The neoclassical approach to induced technical change: From Hicks to Acemoglu

by

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> "A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind – directed to economising the use of a factor which has become relatively expensive."
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> (John Hicks, *Theory of Wages*)

Abstract

This survey article provides a critical overview of the neoclassical theory of induced technical change. From Hicks's introduction of the concept of induced technical change in his *Theory of Wages* up to the recent literature the strengths and weaknesses of the proposed models and the contexts in which they have been developed are outlined. It is shown that induced technical change has been invoked to explain various long-run distribution conundrums which could not be explained with standard neoclassical growth theory. The importance of induced technical change for the long-run distribution of income cannot be doubted. Nevertheless, we show that models of induced technical change are still unsatisfactory in a number of respects. In particular, as recognized by Hicks early on, a sharp distinction between induced technical change and factor substitution is problematic.

1. Introduction

Although technical progress was, and still is, very often treated as exogenous in economic theory, it is quite natural for a neoclassical economist to ask whether the market mechanism is capable of influencing, and perhaps of providing guidance for, the direction of technical progress. The idea that changes in relative factor prices would not only lead to changes in input proportions, but would also affect the direction of technical change was first introduced

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by John Hicks in his *Theory of Wages* ([1932] 1963). Hicks also provided the first systematic discussion of the effects of induced technical change on income distribution in a neoclassical framework. How will changes in relative factor prices affect the direction of technical progress, that is, the factor-saving bias of innovation? The intuitive answer, which is also the one given by Hicks,[3] is that innovations will tend to replace the factors which have become more expensive: If labour becomes "dearer", for instance, firms will try to invent machines to replace labour. But this intuition is wrong. In perfectly competitive conditions all factors are paid their marginal products, so to say that labour is "dear" is equivalent to saying it is highly "productive" (at the margin). And firms will not seek to economize on their most productive factors. To be sure: Under suitably specified conditions (as, for instance, a Cobb-Douglas production function with capital K and labour L) an increase in relative factor prices (in the wage-rental ratio, w/r) will of course induce firms to substitute the now cheaper factor for the more expensive one along the isoquants of a *given* production function until the factor price ratio equals the ratio of marginal productivities. But when the efficient input proportion has been reached due to factor substitution, the initial change in factor prices provides no incentive to direct the search for new technical knowledge to the saving of labour, rather than to that of capital.[4]

Surprisingly enough, the incompatibility of Hicks's analysis with neoclassical theory was not recognized for almost 30 years. In the mid-1960s, serious efforts were then made by some of the leading neoclassical theorists to explore the influence of economic forces on the rate and direction of technical change, and alternative models of induced technical change were proposed by authors like Fellner (1961), von Weizsäcker (1962, 1966), Kennedy (1964, 1973), Samuelson (1965), and Drandakis and Phelps (1966).[5] Although his name is missing in the "literature surveys" on the induced technical change concept provided by Acemoglu

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3 'Changed relative prices will stimulate the search for new methods of production which will use more of the now cheaper factor and less of the expensive one.' (Hicks [1932] 1963: 120)

4 Solow has observed retrospectively: 'He [Hicks] wanted to argue that the high price of a factor would make it a target for factor-saving inventions. But if firms are minimizing costs, the ratio of each factor price to its marginal product would be the same, and that ratio is the only meaningful measure of "highness" or "lowness". This part of Hicks's analysis was a dead end.' (2010: 1117)

5 There has also been a second tradition of neoclassical approaches to the economic explanation of technical change biases, based on the work of Griliches and Schmookler, which has emphasized the influence of growth in product demand on the direction of technical change. This literature will not be considered here.

(2002, 2009), this line of research was strongly influenced by Nicholas Kaldor. First, because in some of the contributions mentioned above his device of the so-called "technical progress function" (Kaldor 1957) was used and re-formulated, and secondly, because the induced technical change concept, in combination with the Solow-Swan growth model, was employed in order to explain his "stylized facts" (Kaldor 1961). In the 1960s, the concept of induced technical change was reformulated by authors like Kennedy, von Weizsäcker, Samuelson, and Drandakis and Phelps, so as to make it compatible with the neoclassical approach to growth and distribution. However, although formally successful, this reformulation was considered so little satisfactory even by the authors of these models that the idea of induced technical change was not pursued further by the leading neoclassical theorists. More recently, however, the idea re-emerged in the late 1990s in the context of the "New growth theory", where the concept had to be reformulated once more, because the empirical facts which were now sought to be explained by means of induced technical change differed significantly from those which were at the center of attention in the early 1960s. Then the main problem was to provide an explanation for Kaldor's stylized facts on the basis of the neoclassical theory of growth and distribution, while the more recent reformulation of the concept, which was mainly due to Acemoglu (1998, 2002a, 2002b, 2003, 2009, 2010), was mainly directed at coming up with a plausible explanation for two empirical facts, which from a neoclassical point of view seemed rather counter-intuitive: In the USA, but also in other OECD countries, there has been an increase in the wage differential between skilled and unskilled labour although the relative supply of skilled labour has increased. A second empirical finding for which the induced technical change theory was supposed to provide a theoretical explanation was that despite very moderate wage increases since the 1980s the level of unemployment has remained high in many continental European countries.

The following critical literature survey will show that in the more recent contributions to induced technical change some fundamental problems which have already beset Hicks's approach have not been addressed, and that some of the problems associated with the Kennedy-Weizsäcker-Samuelson approach of the 1960s have not been resolved. This concerns, in particular, the problem of distinguishing sharply between factor substitution and induced technical change and the justification for the assumption of a constant elasticity of substitution between capital and labour.

The present paper is organized as follows. In Section 2 we summarize Hicks's analysis of induced technical change and the critique of it. Section 3 provides a critical account of the discussion on induced technical change in the 1950s and 1960s. Section 4 is concerned with the recent attempts to invoke induced directed technical change as an explanation of the falling wage share and the high unemployment rate, and for the rising wage premium on skilled labour. Section 5 summarizes and offers some concluding remarks.

2. Hicks's treatment of induced inventions: A false start

At the turn of the 20th century the question whether progress beneficial to the whole society may be detrimental to the workers, which was of great significance for the classical economists, was discussed by neoclassical authors like Knut Wicksell and Arthur C. Pigou, who analysed this problem in his *Economics of Welfare* (second ed., bk iv, chs. ii and iii). Pigou's approach was criticized by Hicks, because it concerned only one special question: 'Whether anything that is to the advantage of the National Dividend as a whole is likely at the same time to be to the disadvantage of the poorer members of society' (1932: 112). This is not wholly satisfactory, Hicks argued, because there is also the question raised by Cannan (*The Theories of Distribution*) which needs answering: 'Is economic progress likely to raise or lower the proportion of the National Dividend which goes to labour?' (1932: 113). In chapter 6 of his *Theory of Wages*, entitled "Distribution and Economic Progress", Hicks then made an attempt to analyse systematically the effects of "progress" on the functional distribution of income in both absolute and relative terms. In the opening paragraph he observed that this question 'was inevitably raised by the Ricardian theory of rent' and 'often engaged the attention of the classical economists', but that 'we do not now need to go back to the classical economists; for we possess today, in the marginal productivity theory, a much superior line of approach to it.' (1932: 112)

2.1 Hicks's analysis of induced technical change

At the core of Hicks's analysis of induced technical change was the question how an increase in the supply of capital resulting from accumulation affects the relative distribution of income, supposing the supply of labour to be unchanged. According to Hicks an increase in the relative supply of capital will raise the wage/interest ratio and lead to three kinds of substitution processes:

1) Commodities in the production of which more of the now cheaper factor is used become cheaper, causing an increase in the demand for them (*substitution in consumption*);

2) Methods already known before, which use more of the now cheaper factor and less of the more expensive one, are adopted due to the change in the relative input prices (*substitution in production/factor substitution*);

3) The change in relative input prices stimulates the search for new methods which use more of the cheaper factor and less of the more expensive one (*induced inventions*). (Hicks [1932] 1963: 120)

For the analysis of the distributional effects of these substitution processes Hicks made use of the newly developed concept of the "elasticity of substitution", which, for a neoclassical aggregate production function with two input factors, capital K and labour L, is given by $\sigma = \frac{d\left(\frac{K}{L}\right)}{d\left(\frac{MP_L}{MP_K}\right)} \frac{\frac{MP_L}{MP_K}}{\frac{K}{L}} = \frac{d\left(\frac{K}{L}\right)}{d\left(\frac{w}{r}\right)} \frac{\frac{w}{r}}{\frac{K}{L}}$, where MP_L and MP_K are the marginal products of labour and capital, and r and w designate the rate of interest and the wage rate. If the elasticity of substitution is larger (smaller) than one, an increase in the relative supply of capital will increase the profit share (the wage share).

