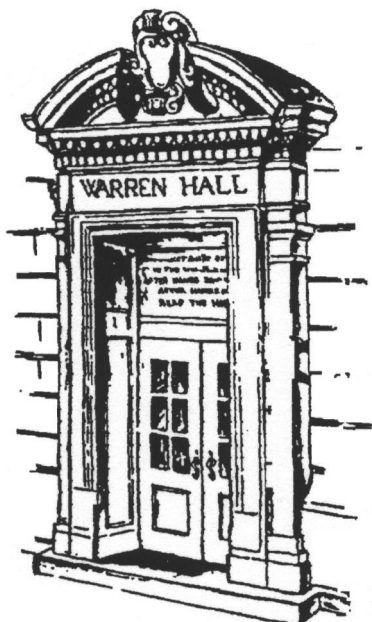


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Endogenous Technical Progress and Spillovers in a Vertically-Linked Model of Economic Geography

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Abstract

Technology has generated vast economic surpluses, but has also driven extreme and growing economic inequality due to the self-reinforcing nature of technical progress and technology diffusion. Economists have recently renewed their interest in the important role of geography in the creation and diffusion of technology – and hence in economic development and inequality. This paper contributes to this effort by introducing a simple endogenous growth process in which labor productivity increases with industry size and spillovers between regions are possible into a core-periphery vertically-linked model(1996). Rather than isolating their effect, this paper studies the implications of adding endogenous growth and spillovers to the existing vertical linkages of the Puga and Venables (1996) model. Multiple equilibria may obtain when endogenous growth with spillovers is added. While endogenous technical progress is generally an agglomeration force and spillovers are a dispersion force, the strength of these forces is mediated by trade costs. Finally, the dispersion forces associated with increasing spillovers and relatively low, falling trade costs mostly operate independently, but there are critical values of trade costs at which the two are strong ‘dispersion complements’ such that a marginal increase in spillover scope significantly reduces the economic inequality between the two regions. The existence of such tipping points suggests that some countries attempting to increase technology spillovers into its economy may enjoy few development benefits while others may reap substantial gains.

Keywords: Technology, Inequality, Economic Development, Industrialization

JEL Classification Codes: O0, O3, O4, F2

I. Introduction

In the global economy, technology inequality is very apparent, at times extreme, and seems to be growing. Today's technology disparities trace their origins most directly to the Industrial Revolution (1780-1860), which emanated from Great Britain and marked the beginning of an age of increasing temporal and spatial technological inequality. The effects of this prosperity wedge between nations persist due to the self-reinforcing nature of technical progress. Consequently, inequalities of income across the globe today, while extreme, may actually be exceeded by inequalities of scientific output and technical innovation (Sachs 1999). Furthermore, technology flows between technically disparate regions are far from frictionless.¹ While expected profitability of a new technology largely determines its rate of diffusion (Griliches 1957), the local diffusion of profitable technologies from firm-to-firm can take up to 50 years (Rosenberg 1982). Recently, Keller (2002) has (2002) examined this link more explicitly, concluding that the geographic half-life of technology, the distance at which only half of the technology stock at the origin remains, is about 1,200 km. Geography, it seems, plays a lead role in the creation and diffusion of technology.

While early economists recognized that economic development hinges importantly on technical progress, the advent of endogenous growth modeling techniques allowed for more rigorous analysis of the interaction between innovation and development (Grossman and Helpman 1991, Romer 1990). More recently, the emerging 'new economic geography' has brought new modeling approaches to bear on the location decisions made by economic agents (Krugman 1991, Krugman and Venables 1995). The intersection of endogenous growth and new economic geography was quickly recognized as a fruitful ground from which insights into the process of technology creation, the spread of industry between countries and economic development could spring (Baldwin and Forslid 2000, Martin and Ottaviano 2001). This paper contributes to this effort by introducing into a two-region economic geography model in the spirit of Puga and Venables (1996) a simple endogenous growth process in which labor productivity increases with industry size and spillovers between regions are possible. Rather than

¹ New ideas are mostly recombinations of old ones and, while nonrival in nature, are generally at least partly excludable thanks to legal and social institutions such as trade secrets and intellectual property. Thus innovation typically shows increasing returns to scale (Romer 1990) and technology stocks are thus less likely than capital stocks to converge across national borders (Sachs 2000). There are also potential environmental, societal,

isolating their effect, this paper studies the implications of adding endogenous growth and spillovers to the existing vertical linkages of the Puga and Venables (1996) model. How do the dispersion forces associated with spillovers and falling trade costs jointly affect the spread of industry from one region to the other? Are falling trade costs and increasing spillovers dispersion substitutes or complements?

Section II reviews the new economic geography and discusses previous efforts to combine these models with endogenous growth. Section III contains the derivation of the basic model, then presents a specification of endogenous technical progress. Section IV presents results from the analysis. Section V discusses possibilities for future research and concludes.

II. Technical Progress and Development in Economic Geography

The basic 'new economic geography' story, summarized succinctly in recent surveys on the topic (see Baldwin, et al. 2003, Neary 2001, Schmutzler 1999), goes as follows. Increasing returns to scale make geographical concentration of the production of each good profitable. When transportation costs are added, these agglomeration forces are magnified as producers seek to locate close to their suppliers (input markets) and their consumers (output markets). This concentration is self-reinforcing in that it attracts mobile factors of production to the producers' increasingly concentrated location, thus building a local output market. These forces are 'second-nature' since they are a function not of natural endowments, but of the existence of consumers and other firms. Dispersion forces, which repel economic agents from concentrated locations, typically arise from input and output prices being driven up in response to increasing local competition for resources.

