Capital-Skill Complementarity and Wage Outcomes following Technical Change in a Global Model*

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Abstract

We estimate the extent of factor bias in technical changes consistent with observed changes in skill premia. To control for the effects of expanded trade on wages we use a structural model with multiple regions and comparative static analysis. Two alternative biased technical change stories emerge: skill enhancement when capital and skill are substitutes and capital enhancement when capital and skill are complements. These imply different underlying technical change processes and macroeconomic behaviour in response to technical change shocks. Capital enhancement offers the more credible process, however, and is consistent with observed rises in the "equipment content" of the capital stock.

1. Introduction

The recent growth in the skill premium in developed countries is well documented and a substantial empirical literature has emerged to explain it. Demand side influences were quickly found to dominate and the early debate then focussed on the apportionment of the effects between expanded trade with low-wage countries and skill-biased technical change, or skill upgrading.[1] While the expansion of trade was often found to have contributed, the dominant force appears to have been technical change and, in particular, skill-biased change due to automation associated with the introduction of computers.[2]

One clear statement of the technical change story underpinning this work is by Kahn and Lim (1998). Their focus, which is typical in this literature, is on the two factors labour and skill, which are seen to be elastic substitutes (to have a larger than unit substitution elasticity). Computer-based automation enhances skilled labour time, increasing "effective" skill hours per actual skilled worker and hence raising the marginal product of skilled relative to unskilled workers.[3] This two-factor focus yields the implication that computerisation is

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[1] See, for example, Bound and Johnson (1992), Berman, Bound and Griliches (1994) and Autor et al. (1998) for the U.S. evidence, and Berman, Bound and Machin (1998) and Machin and Van Reenen (1998) for evidence from other regions.

[2] Sachs and Shatz (1994) and Wood (1994), among others, find some role for trade, while Abraham and Taylor (1996) and Feenstra and Hansen (1996) focus on the contribution of out-sourcing and its associated effects on both trade and home technology. Haskel and Heden (1999) and Haskel and Slaughter (1998, 1999) emphasise the evidence favouring skill-biased technical change associated with computerisation. The dominance of the latter is confirmed for the U.S. in a more recent empirical analysis by Morrison Paul and Siegel (2000).

[3] When substitution between labour and skill is elastic, the unit isoquant is drawn further inward the more skill intensive is the technique and so, even at constant factor prices, the cost share of skill rises. The common presumption that automation enhances labour (is "labour saving") is only consistent with a rise in the skill share if the elasticity of substitution between skill and labour is less than unity.

"unleashing" skilled workers within firms and through their enhancement raising firm productivity.

A similar, yet importantly distinct, story emerges if a more explicit role is provided for capital as a third factor. Then capital and skill can be complementary. Early on, Griliches (1969) identified capital-skill complementarity in US data. More recently, Acemoglu (1998) has suggested that recent growth in the relative supply of well-educated workers has induced innovations that have fostered complementarity between capital and skill. Goldin and Katz (1998) take the view that skill-capital complementarity was a key determinant of the US skill premium throughout the 20th century. The latter view is examined more formally by Krusell et al. (1997) who focus on the period between 1963 and 1991. They conclude that changes in US skill premia in this period can be explained without resort to any significant factor bias in technical change, finding that skill premia are explained almost entirely by readily observable factor accumulation.

A key element of the Krusell et al. analysis is the disaggregation of the capital stock between "equipment" and structures. In the US there has been comparatively strong growth in the equipment component and an associated decline in its relative price (Greenwood et al. 1996). The complementarity of interest is then between skill and equipment. This implies an underlying model of the technical change process that is driven by the cheapening of equipment relative to other factors and hence a change in the composition of the capital stock. Because, as documented by Goldin and Katz, this equipment requires skilled workers to operate it the demand for skill rises. While-ever skill supply lags and where wages are sufficiently flexible, there follows a rise in the skill premium. Yet this rise in the relative skill price is not sufficient to offset the cost advantage of the new equipment to firms.

In this paper we use structural comparative static analysis to estimate the extent of factor bias required to explain observed increases in skill premia since 1975. We model a multi-region global economy in general equilibrium. While this may seem extensive for the purpose, a multi-region model in which labour and skill intensive goods and services are distinguished is essential if we are to control explicitly for the effects of trade liberalisation on labour market behaviour and so isolate the effects of technical change. This approach contrasts with the econometric work on the subject that has always had a single country focus and, often, also a single sector focus. Such studies cannot satisfactorily control for the effects of expanded trade. Our model also allows us to account for the regional differences in labour market behaviour highlighted by Davis (1998).

We focus on the older industrial regions: the United States (US), the European Union (EU) and an amalgam of Canada and Australasia (C,A,NZ). For each region, and each industry within it, we depart from the traditional representation of factor demand in such models[4] by constructing alternative technologies, in the form of nested constant elasticity of substitution (CES) production systems, with and without capital-skill complementarity. We use these in a long run comparative static backcast over the period 1975-1995 to examine the implied changes in technology parameters in each case. The backcast incorporates observed changes in primary factor use, trade distortions and total factor/input productivity (TIP) over two decades.[5] Significantly, for the number of different regions incorporated, there is only a single standardised measure of the capital stock available. The capital composition changes that proved important in the study by Krusell et al. are therefore not incorporated directly.

When the implied technical changes are forced to be factor neutral (amongst the parameters describing technology, only TIP is allowed to change) the model suggests that skill premia would have fallen in all regions between 1975 and 1995. The fact that this did not occur confirms the presence of some bias, the extent of which is then estimated by imposing the observed skill premium changes exogenously. The magnitudes of the implied changes in bias-related technical parameters, with and without capital-skill complementarity, are then compared. The two technical change stories mentioned previously then emerge as equivalent in explaining the long run changes.

In both these technical change stories the primary change is in the composition of the measured capital stock. A pure change in this composition, with no associated rise in the measured capital stock, enhances skill according to one story and enhances capital (as measured) according to the other. Although the two stories appear to offer equivalent explanations for long term change in the two decades of the “globalisation” era, it is likely that they have quite different implications for macroeconomic responses to technology shocks in the modern era of highly mobile capital. The global distribution of new investment now

[4] It has been the accepted practice in general equilibrium analysis to assume simple factor demand structures implying unit elasticities of substitution between capital and labour. See Shoven and Whalley (1992: 5.4) and Dixon et al. (1992: 220). For an application to labour markets, see Burfisher et al. (1994).

[5] The exercise is similar to that described by Tyers and Yang (1997). In that paper, however, we constructed only a partial backcast, focussing on how the 1990 world economy might have differed had observed trade and technological changes since 1970 not occurred. Here we devise a full two-decade backcast.

depends on expectations about capital returns, which will be differently affected by technical change shocks consistent with each story.

The model used is described in Section 2. The backcasting experiment is discussed in Section 3, the choice between the two technical change stories is examined in Section 4 and Section 5 offers conclusions.