The fact that a change in relative factor supplies does not only lead to input substitution and substitution in consumption but also to induced inventions implies that 'we cannot really separate, in consequence, our analysis of the effects of changes in the supply of capital and labour from our analysis of the effects of invention' ([1932] 1963: 120). But according to Hicks not all technical change is *induced*, there is also *autonomous* progress not prompted by changed factor endowments. According to Hicks, the important difference between the two kinds of technical change is that the latter exhibits no particular systematic bias – it is *neutral* – whereas *induced* inventions are supposed to exhibit a systematic bias in the sense that an increase/decrease in the relative supply of capital can be supposed to lead to inventions with a labour-saving/capital-saving bias. Hicks's classification is orientated at the change in marginal factor productivities: Technical progress is labour-saving/capital-saving/neutral according to Hicks, if it raises/lowers/keeps constant the relation between the marginal product of capital and the marginal product of labour. The labour-saving direction of technical change, induced by an increase in the relative capital supply, thus brings about an increase in the profit share (ibid.: 128). The reduction in the wage share, however, must not be mistaken for a decline in wage income in absolute terms. For this question Hicks distinguished between two cases: First, inventions which are introduced because of the change in relative factor prices, but which would not have been introduced before. Secondly, inventions which are introduced at the new relative factor prices, but which also would have been introduced at the previous factor price ratio, had they been known already. These inventions Hicks designated as ‘very labour-saving inventions’, and he explained their existence by a sort of trigger effect of an innovation which has been induced by a change in factor endowments: Research in a labour-saving direction opens up further innovation possibilities in the same direction. While inventions of the first kind only reduce the share of wages, those of the second kind may reduce the wage income in both relative and absolute terms ([1932] 1963: 128-9). Hicks stated as a general tendency that the bias of technical change since the beginning of the industrial revolution had been largely in the labour-saving direction, and that this had been due to *induced* technical progress:

> The real reason for the predominance of labour-saving inventions is surely that which was hinted at in our discussion of substitution. A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind – directed to economising the use of a factor which has become relatively expensive. The general tendency to a more rapid increase of capital than labour which has marked European history during the last few centuries has naturally provided a stimulus to labour-saving invention. (1932: 124-5)

Hicks then analyzed the development of the elasticity of substitution in order to study the effects of capital accumulation and induced directed technical change on the long run distribution of income. At this point a specific characteristic of Hicks’s analysis must be noted. As opposed to modern practice, Hicks did not assume the existence of a CES production function, but rather supposed that the elasticity of substitution would fall with rising capital intensity. In the absence of technical progress the elasticity of substitution would therefore sooner or later fall below one, which would mean that the increase in the amount of capital per worker would raise the wage share. But since the increased capital intensity also induces labour-saving inventions, the fall in σ is counteracted by induced technical change: The induced progress makes labour less scarce and thus counteracts the tendency towards a rising wage share.

Referring to empirical data provided by Bowley, Hicks maintained that the development of income distribution in England (from the 16th to the early 20th century) had been characterized by an initially rising and then a fallinging profit share. This can be explained, Hicks argued, with a continuous increase in the supply of capital with a constant or declining supply of labour, in combination with an initially very high and then progressively falling elasticity of substitution:

> If capital is increasing more rapidly than the supply of labour (and it may fairly be supposed that this has generally been the case in modern English history), a tendency

> towards a diminished elasticity of substitution will generally set in as capital grows. This diminution may be counteracted by invention – it is conceivable that it might be counteracted indefinitely – but clearly invention has a progressively harder task as the process goes on. (Hicks 1932: 132)

For Hicks, the development of relative income distribution therefore depends crucially on the amount of technical progress: If there is only little technical progress, capital accumulation must in the long run result in rising capital intensity, a fall of the elasticity of substitution below one, and an increase in the wage share. On the contrary, if there is enough induced technical progress, the elasticity of substitution will rise or at least not fall below one, so that the profit share need not fall. Overall, Hicks claimed that capital accumulation and technical progress have increased the absolutely income levels of both capital and labour, and that the profit share had increased because of induced technical progress. According to Hicks, then, the long-run distribution of income depends importantly on the amount and direction of induced technical progress, which systematically counteracts the distributional tendencies which emerge from capital accumulation and population growth (or immigration). In the long run, the distribution of income is thus mainly determined by an *endogenous* economic variable: the amount of *induced technical change*.

2.2 Hicks's analysis of induced technical change challenged and discarded

For almost thirty years Hicks's conception of induced technical change remained unchallenged, at least on analytical grounds.[6] It was indeed explicitly endorsed, for instance, by Kurt W. Rothschild in his *Theory of Wages* (1954; second ed. 1960; third ed. 1965), and Hicks himself, when preparing a second edition of his *Theory of Wages* in 1963, saw no reason for recanting his argument. However, in the early 1960s Hicks's conception was seriously criticized by several authors. The incompatibility of Hicks's theory of induced progress with the basic logic of the neoclassical theory was first pointed out by the Australian

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6 It should be noted that Hicks felt that it was necessary, after the extensive debates on the concept of the "elasticity of substitution" in the *Review of Economic Studies* in the mid-1930s, to publish a revised version of the chapter "Distribution and Economic Progress" in 1936 (which he later incorporated in the second ed. of the *Theory of Wages*; see Hicks 1963: 286-303). In a footnote of his 1936 paper, Hicks wrote: 'I shall say nothing here on the subject of inventions, for I have nothing to add at present to what I have already written on that topic.' (Hicks [1936] 1963: 286)

economist W.E.G. Salter in his Cambridge/UK dissertation entitled *Productivity and Technical Change* ([1960] 1966):[7]

> If one takes this to mean that new labour-saving designs are derived *within the fold of existing knowledge*, then this process is equivalent to the substitution within the designing process … It is simply a matter of words whether one terms new techniques of this character inventions or a form of factor substitution. If, however, the theory implies that dearer labour stimulates the search for *new knowledge* aimed specifically at saving labour, then it is open to serious objections. The entrepreneur is interested in reducing costs in total, not particular costs such as labour costs or capital costs. *When labour costs rise any advance that reduces total cost is welcome, and whether this is achieved by saving labour or capital is irrelevant*. There is no reason to assume that attention should be concentrated on labour-saving techniques, unless, because of some inherent characteristic of technology, labour-saving knowledge is easier to acquire than capital-saving knowledge. … *One cannot say ... that the continuing high cost of labour induces labour-saving inventions*. *One may as well speak of the continuing high cost of capital, for the cost of a factor has no meaning except in relation to product or other factor prices*. (Salter [1960] 1966: 43-4; emphasis added)

Independently of Salter, Hicks's concept was also criticized by William Fellner in a paper published in 1961 in the *Economic Journal*, which opened with the statement:

> This note is intended to establish a presumption for the existence of an adjustment mechanism which in market economies directs inventive activity into more or less labour-saving (less or more capital-saving) channels, according as one or the other factor of production is getting relatively scarce on a macro-economic level. *On the conventional static equilibrium assumptions for firms which are very small in relation to the economy, it would be inconsistent to assume the existence of such a mechanism*. (Fellner 1961: 305; emphasis added)

According to Fellner, entrepreneurs will only be led to introduce innovations with a labour-saving bias when they have experienced a *rising* wage-rental ratio in the past and therefore *anticipate* a *rising* trend of the wage-rental ratio also in the future:

> A constant wage-rental ratio – regardless of how high it is – does *not* produce an innovational labour-saving bias, though it does, of course, lead to high capital-intensity

[7] An earlier, but misdirected critique of Hicks's analysis can be found in a paper by an American empirical economist, who maintained: 'Most labor-saving inventions are 'induced,' but they are induced, not by *changes* in relative factor prices, but simply by the *continuing high price of labor*. … Changes in relative factor prices would play a dominant rôle in the motivation of invention if labor costs and capital costs bulked equally large in total costs, but since most production costs are labor costs, invention is naturally biased in this direction, regardless of fluctuations in the ratio of prices of the factors.' (Bloom 1946: 86-87)

> along given production functions. A rising ratio leads not merely to this consequence but also to an innovational labour-saving bias. (Fellner 1967: 663)[8]

To the best of our knowledge John Hicks never responded to the criticisms of Salter and Fellner, but continued to confound factor substitution and technical progress in the second edition of his *Theory of Wages* published in 1963 (see Hicks 1963: 338). In order to make this intelligible it must be noted that a systematic analysis of technical progress on the basis of aggregate neoclassical (Cobb-Douglas) production functions only began after the publication of the contributions to neoclassical growth theory by Solow and Swan. For Solow (1956), factor substitution was unambiguously associated with *movements along the production function*, while technical progress was associated with an upward *shift of the function*. The meaning of an aggregate neoclassical production function was by no means clear in the 1930s and 1940s, and the strict distinction between the two concepts of "factor substitution" and "technical progress" seems to have become generally accepted and widely endorsed only with Solow's contribution of 1956. It also seems apposite to draw attention to the fact that production functions of the CES-type, now so widely used in theoretical and applied macroeconomic analyses, only began to enter into the toolbox of macroeconomists with the paper by Arrow, Chenery, Minhas, and Solow (1962). Hicks's idea of a changing elasticity of substitution as we move along the production function therefore was by no means as strange as it might look to a modern macroeconomist.

3. The revival of the discussion of the effects of induced technical progress on income distribution in the 1960s

Two main facts lead to an intensive debate on the proper conceptualization of induced technical change in the late 1950s and early 1960s: Firstly, the recognition of the incompatibility between Hicks's analysis and the neoclassical approach to factor-pricing in

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8 According to P. A. Samuelson, the reformulation of Hicks's approach proposed by Fellner provides no real solution to the problem: 'All that Fellner seems to end up showing is that, if two improvements seem equally easy to make, the one which involves the least labor will tend to be introduced with greater probability the greater is the expectation of the entrepreneur that wage rates will rise relative to other factors. This near tautology, by itself, conveys little to my mind.' (1965: 354) Fellner retained and defended his formulation, referring also to empirical facts which he claimed supported it (see Fellner 1967, 1971).

fully competitive conditions, and secondly, the challenge posed for the neoclassical theory of growth and distribution by Kaldor's "stylized facts"[9].