Fujita, Krugman and Venables (Fujita, et al. 1999) (henceforth FKV) synthesize the founding new economic geography research (Krugman 1991, Krugman and Venables 1995, Puga and Venables 1996) and suggest a useful approach to modeling geographic agglomeration. Following Krugman and Venables (1995) and Puga and Venables (1996), FKV present in chapter 15 a model of economic development in which firms are vertically-linked through intermediate goods.² With this Core-Periphery Vertically-Linked (CPVL) model,³ they posit a

institutional, economic, and political pitfalls to the process of technology transfer (David 1975, North 1991, Rosenberg 1982, Sagasti, et al. 1994).

² The driving element in new economic geography models is either vertical linkages, as in this paper, or interregional factor mobility. Note that the model presented in FKV chapter 15 is identical in spirit to the Puga and

simple exogenous growth process, constant across sectors and countries, as primarily driving economic change and the spatial expansion of manufacturing industry. The growth process is exogenous because they “are concerned with the spatial implications of growth, and not with its origins” (Fujita, et al. 1999, p.264). Purposely beginning with no inherent differences between countries, the CPVL model highlights that "industrialization in the world economy occurs via a series of dramatic developmental spurts, with a few countries at any given time experiencing surging production and wages while others are for the time being left on the sidelines" (Fujita, et al. 1999, p.277). These rather complex results are driven by the forward and backward linkages built into the model via intermediate goods in the production technology.

Economic geography models developed subsequently have linked industrialization with endogenous growth. This stream of research, summarized nicely in Baldwin et al. (2003, p.186-8), highlights the importance of technological spillovers and spillover scope.⁴ Martin and Ottaviano (1999) extend the CPVL model to allow endogenous growth with either global and local spillovers. They show that even if spillovers are local and industry remains concentrated in one region both regions may benefit from industrial concentration, relative to the symmetric outcome, if the rate of innovation is sufficiently high. Baldwin and Forslid (2000) introduce endogenous growth with spillovers ranging continuously from local to global into a core-periphery model without vertical linkages and conclude that while endogenous growth is an agglomeration force, spillovers are a dispersion force. Martin and Ottaviano (2001) isolate the effect of endogenous growth and show growth can be an agglomeration force independent of interlocational factor mobility or intrasectoral vertical linkages.

The model developed in this paper, like Martin and Ottaviano (1999), extends the CPVL model to include endogenous technical change. A simple endogenous growth process is introduced by allowing labor productivity to grow with (manufacturing) industry size. Unlike Martin and Ottaviano (1999), the growth specification allows spillovers to vary continuously

Venables (1996) model. In developing the model in this paper, I chose to follow the model contained in FKV chapter 15, while recognizing that the original version of the model is contained in Puga and Venables (1996).

³ This helpful taxonomy is borrowed from Baldwin et al. (2003).

⁴ Spillovers are local when positive productive externalities (e.g., knowledge/information leaks) are contained within regions. Spillovers are global when these externalities benefit both regions equally, regardless of their origin. Spillovers are conceptually distinct from technology transfer—spillovers are incidental and organic whereas technology transfer is deliberate and structured—but in the abstract both represent an inter-regional productivity linkage and are thus indistinguishable. Throughout this paper I use the term ‘spillovers,’ while recognizing that given the formulation of the model ‘technology transfer’ is an equally-valid interpretation of the inter-regional productivity linkage.

from local to global. Rather than isolating the effect of endogenous growth as in Martin and Ottaviano (2001), this paper studies the implications of adding endogenous growth with spillovers to the existing forces of the CPVL model. Ultimately, the paper evaluates how the dispersion forces associated with spillovers and falling trade costs jointly affect the spread of industry from one region to the other. Instead of focusing explicitly on the stability of the symmetric equilibrium, this paper assesses the impact of endogenous technical change on the spread of industry and real wage inequality in the spirit of Puga and Venables (1996) and FKV (1999, chapter 15).

III. An Economic Geography Model with Endogenous Growth

This section's presentation of the CPVL economic geography model follows FKV (1999), but also borrows from the excellent description of the model in Baldwin et al. (2003, chapter 8). The emphasis herein is on the key elements of the CPVL model, and readers interested in greater detail are referred to FKV (1999). After describing the model, I propose, discuss and incorporate a functional specification of endogenous technical change in which labor productivity increases with manufacturing industry size. The endogenous growth function is specified to facilitate interpretation and to fit into the CPVL model with minimal modification.

The CPVL model assumes there are two identical regions, 1 and 2 , and two sectors, a perfectly competitive agricultural sector (A) producing a single homogeneous good, and an imperfectly competitive manufacturing sector (M) producing a large variety of differentiated goods along a continuous product space. Competition in the M sector is modeled as Dixit-Stiglitz monopolistic competition (Dixit and Stiglitz 1977). Goods from the A sector are traded costlessly, as are M goods traded *locally* (i.e., intra-regionally). To trade one unit of M inter-regionally, however, an M firm must ship $T > 1$ units (i.e., iceberg trade costs). Labor is mobile within, but not between, regions so that equilibrium wage rates for sectors A and M are equalized within, but not necessarily between, each region.