2. A Global Comparative Static Model

The isolation of the effects of technical change on labour markets requires that we control for the effects on labour markets of expanded trade. We therefore need a model with multiple regions in which products and services are distinguished according to their factor intensity and subject to trade policy distortions. It is also important to account for long term changes in the current account balance and hence for the model to reflect open capital accounts that allow savings in one region to finance investment in others.[6] These key requirements are met by the already well established GTAP general equilibrium framework.[7] In its original form, it is a conventional neoclassical multi-region comparative static model in real variables with price-taking households and all industries comprising identical competitive firms. It offers the following useful properties.

(1) a capital goods sector to service investment and explicit savings in each region, combined with open regional capital accounts that permit savings in one region to finance investment in others,

(2) multiple trading regions, goods and primary factors,

(3) empirically based differences in tastes and technology across regions with non-homothetic preferences that allow income effects to vary across commodities in a manner important for long run analysis,

(4) explicit transportation costs and indirect taxes on trade.

The key assumptions underlying the original model are summarised in Table 1. A complete description is impossible in the space provided here and the reader interested in detail peripheral to this exercise is referred to Hertel (1997). Such reference should generally prove unnecessary, however, since in all respects the model's behaviour is intuitively neoclassical. We therefore turn to our adaptation of the model and our modifications to it.

[6] Much is made of the current account balance as a determinant of wage changes by Bound and Johnson (1992).
[7] For a detailed description of the standard version of this model, see Hertel (1997).

The aggregation we use has seven regions, six goods/services and five primary factors, as detailed in Table 2. Skill is separated from unskilled labour on occupational grounds, with occupations in the "professional" categories of the ILO classification included as skilled.[8] This departs from the common use of human capital measures in country level studies of the skill premium. Unfortunately, human capital data are as yet insufficiently standardised across countries for use in the assembly of a complete global database.

The most important changes to the original model concern the production technology and, in particular, the structure of input and primary factor demand. We adopt two alternative technologies, both of which are nested CES structures that differ from the original model. For the case in which capital and skill are substitutes we use the three level nest illustrated in Figure 1.[9] It allows the substitutability between raw labour and skill to differ from that between these and other factors and it makes it possible to vary the degree of substitutability between labour and skill without changing that between other factor pairs.

The weak separability essential to nested CES structures allows firms' choices amongst expendable inputs as a group and primary factors as a group to be separable from those that determine the mixes of inputs and primary factors used. The top-level choice is then based on the following production function:

$$Y = \alpha_Y \left[\phi_{VI}\left(\delta_{VI} VI\right)^{-\rho_Y} + \phi_{VA}\left(\delta_{VA} VA\right)^{-\rho_Y}\right]^{-\frac{1}{\rho_Y}} \qquad (1)$$

where VI is the composite of intermediate inputs and VA is the value added composite of all primary factors, α_Y, δ_{VI} and δ_{VA} are technology shifters to be used subsequently and ϕ_{VI} and ϕ_{VA} are parameters that depend on the shares of VI and VA in total cost.[10] The top-level elasticity of substitution is $\sigma_Y = 1/(1+\rho_Y)$. Following the primary factor branch of the nest, the value-added composite is then

$$VA = \alpha_{VA} \left[\phi_{VL}\left(\delta_{VL} VL\right)^{-\rho_{VA}} + \phi_K\left(\delta_K K\right)^{-\rho_{VA}} + \phi_R\left(\delta_R R\right)^{-\rho_{VA}} + \phi_A\left(\delta_A A\right)^{-\rho_{VA}}\right]^{-\frac{1}{\rho_{VA}}} \qquad (2)$$

[8] See Vo and Tyers (1995) and Liu et al. (1998) for the method adopted.
[9] The original model has a two level structure with a Leontief split between intermediates and primary factors (value added) and labour and skill are treated in the same way as the other three factors.
[10] In such CES structures the number of independent parameters is equal to the number of factors or inputs. Here only the ϕs are independent and derived from the database. The αs and the δs are shifters set to unity unless the technology changes.

where VL is value added in labour and skill (a labour-skill composite) and the parameters play the same roles as in (1), above. The elasticity of substitution at this level is $\sigma_{VA}=1/(1+\rho_{VA})$. To complete the nest, then, a similar formulation is offered for the labour-skill component of value added, VL:

$$VL = \alpha_{VL}\left[\phi_L(\delta_L L)^{-\rho_{VK}} + \phi_S(\delta_S S)^{-\rho_{VL}}\right]^{-\frac{1}{\rho_{VL}}} \qquad (3)$$

where L is raw labour and S is skill and the level-specific elasticity of substitution between them is $\sigma_{VL}=1/(1+\rho_{VL})$.

Again, the initial values of the technology shifters, α and δ, are unity and the remaining parameters are derived from the GTAP Version 4 database for each region.[11] Recommended values of the branch elasticities of substitution at the value added level form a "standard" set that is used in most GTAP applications. We modify these according to length of run, as described in the following two subsections. The combination of (1) – (3) allows the proportional change in the demand for any factor or intermediate input, X_i , denoted lower case as x_i, to be expressed in terms of the corresponding proportional changes in output, y, and proportional changes in all of the factor prices, p_j, as

$$x_i = y + \sum_j \eta_{ij}\ p_j \qquad (4)$$

where η_{ij} is the conditional elasticity of demand for input or factor i with respect to the price of input or factor j. These demand elasticities, $[\eta_{ij}]$, follow from the Allen partial elasticities of substitution, $[\sigma_{ij}]$ via $\eta_{ij} = \sigma_{ij}\,\theta_j$, where θ_j is the share of factor or input j in total cost. The Allen partials are conditional (output constant) elasticities of substitution for pairs of inputs when more than two are used and where they are combined in a multi-level nest. In the two-factor single-level case they collapse to the branch elasticity (Allen 1938: 341, Hamermesh 1993: 23, 39). They are symmetric ($\sigma_{ij} = \sigma_{ji}$) and can be derived from the branch elasticities of substitution, σ_Y, σ_{VA}, and σ_{VL} by the method of Keller (1980: Ch.5, Appendix). Those of special interest for our present purpose are the own price elasticities for labour, η_{LL}, skill, η_{SS} and capital, η_{KK} and the associated cross price elasticities, η_{LS}, η_{SL}, η_{LK}, η_{KL}, η_{SK} and η_{KS}. The own price elasticity for labour, for example, takes the following form:

[11] See McDougall et al. (1998a).

$$\eta_{LL} = -\theta_L \left[\sigma_{VL}\left(\theta_L^{-1} - \theta_{VL}^{-1}\right) + \sigma_{VA}\left(\theta_{VL}^{-1} - \theta_{VA}^{-1}\right) + \sigma_Y\left(\theta_{VA}^{-1} - 1\right)\right] \qquad (5)$$

where θ_L is the share of raw labour, θ_{VL} the combined share of labour and skill and θ_{VA} the share of value added in total cost.[12] And the cross elasticities between labour and skill and labour and capital are:

$$\eta_{LS} = \sigma_{LS}\theta_S = \theta_S\left[\sigma_{VL}\theta_{VL}^{-1} - \sigma_{VA}\left(\theta_{VL}^{-1} - \theta_{VA}^{-1}\right) - \sigma_Y\left(\theta_{VA}^{-1} - 1\right)\right] \qquad (6)$$

$$\eta_{LK} = \sigma_{LK}\theta_K = \theta_K\left[\sigma_{VA}\theta_{VA}^{-1} - \sigma_Y\left(\theta_{VA}^{-1} - 1\right)\right] \qquad (7)$$

where σ_{LS} and σ_{LK} are the Allen partial elasticities of substitution. The remaining own and cross price elasticities follow similarly.