3.1 Kaldor's heresy

Because the stylized facts were incompatible with the predictions of the standard neoclassical theory as epitomized in the Solow-Swan model, Nicholas Kaldor set out to develop an alternative model of growth and distribution. In Kaldor's view the neoclassical growth theory emphasizes savings, capital accumulation and technical progress, but overlooks that these factors are subject to change endogenously. In an economy in which the capital stock is continuously increasing, the increase in output induced by a rising capital intensity depends on how quickly additional capital can be used productively. The productive use of additional capital is always associated with changes in the methods of production, because 'the use of more capital per worker […] inevitably entails the introduction of superior techniques which require "inventiveness" of some kind' (Kaldor 1957: 595). Countries which are economically successful differ from less successful ones in their adaptiveness, that is, in their capacity to make use of new capital. Distinguishing between factor substitution (the adoption of methods which were already known, but not previously used) and technical change (the adoption of newly invented methods not previously available), between autonomous and induced progress, and between labour-saving and capital-saving technical progress (1957: 595 ff.) is said to make no sense, because it all depends on how fast new additional capital can be employed efficiently.

According to Kaldor, we can find in each economy a systemic relation between capital accumulation and output growth that can be depicted by a 'technical progress function'. The latter is assumed to be exogenously given and shaped concavely, because the higher is the capital intensity the more difficult it becomes to use additional capital productively. The 'technical progress function' describes the technical change induced by additional capital, but at the same time it also shows the profitability of new investments and therefore the speed of capital accumulation. Because of this two-way causal relationship between technical progress and capital accumulation it is impossible, in Kaldor's view, to use standard aggregate

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9 Kaldor (1961, 1957) found that in the long run the output-labour ratio and the capital-labour ratio were steadily rising, while the capital-output ratio remained approximately constant, as did also the profit rate which showed no clear trend either upwards or downwards.

neoclassical production functions. Kaldor therefore suggested depicting the relation between capital accumulation $\frac{1}{K_t}\frac{dK}{dt}$ and output growth $\frac{1}{O_t}\frac{dO}{dt}$ without making use of aggregate neoclassical production functions.[10]

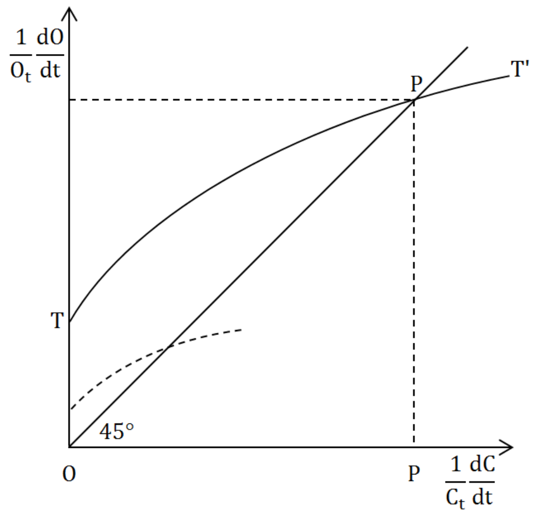

Fig. 1: Kaldor's Technical Progress Function (Source: Kaldor 1957: 595)

With $\frac{1}{K_t}\frac{dK}{dt}$ being the capital accumulation and $\frac{1}{O_t}\frac{dO}{dt}$ output growth, for an economy which is to the left (right) of point P, output increases faster (slower) than the capital stock, thus raising (lowering) the rate of profit on newly invested capital, which in turn accelerates (slows down) the accumulation of capital. In the long run the system therefore tends towards point P, where the rate of capital accumulation coincides with the rate of output growth, keeping the rate of profit and the relative income distribution constant. In Kaldor's analysis the functional income distribution is therefore determined, much like in Hicks's analysis, by the amount of technical progress – the slope of the TT'-curve. Kaldor's rejection of neoclassical concepts such as the aggregate production function and the elasticity of substitution made his model difficult to swallow for more "orthodox" neoclassical economists. At the same time, however, it was clear that the stylized facts could not be explained by the Solow model. Due to the rejection of Kaldor's model and the need of providing an explanation for the stylized facts neoclassical economists began to revive the concept of induced technical progress by making use of their standard instruments (aggregate production functions, elasticity of substitution, distinction between factor substitution and technical progress, etc.).

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[10] Kaldor's attempt to dispense with the concept of the aggregate neoclassical production function and to replace it with the newly developed concept of the "technical progress function" was not successful. As Black (1962) has shown, the production function can be derived from the technical progress function.

3.2 The "neoclassification" of the induced technical change bias

In his paper entitled "Induced Bias in Innovation and the Theory of Distribution" (1964) Charles Kennedy set out to defending Hicks's analysis against the critique of Salter, who had argued that producers have no reason to prefer progress with a particular bias over other forms of technical change, since each dollar saved per unit of output is equally welcome, regardless of whether it is saved on wage or capital costs. Kennedy tried to demonstrate that Hicks had rightly insisted that 'a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind – directed to economising the use of a factor which has become relatively expensive' ([1932] 1963: 124). For this purpose Kennedy introduced a so-called "invention possibility frontier", the shape and location of which was taken to be exogenously given on purely technical – not economic – grounds:

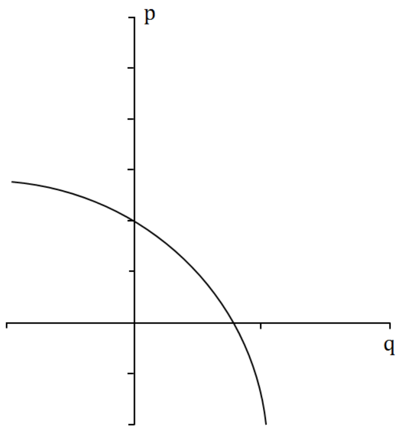

Fig. 3: Kennedy's invention possibility frontier (Source: Kennedy 1964: 545)

Technical progress is taken to reduce the labour input per unit of output by p and the capital input per unit of output by q, with $p = f(q)$, $\frac{dp}{dq} < 0, \frac{d^2p}{dq^2} < 0$. From this convex transformation curve producers can choose freely the optimal combination of labour-saving and capital-saving technical progress, given the factor price ratio: more labour-saving technical progress can be obtained only at the expense of less capital-saving technical progress. The problem of the "choice of directed technical progress" is thus treated in analogy to the usual choice of technique problem in neoclassical theory: While the latter concerns substitution between the factors of production, that is, labour and capital, the former concerns substitution between labour input-reducing and capital input-reducing technical progress. Kennedy noted that his 'innovation possibility function is really a disguised form of Kaldor's famous technical progress function. … If the technical progress function is known, the innovation possibility function can be derived from it' (1964: 547, note 1). Kaldor's TT'-

curve consists indeed of points which provide information about the output variation which arises from induced labour-saving and capital-saving technical progress *and* from the induced factor substitution deriving from capital accumulation. Disregarding Kaldor's argument that it is impossible and indeed futile to try to separate induced progress and factor substitution, Kennedy circumnavigated this problem by assuming fixed factor proportions and fixed factor price ratios, so that no factor substitution is possible at all (Brugger 2013: 63).

On the basis of this simple model Kennedy showed that producers would always choose innovations which use less of that factor which exhibits higher costs per unit of output: If wage costs per unit of output are higher than capital costs, producers will adopt a point on the transformation curve at which the reduction in the input of labour is larger than the reduction in the input of capital. Thus with constant relative factor supply, the model generates biased technical progress, biased towards relatively more saving of the more "expensive" factor (the one with the higher cost share). Therefore, the economy tends towards a state which we may call - following Samuelson's "Kindleberger-Effect"[11] - a "Kindleberger distribution", where the wage share and the profit share are equally large, that is, where each amounts to exactly 50 per cent. This long-run equilibrium exhibits Hicks-neutral technical progress, since labour costs and capital costs per unit of output are the same. But if the wage-interest ratio rises because of continuous capital accumulation, there is labour-augmenting technical progress and a constant distribution between wages and profits (see Kennedy 1964: 545 ff.). The constancy of the profit rate remains a problem, because in our view Kennedy fails to give a convincing explanation of its constancy. Kennedy believed to have developed an alternative theory of income distribution along Hicksian lines in which in the long run distribution depends 'only' on induced technical change, but Samuelson disagreed strongly with this view:

> Kennedy, although he thinks he is fulfilling the Hicks program of labor-saving bias, in fact deduces an asymptotic state of Hicks-neutral technical change (which I show to be stable if, and only if, the elasticity of substitution can be assumed to be less than unity). This is not a theory of constant relative shares so much as a theory that technical change itself will not ultimately contribute toward a change in relative shares when the ratio of factor prices or of factor supplies is not exogenously changing. (Samuelson 1965: 354)

Moreover, Kennedy also misunderstands Salter's objections to Hicks's analysis. Salter ([1960] 1966) conducted his analysis in a two-sector model, where the first sector produces capital goods which are used in the second sector in the production of consumption goods. Technical progress in the first sector will then lower the prices of capital goods inputs, and this reduces the costs of the producers of consumption goods, even though it is capital costs and not labour costs which have been reduced. That Kennedy's paper attracted such a great deal of attention can only be explained by the simplicity of the "invention possibility frontier", because the rest of his model contains many assumptions which are hard to swallow. Kennedy's model eschews neoclassical production functions and capital-labour substitution. The main reason for its being famous is Kennedy's use of the convex transformation frontier, which in spite of the criticism it has attracted is still widely used in neoclassical analyses of induced technical change (see Brugger 2014: 66).

A real „neoclassification" of the induced technical change bias was achieved by Paul A. Samuelson in his 1965 article entitled "A Theory of Induced Innovation along Kennedy-Weisäcker{*sic*} Lines".[12] In this paper Samuelson explored the possibility of explaining Kaldor's "stylized facts" of constant income shares and a constant rate of profit endogenously by means of biased technological change induced by changes in relative factor prices. But unlike Kaldor and Kennedy, Samuelson rigorously applied the concepts of an aggregate production function, factor substitution, the elasticity of substitution and factor pricing based on marginal productivities (see Brugger 2014: 66). In the main part of his paper Samuelson adopted Kennedy's transformation curve, although he was highly critical of it.

