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INEQUALITY AND THE DUAL ECONOMY: TECHNOLOGY ADOPTION WITH SPECIFIC AND GENERAL SKILLS

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Inequality and the Dual Economy: Technology Adoption with Specific and General Skills

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Abstract

Slow technology diffusion has important consequences for income inequality. Across countries, it can account for much of world inequality. Within countries, the arrival of new technologies often causes popular concern that the wages of some workers will fall. In developing countries, diffusion is often represented in the stylized form of a "dual economy," in which a gradually increasing fraction of workers use modern technology, while the remainder use traditional technology. This paper generates this pattern of technology adoption endogenously, and shows that it causes the wages of some workers to fall. Diffusion is slow because production requires both skills that are equally useful with any vintage of technology and skills that are imperfectly transferable across vintages. When these skills are sufficiently specific, a dual economy is optimal, even though intermediate technologies are also available. Workers with transferable skills disproportionately join the modern sector, leaving those with specific skills worse off. As in classical trade models, changes in factor supplies affect the allocation of labor across sectors, but not factor rewards. A dynamic extension shows that workers without transferable skills become worse off throughout the period of transition to the modern technology. A further dynamic extension applies the model to developed countries.

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1 Introduction

Slow technology diffusion has important consequences for income inequality. Most obviously, a large fraction of cross-country income differences can be explained by differences in technology.[1] The way in which developing countries adopt technology is therefore of considerable interest. This is often represented in the stylized form of a "dual economy," in which a gradually increasing fraction of workers use modern technology, while the remainder use traditional technology.[2] This process is a common justification for the Kuznets Curve, according to which inequality increases early in modernization and later decreases. The dual economy is therefore one example of the way in which technology diffusion can affect income inequality within countries, as well as across them. In fact, it is often claimed that new technologies not merely raise inequality, but can actually leave some workers worse off in absolute terms. This was notoriously believed to be the case, for instance, by the Luddites during the Industrial Revolution. Their claims had at least superficial plausibility: the handloom weavers of Lancashire, for example, lost three quarters of their earnings over a thirty year period from the 1790s to the 1820s.[3] More recently, technical change is often cited as a reason for increased inequality in the US since the 1970s, and sometimes as an explanation for the falling wages of many US workers over much of that time.

This paper presents a simple framework to unify these observations on technology diffusion through a dual economy and its effect on wages. Any vintage of technology requires for production both general skills that can easily be transferred across vintages and specific skills that are imperfectly transferable. Technologies diffuse slowly because, on arrival, new technologies are biased towards general skills. As a result, so long as specific skills are sufficiently specific, and there is a large enough supply of them, two vintages of technology are simultaneously in use. Because the modern technology favors general skills, the modern sector is relatively general-skill intensive. This reduces the absolute wage of specific-skill workers, who mainly work with the old technology but with fewer complementary inputs. Wages are set by relative productivity in the two sectors, independent of factor supplies. An economy is "developed" when it is optimal to close the traditional sector entirely, and use only modern technology instead. Much of the intuition for the model is exactly parallel to that of a small open economy in classical trade models.

While the static model illustrates why wages of some workers fall on arrival of new technology, it cannot describe the process of diffusion or changes in wages during modernization. The

[1] See, for example, Hall and Jones (1999).

[2] For a recent example, see Banerjee and Newman (1998). For the canonical discussions, see Lewis (1954) and Harris and Todaro (1969).

[3] For more on the plight of the handloom weavers, see Blythell (1969).

dynamic model considers these questions. In the dynamic model, external learning-by-doing yields a gradual increase in the specific skills required for the modern technology.[4] Eventually, enough skills are acquired in the modern sector so that the traditional sector closes entirely. Wages of workers with specific skills continue to fall throughout the transition, and only start to recover when the traditional sector closes. The model therefore generates a strong form of Kuznets Curve. The model is easily extended to developed countries. In developed countries, there is a balanced growth path involving the use of this period's frontier technology and last period's frontier technology. Economies endowed with more workers with transferable skills have larger modern sectors, and as a result equilibrium efficiency of specific-skill workers is higher in both sectors. An increased rate of technical progress and increased transferability of specific skills each have ambiguous effects on equilibrium inequality, although increased transferability certainly increases inequality initially.

The idea that some human capital is vintage specific has been explored in several previous papers. The key paper in the literature is Chari and Hopenhayn (1991). In Chari and Hopenhayn, all human capital is equally vintage-specific, and this leads to their interest in the response of the lifetime pattern of earnings to changes in technical progress. In particular, they are interested in the complementarity between experienced and inexperienced workers in the same vintage. Most other models of vintage human capital do not emphasise the complementarity between types that is the focus of interest here. These include Aghion, Howitt and Violante (2002), who consider the effect of GPTs, Krueger and Kumar (2004), and Galor and Tsiddon (1997), who develop a rich model of growth focusing on intergenerational mobility and ability.

Much of the extensive literature investigating why developing countries adopt new technology slowly or not at all does not consider technology diffusion through a dual economy. Instead, it assumes that developing countries as a whole adopt a succession of better technologies. Most of the time, this is implicit, and slow adoption is the result of exogenous country differences such as productivity differences (Zeira (1998)) or barriers to adoption (Parente and Prescott (1994)). Keller (1996) is somewhat closer to the current paper in considering the relationship between technology opening and human capital.[5] In Basu and Weil (1998), this approach is explicit, as developing countries develop by using "appropriate technology," that is technology intermediate between the traditional technology and the frontier.

By contrast, most existing papers on a dual economy assume the existence of precisely two modes of production, rather than generating this as an optimal outcome, as here. An

[4] Stokey (1991) has considered learning-by-doing with human capital. Famous empirical examples of the importance of learning-by-doing include David (1975) and Lucas (1993).

[5] Another paper concerned with slow adoption caused by human capital is Kremer and Thomson (1998).

example is Beaudry and Francois (2004), who assume exactly two technologies and emphasize a complementarity between experienced and inexperienced workers different types of workers in learning about the new technology.[6] In other papers, the older technology survives because some non-competitive factor retards adoption of the new technology.[7]

A vast literature considers the interaction between technical change and inequality. The possibility that new technology can make some workers worse off in absolute terms has also been of persistent interest to economists at least since Ricardo's famous chapter on "Machinery" in the 1821 edition of his *Principles*. Only a few papers generate this prediction, and most of these rely on complementarity between different types of workers. In Acemoglu (1999), the complementarity arises because the economy is not perfectly competitive, but involves instead search and screening. Kremer (1993 and 1997) and Kremer and Maskin (1995) are closer in spirit to the present model, in that the O-ring production function can generate behaviour similar to that described here even with perfect competition. But the production function is highly non-standard, and they do not consider the transition to a modern economy. Beaudry and Green (2002) also generate falls in wages for some workers derived from complementary factors and two possible production technologies. However, their model focuses on explaining recent changes in the US wage distribution by considering a one-time introduction of a new, permanently skill-biased technology to a developed economy.

The paper proceeds by developing static results in Section 2 , before turning to dynamic results and learning in Section 3. Some possible extensions to allow for supply responses and multi-good settings are discussed in Section 4. Section 5 concludes.

2 The Static Model

This section introduces the static model of technology adoption with vintage-specific human capital. Interpreted literally, the static model represents the effect on an economy in steady state of the exogenous introduction of a set of new, but not fully understood, technologies. Such a pure experiment may occasionally have occured, for instance after the fall of the Tokugawa Shogunate in Japan or the loss of the Opium Wars in China. More broadly, however, it approximates the many instances when developing countries have switched from inward-looking policy regimes to policies favoring trade and foreign investment. To establish the intuition for the model, I first use Lerner diagrams to describe a dual equilibrium geometrically, before

[6] In an extension, they consider multiple technology steps, that could lead to an endogenous dual economy. But their main interest is in comparing steady states rather than exploring this possibility.

[7] Banerjee and Newman (1998), for example, are concerned with imperfect credit markets. Acemoglu and Shimer (2002) generate technology dispersion from search, although they do not impose exactly two technologies.