We contrast this production structure with one that allows complementarity of capital and skill, illustrated in Figure 2. The highest level of the nest is the same as previously, with the level of output indicated by equation (1). Following the primary factor branch of the nest, the value-added composite is now

$$VA = \alpha_{VA}\left[\phi_{VKL}\left(\delta_{VKL}VKL\right)^{-\rho_{VA}} + \phi_R\left(\delta_R R\right)^{-\rho_{VA}} + \phi_A\left(\delta_A A\right)^{-\rho_{VA}}\right]^{-\frac{1}{\rho_{VA}}} \qquad (8)$$

where VKL is value added in capital, labour and skill. Also as before, the elasticity of substitution at this level is $\sigma_{VA}=1/(1+\rho_{VA})$. The capital-labour-skill component of value added, VKL is then:

$$VKL = \alpha_{VKL}\left[\phi_{KS}\left(\delta_{KS}KS\right)^{-\rho_{VKK}} + \phi_L\left(\delta_L L\right)^{-\rho_{VKL}}\right]^{-\frac{1}{\rho_{VKL}}} \qquad (9)$$

where L is raw labour and KS is a capital-skill composite. The level-specific or branch elasticity of substitution is then $\sigma_{VKL}=1/(1+\rho_{VKL})$. Finally, there is an additional level that divides capital and skill:

$$VKS = \alpha_{VKS}\left[\phi_K\left(\delta_K K\right)^{-\rho_{VKS}} + \phi_S\left(\delta_S S\right)^{-\rho_{VKS}}\right]^{-\frac{1}{\rho_{VKS}}} \qquad (10)$$

where the branch elasticity of substitution at this lowest level is $\sigma_{VKS}=1/(1+\rho_{VKS})$.

In this case, the own price elasticity for capital takes the following form:

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[12] For a single level system in which the elasticity of substitution is σ this collapses to $-\theta[\sigma(\theta_L^{-1}-1)]=-(1-\theta_L)\sigma$, consistent with the treatment by Hamermesh (1993).

$$\eta_{KK} = -\theta_K \left[\sigma_{VKS}\left(\theta_K^{-1} - \theta_{VKS}^{-1}\right) + \sigma_{VKL}\left(\theta_{VKS}^{-1} - \theta_{VKL}^{-1}\right) + \sigma_{VA}\left(\theta_{VKL}^{-1} - \theta_{VA}^{-1}\right) + \sigma_Y\left(\theta_{VA}^{-1} - 1\right)\right] \qquad (11)$$

where θ_K is the share of capital, θ_{VKS} the combined share of capital and skill, θ_{VKL} the combined share of capital, skill and labour, and θ_{VA} is the share of value added in total cost. Since capital and skill are here treated symmetrically, the own price elasticity of demand for skill takes a corresponding form. And the cross elasticities between capital and skill and capital and labour are:

$$\eta_{KS} = \sigma_{KS}\theta_S = \theta_S \left[\sigma_{VKS}\theta_{VKS}^{-1} - \sigma_{VKL}\left(\theta_{VKS}^{-1} - \theta_{VKL}^{-1}\right) - \sigma_{VA}\left(\theta_{VKL}^{-1} - \theta_{VA}^{-1}\right) - \sigma_Y\left(\theta_{VA}^{-1} - 1\right)\right] \qquad (12)$$

$$\eta_{KL} = \sigma_{KL}\theta_L = \theta_L \left[\sigma_{VKL}\theta_{VKL}^{-1} - \sigma_{VA}\left(\theta_{VKL}^{-1} - \theta_{VA}^{-1}\right) - \sigma_Y\left(\theta_{VA}^{-1} - 1\right)\right] \qquad (13)$$

where, again, σ_{KS} and σ_{KL} are Allen partial elasticities of substitution. The remaining cross price elasticities follow similarly.

There are a number of significant differences in the model structure between its application to the long run effects of factor endowment shocks and technical change on the one hand and short run policy shocks to which such models are commonly subjected. These concern the allocation of the global savings pool across regions as investment, the choice of elasticities in the production structure and the addition of nominal variables to short run formulations. Although we maintain a short run version of the model for macroeconomic policy applications (Yang and Tyers 2000) for which capital (more precisely, savings) is assumed mobile between regions, all short run behaviour is disabled here and only long run elasticities are used.[13]

Our long run shock is a 20-year backcast and so it incorporates very large changes in the magnitudes of installed capital stocks. Over this long period there were substantial changes in the mobility of savings and hence the determinants of the regional allocation of investment. Our focus on technical change and factor demand makes it needless to attempt to make investment endogenous. It is therefore made exogenous and shocked back to recorded levels for 1975.

To serve our current purpose, we have made the branch elasticities of substitution on both the demand and supply sides identical across regions. Of course, this does not imply common tastes and technology since the shares, θ, and the associated parameters ϕ are all estimated from the regional input-output tables embodied in the database and hence they differ between regions.[14] The branch elasticities of substitution in direct and indirect product demand are listed in Table 3. The corresponding branch elasticities of substitution in factor demand are listed in Tables 4 and 5 and the implied price elasticities of factor demand are listed in Table 6. In choosing elasticities for the long run backcast, we draw on the analysis of long run shocks by Hertel et al. (1996) and from the associated research by Gehlhar (1994) and Gehlhar et al. (1994). The long run values of the product substitution elasticities and the corresponding value added branch elasticities of substitution on the production side are set larger than the "standard", which was originally designed to represent a "two-year" response. Morrison Paul and Siegel (2000) also offer evidence that, even when all factors are variable, the elasticities determining firms' choice of technique are larger in the long run. The branch elasticities of substitution on the production side are more arbitrarily chosen. Our choices are informed by the studies reviewed by Hamermesh (1993) and the estimates of Krusell et al. (1997).

3. A Long Run Backcast: Factor Bias in Technological Changes, 1975-1995

We begin with a base period (1995) global general equilibrium and shock the model back to 1975 by changing trade distortions, technology and factor endowments. We begin with basic shocks to factor use (factor endowments[15]), to total factor (and input) productivity (TIP, or shocks to the parameter α_Y in equation 1) and to trade protection.