Consumers have two-tiered preferences over A and M . The upper tier consists quasi-homothetic preferences specified as a linear expenditure system in which a subsistence quantity of A , denoted \bar{Y} , must be consumed before any M goods. The lower tier consists of a Constant

Elasticity of Substitution (CES) aggregation of each variety of manufactured good available. Formally,

$$(1) \quad \begin{aligned} U &= M^m (A - \bar{Y})^{1-m}, \\ M &= \left[\int_0^n m_j^{(s-1)/s} dj \right]^{s/(s-1)} \end{aligned}$$

where μ is the expenditure share of M goods ($0 < \mu < 1$), m_j represents the consumption of each variety available, n is the range of varieties produced, and σ is the elasticity of substitution between varieties ($\sigma > 1$).⁵ The subsistence requirement ensures that consumers' demand for M increases with their income. In maximizing utility, consumers must first choose m_j to minimize the cost of attaining a given level of M before choosing their consumption of A and M to maximize utility subject to their budget constraint. Assuming income is measured in terms of A , the budget constraint is the following in region i :

$$(2) \quad G_i M + A = Y - \bar{Y}$$

where G_i is a price index for M goods in region i and the right hand term is discretionary or supernumerary income. The upper tier maximization problem yields

$$(3) \quad \begin{aligned} M_i &= \frac{m}{G_i} (Y - \bar{Y}), \\ A_i &= \bar{Y} + (1-m)(Y - \bar{Y}) \end{aligned}$$

Combining these results with the lower tier preference maximization yields uncompensated consumer demand functions for each variety, m_j , of M as⁶

$$(4) \quad m_j = \frac{m}{G_i^{-(s-1)}} (Y - \bar{Y}) p_j^{-s}$$

Increasing returns to scale production in the M sector requires both a marginal (c) and a fixed (F) level of a single input. That is, the production of output q requires $F + cq$ units of the input. Following FKV (1999, chapter 14), the production technology is defined indirectly in terms of a price index of production. The single input is a Cobb-Douglas composite of labor and intermediate goods with a as the share of intermediate goods in the input. Thus the price of this composite input is $w_i^{1-a} G_i^a$, where w_i is the wage rate in region i . Assuming intermediate goods

⁵ While σ is defined as an elasticity of substitution between varieties, it ultimately dictates the economies of scale at equilibrium (see Krugman 1991, Neary 2001).

⁶ This is a standard CES demand function derivation. For details on the derivation in the context of this model see FKV (1999, p.46-8).

are aggregated according to a CES function with the same elasticity of substitution (σ) as in the consumers' lower tier utility function in equation (1), the price index is defined as

$$(5) \quad G_1 = [n_1 p_1^{1-\sigma} + n_2 (T p_2)^{1-\sigma}]^{1/(1-\sigma)}$$

where n_i represents the range of varieties in region i and price indices in region 2 are defined analogously. If firms set their output price, p , taking the price indices as given, then σ is the perceived elasticity of demand and the profit maximizing pricing rule is

$$p_1(1-1/\sigma) = c w_1^{1-a} G_1^a$$

or

$$(6) \quad p_1 = c w_1^{1-a} G_1^a \left[\frac{a}{a-1} \right]$$

Choosing units such that $c=(a-1)/a$ —implying that the marginal input required by the production technology equals the price-cost markup—ensures that firms in region 1 set their output price according to

$$(7) \quad p_1 = w_1^{1-a} G_1^a$$

As a result of increasing returns to scale, consumers' preference for variety, and the unlimited potential varieties of manufacturing goods, each variety is produced in only one location by a single firm. The number of varieties available is thus precisely the number of firms in operation, and the number of varieties, n , is determined at equilibrium by the exit and entry decisions by profit maximizing M firms. With intermediate goods as a factor of production a firm benefits from locating closer to other producers since other firms are potentially both 'consumers' of the firm's production (forward linkages) and suppliers of an input to the firm's production process (backward linkages).

Assuming both regions have the same labor endowment, which is normalized such that total labor in each region is unity, production technology in the A sector is described by the strictly concave function (as in FKV 1999, chapter 14):

$$(8) \quad A(1-l_i) = \frac{K}{h} \cdot \left(\frac{1-l_i}{K} \right)^h$$

where λ_i is the share of labor in region i devoted to the M sector, K is a constant normalized such that it represents the total stock of a fixed production input (e.g., land) and η is the share of labor in A .

Total expenditures on M in region 1, E_1 , comes from (i) final consumers who devote share μ of their discretionary income to purchasing M and (ii) other firms using intermediate goods as a factor of production. At equilibrium in the M sector, assume firms sell quantity q^* . Because firms have zero-profits at equilibrium, total costs at q^* equals the total value of production, $n_1 p_1 q^*$, and a share α of total production costs pays for intermediate M goods. Thus,

$$(9) \quad E_1 = m(Y_1 - \bar{Y}) + \alpha n_1 p_1 q^*$$

where the first and second terms on the left are consumer and intermediate good expenditures, respectively. Since λ_1 is the share of labor in sector M of region 1 and $(1-\alpha)$ is the share of labor in the composite input, the manufacturing wage bill is defined as,

$$(10) \quad w_1 l_1 = (1-\alpha) n_1 p_1 q^*$$

Following FKV (1999), when units are chosen such that $q^* = 1/(1-\alpha)$ this simplifies to

$$(11) \quad n_1 = \frac{w_1}{p_1} l_1$$

Since labor allocation, λ_i , and wages, w_i —rather than the number of firms, n_i , and prices, p_i —are of primary interest, the price index equation in (3) can now be rewritten in λ and w terms alone. Specifically, substituting equations (7) and (11) into the price index equation in (3) yields the following price index for region 1

$$(12) \quad G_1 = \left[(l_1 w_1^{1-s(1-a)} G_1^{-as}) + (l_2 w_2^{1-s(1-a)} G_2^{-as} T^{1-a}) \right]^{1/(1-s)}$$

with the price index of region 2 derived analogously.