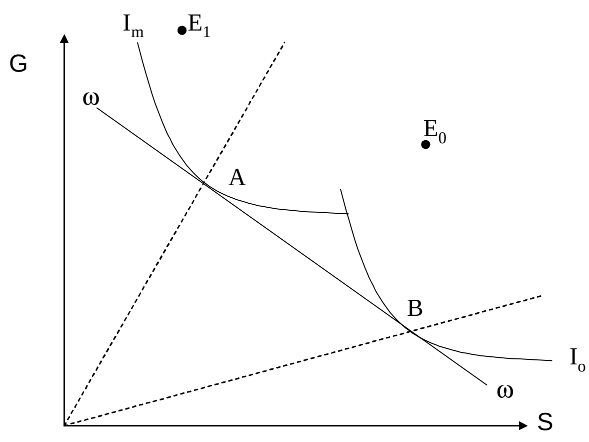

Figure 1: Equilibrium with Two Technologies

describing the model algebraically. I establish the conditions under which the dual or separating equilibrium involves using the traditional technology and the frontier technology, rather than a single interior technology.

2.1 A Graphical Representation

As foreshadowed in the introduction, much of the intuition in the present model is similar to the intuition that comes from considering a small open economy in classical trade models. Adapting the graphical analysis from that literature highlights three key points about the dual equilibrium. First, it shows the circumstances under which a dual economy, rather than universal adoption of an intermediate technology, will indeed be optimal. Second, it highlights the importance of factor endowments and the cone of diversification. An economy insufficiently endowed with general skills never opens a modern sector, while an economy with enough workers with general skills operates only the modern sector. Finally, it highlights that wages in an economy within the cone of diversification are determined purely by the relative position of the isoquants, independent of relative factor supplies.

In the Lerner diagram in Figure 2.1, perfectly competitive firms choose their factor inputs and production technology, subject to factor prices. The quantity of general-skill labor appears on the vertical axis, that of specific-skill labor on the horizontal axis. The endowment of this economy, which consists of supplies of general and specific-skill labor, is at point E_0. The two

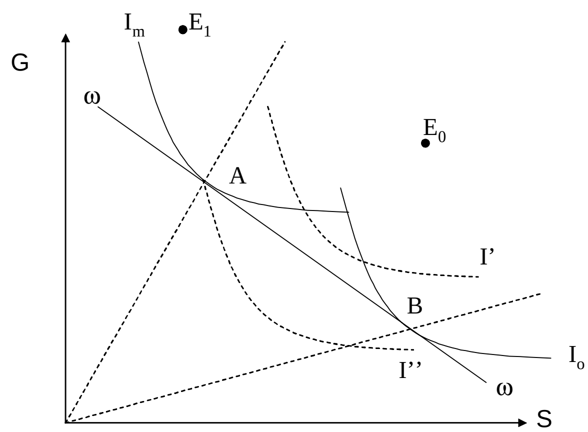

Figure 2: Intermediate Technologies

available technologies are represented by the isoquants I_o and I_m. I_m, the modern technology, is general-skill biased, since at any given factor-price ratio it employs relatively more general-skill labor.[8]

In equilibrium, both technologies are used so long as the endowment of the economy lies within the cone of diversification, defined by the area between the rays OA and OB. In that case, factor prices are determined solely by the relative position of the two isoquants, as illustrated by the factor price line, $\omega\omega$: relative supplies do not affect relative prices. The factor price line can also be interpreted as an isocost line.

If the endowment is at a point such as E_1, the supply of general skill is so great that the specific-skill intensive technology is not used. This is because no convex combination of the rays OA and OB can attain point E_1, so factor markets cannot clear. With endowment E_1, firms use only the technology represented by isoquant I_m, and relative supplies once again determine factor prices. The relative price of the abundant factor, G, must be lower than when both technologies are in use.

Now consider introducing other technologies whose factor bias lies somewhere between that of I_o and I_m. Facing the same factor prices, these technologies will be used if and only if some point on the new isoquants lies below the factor price line. In Figure 2.2, the technology

[8]In the trade literature, these are "unit value" isoquants, which can be drawn because output prices are fixed in a small open economy. Here, they are simple isoquants, because all firms produce the same good.

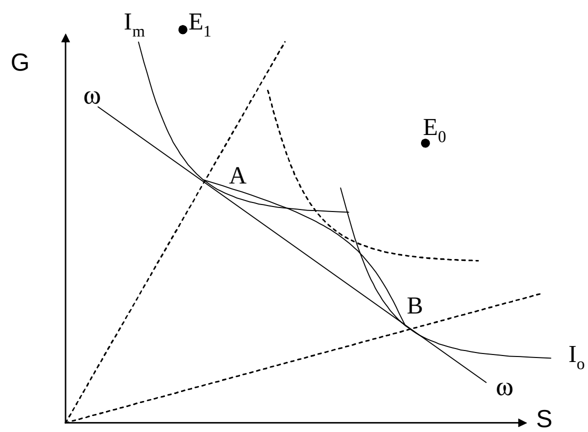

Figure 3: An Equilibrium Dual Economy

associated with isoquant I' is unprofitable, whereas the technology represented by isoquant I'' will replace one or both of the previous technologies. Which one is replaced depends on the factor endowment of the economy. If there is a continuum of technologies such as I' or I'', none will be used so long as none of them have isoquants that cross the factor price line. In this case, the two extreme technologies, I_o and I_m, are used. This is the dual economy equilibrium.

Because isoquants are convex, the isoquant crosses the factor price line if and only if it is below the factor price line at the point where its tangent is parallel to it. Therefore, the two extreme technologies are used so long as the set of these points lies entirely above the factor price line, as in Figure 2.3. A sufficient but not necessary condition for characterising this set is that it be weakly concave. Economically, this requires that new technologies be "sufficiently" skill-biased.

Having established informally the key features of a dual equilibrium relating to factor endowments, factor prices and the characteristics of technology, I turn to the algebraic analysis.

2.2 Production

The economy consists of perfectly competitive firms, all of which have access to a well understood constant returns to scale production technology. The productivity of this technology is indexed by a^o. Production uses only specific skills and general skills. Consider the introduction of a continuum of new technologies, indexed by $a \in (a^o, a^m]$, where a^m is the most modern technology available, assumed to be the world technology frontier. The key assumption here is that firms face a menu of possible technological choices: they are not constrained to use either the frontier or the traditional technology. This assumption seems quite reasonable. For example, it seems reasonable to suppose that technical progress continually expands the technological frontier, without eliminating the previous frontier technologies. This issue will be explored further in the dynamics.

Production by firm i takes the CES form:

$$\tilde{Y}_i = a_i[\lambda S_i^\rho + (1-\lambda)G_i^\rho]^{1/\rho},$$

where S_i and G_i are the effective inputs of specific and general skill labor demanded by the firm and a_i is the vintage of technology chosen by the firm. Note that $\rho \in (-\infty, 1)$ and that the elasticity of substitution is $\sigma = \frac{1}{1-\rho}$. For convenience, normalise output by a^o:

$$Y_i = \frac{\tilde{Y}_i}{a^o} = r_i\left[\lambda S_i^\rho + (1-\lambda)G_i^\rho\right]^{\frac{1}{\rho}}, \tag{1}$$

where $r_i \in [1, m]$ is equal to $\frac{a_i}{a^o}$, the ratio of output produced using the new technology to output produced using the old technology, for the same effective factor inputs to each.

Workers are endowed with either specific human capital or general human capital, or some combination of the two. To aid discussion, it is often convenient to assume that each worker is endowed with one unit of either specific or general human capital. Accordingly, the units of each type demanded by the firm can also be thought of as workers of each type. A worker endowed with one unit of general human capital can supply one efficiency unit to any vintage of technology. A worker endowed with one unit of specific human capital can supply one efficiency unit of specific capital to firms using a^o, but strictly less to firms using other vintages of technology. The number of efficiency units of specific human capital supplied by a specific-skill worker is described by the declining function $e(r_i)$, which by definition is equal to one when r_i is equal to one. This is the transferability function.