Although the shocks to factor use are available from the record, those to productivity and trade protection are not. In the case of the productivity change we take advantage of the fact that GDP values are also available from the record and so we make these exogenous and shock them as observed, allowing the model to find endogenous region-wide changes in TIP or the parameter α_Y. For trade distortions, because the effective changes in these incorporate changes in non-tariff barriers and infrastructural costs that are not available from the record, we make each region's imports by product category exogenous and shock it as observed. The corresponding power of the tariff in each is then endogenous. Finally, since investment is made exogenous and shocked as observed in each region, and trade flows are also exogenous as indicated above, savings in each region is determined by the balance of payments condition

[13] For companion applications to technology shocks in the short run, see Tyers and Yang (2000b).
[14] See McDougall et al. (1998a).
[15] In the case of labour, to allow for differences in unemployment rates between 1975 and 1995, we track total labour use (employment) rather than changes in the labour force.

$I - S = M - X$. The coefficient of the equation linking consumption and disposable income is therefore set endogenous so that the results reflect implied changes in savings rates over the two decades. For our purpose, a particularly important point about these initial backcast shocks is that the only technical change included has no factor bias.

For each of the three regions we then observe the simulated changes in unit factor rewards, the skill premium and the "capital share", or the share of physical capital in GDP at factor cost. The results are listed in Table 7. They indicate that the changes in factor use, combined with the neutral technology and trade policy shocks, would have reduced skill premia in all three regions. At the same time, they suggest that capital shares would have expanded by more than we have observed. These results should not surprise us, since the use of skilled workers grew very much faster over the two decades than that of unskilled workers. Had there been no factor bias in technical change over the period, the skill premia would have been lower as would the combined GDP shares of labour and skill, thus yielding the higher than observed capital shares.[16] It is therefore clear that some factor bias is required in the technical change in order that the observed changes might be reproduced. This is true even when the technology exhibits capital-skill complementarity although the extent of the required bias already appears smaller in that case.

The simulation is then repeated, this time imposing as exogenous both the observed skill premium changes and the observed changes in the capital share indicated in the last two columns of Table 7. Since we are making two previously endogenous variables exogenous, we can make only two previously exogenous technology parameters endogenous. We are interested, however, in four such parameters, the TIP shifter, α_Y, and the three factor enhancement shifters δ_K (capital), δ_S (skill) or δ_L (unskilled labour). Yet the TIP shifter, α_Y, is already endogenous in each simulation (swapped from the outset in this long run backcast for GDP, which is exogenous in each case). In the simulations of Table 7 there are therefore three exogenous parameters in each industry's production function that we would like to make endogenous.

We repeat the simulation in which the skill premia and capital shares are exogenous three times in order to cover all pairwise combinations of the factor enhancement shifters. Of

[16] The simulated no-bias capital shares are larger overestimates in the case when capital and skill are complements. This is because the growth in capital use over the period is comparatively rapid and the capital-labour cross elasticities are larger when capital and skill are complements (Table 6). The capital growth

course, if each region had a single product and therefore a single three-factor production function, the endogeneity of the TIP shifter and two factor enhancement shifters would be sufficient to fully specify changes to the function and no repetition would be necessary. In our model, however, each region has five primary factors and these are used by six different sectors in combination with six commodity inputs. The pattern of changes in output between the sectors therefore differs according to which combination of the region-wide shifters is made endogenous.

In interpreting the results it is useful to recall from equations (1)-(3) that the number of independent parameters in the CES function is equal to the number of primary factors and inputs. Our independent parameters, drawn from the model database for 1995, are the ϕs. We think of δ_K, δ_S, δ_L and α_Y as shifters that are unity in the initial equilibrium and in all simulations where technical change does not occur. Because the function is linear homogeneous, the α_Y can be absorbed so that the enhancement shifters for capital, skill and labour are $\alpha_Y\delta_K$, $\alpha_Y\delta_S$, $\alpha_Y\delta_L$, while the corresponding enhancement shifter for the other factors and inputs is simply α_Y. The results from this exercise are summarised in Table 8.

Consider first the results in the upper block of the table, which stem from the version of the model with all primary factors substitutes. Looking forward from 1975 to 1995, whichever pair of factor shifters is made endogenous the dominant pattern is one of skill-enhancement. This is obvious from the two cases in which δ_S is endogenous. The skill enhancements are the largest changes in all three of the older industrial regions. When only the capital and labour shifters are endogenous, these factors appear diminished, while the remaining factors and inputs are enhanced through the α_Y. Again this suggests skill enhancement.

When the technology has capital and skill complementary the changes in the implied TIP and factor use shifters tend to be smaller. This is true in part because less factor bias is required in the first place with this technology, as evidenced by the results in Table 7. Since capital use grew more quickly in all three regions than either skill or labour use (see the appendix), capital-skill complementarity would have necessitated greater growth in skill demand than in labour demand even in the absence of bias. When the observed skill premia are imposed, however, the dominant bias required is capital enhancement. Although the

therefore causes smaller increases in the wage of raw labour. The share of labour in GDP at factor cost falls by more than the share of skill rises and these changes are larger when capital and skill are complements.

results offer some support for labour enhancement (in the US and Canada-Australasia) and skill diminution (in the EU) capital is strongly enhanced when δ_K is endogenous as are "other factors and inputs" when only δ_S, δ_L are endogenous. Thus, we have two alternative factor bias stories: skill enhancement (when all factors are substitutes) and capital enhancement (when capital and skill are complementary).

4. Choosing Between Two Technical Change Stories

The above results establish that the broad economic changes that took place between 1975 and 1995 are consistent with either skill-enhancement with capital-skill substitution or capital enhancement with capital-skill complementarity. If so, why should it matter which is the more accurate characterisation? Here we suggest the appropriate choice first and consider its significance later. We favour the version of the model with capital-skill complementarity and the characterisation of the bias as capital augmentation, for the following reasons:

1. The separation by Kahn and Lim (1998) and Krusell et al. (1997), among others, of capital into equipment and structures suggests that the complementarity is really between equipment and skill. This separation is not possible in our global analysis because standardised data on the components of capital are not generally available. Moreover, at least in the US, the stock of equipment has grown, and its price has fallen, much more rapidly than for capital as a whole. If the "equipment content" of capital is what is important, and if this has grown faster than the overall capital stock, then we expect simulation experiments of the type conducted here, which incorporate only changes in the aggregate capital stock, to show evidence of capital augmentation.
2. There is now considerable empirical evidence for the existence of capital-skill complementarity, with both capital and skill being substitutes for labour. The survey of econometric studies by Hamermesh (1993) suggests this, as does the historical evidence presented by Goldin and Katz (1998). And the estimation procedure used by Krusell et al. (1997) is particularly convincing for the US in the period 1963-1991.
3. In accordance with "Occam's razor", explanation in terms of capital augmentation tends to require the least change in the fundamental parameters of the production function.