Given the demand function in (4) and q^* as defined above, the manufacturing wage in region 1 that is consistent with zero profits by firms in region 1 is defined implicitly by⁷

$$(13) \quad \frac{(w_1^{1-\alpha} G_1^\alpha)^\sigma}{1-\alpha} = G_1^{\sigma-1} E_1 + G_2^{\sigma-1} E_2 T^{1-\sigma}$$

where, combining equations (9) and (10)

$$(14) \quad E_1 = m(Y_1 - \bar{Y}) + \frac{\alpha w_1 l_1}{1-\alpha}$$

Lastly, consumers' income in region 1 is composed of both agricultural and manufacturing income. Agriculture production is given in equation (8). Since A is taken as the numeraire, agricultural income in region 1 is simply total agricultural production in the region. Total

⁷ Details and discussion of the derivation of this wage equation are found in FKV (1999, p.49-53).

manufacturing income is the product of wages earned and the size of the labor force in the M sector, λ_i .

$$(15) \quad Y_i = w_i l_i + A(1 - l_i)$$

The price index, wage, income, and expenditure equations derived above and presented in (12)-(15) describe the short-term equilibrium of the model. The short-term equilibrium consists of wages and prices in regions 1 and 2 (i.e., w_1, w_2, G_1, G_2). In the long-term, sector labor shares in each region adjust to intersectoral wage gaps, δ_i , where

$$(16) \quad d_i \equiv w_i - A'(1 - l_i)$$

for $i=1,2$. The adjustment dynamic proposed by FKV (1999) and discussed more generally by Baldwin et al. (2003, p.16) implies that within each region, labor moves to the sector with highest wage offering. That is, labor in region i moves to M (A) when δ_i is positive (negative). Thus, a long-term equilibrium consists of wages, prices *and* sector labor shares in regions 1 and 2, where these variables jointly satisfy equations (12)-(15) and the following sector labor share conditions

$$(17) \quad \begin{aligned} w_i &= A'(1 - l_i), & \text{if } l_i &\in (0,1) \\ w_i &\geq A'(1 - l_i), & \text{if } l_i &= 1 \\ w_i &\leq A'(1 - l_i), & \text{if } l_i &= 0 \end{aligned}$$

Endogenous technical change can be added to the CPVL model presented thus far in a simple and straightforward manner. Puga and Venables (1996) and FKV (1999, chapter 15) introduce an exogenous growth process by simply assuming “that technical progress steadily augments all primary factors” (FKV, 1999, p.264) and that technical progress is symmetric across both regions and sectors. Primary factors (labor) are then measured in efficiency units. Thus when labor share λ_i is devoted to manufacturing in region i , the number of efficiency units in manufacturing in region i is $L\lambda_i$, where L denotes the efficiency level. Equilibrium wage rates, w_i , in this augmented model now represent the wage per efficiency unit of labor. The empirical analog to L is total factor (labor) productivity, an index measuring efficiency relative to a base year.⁸ Puga and Venables (1996) and FKV (1999) conclude that forward and backward linkages in the presence of technical progress can generate “dramatic developmental spurts” (p.277). How sensitive is the spread of industry to technology equality across regions? Might endogenous

technology inequalities in the presence of vertically-linked forward and backward linkages yield a different pattern of development?

To endogenize technical progress with minimal modification to the CPVL model, let the efficiency level of region 1 be specified as follows

$$\begin{aligned}
 L_1 &= L_1(l_1, l_2) \\
 (18) \quad &= 1 + \frac{l_1(l_1, l_2)}{100} \\
 &= 1 + \frac{(100l_1)^q (100l_2)^f}{100}
 \end{aligned}$$

where the function l_l maps the M labor shares of regions 1 and 2 measured as percentages⁹ into a factor (labor) productivity growth rate, also measured as a percentage. L_2 is specified analogously. This form has the convenient property that the parameters θ and φ ($\theta \geq \varphi$) are elasticities and therefore readily interpreted. θ is the elasticity of the growth rate with respect to *domestic* industry size, where industry size can be construed in terms of the labor share or the number of M firms at equilibrium given the relationship in (11). φ is the elasticity of the growth rate with respect to *foreign* industry size and captures spillovers between regions. Thus $\varphi > 0$ implies non-local spillovers. The growth rate is assumed to be inelastic to changes in industry size, whether domestic or foreign. Since spillover scope hinges on the relative size of θ and φ , it is convenient to define v as the ratio of the growth rate elasticity of foreign industry size to that of domestic industry size

$$(19) \quad u \equiv \frac{f}{q}$$

where by assumption $v \in [0, 1]$ and $v=1$ implies global spillovers.

Allowing for endogenous technical progress as proposed in equation (18), the four sets of equations—price indices, wage, expenditure and income equations—are fully specified as follows

$$(20) \quad G_1 = \left[(L_1 \lambda_1 w_1^{1-\sigma(1-\alpha)} G_1^{-\alpha\sigma}) + (L_2 \lambda_2 w_2^{1-\sigma(1-\alpha)} G_2^{-\alpha\sigma} T^{1-\alpha}) \right]^{1/(1-\sigma)}$$

⁸ This very simple introduction of a growth process into the model simplifies interpretation, but has the disadvantage of being amenable to various alternative interpretations. For example, because growth is assumed in this formulation to enter only by augmenting labor, an alternative interpretation is that L measures population growth.