The available technology is given by an aggregate neoclassical production function $\mathrm{F}\left(\frac{\mathrm{L}}{\lambda\mathrm{L}}(\mathrm{t}), \frac{\mathrm{K}}{\lambda\mathrm{K}}(\mathrm{t})\right)$, with $-\frac{\dot{\lambda\mathrm{L}}}{\lambda\mathrm{L}} = p$ and $-\frac{\dot{\lambda\mathrm{K}}}{\lambda\mathrm{K}} = q$. Factor input ratios $\frac{\mathrm{L}}{\mathrm{F}} = \alpha_{\mathrm{L}} = \frac{\mathrm{L}}{\mathrm{F}}\frac{\partial \mathrm{F}}{\partial \mathrm{L}}$ and $\frac{\mathrm{K}}{\mathrm{F}} = \alpha_{\mathrm{K}} = \frac{\mathrm{K}}{\mathrm{F}}\frac{\partial \mathrm{F}}{\partial \mathrm{K}}$ are determined in the neoclassical fashion in accordance with marginal factor productivities. Producers can save costs in the amount of $M = (\alpha_{\mathrm{L}} p + \alpha_{\mathrm{K}} q)$ with directed technical change. Since each producer seeks to maximize *M*, but is constrained by the transformation curve of technical progress $\mathrm{f}'(p)$, cost-minimizing producers will chose biased technical change such that $\frac{\alpha_{\mathrm{L}}}{\alpha_{\mathrm{K}}} = \mathrm{f}'(p)$. Accordingly, the direction of technical change is determined by the factor input ratio (which determines the slope of the equi-unit cost lines) and the shape of the technical progress frontier. The tangency point gives the short-run equilibrium of technical change bias:

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12 Samuelson's paper of 1965 was apparently stimulated by presentations given by C.C. von Weizsäcker in 1962 and by Charles Kennedy in 1964 in the MIT research seminar. Weizsäcker's paper, however, remained unpublished until 2010. At the time, von Weizsäcker only published a two-sector version of his model (1966a) and also a book on induced technical change in German (1966b). However, because Samuelson (1965) and Drandakis/Phelps (1966) refer mainly to Kennedy's contribution, von Weizsäcker's contributions have been set aside in this paper.

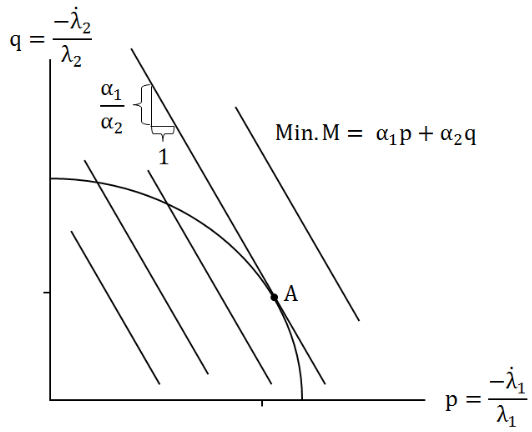

Fig. 4: Short-run equilibrium in the Samuelson model (Source: Samuelson 1965: 344)

With Kennedy's assumption of constant relative factor prices or constant relative factor endowments ($\frac{K}{L}$ constant) Samuelson's model also converges, like Kennedy's, to a "Kindleberger distribution" and Hicks-neutral technical progress (see point E in Fig. 5); in this case the factor shares α_K, α_L are determined in the long run exclusively by the direction of technical change.[13] However, if the capital stock steadily rises relatively to the supply of labour – as is suggested by Kaldor's stylized facts, according to which the average annual increase in capital intensity is roughly 2 to 3 per cent – things are different. Then the effects of the increasing capital intensity depend on the elasticity of substitution. Samuelson shows that a steady increase in capital leads to a stable equilibrium with labour-augmenting technical change – see point E' in Fig. 5 – if the elasticity of substitution is less than one.

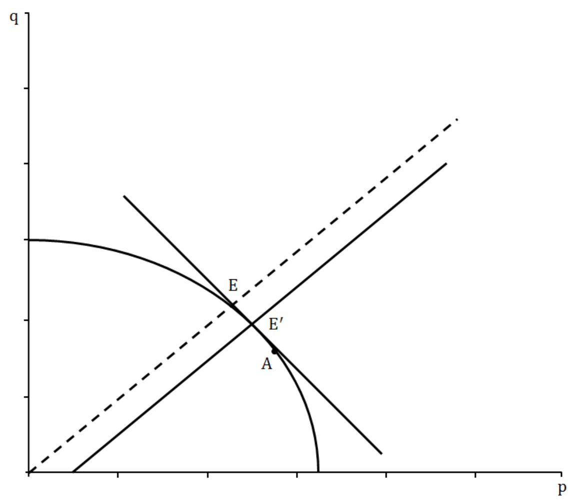

Fig. 5: Long run equilibrium and biased technical change (Source: Samuelson 1965: 349)

13 If $\alpha_L > \alpha_K \rightarrow p > q \rightarrow \frac{\alpha_L}{\alpha_K} \downarrow$, until $\alpha_L = \alpha_K$ holds, that is, until a "Kindleberger distribution" has been achieved.

In this long-run equilibrium the income shares are constant, with a larger share going to wages. However, Samuelson's model could not explain the Kaldor fact of a constant profit rate: In the long-run equilibrium both the wage rate and the profit rate are steadily increasing. Shortly later, Drandakis/Phelps (1966) solved the problem of profit rate constancy by introducing the assumption of savings as a constant fraction of income into the Samuelson model (Drandakis/Phelps 1966: 837).[14]

Although Samuelson and Drandakis/Phelps accomplished the explanation of Kaldor's stylized facts by integrating Kennedy's invention possibility frontier into the aggregate neoclassical model of growth and distribution, they were highly skeptical about the relevance of their results. This skepticism derived from the fact that they considered a central element of their models – the invention possibility frontier – an inappropriate and misleading device for capturing the economic influences on the generation of new technical knowledge. The transformation curve completely disregards exogenous research trends, which however have played a prominent role in the history of technical progress (Samuelson 1965: 353). Moreover, it is assumed that a producer can choose any point on the frontier without incurring any costs. In addition, current invention possibilities are supposed to be independent of past decisions on the direction of technical change: There is no path-dependence (Nordhaus 1973: 212-213). Drandakis and Phelps (1966: 838) observed that the isoquants of inventions which are not in the first quadrant of the invention possibility frontier (that is, for which either q or p assumes a negative value) can intersect with the isoquants of other techniques. This would imply that techniques which are no longer utilized could be adopted again with a change in relative factor prices. Furthermore, the position and the slope of Kennedy's invention possibility frontier are supposed to be determined by technical factors alone – possible economic factors which could also influence the shape and position are disregarded. Finally, the Kennedy curve implicitly assumes that inventions or technical progress can be perfectly planned (and then be carried out as planned): It assumes that there is perfect information with regard to invention possibilities. However, one need hardly emphasize that there are few other

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14 Samuelson summarized the results of Drandakis/Phelps concisely: 'If a constant fraction of income, s, is always saved, then a standard system with elasticity of substitution less than one and subject to a Kennedy technical change transformation frontier will have an asymptotical generalized golden-age state with: i) Harrod-neutral technical change, ii) Asymptotical constant relative factor share … iii) Asymptotical constant interest rate …iv) Real wage that is asymptotically growing at the rate of labour augmenting technical change … v) Output and capital stock will asymptotically grow at the rate of population growth plus of ultimate labor-augmentation … vi) All the above asymptotic states are stable if $\sigma < 1$ ….' (Samuelson 1966: 447)

areas in which information is lacking as much as in the generation of new technical knowledge (see Brugger 2014, 73 f.). Atkinson and Stiglitz (1969) pointed out that technical progress is typically “locally bounded”, that is, it does not affect the entire spectrum of the available techniques, but only a small subset of it. On the assumption employed by Kennedy, Samuelson and Drandakis/Phelps that induced technical progress leads to a shift of the entire production function they commented: ‘Would a firm that undertakes R&D on transportation methods really want to raise productivity on handcarts as well as forklift trucks?’(1969: 577) William D. Nordhaus (1967, 1973) critisized the entire literature on induced innovations of the 1960s because it lacks “microfundations”: It is not clear who undertakes the R&D, what are the costs involved and how these are financed. He concluded that the model of induced innovations employed by Kennedy, Samuelson and Drandakis/Phelps ‘is too defective to be used in serious economic analysis’ (1973: 208).