Denote by s_i the number of units of specific-skill capital that a firm hires, and g_i the number of general-skill units. Then the effective quantity of labor used by the firm is:

$$\begin{aligned} S_i &= e(r_i)s_i \text{ where } e(1) = 1,\ e'(r_i) \leq 0\ \forall\ r_i \in [1, m] && (2) \\ G_i &= g_i && (3) \end{aligned}$$

The key assumption is that efficiency units of specific-skill labor supplied per worker decrease as the technology used becomes increasingly remote from the accustomed technology. Although it is not essential to the results that $e(r_i)$ be differentiable or continuous, this is assumed for now.

Since firms are perfectly competitive, they choose r_i, s_i and g_i to maximise

$$\pi = r_i[\lambda e\left(r_i\right)^{\rho} s_i^{\rho} + (1-\lambda) g_i^{\rho}]^{\frac{1}{\rho}} - (w_S s_i + w_G g_i), \tag{4}$$

where the price of output is normalised to one.

There are no externalities in this problem, and hence, although it is non-convex, the First Welfare Theorem applies. That is, the perfectly competitive equilibrium is Pareto optimal. The mathematical appendix shows that the competitive equilibrium allocation is the same as the social planner's allocation. This is true whether or not the economy lies within the cone of diversification defined by the available technologies, and hence whether or not the dual equilibrium is optimal.

2.3 Technology Choice

It is helpful to rewrite the production function, equation 1, as

$$Y_i = [\lambda \xi(r_i)^{\rho} s_i^{\rho} + (1-\lambda) r_i^{\rho} g_i^{\rho}]^{\frac{1}{\rho}}. \tag{5}$$

where $\xi(r_i) \equiv r_i e(r_i)$. This formulation highlights that, for given factor inputs, production is an increasing function of both r_i and $\xi(r_i)$. If $\xi'(r_i) > 0$, better technology automatically raises production, and all firms use the newest technology. Older technology is therefore only ever used under the following assumption.

Assumption A2: *Assume that* $\xi(1) = 1, \xi'(r) < 0, \xi''(r) > 0$.

Although the assumption that $\xi'(r) < 0$ is necessary in order to allow older technologies to be useful, the assumption of convexity is less obvious. So long as the efficiency of specific-skill workers is always strictly positive, some segment of the function will asymptote towards zero (or a positive constant) and hence be concave over this range. In fact, this is all that is required for a dual equilibrium.[9] Since it seems likely that an extra worker could always do something useful, this assumtion seems reasonable. In particular, if there are no problems in contracting, a worker can always pay for the cost of any training, so the remainder of their time must have weakly positive marginal product.

Associated with the CES production function is the unit cost function,

$$c_i(w_s, w_g, r_i) = \frac{1}{r_i}\left[\frac{w_s^{\eta}}{\lambda e(r_i)^{\eta}} + \frac{w_g^{\eta}}{(1-\lambda)}\right]^{\frac{1}{\eta}} \text{ where } \eta = \frac{\rho}{\rho-1}. \tag{6}$$

[9] For appropriate factor endowments, so long as there is some technology $\tilde{r}$ for which the assumption is true $\forall\ r \geq \tilde{r}$, a dual equilibrium exists, although the "traditional" technology in that case will be $\tilde{r}$. This property is discussed in more detail in the dynamics.

This is a convenient way to consider the firm's optimal choice of technology, because it requires optimising only over r_i, rather than simultaneously over the factor input ratio. The following lemma and proposition establish the conditions under which a dual equilibrium exists.

Lemma 1 *If a dual equilibrium exists, the unit cost function must exhibit a turning point somewhere in the range $r \in [1, m]$.*

Proof. *The unit cost function is a continuous function in r whose domain is the compact subset $r \in [1, m]$. Therefore, by Weierstrass's Theorem, it must attain its global maximum and minimum on the domain. If a dual equilibrium exists, profits must be zero at $r = \{1, m\}$. Hence, by the mean value theorem, there must be a point $r^t \in (1, m)$ such that $c'(r^t) = 0$.* ■

Proposition 1 *If a dual equilibrium exists, Assumption A2 is a sufficient condition for it to be unique.*

Proof. *If the dual equilibrium exists, the turning point in the cost function must be a maximum. Differentiating the unit cost function, equation 6, shows that at a turning point,*

$$\frac{-1}{r^2}\left[\frac{w_s^\eta}{\lambda e(r)^\eta} + \frac{w_g^\eta}{(1-\lambda)}\right]^{\frac{1}{\eta}-1}\left\{\frac{w_s^\eta \xi'(r)}{\lambda e(r)^{\eta+1}} + \frac{w_g^\eta}{(1-\lambda)}\right\} = 0. \tag{7}$$

Equivalently, the turning point occurs when

$$\frac{\xi'(r)}{e(r)^{\eta+1}} = -\left(\frac{w_g}{w_s}\right)^\eta\left(\frac{\lambda}{1-\lambda}\right).$$

Evaluated at the turning point, the second derivative has the opposite sign to

$$\xi''(r)e(r)^{\eta+1} + \sigma e(r)^\eta e'(r)\,\xi'(r), \tag{8}$$

where $\sigma = -(\eta+1) > 0$. But under assumption A2, this expression is always greater than zero. Therefore, any turning point must be a maximum, and must therefore also be unique. ■

2.4 Static Equilibrium

Proposition 1 establishes that, if a turning point exists, it is unique and a maximum, and that therefore all firms will use either the traditional technology or the modern technology. However, the proposition does not establish the conditions under which such a turning point exists, since these depend on the equilibrium factor price ratio. To proceed, it is therefore most convenient to solve for a dual equilibrium on the assumption that one exists, and then solve for the conditions under which this is indeed the equilibrium.

Assuming that the dual equilibrium exists, what are its properties? The system contains six variables, the two wage rates and four employment outcomes, namely general and specific employment in the modern and traditional sectors. The traditional (old) sector is denoted with an o subscript, the modern sector with an m subscript. (With constant returns to scale, it is of course unnecessary to distinguish sectoral choices from firm choices). Efficiency of specific-skill labor in the modern sector, $e(m)$ is written e_m. Economy-wide supplies of specific and general skill labour are $\bar{s}$ and $\bar{g}$. The equilibrium conditions are:

$$w_S = \lambda s_o^{\rho-1}[\lambda s_o^\rho + (1-\lambda)g_o^\rho]^{\frac{1-\rho}{\rho}} \tag{9}$$

$$= \lambda e_m^\rho s_m^{\rho-1} m[\lambda e_m^\rho s_m^\rho + (1-\lambda)g_m^\rho]^{\frac{1-\rho}{\rho}} \tag{10}$$

$$w_G = (1-\lambda)g_o^{\rho-1}[\lambda s_o^\rho + (1-\lambda)g_o^\rho]^{\frac{1-\rho}{\rho}} \tag{11}$$

$$= (1-\lambda)g_m^{\rho-1} m[\lambda e_m^\rho s_m^\rho + (1-\lambda)g_m^\rho]^{\frac{1-\rho}{\rho}} \tag{12}$$

$$s_o + s_m = \bar{s} \tag{13}$$

$$g_o + g_m = \bar{g} \tag{14}$$

Taking the ratio w_G/w_S with respect to both technologies and equating yields the equilibrium relationship between factor ratios in the two sectors. It is convenient to switch variables and work in terms of ϕ_i, the ratio of general-skill to specific-skill labour in each industry.

$$\left(\frac{\phi_m}{\phi_o}\right) = e_m^{\frac{\rho}{\rho-1}}. \tag{15}$$

It is clear from equation 15 that the modern sector is relatively general-skill intensive if and only if $e_m^{\frac{\rho}{\rho-1}} > 1$. Since $e_m < 1$, this can be true only if $\frac{\rho}{\rho-1} < 0$, that is $\rho > 0$ ($\sigma > 1$). Most existing estimates of labor substitution elasticities suggest that different types of labor have have a greater than unit substitution elasticity. For example, if general capital is associated with higher levels of education, the consensus estimates of the elasticity of substitution cluster around 1.5 or so.[10] Other types of human capital, such as different potential experience groups, appear to be still more easily substitutable.[11] Since the limited evidence on the topic accords with the intuition that holders of general skills should be those to gain from technical change, I make the following assumption.[12]

Assumption A3: *$\rho > 0$, or equivalently $\sigma > 1$: factors are gross substitutes.*

Given that $\rho > 0$, equation 15 shows that the frontier sector is more general-skill biased relative to the traditional sector when specific skills are relatively inefficient at the frontier. That is, a fall in e_m increases the factor bias of the frontier sector compared to the traditional sector.