⁹ Sector labor shares are measured in percentage terms to insure that $\frac{\partial l_i}{\partial q} > 0$ and $\frac{\partial l_i}{\partial f} > 0$

$$G_2 = \left[(L_2 \lambda_2 w_2^{1-\sigma(1-\alpha)} G_2^{-\alpha\sigma}) + (L_1 \lambda_1 w_1^{1-\sigma(1-\alpha)} G_1^{-\alpha\sigma} T^{1-\alpha}) \right]^{1/(1-\sigma)}$$

$$(21) \quad \frac{(w_1^{1-\alpha} G_1^\alpha)^\sigma}{1-\alpha} = G_1^{\sigma-1} E_1 + G_2^{\sigma-1} E_2 T^{1-\sigma}$$

$$\frac{(w_2^{1-\alpha} G_2^\alpha)^\sigma}{1-\alpha} = G_2^{\sigma-1} E_2 + G_1^{\sigma-1} E_1 T^{1-\sigma}$$

$$(22) \quad E_1 = \mu(Y_1 - \bar{Y}) + \frac{\alpha w_1 L_1 \lambda_1}{1-\alpha}$$

$$E_2 = \mu(Y_2 - \bar{Y}) + \frac{\alpha w_2 L_2 \lambda_2}{1-\alpha}$$

$$(23) \quad Y_1 = w_1 L_1 \lambda_1 + A((1-\lambda_1)L_1)$$

$$Y_2 = w_2 L_2 \lambda_2 + A((1-\lambda_2)L_2)$$

IV. Analysis of Endogenous Growth, Spillovers and Trade Costs

Before delving into the analysis of the CPVL model with endogenous technical progress, it is helpful to describe intuitively the forces at play. Since location choices are central to the CPVL model, the key forces are those that promote agglomeration and those that promote dispersion. Endogenous growth, as it has been specified in previous models, is an agglomeration force (Baldwin and Forslid 2000, Martin and Ottaviano 2001). Similarly, endogenous technical progress as specified in equation (18) exerts agglomeration pressure by rewarding industrializing regions with higher factor productivity. That is, when a worker in region 1 switches from A to M employment, she raises the productivity of both A and M workers, offering clear incentives for concentration of manufacturing activity.

An additional agglomeration force arises from the linear expenditure system formulation of consumer preferences. As L_i increases, whether it is exogenous or endogenous, so too does household income (equation (23)). Given the subsistence requirement, $\bar{Y} > 0$, the share of total income devoted to manufactured goods expands relative to the share of agricultural goods, which as in 1(b) of Table 1 drives up manufacturing wages. This agglomeration force associated with

increases in L makes possible the spread of industry highlighted in Puga and Venables (1996) and FKV (1999, chapter 15).¹⁰

Agglomeration and dispersion forces can be further understood by considering the effects of increasing the manufacturing labor share in region 1, λ_1 , on the wage gap in that region, δ_1 (FKV, 1999, p.245). Table 1 summarizes the agglomeration and dispersion forces at play in the standard CPVL model and compares these forces to those of models with exogenous technical progress and with the endogenous technical progress specified in the previous section.

Agglomeration forces are amplified when technical progress, whether exogenous or endogenous, is added. When technical progress is endogenous and spillovers are non-local, however, backward linkages in region 1 are further strengthened by the spillover connection to region 2. Demand for region 1 intermediate goods increases as λ_1 increases because both E_1 and E_2 in equation (21) increase as a result (see equation (22)). This drives up wages in region 1. The dispersion force due to product market competition is doubly amplified with endogenous technical progress for a similar reason. The dispersion force due to a fall in the marginal product of labor in A , however, is diminished with endogenous technical progress since labor productivity in A increases with λ_1 .

To understand the structure of the equilibria of the model, FKV (1999, chapter 14) suggest graphing each region's equilibrium wage in λ_1 - λ_2 space. While FKV use this graphical tool to show the effects of trade costs, in this model it also illustrates the effects of the growth rate elasticities, θ and φ , on equilibria. Figure 1 contains four panels with these wage curves as a function of manufacturing labor shares, where effective units of labor in agriculture are denoted by $\ell_i = (1-\lambda_i)L_i$.¹¹ Since the effect of T is not the primary focus here, T is set at 2.2 in all four panels.

As in FKV, the wage curves in Figure 1 show the levels of λ_1 and λ_2 at which wages are equalized between sectors in each region. To the right of the $w_1 = A'(\ell_1)$ curve wages are higher

¹⁰ For this reason, the increasing share of manufacturing expenditure is the “driving force” in the exogenous technical progress model (FKV, 1999, p.265). As FKV show (1999), the spread of industry under perfect technology equality, proceeds in three steps: (i) the manufacturing concentration in country 1 leads initially to relatively high country 1 wages, (ii) the imposed linear expenditure system form causes the demand for manufactures to increase relatively rapidly as wages increase, thus reinforcing the advantages of agglomeration in country 1, (iii) ultimately, however, the wage gap between countries 1 and 2 becomes unsustainable and manufacturing firms begin migrating to country 2 in order to benefit from lower labor costs.

in A than in M (i.e., $w_I < A'(\ell_1)$) and labor is assumed to move from M and to A ; to the left, $w_I > A'(\ell_1)$ and labor moves from A to M . The horizontal arrows in each panel depict these dynamics. The $w_2 = A'(\ell_2)$ curve is defined analogously except it is oriented to the vertical axis. The vertical arrows therefore describe the intra-sectoral labor dynamics in region 2. In each panel in Figure 1, there are two sets of wage curves. The first set drawn with thin lines corresponds to $\theta=0, \varphi=0$, which approximates the standard CPVL model. This set of wage curves shows the single, symmetric equilibrium $\lambda_1 = \lambda_2 \approx 0.4$ and is included in each panel to provide a benchmark. The second set of curves corresponds to the values of θ and φ indicated in the panel subtitles. As shown in panels (a) and (b), increasing θ while $\varphi=0$ pushes the (still) symmetric equilibrium away from the origin, making the wage curves increasingly concave to the origin. Generally, this effect is due to the additional labor productivity advantage conferred by higher manufacturing labor shares. The introduction of endogenous productivity growth, even if both sectors enjoy higher labor productivity, causes manufacturing wages, w_I , to increase faster than the marginal product of agricultural labor, $A'(\ell_1)$.