Samuelson also explored the idea, suggested by Salter, that producers regard each dollar of costs as equally worthy of cost reduction, irrespective of whether it is a dollar spent on wage payments or on capital inputs. Samuelson showed that this would imply that the invention possibility frontier depends on factor prices and factor costs, so that changes in relative factor prices lead to shifts of the invention possibility frontier (1965: 352-3). In this case a long-run equilibrium with *unbiased* technical change can be shown to exist (1965: 353). His paper therefore closes with a statement which raises serious doubts about the relevance of the findings which he had derived in the main part of his paper:

> The model leading to this conclusion [i.e., to the conclusion that ‘steady growth of the capital/labor ratio will lead to a long-run equilibrium in which there is induced relatively greater labor-augmenting or labor-saving inventions to just the degree needed to keep the ratio of capital (in efficiency units) to labor (in efficiency units) constant’] is shown to be only one of a number of economically important models – as, for example, the simple view that each dollar of costs tends to merit an equal research effort toward cost reduction, with *no* implied bias of innovation. (1965: 356)

The disillusionment with the concept of induced technical change bias is captured well in a comment by Nathan Rosenberg, who suggested in 1969 that it is necessary to go beyond ‘the more conventional framework of economic reasoning’ because of ‘the extreme agnosticism to which one is led on the subject of technological change by recent theorizing. *It used to be thought possible to explain the factor-saving bias, which inventions took, in purely economic terms*’ (1969: 1; emphasis added). According to Rosenberg, by the late 1960s it was generally agreed that this was not possible:

> The current position … is that under competitive conditions an individual firm is simply not interested in the particular factor-saving bias of technical improvements. The argument is that a firm always has an incentive to reduce any portion of its costs. *The market mechanism provides no incentive to look for inventions which have any particular factor-saving bias*. Indeed, the position is that in competitive equilibrium it does not even make sense to speak of "dear" labor or "cheap" labor. After all, when each factor is being paid the value of its marginal product, then all factors are equally "cheap" and equally "dear" in the eyes of a competitive firm. (1969: 2)

Rosenberg therefore drew attention to "focusing devices" and "inducement mechanisms" such as strikes, shortages, technological imbalances etc: 'Strikes or fear of strikes have served, historically, as a powerful agent for directing the search for new techniques in a particular direction. The preoccupation with substituting capital for labour (especially skilled labour) was more than just a matter of wage rates' (1969: 17). The general point of Rosenberg's paper was that a theoretical explanation of induced innovation or a particular factor-saving bias makes it necessary to go beyond the competitive framework, and to introduce market power or uncertainty into the model.

To sum up, in the 1950s and 1960s attempts were made by various schools of thought to integrate directed technical progress into the analysis of growth and income distribution as a possible explanation of empirically observed distributional phenomena which are unexplainable by standard macroeconomics. The direction of technical change or the relation between capital accumulation and technical progress was supposed to be the missing element in economic theory for explaining endogenously Kaldor's stylized facts of constant income shares. Although the goal of an endogenous explanation of Kaldor's stylized facts was formally achieved by Samuelson and Drandakis/Phelps, the necessary assumptions were so rigid that even the authors of the models were highly critical of their results. The underlying model of technical change in terms of the Kennedy transformation curve was considered so unrealistic and incomplete that the concept almost completely disappeared for the next 30 years from the economic research agenda.[15] It was only in the late 1990s that a second "renaissance" of the concept of induced directed technical change occurred. While the recent discussion of directed technical change is carried out in a different modelling framework from the one adopted in the 1960s – emphasizing in particular the heterogeneity of labour and capital (or of "variants" of a single capital good), and introducing monopolistic competition – it was again novel empirical findings about distributional developments which were difficult

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[15] From the mid-1970s to the late 1990s there were only few contributions to the theory of induced inventions; see, however, Binswanger (1974, 1978).

to reconcile with standard neoclassical theory which triggered the renewed interest in induced technical change.[16]

4. The recent discussion of biased technical change

The relative income distribution between capital and labour was for a long time approximately constant, as shown by Kaldor. However, in the late 1960s and early 1970s the wage share increased rapidly in many industrialized countries. In the mid-1970s or early 1980s this trend was suddenly reversed, and in most Continental European countries and Japan the wage share began to fall (see Bentolila/Saint-Paul 2003, Bassanini/Manfredi 2012). In the early 1990s the decline in the wage share has been even more pronounced, and extended to almost all OECD countries (OECD 2012). However, across OECD countries the strength of the decline in the wage share has been very different. It was moderate in the USA, where historically the wage share was always small (Bassanini/Manfredi 2012), and in Great Britain (Hutchinson/Persyn 2012) and Denmark (Sweeney 2013) the decline is not clearly visible at all, while in many countries in Continental Europe (Germany, France, Austria, Italy, Ireland) and Asia (Korea, Japan) the decline in the wage share has been rather pronounced. Furthermore, there are considerable differences with regard to the development of the wage share across sectors (Arpaia et al. 2009). Thus overall the wage share has fallen in most industrialized countries since the early 1980. In the 1950s and 1960s the increases in real wages went hand in hand with productivity increases, so that rising real wages led neither to higher unemployment nor to marked changes in the relative distribution of income, but in the 1970s there was a de-coupling of productivity increases and real wage increases (Caballero/Hammour 1998). The sharp rise of wages in the 1970s was accompanied by low increases in productivity, resulting in rising unemployment and increasing wage shares. But the moderate increases in real wages in the 1980s have not led to a reduction of unemployment (as suggested by standard neoclassical theory) in most countries; in many countries in Continental Europe the latter has remained high or has even increased (Nickell et al. 2005, BLS 2013). Rising unemployment and falling wage shares in the 1980s are explained by some authors with overly high wage increases in the late 1970s (Blanchard 1997), which have caused delayed induced substitution of capital for labour in the 1980s

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16 Kennedy's "invention possibility frontier" has also been combined with a Marx-Goodwin model of cyclical growth (Shah/Desai 1981) and with a classical model of growth and distribution (Foley 2003).

(Caballero/Hammour 1998). However, when unemployment remained high and the wage share continued to fall in the 1990s, this could not be explained by standard macroeconomic substitution theory.[17] This has led to a renaissance of induced directed technical change as a possible explanation of the long run income distribution.[18]A further reason for renewed interest in the concept of induced technical change was the widening of the wage gap between skilled labour and unskilled labour, which was observed particularly in the USA. The increase in the relative supply of skilled labour (that is, in the ratio of skilled to unskilled labour) since the 1970s at first went along with the expected effect of a fall in the relative wage of skilled labour. At the beginning of the 1980s, however, this trend was reversed and since then the steady increase in the relative supply of skilled labour was accompanied by a steady increase in relative wages of skilled labour (see Acemoglu 1998; Autor et al. 1998; Katz/Murphy 1992; Kiley 1999) – notably the increase of the wage premium for skilled workers was much less pronounced in continental Europe (Hornstein et al. 2005). In order to explain this paradox, several authors have suggested induced skill-biased technical change as a possible explanation. Among the authors who suggested this explanation, there are different approaches: While some authors argue that the skill-bias results from exogenous research trends such as computerization, which can be understood as a diffusion of an exogenously available general purpose technology (GPT) – there is evidence that technical change in the last 30 years was of a GPT nature (Hornstein et al. 2005) –, others have argued that the skill-bias was induced by the changed relative supply of skilled labour (Kiley 1999; Machin/Manning 1997; Acemoglu1998, 2002a, 2002b, 2007, 2009; Acemoglu/Zilibotti 2001), and thus can be explained endogenously (Brugger 2014: 77 ff). A third explanation is the so-called “capital-skill complementarity” hypothesis, according to which capital goods are generally complements of skilled labour and substitutes of unskilled labour (Griliches 1969). Thus according to this theory the increasing capital intensity, which was induced by falling prices (and costs) of capital goods, led to an increased (reduced) demand for skilled (unskilled) labour (Krusell et al. 2000; Hornstein et al. 2005).

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17 ‘During the 1970s, … unemployment increased, but so did wages and the labor share. … Analysts of that period saw in the widening “wage gap” apparent in the growth of wages and of the labor share, evidence that points to unemployment of the Classical type. While unemployment kept rising in the 1980s, wage growth slowed below productivity, the labor share plummeted, and the deal turned sour of labor. Unemployment had turned non-Classical.’ (Caballero/Hammour 1998: 3)

18 Some new growth theorists have also questioned the validity and overwhelming importance of Kaldor’s stylized facts, and have suggested a list of “new Kaldor facts” (Jones/Romer2010).

In the following we focus attention on those models in which the direction of technical change is determined endogenously. This is not because those models are empirically more robust,[19] but because we believe that the three explanatory hypotheses are not necessarily in conflict with each other. The "capital-skill complementarity hypothesis" assumes, like the models of Salter ([1960] 1966) and Acemoglu (1998, 2002a, 2007, 2009), that the direction of technical change is determined by changes in the *prices of capital goods* (or in the productivity of capital goods) – and not by changes in the interest rate. As opposed to Salter, however, for whom capital goods are simply substitutes of (homogenous) labour, and also to Acemoglu, for whom capital goods can be either skilled-labour complements or unskilled-labour complements, the "capital-skill complementarity" hypothesis assumes that capital goods must always be complements of skilled labour and substitutes of unskilled labour. While "capital-skilled labour complementarity" seems indeed to exist in some branches, as for instance in the IT sector (Caselli/Coleman 2001), as a general presumption it seems unfounded. Although in the 20th century capital and skilled labour were often complementary (Goldin/Katz 1998), the history of capitalist development provides many examples of innovations which were associated with complementarity between capital and unskilled labour (Brugger 2014). If we reject capital-skill complementarity as a universal law on historical grounds, then the "capital-skill complementarity hypothesis" must be supplemented by a theory which explains – exogenously or endogenously – the direction of technical change. The sharp decline in capital intensity in the early 1970s and the subsequent increase since the mid-1970s (Krusell et al. 2000) is an empirical predictor of a change in the direction of embodied technical change. The development of the capital intensity could be interpreted as indicating that firms in the period from 1970 reacted to the changed labour supply conditions by de-investment into unskilled labour complementary capital goods, and only after 1975 began to invest into new skilled labour complementary capital goods. Thus the empirical fact of capital-skill complementarity needs the theory of directed technical change as a supplement for explaining why embodied technical change has had this kind of direction. Moreover, we believe that there is no contradiction between the theory of induced skill-biased technical change and exogenous research trends in the form of "General Purpose Technologies" (GPT's) – whose occurrence

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[19] Empirical tests of models which seek to determine the direction of technical change endogenously have been contradictory and ambiguous (Brugger 2014:91 f.), while both the "capital-skill complementarity"-hypothesis (Krusell et al. 2000) as well as the GPT-diffusion hypothesis according to which the introduction of the GPT "Information and communication technology" has been particularly skill-intensive (Aghion 2002), is largely confirmed by the empirical data.

cannot be explained in purely economic terms (Bresnahan/Trajtenberg 1995, Mokyr 1990). The existence of a GPT does not necessarily imply that it can be used only as either a skill-biased or as an unskilled labour-biased technology. If we think of computers, for instance, it could be imagined that this technology – depending on the economic situation – could be adapted to skill-biased or unskilled-biased uses, or rather that it could lead to further adaptive innovations which are either skill-biased or unskilled-biased. Hence it would be conceivable that the same GPT may be adapted in an unskilled and skilled labour complementary manner. But it remains an open question why other GPTs have not been adapted for skilled-labour intensive usage in spite of the large supply of skilled labour (Aghion 2002).