[10] See Katz and Murphy (1992), Card and Lemieux (2001), and Johnson (1997).

[11] See Card and Lemieuz (2001) and Borjas (2003).

[12] The assumption is important for the interpretation of the results, but not for the results themselves. That is, a dual economy can certainly exist with a lower substitution elasticity, in which case the winners and losers from new technology are reversed relative to the analysis here.

This expression can be used to gain quantitative estimates of the magnitude of differences in skill-ratios across sectors. If σ is about 1.5, approximately the rate of substitution estimated in various US studies between college graduates and high-school educated workers, then if $e_m = \frac{1}{2}$, the modern sector will be about 1.4 times as general-skill intensive as the traditional sector. If efficiency is much lower, say $e_m = \frac{1}{5}$, then the modern sector will be about 2.2 times as general-skill intensive as the traditional sector. Allowing for a larger elasticity of substitution produces larger effects; for $e_m = \frac{1}{2}$, the frontier sector is twice as general skill intensive as the traditional sector when $\sigma = 2$ and four times as intensive when $\sigma = 3$.

Equating specific and general skill wages across sectors yields the equilibrium factor ratio in the traditional sector (for convenience, written to the power ρ):

$$\phi_o^{\rho} = \left(\frac{\lambda}{1-\lambda}\right)\left(\frac{1-(me_m)^{\frac{\rho}{1-\rho}}}{m^{\frac{\rho}{1-\rho}}-1}\right). \tag{16}$$

Equilibrium requires that $me_m < 1$, which is guaranteed by Assumption A2. Note that the equilibrium factor ratio is determined purely technologically: factor supplies play no role. Combining equations 15 and 16 to solve for ϕ_m shows that ϕ_m relies on exactly the same set of variables as ϕ_o, namely technological variables but not factor supplies.

Since relative factor supplies do not affect industry factor intensities, nor can they affect relative wages. The equilibrium wage ratio is a simple transformation of factor intensity in the traditional sector:

$$\frac{w_G}{w_S} = \left(\frac{1-\lambda}{\lambda}\right)\phi_o^{\rho-1} \tag{17}$$

The ratio of general to specific-skill wages is increasing in specific-skill intensity in the traditional sector. This is intuitive: relative wages of general skill workers (the "wage premium") are higher when they are relatively scarce in the traditional sector.

It remains to solve for the equilibrium allocation of workers between the two sectors. The market clearing relationships, equations 13 and 14, can be rearranged as follows:

$$\begin{aligned}(1-\delta)\phi_o + \delta\phi_m &= \bar{\phi} \text{ and} \\ (1-\gamma)\frac{1}{\phi_o} + \gamma\frac{1}{\phi_m} &= \frac{1}{\bar{\phi}},\end{aligned}$$

where δ is the fraction of specific skill workers employed in the modern sector, and γ is the corresponding variable for general skill workers.[13]

[13] These equations can be derived as follows. Dividing the g market clearing equation by $\bar{s}$ gives

$$\frac{\bar{g}}{\bar{s}} = \frac{g_m}{\bar{s}} + \frac{g_o}{\bar{s}}$$

Now just multiply the first term on the right by $\frac{s_m}{s_m}$, the second by $\frac{s_o}{s_o}$ and rearrange.

Using these as the market clearing variables,

$$\delta = \frac{\bar{\phi} - \phi_o}{\phi_o \left(e_m^{1-\sigma} - 1\right)}, \text{ and} \tag{18}$$

$$\gamma = \left(\frac{\bar{\phi} - \phi_o}{\bar{\phi}}\right)\left(\frac{e_m^{1-\sigma}}{e_m^{1-\sigma} - 1}\right) \tag{19}$$

Since factor intensity within each sector is unrelated to the economy-wide factor ratio, it is clear from equations 18 and 19 that both δ and γ are unambiguously increasing in $\bar{\phi}$. The more general-skill workers an economy possesses, the greater the fraction of both general and specific-skill workers allocated to the modern sector. While the economy maintains a dual structure, a greater fraction of general-skill workers than specific-skill workers will always work in the modern sector, since

$$\gamma = \delta \frac{\phi_o e_m^{1-\sigma}}{\bar{\phi}} = \delta \frac{\phi_m}{\bar{\phi}} > \delta.$$

In short, changes in factor supplies change the allocation of labor between the traditional and modern sectors, but do not affect relative factor intensities, just as the graphical analysis suggests. However, if factor supplies change to the point where the economy lies outside the cone of diversification, there are important consequences. An economy insufficiently endowed with general skill labor to lie within the cone of diversification uses only the traditional technology, and never adopts the new technology. Conversely, an economy abundantly endowed with general skill labor may also lie outside the cone of diversification, and close the traditional sector entirely.

Since δ and γ must both be between 0 and 1, the market clearing conditions formally provide the conditions under which the dual economy exists. The economy is backward, meaning no modern sector opens, if

$$\bar{\phi} \leq \phi_o = \left[\left(\frac{\lambda}{1-\lambda}\right)\left(\frac{1-(me_m)^{\sigma-1}}{m^{\sigma-1}-1}\right)\right]^{\frac{\sigma}{\sigma-1}}. \tag{20}$$

The economy is modern, meaning the traditional sector closes entirely, if

$$\begin{aligned} \bar{\phi} &\geq \phi_m = \phi_o e_m^{1-\sigma} \\ &= \left[\left(\frac{\lambda}{1-\lambda}\right)\left(\frac{1-(me_m)^{\sigma-1}}{m^{\sigma-1}-1}\right)\right]^{\frac{\sigma}{\sigma-1}} e_m^{1-\sigma}. \end{aligned} \tag{21}$$

Whether the economy lies within the cone of diversification is therefore determined by comparing the factor endowment of the economy with the required factor ratios of the traditional and modern sectors. Other things being equal, the cone of diversification is wider when e_m is lower, that is, there is a greater difference between the desired factor ratios in the two sectors.

2.5 Comparative Statics

How does the dual equilibrium change in response to parameter changes? Since the factor intensity of the traditional (and modern) sector is independent of factor supplies, it changes only with changes in technology. In particular, consider the effects of greater technological backwardness (a greater value of m), and of greater specific-skill efficiency (greater e_m). Since frontier efficiency depends on the distance to the frontier, $e_m = e(m)$, there is both a direct and an indirect effect of changes in m. In the comparative statics that follow, I consider the direct effect of m in isolation before considering the total effect of a change in m. In most cases the indirect effect offsets the direct effect, and without specifying a functional form for $e(m)$ it is not possible to determine which effect dominates.

Turning first to technological backwardness, take the partial derivative of equation 16 holding efficiency constant, in order to isolate the pure effect of being more relatively backward:

$$\frac{\partial \phi_o^\rho}{\partial m} = \left(\frac{\lambda}{1-\lambda}\right)\left(\frac{-(\sigma-1)\, m^{\sigma-2}}{\left(m^{\sigma-1}-1\right)^2}\right)\left[1 - e_m^{\sigma-1}\right] < 0.$$

Therefore, the general-skill intensity of the traditional sector declines in initial backwardness. If a relatively more advanced technology becomes available, or if a more backward country opens to world technology, the traditional sector becomes less general-skill intensive. Turning to changes in the efficiency of specific skills,

$$\frac{\partial \phi_o^\rho}{\partial e_m} = \left(\frac{\lambda}{1-\lambda}\right)\left(\frac{-(\sigma-1)\, m^{\sigma-1} e_m^{\sigma-2}}{m^{\sigma-1}-1}\right) < 0$$

When skills are less specific (e_m is relatively high), the general skill intensity of the traditional sector also falls. This result is more surprising: when specific-skill workers are more efficient at working in the modern sector, the traditional sector becomes less general-skill intensive, that is, employs relatively more specific-skill workers.