The symmetric equilibrium of the benchmark case, $\theta=0, \varphi=0$, is below and to the left of the equilibrium when $\theta > 0$, implying that $w_I > A'(\ell_1)$ at the benchmark equilibrium and that w_I increased faster than $A'(\ell_1)$. This is due to the strictly concave agricultural production function. Panels (c) and (d) show that increasing ν primarily affects the tails of the wage curves, suggesting that the relative contribution of foreign industry size to domestic growth is greatest when industry size disparities are greatest. This effect arises from the constant elasticity specification of the productivity growth function and from the assumption that the elasticity of productivity growth with respect to foreign industry size is less than unity.

Graphing the wage gap for one region, so called ‘wobble diagrams,’ is an alternative and common depiction of the equilibria of the model. Wobble diagrams are shown in Figure 2 for $T=1.6$ (same parameter values as Figure 1). The vertical axis in these diagrams is the wage gap in region 1; the horizontal axis is manufacturing labor share in region 1. Given the assumptions on the movement of workers between sectors, a positive wage gap causes workers to move into the M sector and a negative one causes workers to move out of the M sector. A stable equilibrium, represented with filled dots, obtains whenever (i) the wage gap curve intersects the

¹¹ Parameter values for these figures are $\bar{Y}=0.5, \mu=0.8, \alpha=0.4, \sigma=6$. Parameter values in the agriculture production function are as in FVK (1999, chapter 14, 15), namely, $\eta=0.95, K=1$.

zero line with a negative slope or (ii) the wage gap curve intersects the vertical axis below the zero line (i.e., corner solution, $\lambda_I=0$). An unstable equilibrium, represented with hollow dots, obtains whenever the wage gap curve intersects the zero line with a positive slope since the movement of one worker into the M sector increases the wage gap and entices more workers into the sector. In these panels, as before, the benchmark case ($\theta=0, v=0$) is drawn with thin lines.

Consider panel (a) in Figure 2. Relative to the benchmark of $\theta=0, v=0$, introducing $\theta=0.5$ affects the wiggle diagram in two ways. First, it shifts the stable symmetric equilibrium to the right such that the equilibrium level of λ_I increases. This is expected as explained above for Figure 1. Second, it causes the wiggle diagram to rotate counterclockwise around the new stable symmetric equilibrium. This rotation suggests that introducing endogenous technical progress into the CPVL model causes the wage gap to shrink for all levels of λ_I . As v increases, the stable equilibrium shifts yet further right as explained with Figure 1 above. Increasing v also changes the shape of the wiggle diagram in a way that counteracts the counterclockwise rotation due to $\theta>0$, suggesting that spillovers causes wage gaps to widen for all levels of λ_I .

From panel (b) of Figure 2, it is clear that increasing θ further to 0.9 amplifies these effects. Indeed, the shrinkage in the wage gap when $v=0$ (as shown by the counterclockwise rotation) is now so pronounced that multiple equilibria obtain. The core-periphery equilibrium, which failed to emerge when $\theta=0.5$, now obtains for sufficiently low levels of v . This logical result implies that when the productivity gains to an expansion in manufacturing labor are high, but spillovers are only local, one region can easily get left behind. There are also two unstable asymmetric equilibria when $v=0$. The effect of increasing v is similar to panel (a), but amplified dramatically since φ is increasing in both θ and v . When spillovers are global ($v=1$), the wage gap explodes at low levels of λ_I and the equilibrium labor share approaches $\mu=0.8$. At intermediate levels of spillovers, the core-periphery equilibrium becomes unstable, then non-existent.

Figure 3 also shows wiggle diagrams, this time calculated at low trade costs ($T=1.1$). First note that at relatively low trade costs the core-periphery equilibrium obtains for the benchmark case, as well as for most values of v and θ . Only when $\theta=0.9$ and $v>>0.65$ does the CP equilibrium fail to obtain. At low trade costs, the periphery region only industrializes if spillovers are significantly global. Importantly, whereas increasing v when trade costs are relatively high shifts equilibria to the right (Figure 2), increasing v when trade costs are relatively low shifts them

to the left. Broader spillovers lead to smaller equilibrium industry size in both regions when trade costs are low and linkages are consequently weak. The reverse is true when trade costs are high. This asymmetric effect of trade costs on the CPVL model with endogenous technical progress can be explored further using the common sustain-break analysis (see Puga and Venables 1996, FKV 1999, Baldwin et al. 2003).

Assume that manufacturing is initially concentrated in region 1 (i.e., $l_1 > 0$ and $l_2 = 0$). As in FKV (1999), relative manufacturing wages in regions 1 and 2 can then be derived from the price index and wage equations (equations (20) and (21)) as

$$(24) \quad \left(\frac{w_2}{w_1} \right)^{(1-a)s} = T^{-as} \left(\frac{E_1}{E_1 + E_2} T^{1-s} + \frac{E_2}{E_1 + E_2} T^{s-1} \right)$$