4.1 Induced skill-biased technical change

In the following we refer to the models presented in Acemoglu (2002a, 2009). The models exhibit some similarities with the one presented by Salter ([1960] 1966). Both authors adopt a "multi-sector" representation of the economic system: Salter's model consists of a consumer goods sector and a capital goods sector; Acemoglu's of a capital good sector, an intermediate goods sector and a consumption good sector. Technical progress is embodied in the capital good and consists of an expansion of the amount of capital good varieties (Acemoglu) or in cost reductions of the capital goods (Salter), which are used in the intermediate goods and the consumption goods sector. In both models the demand for capital goods from the intermediate or consumer goods sector determines the choices of the capital good producers regarding the future characteristics (the 'design') of the capital goods (or of the capital good variants), and thus the direction of technical change. In Acemoglu's model the endowment of the economy with skilled and unskilled labour determines the intermediate good sector's demand for the different types of capital goods – and thus whether producers of new capital goods decide to "invent" or "design" new capital goods which are complementary to skilled labour or rather to unskilled labour. If the majority of capital goods producers decide to develop capital goods which are complements of skilled labour (unskilled labour), technical progress is skilled-labour-augmenting (unskilled labour-augmenting). Something similar also holds in the Salter model, where producers of capital goods always have in view the cost structure of consumer goods producers and try to anticipate future changes in their cost situation. If they expect that the consumer goods producers will face rising labour costs in the future, they "design" the capital goods in such a way that they can be utilized with high capital intensity. As opposed to Salter, however, who supposes labour to be homogeneous and labour and capital goods to be substitutes, so that continuous technical progress in the capital goods sector leads to a permanent substitution of capital for labour in the consumer goods sector, Acemoglu assumes that there is always complementarity between a capital good variant and one of the two types of labour (skilled or unskilled labour).

The basic structure of Acemoglu's model (2002a, 2009) can be summarized as follows: An increase in the relative supply of skilled labour – as experienced in the USA since the 1970s – produces two potentially counteracting effects on the relative profitability of technologies for capital goods producers, who operate on a capital goods market with monopolistic competition: a price effect and a market size effect. The price effect means that there is an incentive for capital goods producers to undertake R&D and invent capital goods variants which can be utilized in the production of goods that command higher prices. The increase in the relative supply of skilled labour reduces the price for this sort of labour and therefore the price of intermediate goods produced with skilled labour. The price effect thus creates incentives to invent capital goods variants which are complementary to unskilled labour. Casually speaking, as intermediate goods produced with unskilled labour are becoming relatively more expensive capital goods producers try to get a piece of the bigger cake by inventing new unskilled labour complementary capital goods. However, there is not only a price effect but also a market size effect: The larger is the market for any particular type of capital good, the larger is the incentive for capital goods producers to invent new variants of this type. With an increase in the relative supply of skilled labour the market for capital goods which are complementary to skilled labour increases, so there is an incentive for capital goods producers to develop new variants which are skilled labour complements. Hence the price effect and the market size effect are counteracting each other. Which of the two effects is stronger depends on the elasticity of substitution between skilled and unskilled labour. When the elasticity is larger (smaller) than one, the market size effect (the price effect) dominates and therefore technical progress will be skilled-augmenting (unskilled-augmenting). However, whether the increase in the relative supply of skilled labour raises or lowers the relative marginal product of skilled labour does not depend on whether induced technical progress is skilled- or unskilled-augmenting alone. In order to determine how directed technical change affects the relative marginal productivity, the relative demand for, and the relative price of skilled labour Acemoglu employed the concept of "biased technological change". While the augmentation informs us whether more new skilled or unskilled labour complementary capital goods varieties are developed, the form of the "biased technological change" informs about which factor benefits more. When the elasticity of substitution between skilled and unskilled labour is larger (smaller) than one, a factor-augmenting progress always leads to "biased technological change" of the same (of the other) factor; hence skilled labour-augmenting (unskilled labour-augmenting) progress causes skill-biased (unskilled-biased) technological change. Hence in the case of an elasticity larger (smaller) than one skilled labour-augmenting progress leads to an increase in the relative marginal productivity, the relative demand for, and the relative price of skilled (unskilled) labour. The intuitive explanation of this surprising result is simple: If the elasticity of substitution is smaller than one there are insufficient substitution possibilities in order to utilize more intensively the factor which has become more abundant through the induced technical progress. This leads to an increase in the demand for the other, non-augmented factor, raising its marginal product and its remuneration. With an elasticity of substitution larger than one, however, the augmented factor is substituted for the non-augmented one, which raises the demand for and the marginal productivity and relative price of the augmented factor. This means: When the elasticity of substitution is larger than one an increase in the supply of skilled labour causes skilled-augmenting and, because of the 'high' elasticity, skill-biased technical change. When the elasticity of substitution is below one the increased skilled labour endowment induces unskilled-augmenting technical change which, because of the 'low' elasticity, has a skilled-labour bias. Thus with an increase in the relative supply of skilled labour the technical progress is *always* skill-biased: skilled labour-augmenting and skill-biased if the elasticity of substitution exceeds one, and unskilled labour-augmenting and also skill-biased if it is smaller than one. This means that technical progress – independently of the value which the elasticity of substitution assumes – is always skill-biased as the relative supply of skilled labour increases, and thus raises the demand for and the relative marginal productivity and relative price of skilled labour. (One could say that the Acemoglu model is constructed on the „Heads I win, tails you lose"-principle.)

Acemoglu designated the case in which the increased supply of a factor always leads to biased technical change of the same factor as a "weak equilibrium", and noted: 'There is always weak equilibrium (relative) bias in the sense that an increase in $\frac{\mathrm{H}}{\mathrm{L}}\left[\frac{\text{skilled labour}}{\text{unskilled labour}}\right]$ always induces relatively H [skilled labour]-biased technological change.' (Acemoglu 2009: 510) Since a "weak equilibrium" always exists, the price effect is always outweighted by the market size effect. However, the existence of a "weak equilibrium" does not necessarily lead to an increase in the wage premium of skilled labour. This is because in addition to the effect of technical change on income distribution there is also the effect of substitution which arises from the increased supply of a factor, which tends to reduce the marginal productivity of skilled labour. If the bias of technical change is strong enough to outweigh the substitution effect, that is, if an increase in the supply of skilled labour raises the wage premium of skilled labour, there is what Acemoglu calls a “strong equilibrium”. The following figure shows the development of relative wages in “weak equilibrium”, “strong equilibrium”, and without any technical change; with W_S being the wage for skilled and W_U the wage for unskilled labour; W is the relative wage rate.

Fig. 6: Relative wages in the Acemoglu model (Source: Acemoglu 2009: 511)

In order to derive conditions under which the system provides a strong equilibrium it is not sufficient to look only at the ‘demand side’ of technical change – as we have done above. It is necessary to take also the ‘supply side’ of innovations into account. Hence an innovation possibilities frontier is needed. Satisfying balanced growth, the innovation possibilities frontier may have one of two “micro foundations” – both outlined by Rivera-Batiz and Romer (1991): the one is a lab equipment form in which R&D is ‘produced’ by a fixed amount of final good input – or by the same inputs as are used in the production of final goods; the R&D production function and the final good production function are therefore of the same degree of homogeneity. This implies that in the case of a lab equipment specification neither exogenous influences nor knowledge spillover effects can be found in equilibrium. Hence with a lab equipment specification in equilibrium there is no state dependence and the innovation possibilities frontier is similar to Kennedy’s. The other is the knowledge-driven specification. In this case R&D is ‘produced’ by two ‘inputs’, human capital (scientists) and knowledge which scientists have acquired in past research; thus in this case the homogeneity in the knowledge production is higher than in the final good production, so that there is knowledge spillover or a positive external effect. Hence, unlike in the lab equipment and Kennedy case, for the knowledge-driven specification past research is influential. In case of the lab equipment specification a strong equilibrium will only be reached with an elasticity of substitution larger than two. Like in the previous sections, with a lab equipment specification the distribution effect of an increase in one factor's supply depends on whether the elasticity of substitution is above or below one; in the first case the factor share increases with its relative abundance, while in the second it decreases. But in the case of a knowledge-driven specification - current research benefits from past research ("standing on the shoulder of giants") - less substitutability is needed to reach a strong equilibrium. Hence with state dependence even in the case of a substitution elasticity smaller than two a strong equilibrium is possible. Of course, the higher the state dependence the easier a strong equilibrium will be reached (Acemoglu 2009: 514 ff.). Furthermore, with path dependence the distribution share of skilled workers may increase with its relative abundance even if the elasticity of substitution is below one. This shows 'that in addition to the elasticity of substitution, the degree of state dependence in the innovation possibilities frontier will have an important effect on the direction of technical change'(Acemoglu 2002a: 791). Owing to the fact that the elasticity of substitution between skilled and unskilled labour is difficult to measure, the existing empirical studies arrive at rather divergent results: Gancia et al. (2011: 22) calculated an elasticity larger than two, while Ciccone/Perri (2005) arrived at values between 1,2 and 2. However, according to a number of studies there is empirical evidence that skill-biased technological change – irrespective of how it has come about – has been one of the reasons for the increase of the "wage premium" for skilled labour (Autor/Katz 1999; Autor et al. 2003; Hornstein et al. 2005; Goos/Manning 2007; OECD 2012; Oesch/Rodriguez/Menés 2010).