What about the total effect of a change in m? This is

$$\frac{d\phi_o^\rho}{dm} = \frac{-\lambda}{1-\lambda}\frac{(\sigma-1)\, m^{\sigma-2}}{\left(m^{\sigma-1}-1\right)^2}\left[e_m^{\sigma-2}\left(e_m + me'(m)\right)\left(m^{\sigma-1}-1\right) + 1 - \left(me_m\right)^{\sigma-1}\right]. \qquad (22)$$

The direct effect dominates if equation 22 is less than zero. This is true if

$$e_m\left(\frac{e_m^{1-\sigma}-1}{m^{\sigma-1}-1}\right) + me'(m) > 0.$$

Intuitively, this condition says that the direct effect dominates so long as the indirect effect on efficiency, $me'(m) < 0$, is not too great. Recall that by assumption, $e_m + me'(m) < 0$.

Therefore, the direct effect can dominate only if $\frac{e_m^{1-\sigma}-1}{m^{\sigma-1}-1} > 1$. However, assumption A2 also guarantees that this is true, since $(me_m)^{\sigma-1} < 1$. Therefore, no unambiguous prediction for the total effect of technological backwardness on factor intensity in the traditional sector is possible. For the other comparative statics, I therefore focus on the direct effect alone.

For the frontier sector, the corresponding partial derivatives are:

$$\begin{aligned}\frac{\partial\phi_m}{\partial m} &= \frac{\partial\phi_o}{\partial r_m} e_m^{1-\sigma} < 0 \\ \frac{\partial\phi_m}{\partial e_m} &= \frac{\partial\phi_o}{\partial e_m} e_m^{1-\sigma} - (\sigma-1) e_m^{-\sigma}\phi_0 < 0\end{aligned}$$

The frontier sector is less general-skill intensive when relative backwardness is greater, and when specific-skills are more efficient at the frontier. Factor intensity in the frontier sector therefore behaves in the same way as factor intensity in the traditional sector, rather than, as perhaps may have been expected, offsetting it.

Since, holding efficiency constant, a more relatively backward economy (greater m) is less general-skill intensive in each sector, the general-skill intensive sector, namely the frontier, must be larger. Similarly, for a given level of relative backwardness, if specific-skill workers are more efficient at the frontier, the frontier sector is larger. These results are summarised below, with reference to the fraction of specific-skill workers (δ) and general-skill workers (γ) employed in the frontier sector.

$$\begin{aligned}\frac{\partial\delta}{\partial m} &= \frac{-\bar{\phi}}{\phi_o^2}\frac{\partial\phi_o}{\partial m}\left(e_m^{1-\sigma}-1\right)^{-1} > 0 \\ \frac{\partial\delta}{\partial e_m} &= \frac{-1}{\phi_o\left(e_m^{1-\sigma}-1\right)}\left[\frac{\bar{\phi}}{\phi_o}\frac{\partial\phi_o}{\partial e} - \frac{e_m^{-\sigma}(\sigma-1)\left(\bar{\phi}-\phi_o\right)}{\left(e_m^{1-\sigma}-1\right)}\right] > 0 \\ \frac{\partial\gamma}{\partial r_m} &= \frac{-1}{\bar{\phi}}\left(\frac{e_m^{1-\sigma}}{e_m^{1-\sigma}-1}\right)\frac{\partial\phi_o}{\partial m} > 0 \\ \frac{\partial\gamma}{\partial e_m} &= \frac{-e_m^{-\sigma}}{\bar{\phi}\left(e_m^{1-\sigma}-1\right)}\left[e_m\frac{\partial\phi_o}{\partial e_m} - \frac{(\sigma-1)\left(\bar{\phi}-\phi_o\right)}{\left(e_m^{1-\sigma}-1\right)}\right] > 0\end{aligned}$$

As with factor intensity, the offsetting effects of technological backwardness and specific-skill efficiency render impossible an unambiguous prediction for the total effect of technological backwardness. If, empirically, greater initial backwardness slows adoption of new technology, this suggests that the indirect effect through reduction of specific skills dominates. Leapfrogging-type hypotheses would be consistent with a smaller indirect effect.

Turning to relative wages, equation 17 establishes a simple relationship between the wage premium ($\frac{w_G}{w_S}$) and the general-skill intensity of the traditional sector. The wage premium is rising with technological backwardness, since

$$\frac{\partial(\frac{w_G}{w_S})}{\partial m} = \left(\frac{1-\lambda}{\lambda}\right)(\rho-1)\phi_o^{\rho-2}\frac{\partial\phi_o}{\partial m} > 0.$$

Similarly, with regard to the efficiency of specific skills,

$$\frac{\partial(\frac{w_G}{w_S})}{\partial e_m} = \left(\frac{1-\lambda}{\lambda}\right)(\rho-1)\phi_o^{\rho-2}\frac{\partial\phi_o}{\partial e_m} > 0.$$

The wage premium is therefore *increasing* in the efficiency of specific skills. This is surprising, since increases in the efficiency of specific-skill workers in the frontier sector (higher e_m) are effectively just specific-skill augmenting technical changes. In a standard setting with $\sigma > 1$, specific-skill biased technical change reduces the premium to general-skill labour. In this setting, by contrast, increases in the efficiency of specific-skill workers make the frontier sector relatively more productive, and hence expand the frontier sector. Since the frontier is relatively general-skill intensive, however, this requires reducing the general-skill intensity of both sectors. But this leaves specific-skill workers relatively worse off than before, as now in both sectors they have fewer complementary general-skill workers with whom to work.

While the comparative statics have focused on relative wages, in fact the wage of specific-skill workers falls in *absolute* terms. How can this be? As frontier efficiency increases, the general-skill intensity of both sectors falls. Workers in the traditional sector have not gained directly from increases in efficiency at the frontier; their technology is exactly as it was before. But now specific-skill workers in the traditional sector, using the same technology, have fewer complementary inputs, in the form of general-skill workers, with whom to work. Therefore, their marginal product, and thus also their wages, must have declined. Specific-skill workers are worse off in absolute terms than before the introduction of new technology throughout the entire range of e_m for which the dual economy persists.

Most models of biased technical change do not predict that wages of some workers actually fall. As noted in the introduction, those that do typically rely on settings deviating from perfect competition, or unusual production functions such as the O-ring production function. In contrast, the prediction is generated here using an entirely standard neo-classical setting and production function, and requires only that different types of workers are both required for production. The model is intuitive in that losers from technical progress are those who disproportionately continue for some time to use older technology. However, this is a more subtle prediction than simply that the losers will be those left behind using the old technology - the losers are those who have a comparative advantage in the use of old technology, whether or not they as individuals actually continue to use it. For example, the model predicts that the

Lancashire handloom weavers lose wages during the Industrial Revolution. But more broadly, workers whose skills are close substitutes, such as many mill workers at the time, are also predicted to suffer wage losses relative to before the introduction of new technology.

3 Dynamics

The model discussed so far represents a one-time opening of an economy to a new technology. However, the broader questions are how countries modernize after they open, and what happens to wages over the course of modernization. I consider the dynamics first with a fixed frontier and then with a moving frontier. The first case is useful in fixing intuition and, it turns out, is a reasonable approximation to the case of a developing country opening to new technology.

The second case is particularly interesting in the context of developed countries, and allows comparison with some of the literature on GPTs. Moreover, it highlights the role of general human capital, not merely as a factor of production alongside specific skills, but in helping achieve a higher equilibrium level of efficiency when there is ongoing technical progress. This ties the idea of general human capital back to the Nelson-Phelps literature on human capital as aiding adaptability.[14]

3.1 A fixed frontier

Assume there is an overlapping generations economy, in which workers live for two periods. In the first, they either go to school to gain general skills or gain experience and specific skills on the job. Assume the choice between the two is exogenous, and that the marginal productivity of workers gaining specific skills on the job is zero in their first period of life. In the second period of their lives, everyone works and participates in training (costlessly) the members of the next generation.