A first reason for the significance of this choice lies in the implied characterisation of the technical change process. The data examined by Krusell et al. (1997) indicate that the US stock of equipment grew almost three times as fast as that of structures after 1975 (7.5 as against 2.6 per cent per year). While the price of equipment fell relative to that of non-durable consumption the price of structures maintained rough parity. The capital enhancement story then suggests that the process is led by the spontaneous cheapening of skill-complementary equipment. The cost advantage of the new equipment is large enough to more than offset the by-product skill scarcity and the associated rise in the skill premium. The new equipment is therefore widely adopted and the composition of the capital stock changes. Importantly, however, this story maintains that the productivity gain comes from the equipment and not from any enhancement of individual skilled workers. As emphasised by Goldin and Katz (1998), the demand for skill arises from the need for skilled workers to operate the equipment. The alternative technical change story would suggest the change in the equipment content of capital is profitable because it enhances skill by more than the associated rise in the skill premium raises cost. In that case the productivity gain comes from the skill enhancement. The new equipment merely allows better exploitation of the human capital common to skilled workers.

Second, if the capital enhancement story is correct, and if we were able to document standardised changes in capital composition in all regions, it is possible the single-product single-region analysis of Krusell et al. would be borne out here. Observed changes in factor markets would be explained almost entirely by factor accumulation alone. This is significant because it would then be a simpler matter to model recent technology shocks, provided changes in factor use are measured correctly. They could be represented as simple factor endowment shocks.

Third, the presence of capital-skill complementarity makes our simulations more sensitive to the accuracy with which the quantities of each factor used are measured. The extent of this sensitivity is indicated in Table 9. The results imply that a one per cent error in the data on skill use results in a four per cent error in the model's estimate of capital enhancement if capital and skill are complements and a 2-3 per cent error if they are substitutes. Since our model has been parameterised based on occupational data that subdivide labour as between production (low skill) and non-production (high skill), we have used the same data to impose the backcast shocks. The accuracy of data on the intertemporal changes in labour supply by occupational group is therefore particularly important in interpreting implied technical changes and the more so when capital and skill are complements.

Finally, even though the two technical change stories have equivalent implications in our long run backcast to 1975, their effects are unlikely to be equivalent in short run analysis when savings are mobile between regions. Recall that investment is not endogenous in our backcast. Capital mobility has evolved substantially over the two decades and, since our purpose was not to explain changes in investment, it was best to introduce these directly from the record. Any forecasting of the effects of future technology shocks will, however, require endogenous investment. It is possible then, that the behaviour of investment will be affected by technology shocks in different ways, depending on the technology story adopted. For example, in our companion short run comparative static analysis (Tyers and Yang 2000b), we assume savings are fully mobile between regions and use the following investment demand equation for each region, *i*.

$$\frac{K_i + I_i}{K_i} = \beta_i \left(\frac{1 + r_i^c}{1 + r^w (1 + \pi_i)} \right)^{\varepsilon_i} \qquad (14)$$

Where K_i is the (exogenous) installed capital stock, I_i is (net) investment, r_i^c is the average net rate of return on installed capital (the marginal product of capital net of depreciation, averaged across industries), r^w is a global "expected return" and π_i is a region-specific risk premium. The other region-specific parameters are β_i, a positive constant and ε_i, a positive elasticity.

When investment has this behaviour, the nature of the technology shock is quite important in short run analysis. Imagine a length of run over which the installed capital stock is fixed. Investment only affects capital use in a subsequent period. Imagine, further, that there is a permanent technology shock in a single region that is not very large and so the global effects of the shock are small and there is therefore negligible change in the denominator of (14). The global distribution of investment then depends on a comparison of the rates of return on installed capital across regions and hence on how the shock affects the marginal product of capital in each.

If the shock takes the form of capital augmentation, with capital and skill complements, then there will be a rise in the skill premium the (negative) cross effects of which will tend to depress the marginal product of capital. Since it is likely that the short-run price elasticity of demand for capital is less than unity, the proportional decline in the price of effective capital would exceed the proportional rise in its quantity used. Since the capital stock is fixed, this implies that the marginal product of actual capital would decline unambiguously in the region subjected to the shock. If, on the other hand, the technology shock takes the form of a skill-enhancement with capital and skill substitutes, the increase in effective skill use would ensure that the marginal product of capital rises unambiguously.

In each case the magnitude of the change in the marginal product of capital in the focus region depends on the sizes of the own and cross price elasticities of capital demand. It is clear, however, that the two technology stories do not yield equivalent short run changes and hence an equivalent redistribution of investment across regions. Indeed, when we impose short run shocks like these on the US they diverge substantially in their predictions as to the changes in output, the balance of payments and the size of the skill premium.

5. Conclusion

A standard global trade model is adopted to isolate the links between technical change and labour markets and to offer a structural comparative static analysis complementing the existing empirical literature. Two alternative production structures are used exhibiting substitution between all factors on the one hand and capital-skill complementarity on the other. A backcast experiment over two decades establishes that at least some factor bias is required in order that the model should explain observed changes in skill premia in the older industrial economies. Two alternative bias patterns emerge as possible explanations: skill enhancement with capital and skill substitutes and capital enhancement with capital and skill as complements.

The bias pattern requiring the least changes in the fundamental parameters of the production functions combines capital-skill complementarity with capital enhancement at a rate that is fastest in the US. This result accords with US research suggesting that it is the “equipment content” of the capital stock that is complementary with skill and that this has grown more quickly than the capital stock as a whole. Were it possible to separate capital into equipment and structures and to represent complementarity between skill and equipment in all regions, little factor enhancement might have proved necessary to explain the observed rises in skill premia. For these reasons, and because there is now considerable empirical evidence for capital-skill complementarity, we favour the capital enhancement technical change story.

The choice between the two technical change stories is significant because they imply different models of the technical change process. It is also important because the two stories have different implications in short run analysis when modern levels of global capital mobility are accounted for. And, finally, it matters because the two stories imply different sensitivities to the quality of the data used in empirical analysis. Indeed, all the results obtained are extremely sensitive to the magnitudes of the intertemporal changes in the endowments of labour, skill and capital but particularly skill. This suggests that small errors in measurement of skill, or changes in the way unskilled and skilled workers are classified, make a very substantial difference to the way structural models like ours characterise recent changes in technology, and this is the more so when capital and skill are complements. These results have quite strong implications for less structural empirical studies that use the same data on labour and skill use to search for implied levels of skill bias.