4.2 Directed technical change as an explanation of a falling wage share and persistent high levels of unemployment

A major factor for the resurgence of interest in the concept of induced technical change has been the empirical finding of falling wage shares. The distribution between wages and profits is of course affected by many factors, including globalization, institutional changes, changes in bargaining power, structural changes, etc. However, econometric studies (OECD 2012; Hutchinson/Persyn 2011; Karabarbounis/Neiman 2013; Driver/Muñoz-Bugarin 2010; Arpaia et al. 2009; Bentolila/Saint-Paul 2003; Bassanini/Manfredi 2012) have attributed a large fraction of the decline in the wage share to technical progress and its direction; according to some studies up to 80 per cent of the decline is explained by directed technical change (Bassanini/Manfredi 2012; OECD 2012).[20]

Following Salter ([1960] 1966), Karabarbounis/Neiman (2013) argue that since 1975 falling capital goods prices have induced continuous substitution of capital for labour, raising capital intensity. Given their elasticity of substitution between capital and labour estimate of 1,25, the capital-labour substitution has contributed significantly to the reduced wage share. According to Karabarbounis and Neiman the substitution effect explains up to 50 per cent of the decline in the wage share, while Bassanini/Manfredi (2012) find that only 16 per cent of the declining wage share can be attributed to rising capital intensity. Furthermore, Karabarbounis and Neiman show that countries in which investment goods prices fell more quickly exhibited larger declines in wage shares. Problematic is their distinction between substitution effects and factor-augmenting progress as well as the estimated value of the elasticity of substitution. In this study capital-augmenting progress is merely attributed to change in the wage share, which is not explained by the cheapening of the capital goods; so capital-augmentation is a residual. But capital has not just become cheaper since 1975, but also vastly more productive (however measured), this distinction appears to be rather ad hoc. Hence these studies disregard embodied technical change. But allowing for embodied as well as disembodied change is important with regard to income distribution because there is some evidence that in the last 40 years embodied change was strongly biased toward unskilled and disembodied change toward high-skilled workers (OECD 2012). Acemoglu (2010: 1063) shows that embodied technical change creates a natural tendency for very labour-saving technical change in the Hicksian sense. For the elasticity of substitution empirical studies have come up with very different results, ranging from values significantly above one (Karabarbounis/Neiman 2013; Masanjala/ Papageorgiou 2003) to values below one (Antras 2004; Klump et al. 2004; Young 2010). In some sectors like chemical industries or mining the elasticity of substitution is estimated to be larger than one, while for others like building and construction or social services elasticities of substitution smaller than one have been calculated (Bentolila/Saint-

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[20] But these findings have also been contested; see, for instance, Lavoie/Stockhammer (2012) and Stockhammer (2013).

Paul 2003).[21] For Karabarbounis and Neiman's argument to hold, however, the elasticity of substitution must be strictly larger than one.

Bentolila/Saint-Paul (2003) found significant empirical evidence for capital-augmenting progress and its impact on wage shares. They show that capital-augmenting progress caused the break-down of the "one-for-one relationship" between capital intensity and the wage share. By "one-for-one relationship" Bentolila and Saint-Paul mean the relation between changes in capital intensity and the wage share if the standard assumptions of Harrod-neutral progress and constant returns to scale hold. Assuming a "one-for-one relationship" and a CES production function there exists a constant relation between capital intensity and the wage share, which can be positive or negative depending on the elasticity of substitution. In the case of capital-augmenting progress this relation is no longer stable. This means that capital-augmenting technical change reinforces the effect of rising capital intensity. Hence with an elasticity of substitution larger than one, capital-augmenting progress leads to a reduction in the wage share (Bentolila/Saint-Paul 2003; OECD 2012).

If we accept that directed technical change is an important factor for explaining the falling wage share the question remains whether this wage share reducing form of technical change was induced or not. Blanchard (1997) and Caballero/Hammour (1998) take the view that 'high' wages in the 1970s have shifted the technological path into a more labour saving direction. According to Blanchard (1997) there are three possible explanations why wage shares are still falling and unemployment remains high, notwithstanding the moderate wage policies since early 1980s: lagged factor substitution, shifts in rent distribution and biased technical change. The first means that after a wage shock it takes very long to substitute capital for labour until a new efficient factor input combination is reached. Caballero and Hammour (1998) argue that in the short run the elasticity of substitution is very small; production functions being of a putty-clay form. Therefore labour shares have increased after the wage shock. But in the long run the technology used may be changed; hence the elasticity of substitution is very small in the short run but considerably higher in the long run. Thus the wage shocks induced firms to adapt more 'appropriate' – which means more labour-intensive – technologies. As long run technology adaption has prevailed wage rates may fall below their trend levels and unemployment still persists on a high level. Following the very rigid neoclassical concept of substitution – with a clear distinction between technical change as shifts of production functions and substitution as movements along the production function –

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21 For a survey of empirical results on the elasticity of substitution see Klump et al. (2004)

it would be difficult to imagine that the wage shock induced substitution took 40 years until a new efficient factor input equilibrium was reached. Caballero and Hammour (1998) did not follow the rigid neoclassical definition of substitution but adopted the Hicksian one, which includes induced innovations of new technologies: ‘In response to an appropriation attempt, it [the firm] will select *and develop* technologies that are much less labour intensive.’ (Caballero/Hammour 1998: 3; emphasis added) Hence, Caballero and Hammour argue that “dear” labour (dear in the sense that in the early 1970s the increase in the marginal productivity of labour fell short of the increase in real wages) led to the development and introduction of more capital-intensive machines and methods of production. That rising wages led, historically, to the invention of machines which replaced labour is generally designated as the Habakkuk hypothesis.[22] Acemoglu (2010) has shown that rising wages (relative to the marginal productivity of labour) and labour shortages produce incentives for the development of what has been called by Hicks “very labour saving technologies”, which reduce the marginal product of labour. But in our view this line of reasoning fails to elucidate why moderate wage growth since the early 1980s has not reversed the trend of induced labour-saving technical change. Blanchard favors shifts in the markup distribution from labour to capital and capital-augmenting technical change over long lagged substitution as a possible explanation, but he is aware of the non-distinguishability between substitution and technological change:

> In the same way as labour supply shifts led firms, over time, to move to technologies using less labour and more capital, they may have led firms to develop or adopt new technologies that were biased against labour. Indeed, the distinction between movements along an isoquant (choice among existing technologies) and shifts in the isoquant (development and adoption of new technologies) is probably much sharper in economists’ models than in reality. (Blanchard 1997: 103-104)

Hence, in Blanchard’s view the conundrum of falling wage shares and high unemployment since the early 1980s may be explained by reduced bargaining power of workers and capital augmenting technical change, which was induced by high wages in the 1970s. Acemoglu (2002a) developed a model (based on the one summarized above) by means of which he showed that a ‘wage push shock’ like the European one in the 1970s together with an elasticity of substitution smaller one increases the wage share and decreases employment in the short run; this may be called an “induced substitution effect” with a given technique. But in the long run, given the elasticity of substitution is smaller than one, the applied technique

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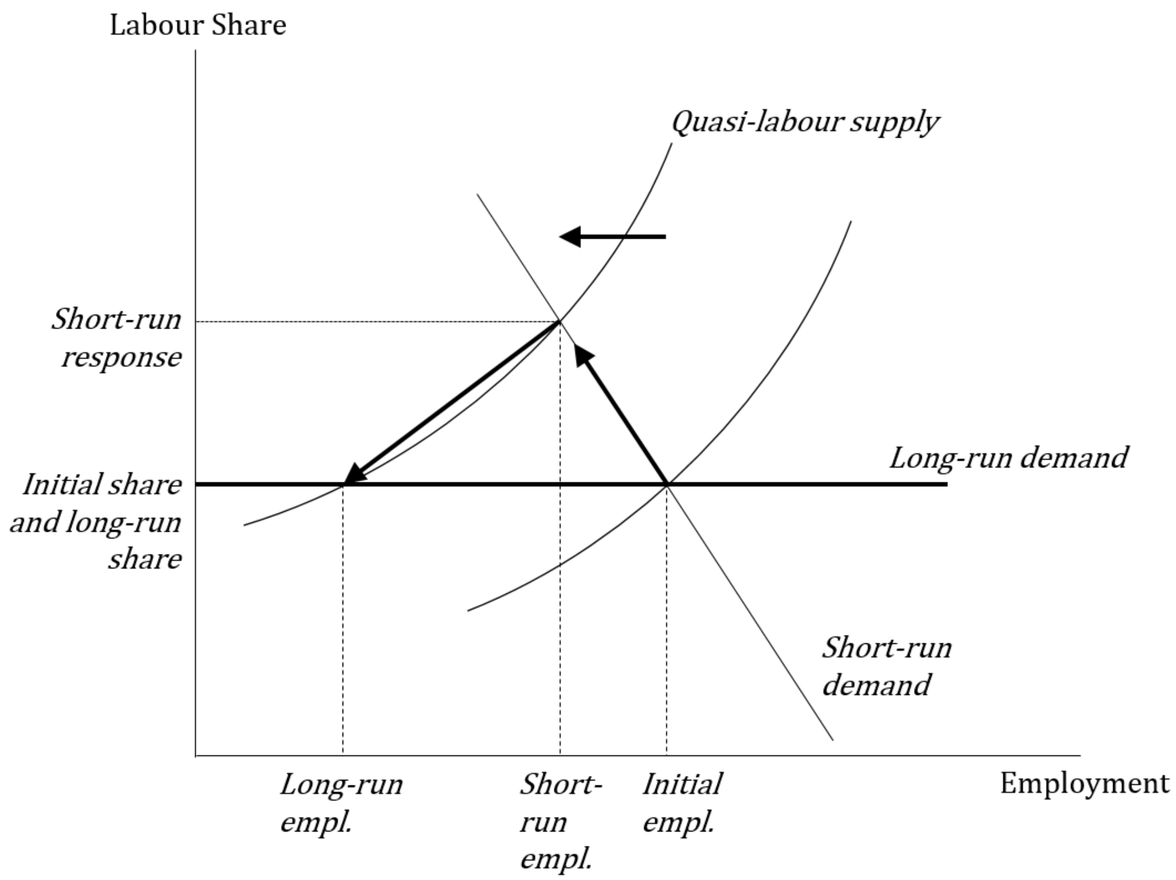
22 Habakkuk (1962) shows how rising wages in the USA in the late 19th century have led to a search for machines as a substitute for labour.