The only choice made by any workers is made by specific skill workers, who choose in what sector to gain experience. Assume perfect foresight, so wages in the two sectors will be equal, exactly as in the static model. Since knowledge is cumulative and young workers receive training in their sector of choice, efficiency in the modern sector increases over time, towards its upper bound of unity. This learning-by-doing is assumed to be entirely external; alternatively, existing workers do not benefit from learning this period and do not take into account the utility of their

[14] Gellner highlights the importance of general human capital to modern, technologically dynamic societies in contrast to traditional societies: "A society ... based in the last analysis on economic growth ... is thereby committed to the need for innovation and hence to a changing occupational structure. From this it follows that certainly between generations ... men must be ready for reallocation to new tasks. Hence, in part, the importance of generic training (Gellner 1983), 32)."

descendants. Assume that knowledge is accumulated according to some function:

$$\begin{aligned} e_{m,t+1} &= \psi\left(\delta_t\left(\bar{\phi}_t, e_{m,t}, m\right), e_{m,t}\right), \qquad (23) \\ \text{where } \psi_\delta &> 0, \psi_{\delta\delta} < 0, \psi_e > 0, \psi_{ee} < 0 \\ &= f(e_{m,t}; \bar{\phi}_t, m), \qquad (24) \\ \text{where } f_e &> 0, f_{\bar{\phi}} > 0, f_m > 0. \end{aligned}$$

Next period's efficiency is an increasing function of this period's efficiency and of the fraction of specific-skill workers employed in the modern sector (since this increases the opportunities for learning). Although the returns to each of these are decreasing individually, this does not guarantee that the function $f(e_{m,t}; \phi_t)$ is concave in $e_{m,t}$. The learning function is guaranteed to be concave in e only if the cross partial, $\frac{\partial\psi}{\partial\delta\partial e}$, is negative. Otherwise, the learning function may be convex or S-shaped in e. Intuitively, the curve might be S-shaped if at low levels of $e_{m,t}$, learning is slow because relatively few workers are in the modern sector, and at high levels of $e_{m,t}$, learning is slow because of the decreasing rate of learning in $e_{m,t}$ despite having almost all labor allocated to the modern sector.

On the reasonable assumption that no learning takes place if the modern sector is not open ($\psi(0, e_{m,t}) = e_{m,t}$), it is clear that a factor endowment that lies below the cone of diversification now has serious implications for the long term growth of the economy. Any economy with a sufficient supply of general skills to open the modern sector at all eventually converges to complete modernization. By contrast, if the economy is insufficiently endowed with general skill labor for the modern sector to open, the economy stagnates, remaining an entirely traditional economy permanently, even with freely available modern technology.

Since, for a given level of efficiency, the rate of learning is determined by δ, the same comparative statics apply to the rate of learning as to δ. In particular, for a given level of initial efficiency, countries with a greater supply of general-skill labor modernize more quickly. This appears quite reasonable and is consistent with historical experience. For example, during the late 19th Century and early 20th Century, Germany and the US both experienced more rapid growth than Britain in the then modern sectors such as the chemical industry. Britain's relative failure to compete in these industries has been blamed in part on the failure of its education system to provide a sufficient supply of scientists and other skilled workers.[15]

Once the learning function is understood, the dynamic path of wages and the sectoral allocation of labor in the economy can easily be analyzed as a sequence of comparative statics. Considering first the input ratios, at the moment of introduction, the modern sector is much

[15] See, for example, Broadberry and Ghosal (2002) on services and Chandler (1990) on manufacturing.

more general-skill intensive than either the economy as a whole or the traditional sector. As e_m increases, the general-skill intensity of both sectors falls, although the general-skill intensity of the modern sector falls more rapidly. Once efficiency rises to the point implicitly defined by equation 21, the desired skill intensity of the modern sector falls to the skill intensity of the economy as a whole: at this point, the traditional sector shuts down.

Turning to the wage premium, since opening reduces the general skill-intensity of the traditional sector, specific-skill wages fall on opening. The wage premium increases monotonically with e_m until the traditional sector shuts down. Only once the economy has fully modernized do further increases in e_m increase earnings of specific-skill workers. Wage inequality returns to its original level when specific-skill workers become fully efficient in the frontier sector. It is interesting to note in this context that the last of the handloom weavers (who perhaps can be taken as a proxy for the traditional sector as a whole) disappeared around the 1840s, around the same time the general level of wages started to increase more noticeably.[16]

Finally, throughout the period of adoption, the fraction of labor of both types working in the modern sector increases monotonically, although a greater fraction of general-skill workers always work in the modern sector, until the economy modernizes.

3.2 A moving frontier

The world technology frontier has so far remained fixed. Consider now exogenous technical progress at rate x, so that the frontier technology at time $t+n$ is described by

$$a_m(t+n) = a_m(t)\, x^n. \tag{25}$$

With a moving frontier, additional assumptions and notation are required concerning efficiency across vintages. Efficiency in vintage i in period t is indexed as $e_{i,t}$. If a sector is the modern sector in period t, its efficiency in period t is denoted $e_{m,t}$. If it was the modern sector in period $t-1$, its efficiency in period t is denoted $e_{\bar{m},t}$. The transferability function generalizes to:

$$e_{m,t} = h\left(e_{\bar{m},t}, x\right) \tag{26}$$

$$\text{where } h_e > 0, h_x < 0, h_{ee} < 0, h_{xx} > 0, h_{ex} < 0$$

The transferability function stipulates that efficiency in the modern sector in period t is a function of two variables, current efficiency in the most advanced sector used last period, $e_{\bar{m},t}$,

[16] See Blythell (1969) on the handloom weavers. Feinstein (1998) surveys the extensive literature on real wages and presents evidence that real wage growth only picked up from the 1850s or 1860s.

and the technological distance between that sector and the modern sector this period, x. The following assumption replaces Assumption A2:

Assumption A4: *Let* $\zeta(e_{\bar{m},t}, x) \equiv xe_{m,t} = xh(e_{\bar{m},t}, x)$. *Then* $\zeta(e_{\bar{m},t}, 1) = e_{\bar{m},t}, \zeta_x < 0, \zeta_{xx} < 0$.

As in the static model, this assumption guarantees that no intermediate vintages between last period's frontier and this period's frontier will be used in equilibrium. However, it does not guarantee that these two vintages will be used in equilibrium. This is because the older, fully-understood traditional technology is still available. From the unit cost function, equation 6, it can be shown that for any given technology, $\tilde{r}$, unit costs are equal to those in the modern and traditional sectors (dropping time subscripts) if

$$\tilde{r}e^*_{\tilde{r}} = \left[1 - \left(\frac{\tilde{r}^{\frac{\rho}{1-\rho}} - 1}{m^{\frac{\rho}{1-\rho}} - 1}\right)\left(1 - (me_m)^{\frac{\rho}{1-\rho}}\right)\right]^{\frac{1-\rho}{\rho}}. \tag{27}$$

If $e_{\tilde{r}} > e^*_{\tilde{r}}$, the traditional sector closes and the economy modernizes: it uses instead the current period's frontier technology and last period's frontier technology.

It follows that, with a moving frontier, an economy in which two sectors are open can be one of two types.

The first type is the developing country case. In this case, the two open sectors are the traditional sector and the current frontier sector, which is continually updated. The continual updating of the modern sector slows learning relative to the fixed frontier case. On the other hand, continual increases in technology favor expanding the modern sector.

If enough learning occurs, eventually the traditional sector will close. This occurs when efficiency in last period's frontier vintage is sufficiently great. In equation 27, this involves $\tilde{r} = \frac{m_t}{x}$. Rewriting the equation, the traditional sector is abandoned if

$$e^*_{\bar{m}} \geq \frac{m_t}{x}\left[1 - \left(\frac{m_t^{\frac{\rho}{1-\rho}} - x^{\frac{\rho}{1-\rho}}}{m_t^{\frac{\rho}{1-\rho}} - 1}\right)\left(\frac{1 - (m_t e_{m,t})^{\frac{\rho}{1-\rho}}}{x^{\frac{\rho}{1-\rho}}}\right)\right].$$

It follows that positive (net) learning need not actually occur in this economy in order for it to eventually abandon the traditional sector, since continued technical advance reduces the critical value of $e^*_{\bar{m}}$ required in order to modernize.