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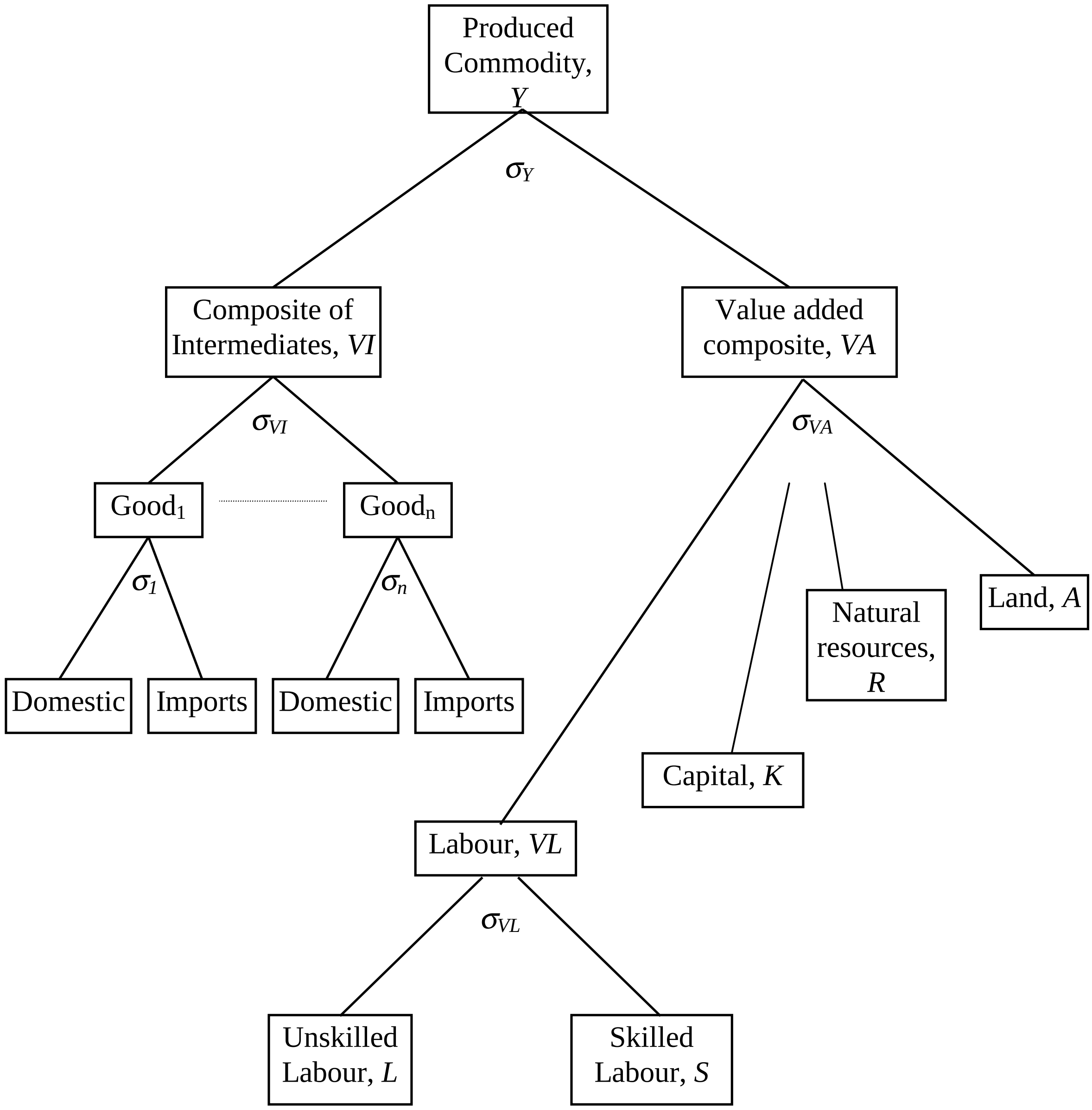

Figure 1: Original factor demand nest

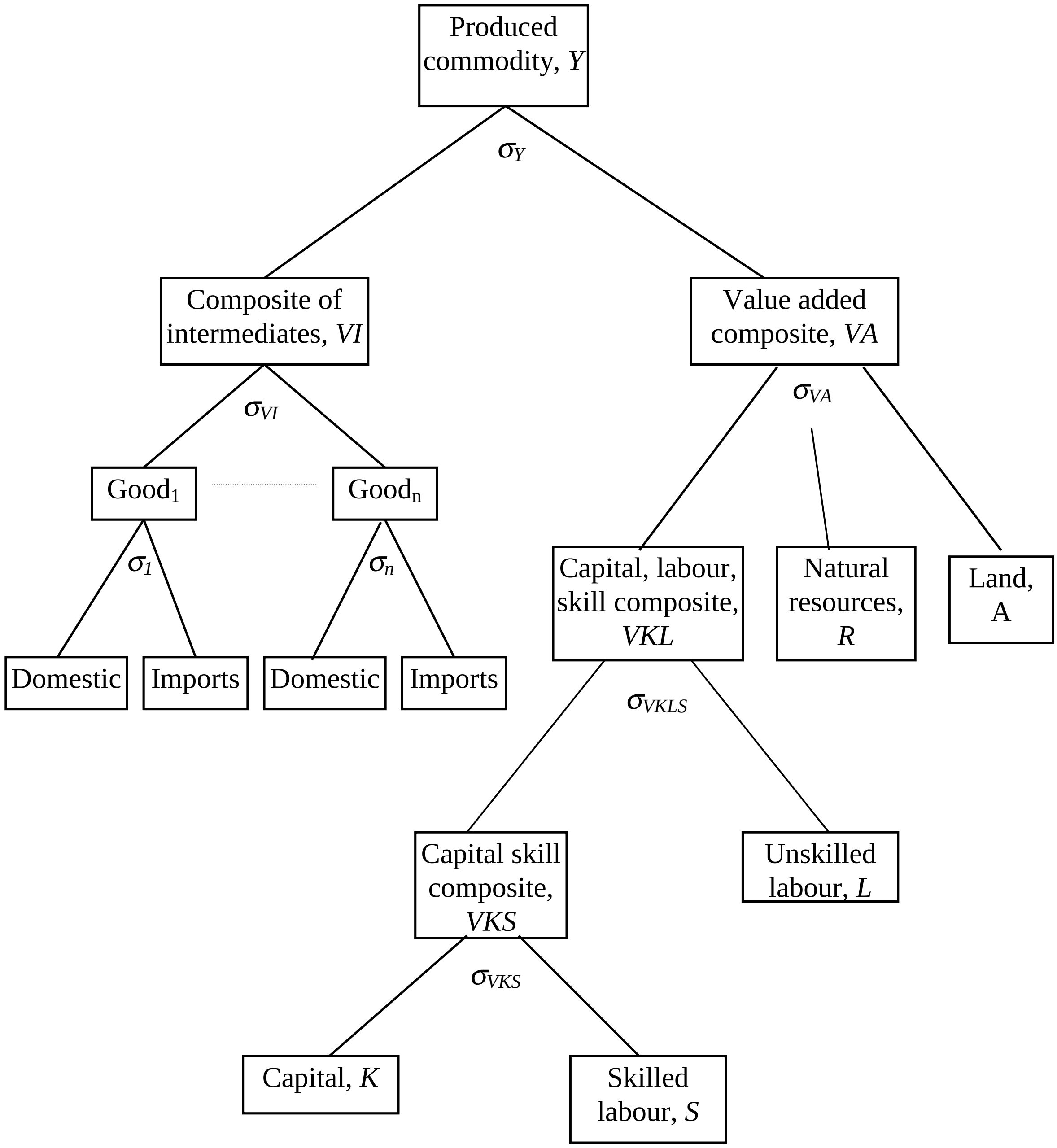

Figure 2: Nest with capital-skill complementarity

Table 1: Standard Model Analytics:

Single household in each region.
Utility Cobb-Douglas in:
private final consumption
government consumption
savings (private plus government)
Private final consumption: CDE[a] expenditure function in goods.
Goods CES composite of home products and imports.
Imports CES composite of imports from all regions of origin.
Government consumption is a Cobb-Douglas composite of all goods.
Savings contribute to a global pool from which regional investment is financed.
Firms are perfectly competitive with constant returns to scale.
Technology is a nested CES combination of intermediate inputs and primary factors, as indicated in Figures 1 and 2.
Intermediate demand for goods is decomposed into home goods and imports as for household final consumption.
Factor specificity: Land specific to agriculture.
Natural resources specific to mining.
Physical capital is intersectorally mobile in the long run considered here.
Labour and skill intersectorally mobile at all lengths of run.
Primary factor supply: in the version used here all factors are inelastic in supply.
Capital returns: no inter-regional ownership, so capital returns are intra-regional.
Investment: global investment is the sum across regions' savings.
When savings are assumed interregionally mobile, investment is endogenous. It is then allocated across regions so that its proportional change is larger in regions, *i*, with high values of the average net rate of return on installed capital, r_i^c (the marginal product of capital net of depreciation). In this process, a global "expected return", r^w, is calculated such that $\Sigma_i S_i = \Sigma_i s_i Y_i = \Sigma_i I_i (r^w, r_i^c, \pi_i)$, where s_i is the domestic saving rate in region *i*, Y_i is total income, I_i is (net) investment and π_i is a region-specific risk premium.
Investment does not affect the current installed capital stock but it does consume capital goods and its pattern of regional allocation has a significant influence on the capital account of each region's balance of payments, and hence on the real exchange rate.

a Constant Difference of Elasticities. See Huff et al. (1997).

Table 2: Model structure

		Share of 1995 world GDP[f]
Regions		
	1. Rapidly growing Asia[a]	5.1
	2. Japan	18.0
	3. China[b]	2.5
	4. European Union[c]	29.0
	5. United States	25.2
	6. Canada and Australasia	3.5
	7. Rest of world	16.8
Primary factors		
	1. Agricultural land	
	2. Natural resources	
	3. Skill	
	4. Labour	
	5. Physical capital	
Sectors[e]		
	1. All agriculture	
	2. Mining and energy (coal, oil, gas and other minerals)	
	3. Skill-intensive manufacturing (petroleum, paper, chemicals, processed minerals, metals, motor vehicles and other transport equipment, electronic equipment and other machinery and equipment)	
	4. Labour-intensive manufacturing (textiles, apparel, leather and wood products, metal products, other manufactures)	
	5. Skill-intensive services (electricity, gas, water, financial services and public administration)	
	6. Labour-intensive services (construction, retail and wholesale trade, dwellings)	

a Korea (Rep.), Indonesia, Philippines, Malaysia, Singapore, Thailand, Vietnam, Hong Kong and Taiwan.

b China excludes Hong Kong and Taiwan.

c The European Union of 15.

d These are aggregates of the 50 sector GTAP Version 4 database. See McDougall et al. (1998a).

e Share of 1995 GDP in US$ measured at market prices and exchange rates.

Table 3: Elasticities of substitution in final and intermediate product demand[a,b]

Sector	In product demand, between domestic and imported	In import demand, between regions of origin
Agriculture	2.3	4.7
Mining	2.8	5.6
Manufacturing: labour intensive	3.0	5.9
skill intensive	3.0	5.9
Services: labour intensive	1.9	3.8
skill intensive	1.9	3.8

a These are group-specific weighted averages across the 50 industries defined in the database. The structure of intermediate demand is as indicated in Figure 1. The CDE parameters governing substitution in final demand are discussed in McDougall et al. (1998b).

b These log run elasticities of substitution in product and service demand are larger than the standard GTAP values, reflecting the long run nature of the simulations to be conducted and the validation results from Gehlhar (1994), Gehlhar et al. (1994) and Hertel et al. (1996, Appendix C: 212).

Source: GTAP Database Version 4.1. See McDougall et al. (1998a).

Table 4: Branch elasticities of substitution in the case where all factors are substitutes

Sector		In production between intermediates and primary factors, σ_Y	In value added, between labour-skill, capital, resources and land, σ_{VA}	Between labour and skill, σ_{VLS}
Agriculture		0.4	0.5	0.9
Mining		0.5	0.5	0.9
Manufacturing:	labour intensive	1.0	1.5	2.5
	skill intensive	1.0	1.5	2.5
Services:	labour intensive	1.0	1.6	2.6
	skill intensive	1.0	1.2	2.2

Source: The value added branch elasticities are larger than the standard GTAP factor substitution elasticities, to reflect the long run as explained in the text. See Table 19.2 of McDougall et al. (1998b).

Table 5: Branch elasticities of substitution in the case where capital and skill are complements

Sector		In production between intermediates and primary factors, σ_Y	In value added, between capital-labour-skill, resources and land, σ_{VA}	Between capital-skill and labour, σ_{VKL}	Between capital and skill, σ_{VKS}
Agriculture		0.4	0.3	0.7	0.3
Mining		0.5	0.3	0.9	0.3
Manufacturing:	labour intensive	1.0	0.7	2.3	0.5
	skill intensive	1.0	0.7	2.3	0.5
Services:	labour intensive	1.0	0.9	2.8	0.7
	skill intensive	1.0	0.7	2.3	0.5

Source: The value added branch elasticities are larger than the standard GTAP factor substitution elasticities, to reflect the long run as explained in the text. See Table 19.2 of McDougall et al. (1998b).

