group inequality — that is, inequality among similarly educated workers, which likely indicates the presence of some new and powerful forces.⁵

Endogenous Technical Change

Why did the demand for skills accelerate over this period? And why has new technology favored more skilled workers throughout the 20th century, but not during the 19th century as was discussed above? One approach views technology as exogenous, stemming from advances in science or from the behavior of entrepreneurs driven by a variety of nonprofit motives. By this approach, demand for skills increased faster during the past 30 years, this approach would maintain, because of a technological revolution led by the microchip, personal computers, and perhaps the Internet.

However, the fact that skill-biased technical change accelerated more or less immediately after the relative supply of more educated workers accelerated, starting in the early 1970s, is a bit of a coincidence. This makes me lean towards a theory that links changes in the relative supply of and the demand for skills, and attempts to explain why new technologies have been skill-biased throughout the 20th century and have become more so during the past 30 years. The first step in the argument is the realization that technology is not simply an outside force acting on the labor market and wage inequality. Rather it is an outcome of

the decisions made by firms and workers, in the same way as the level of employment or wages are. In other words, technology is “endogenous.”⁶

The spinning and weaving machines of the 19th century were invented because they were profitable. They were profitable because they replaced the scarce and expensive factors — the skilled artisans — by relatively cheap and abundant factors — unskilled manual labor of men, women, and children. Similarly, electrical machinery, air-conditioning, large organizations all were introduced because they presented profit opportunities for entrepreneurs. If various new machines and production methods came into being when called forth by profit opportunities, it is also likely that further skill-biased technical change and an acceleration in skill bias are also, at least in part, responses to profit incentives. Put simply and extremely, it can be argued that the increased skill bias of technology throughout the 20th century and its acceleration during the past 30 years resulted from the changes in profit opportunities which were, in turn, a consequence of the steady increase in the supply of skilled workers over the past century and its surge starting in the early 1970s.

Directed Technical Change and the Demand for Skills

But why is the skill bias of technology related to the supply of skilled workers? The basic idea is that technical change will be *directed* towards more profitable areas.⁷ In particular, when developing skill-biased techniques is more profitable, new technology will tend to be skill-biased.

Two factors determine the profitability of new technologies: the *price effect* and the *market size effect*. When relative prices change, the relative profitability of different types of technologies also changes. Technologies used predominantly in the production of goods that are now more expensive will be demanded more, and the invention and improvement of these technologies will become more profitable. Similarly, the potential market size for

a technology is a first-order determinant of its profitability. Everything else equal, it is more profitable to introduce machines that will be used by a larger number of workers because these greater market sizes will enable greater sales and profits for the producers and inventors. It is through the market size effect that an increase in the supply of skills induces technology to become more skill biased. Consequently, when there are more skilled workers around, the market size effect will make the production of skill-complementary machines and technologies more profitable. Somewhat surprisingly, this market size effect can be so strong that the relative demand curve for skills can be upward sloping in contrast to the standard downward-sloping relative demand curve. In this case, the skill premium and returns to education will be higher when there are more skilled workers in the economy.

In this light, the recent acceleration in the skill bias of technology is potentially a response to the rapid increase in the supply of skills starting in the early 1970s. As the market size for skill-complementary technologies such as personal computers or computer-assisted machinery expanded, it became more profitable to create and introduce more such technologies. This hypothesis not only explains the increase in the demand for skills, and the resulting rise in the returns to education and inequality, but also helps us understand the timing of the increase. New technologies take a while to be created and brought to the market. Therefore, the first effect of a large increase in the relative supply of skills might be to move the economy along a downward-sloping constant-technology relative demand curve. However, as new skill-biased technologies are brought to the market, this constant-technology relative demand curve shifts out, increasing returns to education, potentially even beyond its initial level.⁸

What about the secular skill-biased technical change throughout the 20th century? Perhaps there is a natural explanation: the relative supply of skilled workers has been increasing throughout the century, so we should expect steady skill-biased technical change. What about the skill-replacing

technologies of the 19th century? One possible, conjectural argument is that the early 19th century was characterized by skill-replacing developments because the increased supply of unskilled workers in the English cities (resulting from migration from rural areas and from Ireland) made the introduction of these technologies profitable.⁹ Therefore, a theory of directed technical change provides us with an explanation for: secular skill-biased technical change throughout the 20th century; the rise in inequality over the past several decades; and, possibly, the skill-replacing technologies of the early 19th century.

Globalization and Inequality

Another major economic development of the past 30 years is the increased globalization of production, and greater trade between the United States and less developed nations (LDCs). A number of commentators have suggested that globalization and increased trade might be responsible for the rise in U.S. inequality. The arguments above — that technological change has been important in the rise in inequality — do not imply that other factors, such as globalization, have not played a major role.