In the modern economy, there are still two open sectors, but these are now the current frontier (denoted m) and last period's frontier (denoted o, since last period's frontier is the old sector this period). A balanced growth path is achieved when the loss of frontier efficiency caused by moving to the new frontier each period is exactly compensated for by learning over the period during which a particular technology is on the frontier. With constant relative efficiencies, the

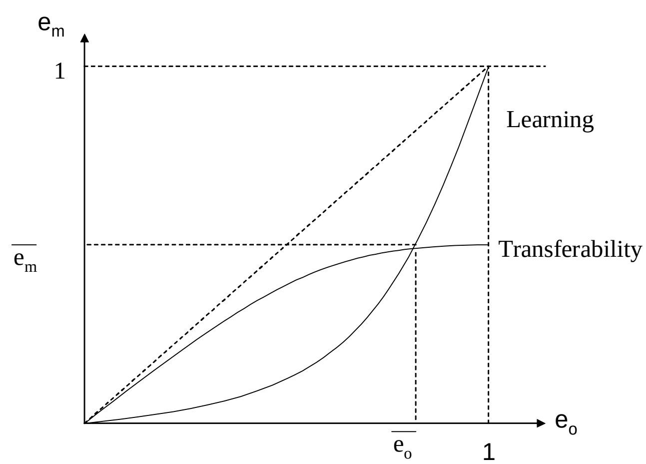

Figure 4: Balanced Growth with a Moving Frontier

allocation of workers between the modern and the older technology is also constant. From equations 24 and 26, this can be seen as the value of e_m such that

$$\bar{e}_m = h\left(f\left(\bar{e}_m, \bar{\phi}, x\right), x\right).$$

A simple example of this fixed point is shown in Figure 2.4. The concave curve is the transferability function, mapping efficiency in this period's old sector to efficiency in this period's frontier sector. The other curve, is the learning function, which maps efficiency in the modern sector this period to efficiency in the old sector next period. In Figure 2.4, the learning curve is convex, and so the equilibrium is unique. As noted, however, the learning curve need not be strictly convex, and with a sufficiently S-shaped learning curve this economy can exhibit multiple equilibria for certain values of $\bar{\phi}$. Increases in the supply of general skills raise the learning function and can thereby eliminate the multiple equilibria.

The response of inequality to changes in parameters is quite complex. The ratio of factor intensities across sectors is now

$$\left(\frac{\phi_m}{\phi_o}\right) = \left(\frac{e_m}{e_o}\right)^{\frac{\rho}{\rho-1}} = \left(\frac{e_m}{e_o}\right)^{1-\sigma}. \tag{28}$$

This implies that skill intensity in the less-advanced sector is

$$\phi_o = e_o^{\frac{-\rho}{1-\rho}}\left[\left(\frac{\lambda}{1-\lambda}\right)\left(\frac{e_o^{\frac{\rho}{1-\rho}} - (xe_m)^{\frac{\rho}{1-\rho}}}{x^{\frac{\rho}{1-\rho}} - 1}\right)\right]^{\frac{1}{\rho}}. \tag{29}$$

Therefore, steady-state income inequality is

$$\frac{w_G}{w_S} = \left(\frac{1-\lambda}{\lambda}\right)^{\frac{1}{\rho}} \left[\frac{e_o^{\frac{\rho}{1-\rho}} - (xe_m)^{\frac{\rho}{1-\rho}}}{x^{\frac{\rho}{1-\rho}} - 1}\right]^{\frac{\rho-1}{\rho}} \tag{30}$$

$$= \left(\frac{1-\lambda}{\lambda}\right)^{\frac{1}{\rho}} \frac{1}{e_o} \left[\frac{1 - (x\frac{e_m}{e_o})^{\frac{\rho}{1-\rho}}}{x^{\frac{\rho}{1-\rho}} - 1}\right]^{\frac{\rho-1}{\rho}} \tag{31}$$

Equation 31 shows that inequality increases when e_m increases, and falls when e_o increases. However, e_m and e_o may often change in the same direction. If e_o increases and $\frac{e_m}{e_o}$ falls, then inequality is unambiguously reduced, but if $\frac{e_m}{e_o}$ rises, there is no clear prediction relating to inequality.

Around the balanced growth path, it is possible to derive a rich set of comparative statics with respect to technical change. Inequality can respond to at least three types of changes in this economy. The first is an increase in skill transferability, such that the function $h(\cdot)$ is shifted up. A second is an increase in the rate of learning, such that the function $f(\cdot)$ is shifted out. Finally, there can be a change in the rate of technical progress, x.

Consider first an increased rate of transferability. This shifts up the transferability curve without affecting the learning curve. In the first generation after such a shock, only e_m increases, and hence inequality increases. In subsequent periods, however, e_o also rises, as the higher starting point feeds into higher efficiency in the less advanced sector. Whether the initial rise in inequality is entirely undone is not clear, since in equilibrium, e_o rises, but so does $\frac{e_m}{e_o}$, so long as the learning curve crosses the transferability curve from below, as shown in Figure 2.4. This is true of any stable equilibrium.[17]

By contrast, it is possible to sign the effect of an increase in learning. Shifting out the learning curve implies that equilibrium occurs at a point further along the concave transferability function. Hence, e_o increases and $\frac{e_m}{e_o}$ decreases, both of which reduce inequality. Adjustment towards the new steady-state is monotonic: inequality decreases gradually towards its new steady state.

The most obvious source of an increase in learning, for a given rate of technical advance, is an expansion in the supply of general-skill labour. This increases learning by increasing the size of the modern sector. Thus, the relative demand curve slopes down, effectively through a quasi-Rybczynski effect.

Finally, consider the effect of a change in the rate of technical progress. Holding relative efficiencies constant, an increase in the rate of technical progress increases the general-skill

[17] The initial shock to inequality when transferability increases is similar to the result in Aghion, Howitt and Violante (2002), although with fixed supplies they argue inequality increases permanently, because they have no general equilibrium effect on efficiency of older vintages.

premium. However, both the learning curve and the transferability curve are drawn for given x, so this is not a satisfactory comparative static. Greater x shifts the transferability curve down. Although this reduces both e_o and e_m, it also implies a fall in $\frac{e_m}{e_o}$, suggesting that the net effect is ambiguous. Similarly, for a given level of efficiency, more resources will now move to the modern sector. Hence, there will be greater learning for a given level of efficiency. It follows that the learning curve must shift outwards as a result of an increase in the rate of technical progress. This provides a further offsetting influence to the initial increase in inequality that occurs as a result of an increased rate of technical progress.

4 Extensions

4.1 Supply Responses

Endogenising the supply of general relative to specific skills adds little to the intuition of the model. The most important results, namely the dual economy and the changes in inequality, are not affected, since these are independent of factor supplies. The first order effect of an increase in e is to increase the premium paid to general skill workers. Therefore, if the supply of general skill workers is not completely elastic, endogenising supply merely hastens the rate at which the traditional economy converges to the modern economy. In the short run, this implies that the wage premium actually goes up faster, the greater the increase in general-skill workers. In other words, a time series regression of the wage premium on the relative supply of general skill workers would be perversely signed.

Another implication of the model is that the process of adopting a new technology creates large temporary quasi-rents to any specific skill workers who manage to acquire extra efficiency units of labour at the frontier. This suggests a possible explanation for the growth of technical education institutions in both developed and developing countries over recent decades, compared to gaining experience on the job as in a traditional apprenticeship. Suppose that instead of gaining experience on the job, it is possible to attend a technical college, which transfers a fixed amount of efficiency units to a specific-skill labourer. Then a specific skill worker gains more from going to technical college at a time of rapid technical change than when technologies are relatively well understood. This is consistent with the general move away from apprenticeship and other on-the-job training programs for specific-skill workers.