This initial concentration of manufacturing in region 1 can be sustained as long as $w_2 < A'(L_2)$ such that there is no incentive for workers to move to M . Since $w_2 = A'((1-l_1)L_1)$, the ‘sustain condition’ given equation (24) becomes

$$\left(\frac{A'(L_2)}{A'((1-l_1)L_1)} \right)^{(1-a)s} \geq T^{-as} \left(\frac{E_1}{E_1 + E_2} T^{1-s} + \frac{E_2}{E_1 + E_2} T^{s-1} \right)$$

or

$$(25) \quad A'(L_2) \geq A'((1-l_1)L_1) \left[T^{-as} \left(\frac{E_1}{E_1 + E_2} T^{1-s} + \frac{E_2}{E_1 + E_2} T^{s-1} \right) \right]^{1/(1-a)s}$$

As discussed in FKV (1999, chapter 15), one can solve for endogenous variables w_1 and λ_1 in L_1 , L_2 and E_1 , E_2 by using the fact that when manufacturing is concentrated in region 1 production in region 1 must meet total demand for manufactures, which generates the following equations:

$$(26) \quad w_1 L_1 l_1 (1-m) = m [A(L_2) + A((1-l_1)L_1) - 2\bar{Y}]$$

$$(27) \quad w_1 = A'((1-l_1)L_1)$$

Departing from FKV (1999), where T and L are the parameters of interest, this paper focuses on the growth rate elasticities θ and v . For what levels of θ and v is the concentration of manufacturing in region 1 sustainable? To answer this question, the sustain points and a sustain curve (S) implied by equation (25) can be mapped in θ - v space. The other set of critical points, composing ‘break’ curves (B), indicate parameter levels at which the symmetric equilibrium is broken and an asymmetric one obtains. The panels in Figure 4 show sustain and break curves in

θ - v space for varying levels of trade costs.¹² Panel (a) shows S and B curves for relatively high trade costs. Panel (b) shows these curves for relatively low trade costs. Suppose trade costs are initially high and steadily fall over time, as commonly assumed in the new economic geography. When $T=1.6$, the concentration in region 1 is only sustainable for high levels of θ and low levels of v . As concentration breaks, so too does all asymmetry between regions. Thus the symmetric equilibrium obtains for all remaining values of θ and v , and the S curve and the B curve are identical. As T falls, the sustain region grows. $T=1.365$ represents a tipping point at which the S and B curves split. As T falls further to 1.3, the concentration in region 1 is only broken with high levels of both θ and v . Over the range depicted in panel (a), therefore, falling trade costs make an initial concentration more sustainable. At intermediate trade costs ($T \in [1.2, 1.3]$), the periphery is able to industrialize only if the domestic growth rate elasticity is high and spillovers are nearly global. In contrast, panel (b) shows that as trade costs continue to fall the S and B curves shift from the northeast to the northwest corner with $T=1.1$ as the analogous tipping point. When trade costs become relatively low, an initial concentration is only sustainable when the domestic growth rate elasticity is high and spillovers are nearly local. As in the classic CPVL model, one with endogenous technical progress hinges importantly—and nonlinearly—on trade costs. These results confirm the intuitive finding that endogenous growth is destabilizing and spillovers are stabilizing—or agglomeration and dispersion forces, respectively (Baldwin and Forslid 2000).

One objective of this paper is to assess the joint effect of vertical linkages, as affected by trade costs, and endogenous growth with spillovers on economic development, yet the analysis thus far has treated trade costs and spillovers independently. To understand this joint effect, consider the development implications of the interaction of T and v . This interaction is empirically relevant since the costs of ‘trade in ideas,’ which affect spillover scope, are typically correlated with trade costs, both of which fall with integration (see Baldwin and Forslid 2000 for an application of this logic to a core-periphery model). To capture economic development, I use real wages for regions 1 and 2, denoted ω_1 and ω_2 , respectively, where

¹² Given the functional form of $A(\cdot)$, equation (26) does not have a closed form solution for l_j . Likewise, equation (25), which is used to produce a graph of the sustain points in T-L space, cannot be solved for T. The system can therefore only be solved by numerical simulation. The author thanks Anthony Venables for his helpful assistance on these numerical solutions.

$$(28) \quad \omega_1 = \bar{Y} + [A((1-\lambda_1)L_1) + w_1\lambda_1L_1 - \bar{Y}]G_1^{-\mu}$$

and ω_2 is defined analogously.¹³ Real wages thus defined are measured in terms of agricultural production and are per efficiency unit. The ratio of real wages, ω_2/ω_1 , then measures the degree of economic equality between regions. An increase in this ratio is evidence of economic development in—or ‘spread of industry’ to—region 2.

To capture the interaction effect of v and T when the model is solved numerically requires three dimensional graphs. Figure 5 shows a graph of the ratio of real wages (i.e., real wage inequality) in v - T space where $\theta=0.5$.¹⁴ Noteworthy are the three regions on this real wage inequality surface. First, equality obtains either (i) when trade costs are very high ($T>1.40$) or very low ($T<1.05$) or (ii) when trade costs are high or low and spillovers are high. The former suggests that equality is inevitable for sufficiently high or low trade costs, a well-established feature of the CPVL model (see FKV 1999, chapter 14 and 15, Puga and Venables 1996). Second, there is a discontinuous and precipitous fall in the real wage ratio for marginal changes in T and decreases in v . The rim defined by the intersection of the first and second regions represents precisely the ‘break’ curve in v - T space since real wage equality necessitates manufacturing symmetry. Third, there is a continuous, slightly convex bottom surface suggesting that at intermediate levels of trade costs and spillovers inequality is increasing in T , but decreasing in v . Cross-sections of this figure provide a clearer picture of the interaction of v and T .