Nevertheless, most economists discount the role of globalization and trade for a variety of reasons. First, the volume of trade is still small. Second, the major intervening mechanism for the trade explanation, a large increase in the relative prices of skill-intensive goods because of greater world demand for these, has not been observed. Third, inequality also has increased in many of the LDCs trading with the United States, whereas the simplest trade and globalization explanations predict a decline in inequality in relatively skill-scarce economies, like the LDCs.

But trade and globalization may have been more important than traditionally assumed. Trade influences what types of technologies are more profitable to develop. In particular, trade creates a tendency for the price of skill-intensive products to increase.

Then, via the price effect emphasized above, the incentives for the introduction of new skill-biased technologies are strengthened. In other words, trade and globalization induce further skill-biased technical change.

With this type of induced technical change, trade can have a larger effect on inequality than traditional calculations suggest. Moreover, it can do so without a large impact on the relative prices of skill-intensive goods because the induced technical change will help boost the supply of these goods. As a result, we may not even see much evidence of the original triggering mechanism, the change in relative prices. Finally, to the extent that the LDCs are also using technologies developed in the United States and the OECD, there will be a force towards increasing inequality in those countries as well, counteracting the static equalizing effects of trade in economies with relative skill scarcity.¹⁰

Changes in the Organization of Production

The increase in the demand for skills and inequality in the U.S. economy may be as much attributable to the changes in the organization of production as to the direct effect of new technologies. Today's production relations, how jobs and monitoring are organized, and how firms recruit employees are all very different from 30 years ago.¹¹

A perspective that views technology, and the organization of production, as endogenous is also helpful in thinking about these issues. An important driving force of the changes in production may be the increased supply of skills. When skilled workers are scarce, it is not profitable for firms to design their jobs specifically for skilled workers and to be extremely selective in their recruitment. In such a world, firms are often happy to hire many low-skill workers, train them, and employ them in relatively well-paid jobs. In contrast, in a world with many skilled workers, it pays to design jobs specifically for them and to be more selective in recruiting. This increases

the productivity and pay of more skilled workers, and effectively excludes low- and medium-skilled workers from well-paid jobs.¹²

Many of the developments in the U.S. labor market, including the recent trends in recruitment and human resource practices, the disappearance of middle-level-pay occupations, reduced training for low-skill employees, the greater dispersion in capital-labor ratios across industries, and the reduced mismatch between workers and jobs, can be explained by a theory based on an induced change in the organization of production and associated changes in recruiting strategies.¹³ Moreover, such an approach can explain the decline in the real wages of low-skill workers — a phenomenon that pure technological theories have difficulty explaining — because technological change, even when it is skill biased, also should increase the wages of low-skilled workers. With organizational change, though, resources will get shifted away from low-skill workers and jobs that paid them high wages will disappear.

Technology, Labor Market Institutions, and Social Norms

Emphasizing technology does not deny that changes in labor market institutions have been important. The erosion in the real value of the minimum wage and the declining role of unions undoubtedly have been important for changes in U.S. inequality, especially at the bottom of the wage distribution.¹⁴ In addition, the late 1980s and the 1990s have seen an explosion in CEO pay, which is difficult to explain with changes in technology alone, and which suggests that there may have been concurrent changes in social norms pertaining to inequality and fairness.¹⁵ Why have labor market institutions and social norms related to inequality changed at about the same time that skill bias of technology accelerated? This may be a coincidence, or the overall changes in inequality may be the result of changing labor market institutions and social norms, and less the product of tech-

nology. In my view, a more fruitful approach is to acknowledge the independent effects of both changes in technology and changes in labor market institutions and social norms, and to link the two.

Recent research suggests how increases in inequality, for example attributable to technological advances, might affect labor market institutions and political preferences about redistribution. Similar arguments also might be used to link social norms of inequality and fairness to technology. Briefly, an increase in inequality might make it harder for certain labor market arrangements, like unions, to survive. Unions typically compress the wage structure, increasing the pay of less skilled workers at the expense of more skilled workers. An increase in the underlying inequality in the economy will make this more costly for high-skill workers, who then will withdraw from the union sectors and from unionized establishments. Similarly, an increase in inequality may reduce the support that highly paid individuals give to the welfare state or to redistributive government programs. These considerations imply that technical change that increases the demand for skills can have much amplified effects on inequality, because it also will change labor market institutions and preferences towards redistribution.¹⁶ These forces might be amplified even more when technology also affects social norms, for example, as it becomes acceptable for CEOs to be paid much more than production workers.