adjusts in a capital-biased way. The technical adjustment reduces the wage share to its initial level but decreases employment even further. Hence in the long run a ‘wage push shock’ merely increases unemployment.



(Source: Acemoglu 2002a: 806)

But the model has some serious shortcomings. With an elasticity of substitution smaller than one for technical change to be capital-biased requires innovations to be predominately labour-augmenting. But what we observe is capital-augmenting change. In Acemoglu’s model the long run distribution returns to its initial level, but what we observe is that at least in many European countries the wage share fell far beyond its initial level (Bassanini/Manfredi 2012). Most important, the model may explain how ‘high’ wages of the late 1970s have led entrepreneurs to search for capital-biased technical change which has decreased the labour share and increased unemployment, but not why moderate wage trends since the early 1980s have not reversed the direction of technical change. Hence even with Acemoglu’s model the distribution conundrum remains unexplained.

Because of its necessity for balanced growth technical change was assumed since the very beginning of neoclassical growth theory to be Harrod-neutral (purely labour-augmenting). As the discussion of induced technical change in the 1960s (see above) failed to provide an economic explanation for technical change being Harrod-neutral, this assumption was without a theoretical foundation. Many students may have asked themselves (or their professors) why technical change should be purely labour-augmenting until Acemoglu (2003, 2009) developed a model with an endogenous determination of the direction of technical progress, in which profit-maximizing entrepreneurs can freely choose between labour-augmenting and capital-augmenting progress. Following the Acemoglu model briefly sketched above the steady increase in the supply of one factor (capital) in combination with an elasticity of substitution smaller than one gives entrepreneurs an incentive to search for labour-augmenting technical change. Hence capital accumulation and an elasticity of substitution between capital and labour less than one leads to technical change being predominantly labour augmenting, but not necessarily Harrod-neutral. Only if one abandons lab equipment specifications of innovation possibility frontiers – the Kennedy case – and instead allows for extreme spillover effects in the knowledge-driven specification case (very strong path dependency), one obtains the beautiful result of a stable long-run equilibrium with Harrod-neutral progress, constant relative shares and a constant rate of profit. Acemoglu's long-run result, in which neither political decisions nor institutions influence the long-run distribution of income is supported by empirical studies which show that the relative income distribution has been approximately constant in the "very long run" (Young/Zuleta 2007; Dew-Becker/Gordon 2005; Gollin 2002). However, in Acemoglu's model, the medium run direction of technical progress may depart from the long-run trend, and can therefore be labour-augmenting as well as capital-augmenting; Bentolila und Saint-Paul (2003), Klump et al. (2004) and Arpaia et al. (2009) find empirical evidence for capital-augmenting technical change. The Acemoglu model is based on very demanding assumptions; allowing for extreme state dependency is an assumption which appears greatly unrealistic.

Doubtless the new literature on induced technical change has some major advantages over the old one associated with Kennedy, Samuelson, Drandakis/Phelps etc.. Technical change and its direction is no longer treated like "manna from heaven", but is conceived of as 'produced' and derived from R&D activities based on profit-maximizing behavior of entrepreneurs. Furthermore, unlike the 'old' models the 'new' ones allow for path dependency. Modeling the market for innovations as a market with monopolistic competition and with entrepreneurs holding a patent for their capital good variety overcomes the problem that the gains from technical change, with innovations being non-excludable and non-rival, cannot be fully endogenized (Romer 1990); of course, under perfect competition there is no space for innovation (Metcalfe 1998; Schumpeter [1942] 2003). At the same time, many problems continue to exist and new ones are added. A major shortcoming of Acemoglu's models with endogenous skill-biased technical change is that they may explain the empirical fact of increasing wage premiums for skilled labour since the 1970s, but fail to explain why the comparable situation of increasing skilled labour supply between 1910-1940 has been accompanied by decreasing wage premiums of skilled workers (Goldin/Katz 1999). No doubt expected profits are an important incentive for research activities (Schmookler, 1966; Mokyr, 1990; Metcalfe,1998; Acemoglu, 2009), but important breakthroughs such as 'general purpose technologies' are not fully explainable by profit-maximizing behavior (Rosenberg,1976; Ceruzzi, 2003; Acemoglu, 2002a). We argued that 'theoretically' general purpose technologies are no contradictions to endogenous skill-biased technical change. But we also doubt that all 'general purpose technologies' may be used in both a skilled- and an unskilled labour-intensive way. Would it really have been possible to use the new communication technology in an unskilled labour complementary way? That is hard to imagine. All the models discussed above assume full information on research outcomes – at least at the aggregate level (Acemoglu 2009: 435) – but uncertainty and luck play an important role in R&D activities, in particular for major "breakthrough" innovations. In addition, there are other incentives and inducements for searching in a certain direction than just profit maximization. Corporate power, for instance, is an important incentive to search for innovation with a certain direction even if this does not (instantly) maximize profits. Rosenberg (1969) shows that research in certain times in the 19th century was focused on innovations which break the bargaining power of skilled workers. Furthermore, some assumptions made in the models are very rigid and may be challenged. The assumption of strict complementarity between particular types of labour and capital goods has the advantage that the problem of a clear-cut distinction between substitution and technical change is circumnavigated. But it is at the same time very rigid. and contradicted by the empirical fact that there is at least some substitutability in production. Furthermore, the assumption of a constant elasticity of substitution neglects Hicks's argument that technical change increases the elasticity of substitution and Caballero and Hammour's argument that the elasticity of substitution is path-dependent.

5. Final remarks

The present paper provides a non-technical account of the development of the concept of "induced technical change" and its significance for the explanation of the functional distribution of income in the long run. It was shown that the formulation of the concept suggested by Hicks in 1932, which was generally accepted for almost 30 years, must be discarded as erroneous when the view prevailing today with regard to the meaning of an aggregate neoclassical production function is adopted. The impulse for the first revival of the concept of induced technical change in the context of neoclassical growth theory came from Nicholas Kaldor: firstly from the challenge posed to the neoclassical theory of growth and distribution to provide some explanation for the "stylized facts", and secondly from his attempt to replace the aggregate neoclassical production function by means of the so-called "technical progress function". Kaldor's "technical progress function" was then reformulated by Kennedy and von Weizsäcker in terms of an "invention possibility frontier", which was used by these authors and by Samuelson and Drandakis/Phelps in order to explain Kaldor's "stylized facts" of constant income shares, a constant profit rate, and a rising capital intensity by means of induced technical change with a labour-saving bias. However, not only external observers but also the authors involved in this line of research considered the concept of the "invention possibility frontier" too defective for serving as a proper depiction of the R&D processes involved in the generation of new technical knowledge, and the idea to explain the long run income distribution by means of induced technical change was therefore no longer pursued by neoclassical theorists. The next revival of the concept only occurred some 30 years later, in the late 1990s, when Acemoglu and others revived the concept in order to explain a rising wage premium for skilled labour in the presence of an increase in the relative supply of skilled labour. Acemoglu's model was shown to share some characteristics with the model presented by W.E.G. Salter in the 1960s, whose critique of Hicks's formulation was instrumental in initiating the first revival of the concept of induced inventions. However, unlike Salter's, Acemoglu's model gives a prominent role to technical complementarities – which introduces a rather non-neoclassical feature into his model. Moreover, the recent literature also contains several attempts to use the concept of an induced technical change bias for the explanation of the falling wage share which can be observed in most industrialized countries since the early 1980s. In these studies the aggregate production function is often assumed to be of the *CES* type. It seems appropriate, therefore, to recall a statement by Paul Samuelson in his 1965 paper on induced inventions: 'Economists should not emancipate themselves from the tyranny of Cobb-Douglas only to enchain themselves in a new Solow

CES tyranny.' (1965: 346) Overall, the discussion on the induced technical change bias shows that directed technical change must be considered as a major factor in the determination of the relative income distribution in the long run. In order to capture the long-run effects of changes in relative factor endowments or factor prices it is indispensable to analyze also their effects on the direction of technological change. But a model which describes induced technical change and its effects satisfactorily is still missing.

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