4.2 Experience Effects

The dynamic section assumed zero marginal product in the first period. Suppose instead that old workers gain some specific capital relative to young workers in the same sector, so that experienced workers supply $(1+\kappa)$ times as much effective labor as young workers. So long as young and old workers are perfect substitutes, however, the ratio of their wages must be fixed. Moreover, so long as κ is the same in each sector, the ratio of young to old earnings must be the same in both sectors. It follows that the lifetime path of earnings must be the same in both sectors. Hence, wages for specific-skill workers must be equalised across sectors in all periods. So a modification that allows young and old workers to be perfect substitutes would have no effect on the model. What if young and old workers are imperfect substitutes, as in Chari and Hopenhayn? For instance, suppose output is produced according to a nested CES function such as:

$$Y = a\left\{\lambda\left[\mu S_1^{\eta} + (1-\mu)\, S_2^{\eta}\right]^{\rho/\eta} + (1-\lambda)G^{\rho}\right\}^{1/\rho},$$

where S_1 is the effective supply of young specific-skill workers and S_2 is the effective supply of experienced specific-skill workers. So long as neither is more relatively substitutable for general skill workers than the other, as in the production function above, this would introduce some life-cycle dynamics along the lines of Chari and Hopenhayn without significantly affecting the relationships of interest here. In fact, this extension would strengthen the results, since the shortage of old workers in the frontier sector would further slow technology adoption. In short, generalising the assumption of zero marginal productivity in the first period would complicate the analysis without adding significantly to the insights of the model.[18]

4.3 More than one good, trade and empirical applications

The model can easily be extended to consider the effect of vintage-specific skills in a context where these skills are also industry-specific. Consider first the effect of technical change in only one sector. This increases output in the sector, reducing the price of the good. This introduces an additional effect beyond that already modelled. The wage of specific-skill labour in this sector must fall, but general skill labour continues to be paid the same amount. Hence, the key prediction is that the wage premium in this sector increases. In general, with skills that are both vintage and sector specific, the model provides a framework for considering industry-specific skill differentials.

Price falls and/or output increases associated with new technology will be associated with two observable developments within the affected sector. First, as described above, intra-industry

[18] Moreover, the complementarity between experienced and inexperienced workers may not be very large. Estimates of the elasticity of substitution of workers across potential experience groups are around 5 to 10 (see Card and Lemieux (2001), and Borjas (2003)). Although this probably overstates the substitutability of workers with different actual experience within an industry, it is substantially different from Chari and Hopenhayn's central case elasticity of about 1.1 ($\eta = .1$). Chari and Hopenhayn's effects are smaller, the larger the elasticity of substitution.

wage differentials rise. Second, the dispersion of skill-intensity across plants within the industry increases. In the most extreme case, a technological opening, plants will go from completely homogeneous to a split between modern, general-skill intensive plants and traditional, specific-skill intensive plants.

What if new technologies simultaneously become available in all industries? The basic prediction arising from a multi-good model is that the fastest-adopting industries will be those that have the greatest steady-state general skill bias. Therefore, the industries that start out as the most general-skill intensive will experience the greatest changes in intra-industry wage differentials and intra-industry plant dispersion early in the period of adoption, while the others follow.

Hence, if a developing country opens technologically, the most general-skill intensive goods should fall furthest in price/grow most in output. Obviously the price prediction is no different from Heckscher-Ohlin trade theory. But with vintage-sector-specific factors, no sector will close entirely, even if prices are set exogenously at the world level. If trade causes prices to fall most in relatively general-skill intensive sectors, specific-skill workers in that sector will be even more adversely affected. Unlike the simple Heckscher-Ohlin model, therefore, this model is consistent with increased inequality in poor countries that open their economies to trade (and other forms of technology transfer).

5 Conclusion

This paper has argued that a simple model of production in which general human capital and vintage-specific human capital are complements in production is useful in thinking about a number of issues in economic growth. The model builds on a couple of observations. First, different vintages of technology are often used at the same time in (roughly) the same place. Second, different workers are tied to particular tasks relating to a given level of technology to greater or lesser degrees, and these workers are not perfect substitutes. Although the ability to transfer skills across vintages is often related directly to ability, this paper has remained agnostic on this point, since endogenising supply makes little difference to the results. Thus, different degrees of transferability could relate to differences in innate ability, years of schooling, or even different types of schooling, such as apprenticeships and university degrees. Finally, new vintages of technology typically appear to benefit from learning-by-doing, and since workers differ in the degree to which their skills are vintage-specific, it would not be too surprising if learning-by-doing were also a biased process.

Developing these observations in the model leads to predictions consistent with some stylised facts of technical change. In the model, different vintages of technology coexist, and there is a dual economy if the economy starts out far enough behind the frontier. Technical change has strong effects on the distribution of wage income. In particular, the introduction of a new technology worsens the position of workers whose skills are relatively vintage-specific, both in relative terms, and, more notably, in absolute terms. This effect is not limited to the workers who continue to use the old technology, but is a general equilibrium effect common to workers with specific-skills in both the old and the new technology. Moreover, the negative effect on the wages of specific-skill workers actually increases as they become better acquainted with the new technology, and it is only after the old technology is abandoned that inequality starts to return to its initial level.

The dynamic version of the model extends these insights. Moreover, it illuminates the similarities between dual economies in developing countries and the ongoing process of technical development in developed countries. The eventual closure of the traditional sector suggests a systematic way to think of the difference between developing and developed economies. The developed country case of the model suggests a number of ways in which different types of technical change can affect inequality. For example, increases in the transferability of skills across vintages have an ambiguous effect in general equilibrium, contrary to what is often found in papers that adopt a partial equilibrium analysis.

The paper suggests that the Luddites can be right: new technology can hurt some workers. But it does not follow that policy should protect old industries. In fact, the reverse is true. Since learning is external, the economy modernises inefficiently slowly, and the best policy is to encourage the closure of old industries. Wages of lower skilled workers will not start to recover until these industries close. In this spirit, it is interesting that the general level of wages during the Industrial Revolution increased decisively only from around the 1840s, just as old technologies, such as handloom weaving, finally disappeared. In a more modern context, the model illuminates the decline of low-skilled wages in the US since the 1970s and the increase in inequality amongst poor countries opening their economies. It also, however, gives some grounds for hoping that these will be temporary phenomena, preceding, in both cases, sustained future wage increases.

6 Mathematical Appendix

6.1 Social Planner's Problem

In this appendix I sketch the proof that the resource allocation decision for the social planner is equivalent to the allocation of resources achieved in competitive equilibrium.

The social planner maximizes

$$\begin{aligned} \max_{f_s(r), f_g(r)} Y &= \int_r r[\lambda e(r)^\rho (f_s(r)\bar{s})^\rho + (1-\lambda)(f_g(r)\bar{g})^\rho]^{\frac{1}{\rho}} d(r) \\ \text{subject to } \int_r f_s(r) d(r) &= 1 \\ \text{and } \int_r f_g(r) d(r) &= 1 \end{aligned}$$

where $f_s(r)$ is the density function of specialists in the economy using a given vintage of technology.

To see the equivalence of this problem to the perfectly competitive problem, note that the text has already shown the conditions under which it is true that, for *any* factor ratio, output is always maximised at either $r = 1$ or $r = m$. Since by definition the social planner wishes to maximize output, it follows that, if those conditions are satisfied, the social planner's allocation will necessarily take the form

$$f(s) = \begin{cases} c & \text{if} \quad r = 1 \\ 0 & \text{if} \quad 1 < r < m \\ 1 - c & \text{if} \quad r = m \end{cases}$$

where c is a constant to be solved for, and $f_g(r)$ can be defined similarly.

It follows that the social planner's problem is a simple constrained maximisation problem as follows:

$$\begin{aligned} \max_{s_0, s_w, g_0, g_w} Y &= [\lambda s_0^\rho + (1-\lambda) g_0^\rho]^{\frac{1}{\rho}} + m[\lambda e_w^\rho s_w^\rho + (1-\lambda) g_w^\rho]^{\frac{1}{\rho}} \\ \text{subject to } s_0 + s_w &= \bar{s} \\ \text{and } g_0 + g_w &= \bar{g}. \end{aligned}$$

It is obvious that the first order conditions of this problem require that the marginal product of a particular type of worker must be equal in either sector. Since this is the same condition as in the perfectly competitive problem and there are no externalities, the social planner's allocation is identical to the perfectly competitive allocation.

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