Cross-Country Differences

While inequality increased in English-speaking economies, there was much less of an increase in many continental European countries. To date, there is no consensus for why there was such a divergence in inequality trends among these relatively similar economies. Considering endogenous technology choices may be useful here. Recent research suggests that labor market institutions compressing the structure of wages, as in many continental European economies,

might induce firms to introduce additional new technologies to be used with their unskilled employees. Wage compression makes unskilled workers more expensive to employ and, conditional on wishing to employ them, it increases the value of raising their productivity.¹⁷

Therefore, labor market institutions, such as binding minimum wages, union wage floors, and generous unemployment insurance programs, may have an amplified role in reducing inequality. They will do so directly and they will do so by encouraging technical change to be less skill-biased.

Overall, however, our understanding of the reasons for cross-country differences in inequality is weak, and much research is necessary on this topic, as well as on the relationship between technology and labor market institutions and social norms.

¹ See L. F. Katz and D. H. Autor, "Changes in the Wage Structure and Earnings Inequality," in *The Handbook of Labor Economics*, Vol. 3, O. Ashenfelter and D. Card, eds., Amsterdam: Elsevier, 2000; or P. Gottschalk, "Inequality in Income, Growth and Mobility: The Basic Facts," *Journal of Economic Perspectives*, 11 (1997) pp. 21-40, for recent surveys of the changes in the U.S. wage structure; and P. Gottschalk and M. Joyce, "Cross-National Differences in the Rise in Earnings Inequality: Market and Institutional Factors," *Review of Economics and Statistics*, 80 (1998), pp. 489-502; R. B. Freeman and L. F. Katz, "Introduction and Summary," in R. B. Freeman and L. F. Katz, eds., *Differences and Changes in Wage Structures*, Chicago: The University of Chicago Press, 1995, pp. 1-22, for cross-country trends.

² See, for example, D. H. Autor, A. B. Krueger, and L. F. Katz, "Computing Inequality: Have Computers Changed the Labor Market?" NBER Working Paper No. 5956, March 1997, and in *Quarterly Journal of Economics*, 113 (1998), pp. 1169-214; E. Berman, J. Bound, and S. Machin, "Implications of Skill-Biased Technological Change: International Evidence," NBER Working Paper No. 6166, September 1997, and in *Quarterly Journal of Economics*, 113 (1998), pp. 1245-80; F. Caselli, "Technological Revolutions," *American Economic*

Review, 87 (1999), pp. 78-102; O. Galor and O. Maor, "Ability Biased Technological Transition, Wage Inequality and Economic Growth," *Quarterly Journal of Economics*, 115 (2000), pp. 469-98; J. Greenwood and M. Yorukoglu, "1974," *Carnegie-Rochester Conference Series on Public Policy*, 46 (1997), pp. 49-95; A. B. Krueger, "How Computers Have Changed the Wage Structure: Evidence from Microdata, 1984-1989," NBER Working Paper No. 3858, October 1991, and in *Quarterly Journal of Economics*, 110 (1993), pp. 33-60. See D. Card and J. E. DiNardo, "Skill-Biased Technological Change and Rising Wage Inequality: Some Problems and Puzzles," NBER Working Paper No. 8769, February 2002, for the case against the role of technology in the changes in the U.S. wage structure.

³ Quoted in H. J. Habakkuk, *American and British Technology in the 19th Century*, London: Cambridge University Press, 1962.

⁴ See, for example, D. H. Autor, A. B. Krueger, and L. F. Katz, "Computing Inequality: Have Computers Changed the Labor Market?" And A. P. Bartel, C. Ichniowski, and K. L. Shaw, "New Technology, Human Resource Practices and Skill Requirements," Carnegie-Mellon mimeo, 2002.

⁵ See D. Acemoglu, "Technical Change, Inequality and the Labor Market," NBER Working Paper No. 7800, July 2000, and in *Journal of Economic Literature*, Vol. 40 (2002), pp. 7-72, for a discussion of the case for and against an acceleration in skill bias.

⁶ See P. David, *Technical Choice, Innovation and Economic Growth: Essays on American and British Experience in the 19th Century*, London: Cambridge University Press, 1975; H. J. Habakkuk, *American and British Technology in the 19th Century*; and especially J. Schmookler, *Invention and Economic Growth*, Cambridge, MA: Harvard University Press, 1966. For early historical discussions of endogenous technology, see P. Aghion and P. Howitt, *Endogenous Growth Theory*, Cambridge, MA: MIT Press, 1998; G. Grossman and E. Helpman, *Innovation and Growth in the Global Economy*, Cambridge, MA: MIT Press, 1991; and P. M. Romer, "Endogenous Technological Change," *Journal of Political Economy*, 87 (1990), pp. 71-102, for analyses of endogenous aggregate technological change.

nous aggregate technological change.