Table 6: Implied elasticities of primary factor demand in the United States[a]

Sector:	Own price			Cross price					
	Labour, L	Skill, S	Capital, K	K-L	L-K	K-S	S-K	S-L	L-S
All factors substitutes:									
Agriculture	-0.45	-0.87	-0.41	0.08	0.09	0.01	0.09	0.45	0.04
Mining	-0.57	-0.76	-0.38	0.05	0.12	0.02	0.12	0.33	0.14
Labour intensive mfg	-1.34	-2.14	-1.15	0.40	0.35	0.12	0.35	1.16	0.36
Skill-intensive mfg	-1.58	-1.86	-1.15	0.33	0.35	0.23	0.35	0.92	0.64
Labour intensive services	-1.27	-2.23	-1.11	0.55	0.49	0.15	0.49	1.33	0.37
Skill intensive services	-1.48	-1.33	-0.97	0.27	0.23	0.33	0.23	0.72	0.87
Capital and skill complements									
Agriculture	-0.50	-0.26	-0.45	0.20	0.22	-0.01	-0.20	0.20	0.02
Mining	-0.73	-0.27	-0.38	0.17	0.42	-0.02	-0.13	0.17	0.07
Labour intensive mfg	-1.54	-0.73	-1.16	0.76	0.68	-0.23	-0.66	0.76	0.24
Skill-intensive mfg	-1.68	-0.78	-0.93	0.62	0.66	-0.28	-0.43	0.62	0.44
Labour intensive services	-1.70	-0.89	-1.32	1.10	0.98	-0.19	-0.62	1.10	0.31
Skill intensive services	-1.67	-0.80	-0.71	0.63	0.54	-0.30	-0.21	0.63	0.76

a These are conditional elasticities for the U.S. Those for other regions will differ as factor shares in total cost differ.

Source: Branch elasticities in Tables 4 and 5 and factor and input shares for the United States in 1995, drawn from the GTAP database (Mcdougall et al. 1998a).

Table 7: Simulated and Observed Changes in the Skill Premium (w_S/w_L) and the capital share of GDP at factor cost (r^cK/VA), 1975-95 (%)[a]

% change:	Simulated (no factor bias)				Observed	
	Substitutes		Complements			
	w_S/w_L	r^cK/VA^b	w_S/w_L	r^cK/VA^b	w_S/w_L	r^cK/VA^b
US	-27.5	3.3	-15.2	4.6	7.0	2.0
EU	-30.5	3.2	-19.3	5.1	1.5	4.0
C,A,NZ	-32.9	3.9	-19.9	6.6	3.1	3.0

a These changes are presented as *forward looking* – the two-decade change as a proportion of the 1975 level. The common elements of the backcast shocks are listed in the appendix.

b The changes in capital shares are in percentage points - percent of GDP at factor cost.

Source: Simulation results are from the long run backcast simulation described in the text. The observed skill premium changes in column 2 are based on original estimates of changes in the non-production/production wage ratio from Vo and Tyers (1995: Table 5), Berman, Bound and Machin (1998: Table II) and Machin and Van Reenen (1998: Table I), with some consideration of the corresponding human capital data for the US as presented in Krusell et al. (1977). The observed capital share changes are rounded averages from the international comparisons by Blanchard (1997), updated from comparable data.

Table 8: Alternative Factor Bias Patterns, 1975-95 (%)[a,b]

% change in:	α_Y, δ_K and δ_S endogenous			α_Y, δ_K and δ_L endogenous			α_Y, δ_S and δ_L endogenous		
	α_Y	$\alpha_Y\delta_K$	$\alpha_Y\delta_S$	α_Y	$\alpha_Y\delta_K$	$\alpha_Y\delta_L$	α_Y	$\alpha_Y\delta_S$	$\alpha_Y\delta_L$
All factors substitutes									
US	0.7	-5.4	90.7	36.8	-33.2	-26.8	-2.2	96.5	3.8
EU	-9.5	23.6	64.5	17.6	-15.2	-34.8	3.0	39.9	-22.8
C,A,NZ	-3.0	-3.2	94.4	35.1	-41.5	-32.3	-3.1	94.6	-2.8
Capital, skill complements									
US	4.2	31.7	-12.5	-4.1	44.0	13.2	16.4	-22.9	-7.2
EU	-3.9	26.2	-5.4	-4.5	27.5	-3.1	8.2	-19.7	-17.3
C,A,NZ	2.0	16.0	-29.9	-12.6	39.4	20.6	8.0	-35.6	-4.0

a These are *alternative*, <u>forward looking</u> percentage changes in the TIP and factor enhancement shifters, each combination being one possible technical change sufficient to explain the difference between the simulated "no bias" skill premium and capital share changes and the corresponding observed changes given in Table 7. The common elements of the backcast shocks are listed in the appendix.

b These production function parameter changes are common to all six sectors. The three experiments do not lead to precisely equivalent effects on production function parameters because there are other factors and inputs and because the mix of output changes across industries depends on which enhancement parameters are made endogenous.

Source: Long run backcast simulation described in the text.

Table 9: Elasticities of Sensitivity – Implied Factor Enhancement to Skill Supply[a]

Region	Skill enhancement when all factors are substitutes[b]	Capital enhancement when skill and capital are complements[c]
US	2.2	3.7
EU	2.1	4.0
C,A,NZ	3.1	4.5

a Percentage point change in the magnitude of implied skill or capital enhancement due to a percentage point increase in the exogenous growth of skilled labour supply over 1975-1995.
b The technology shifters for capital and skill are endogenous.
c The technology shifters for capital and labour are endogenous.
Source: Model simulations discussed in the text.

Table A1: The Backcast Shocks to Factor Use

Region	Capital K	Skill S	Labour L	Resources R	Land A
United States, US	-52	-44	5	0	0
European Union, EU	-59	-53	-2	-20	1
Canada, Australasia, CANZ	-62	-56	-2	-20	-7
Rapidly growing Asia, RA	-78	-46	-10	-20	-8
Japan, J	-78	-55	-8	-40	12
China, C	-76	-46	-10	-40	0
Rest of World, RoW	-18	-30	-4	-20	-32

Source: Capital use estimates are from the Penn World Tables Database as described originally by Summers and Heston (1991), skill and labour use is based on numbers of professionals and production workers in the labour force (Vo and Tyers 1995 and Liu et al. 1998), resource endowments are set to hold resource rents constant on average and land area is shocked according to extensification data from the World Bank World Tables database.

Table A2: The Backcast Shocks to GDP and Total Input Productivity (TIP)

Region	GDP	Total input productivity[a]	
		Factors substitutes	Capital and skill complements
US	-39.2	-4.1	-5.9
EU	-36.0	3.0	0.7
C,A,NZ	-42.4	0.7	-1.8

a Since GDP is made exogenous in each region, a component of the productivity factor α_Y (equation 1) common to all industries is made endogenous. This column gives the region-wide productivity changes implied. These changes depend on the technology assumed (substitute or complementary factors) and on the nature of the factor bias assumed in the technical change. The numbers given here refer to the factor neutral backcast in each case.

Sources: : GDP changes are from the World Bank World Tables database.

Table A3: The Backcast Shocks to Import Volumes

	US	EU	C,A,NZ	RDAsia	Japan	China
Agriculture	5	28	24	-44	31	-58
Mining	-55	3	-6	-67	-33	-98
Mfg labour intensive	-56	-51	-47	-81	-79	-96
skill intensive	-67	-59	-46	-37	-82	-95
Services: labour intensive	-32	-33	-55	-75	-39	-73
skill intensive	-32	-35	-55	-75	-39	-78

Source: United Nations Commodity Trade Statistics, as provided via the GTAP Version IV Database (McDougall 1998a).