⁷ For the basic idea and models of directed technical change, see D. Acemoglu, "Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality," *Quarterly Journal of Economics*, 113 (1998), pp. 1055-90; and D. Acemoglu, "Directed Technical Change," NBER Working Paper No. 8287, May 2001, and in *Review of Economic Studies*, 69 (2002), pp. 781-810.

⁸ D. Acemoglu, "Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality."

⁹ See D. Acemoglu, "Technical Change, Inequality and the Labor Market," and D. Acemoglu, "Directed Technical Change," for more details on this argument.

¹⁰ See D. Acemoglu, "Patterns of Skill Premia," NBER Working Paper No. 7018, March 1999, forthcoming in *Review of Economic Studies*. See A. Wood, *North-South Trade, Employment and Inequality: Changing Fortunes in a Skill Driven World*, Oxford: Clarendon Press, 1994, for the argument that trade with the LDCs may lead to defensive innovations. For more recent models of trade affecting inequality by its impact on technology, see M. Thoenig and T. Verdier, "Trade Induced Technical Bias and Wage Inequalities: A Theory of Defensive Innovations," *Delta* mimeo, 2002, forthcoming in *American Economic Review*, and P. Epifani and G. Gancia, "The Skill Bias of World Trade," MIT mimeo, 2002.

¹¹ See D. H. Autor, F. Levy, and R. J. Murnane, "The Skill Content of Recent Technological Change: An Empirical Exploration," NBER Working Paper No. 8337, June 2001; P. Cappelli and S. Wilk, "Understanding Selection Processes: Organization Determinants and Performance Outcomes," Wharton School mimeo, 1997; and R. J. Murnane and F. Levy, *Teaching the Basic New Skills*, NY: The Free Press, 1996, for changes in the organization of production and the recruitment process; and T. F. Bresnahan, E. Brynjolfsson, and L. M. Hitt, "Information Technology, Workplace Organization, and the Demand for Skilled Labor: Firm-level Evidence," NBER Working Paper No. 7136, May 1999, and in *Quarterly Journal of Economics*, 117 (2002), pp. 339-76; and E. Caroli and J. van Reenen, "Skill-Biased Organizational Change: Evidence from a Panel of British and French Establishments," *Quarterly Journal of Economics*, 116

(2002), pp. 1449-92, for the effect of firm organization on the demand for skills.

¹² See D. Acemoglu, "Changes in Unemployment and Wage Inequality: An Alternative Theory and Some Evidence," NBER Working Paper No. 6658, July 1998, and in *American Economic Review*, 89 (1999), pp. 1259-78; and also M. Kremer and E. Maskin, "Segregation by Skill and the Rise in Inequality," Harvard mimeo, 1999.

¹³ See D. Acemoglu, "Changes in Unemployment and Wage Inequality: An Alternative Theory and Some Evidence," for a summary of this evidence.

¹⁴ See D. Card, "The Effect of Unions on the Structure of Wages: A Longitudinal Analysis," *Econometrica*, 64 (1996), pp. 957-79; J. E. DiNardo, N. M. Fortin, and T. Lemieux, "Labor Market Institutions, and the Distribution of Wages, 1973-1992: A Semiparametric Approach," NBER Working Paper No. 5093, April 1995, and in *Econometrica*, 64 (1995), pp. 1001-44; R. B. Freeman, "How Much Has Deunionization Contributed to the Rise of Male Earnings Inequality?" NBER Working Paper No. 3826, August 1991; and D. S. Lee, "Wage Inequality in the U. S. During the 1980s: Rising Dispersion or Falling Minimum Wage?" *Quarterly Journal of Economics*, 114 (1999), pp. 941-1024, for the effect of the minimum wage and deunionization on inequality.

¹⁵ See E. Saez and T. Piketty, "Income Inequality in the United States: 1913-1998," NBER Working Paper No. 8467, September 2001, forthcoming in *Quarterly Journal of Economics*, on the rise in inequality at the top of the U.S. income distribution, and a discussion of changing social norms.

¹⁶ See D. Acemoglu, P. Aghion, and G. Violante, "Technical Change, Deunionization, and Inequality," *Carnegie-Rochester Conference Series On Public Policy*, 2002, on the effect of inequality on deunionization; and J. Hassler, S. Mora, K. Storlessen, and F. Zilibotti, "Survival of the Welfare State," Stockholm mimeo, 2002, forthcoming in *American Economic Review*; and R. Benabou, "Human Capital, Technical Change, and the Welfare State," Princeton mimeo, 2002, forthcoming in *European Economic Review*.

¹⁷ D. Acemoglu, "Cross-country Inequality Trends," NBER Working Paper No. 8832, March 2002, forthcoming in *Economic Journal*.