Consider first a horizontal cross-section of Figure 5. The ‘break’ curve, defined by the rim in Figure 5, is such a cross-section, but is discontinuous in v over the range $[0,1]$. A continuous curve exists when $\omega_2/\omega_1=0.85$ and is shown in Figure 6. Under the iso-inequality curve, $\omega_2/\omega_1<0.85$. Outside the curve, $\omega_2/\omega_1>0.85$. As trade costs fall the marginal rate of

¹³ To understand the derivation of these real wages, assume first that consumers had Cobb-Douglas utility functions, instead of linear expenditure utility, and that there is no technical progress. Provided the production technology still required intermediate goods, real wages would be calculated simply as $\omega_1=w_1G_1^{-\mu}$, where G_1 adjusts for the price level of manufactured goods and μ represents the expenditure share of manufactures from the Cobb-Douglas utility function. Adding technical efficiency parameter and a linear expenditure system parameter, \bar{Y} , is then straightforward. Thus, the term in brackets represents nominal expenditure *above* subsistence requirements. This is adjusted by the price ratio, which is weighted by the expenditure share of manufactures, μ , and then added to the amount of agricultural product required for subsistence.

¹⁴ The general shape of Figure 5 is independent of θ , but the slope of the bottom surface in this figure does become steeper as θ increases.

substitution between ν and T is first increasing, then decreasing in absolute value and negative.¹⁵ The shape of this curve, like that of the break curve, is due to the non-linear effect of trade costs in the CPVL model.

Falling trade costs are initially an agglomeration force (when trade is economically feasible but backwards and forwards linkages are still strong), but eventually become a dispersion force (when backwards and forwards linkages fade away). Spillovers, contrastingly, are always a dispersion force. Once trade costs are low enough as to exert a dispersion force ($T < 1.25$ in Figure 6), are falling trade costs and increasing spillovers dispersion substitutes or complements? The T cross-sections shown in Figure 7 address this question. Consider the slope of these real wage ratio cross-sections at $\nu = 0.5$. The slope of these curves, which captures the effect of spillovers on the real wage ratio at the given level of T , is non-negative for all values of ν since spillovers are always a dispersion force. As T falls from 1.25 the slope at $\nu = 0.5$ remains roughly constant initially. Then, at $T = 1.10$, it increases sharply. Once $T = 1.05$, equality obtains regardless of ν and the slope is therefore zero. This suggests that falling trade costs and increasing spillovers are initially independent, then suddenly become strongly complementary dispersion forces once trade costs fall below some ‘tipping point.’

V. Conclusion

There are three primary conclusions from the analysis of this paper. First, multiple equilibria or additional equilibria may obtain when endogenous growth with spillovers is introduced to the core-periphery vertically-linked (CPVL) model. Second, while endogenous technical progress is generally an agglomeration force and spillovers are a dispersion force, the strength of these forces, both relative to each other and to the backward and forward linkages of the model, is dictated by trade costs. Third, the dispersion forces associated with increasing spillovers and relatively low, falling trade costs in the CPVL model mostly operate independently. However, there are critical values of trade costs at which the two are strong ‘dispersion complements’ such that a marginal increase in spillover scope significantly reduces the economic inequality between the two regions. The existence of such ‘tipping points’ suggests that some countries attempting to increase technology spillovers into its economy may enjoy few development benefits while others may reap substantial gains.

¹⁵ Marginal rates of substitution are defined as the negative of the slope of an iso- curves.

There are several possibilities for future research along the lines of this analysis. One possibility for future research is extending the model to include multiple countries and multiple sectors. Another possibility is to extend the simpler economic geography models proposed by Baldwin, et al. (2003), which have analytic solutions, in a similar manner. Studying the interaction of multiple location forces when analytic solutions are in hand would be clearer and more insightful.

References

- Baldwin, R. E., and R. Forslid. "The Core-Periphery Model and Endogenous Growth: Stabilizing and Destabilizing Integration." *Economica* 67, no. 267(2000): 307-24.
- Baldwin, R. E., et al. *Economic geography and public policy*. Princeton, N.J.: Princeton University Press, 2003.
- David, P. A. *Technical choice innovation and economic growth : essays on American and British experience in the nineteenth century*. London: Cambridge University Press, 1975.
- Dixit, A. K., and J. E. Stiglitz. "Monopolistic Competition and Optimum Product Diversity." *American Economic Review* 67, no. 3(1977): 297-308.
- Fujita, M., P. R. Krugman, and A. Venables. *The spatial economy cities, regions and international trade*. Cambridge, Mass.: MIT Press, 1999.
- Griliches, Z. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25(1957): 501-522.
- Grossman, G. M., and E. Helpman. *Innovation and growth in the global economy*. Cambridge, Mass.: MIT Press, 1991.
- Keller, W. "Geographic Localization of International Technology Diffusion." *American Economic Review* 92, no. 1(2002): 120-42.
- Krugman, P. "Increasing Returns and Economic Geography." *Journal of Political Economy* 99, no. 3(1991): 483-99.
- Krugman, P. R., and A. J. Venables. "Globalization and the Inequality of Nations." *Quarterly Journal of Economics* 110, no. 4(1995): 857-80.
- Martin, P., and G. I. P. Ottaviano. "Growing Locations: Industry Location in a Model of Endogenous Growth." *European Economic Review* 43, no. 2(1999): 281-302.
- Martin, P., and G. I. P. Ottaviano. "Growth and Agglomeration." *International Economic Review* 42, no. 4(2001): 947-68.
- Neary, J. P. "Of Hype and Hyperbolas: Introducing the New Economic Geography." *Journal of Economic Literature* XXXIX(2001): 536-561.
- North, D. C. "Institutions." *Journal of Economic Perspectives* 5, no. 1(1991): 97-112.
- Puga, D., and A. J. Venables. "The Spread of Industry: Spatial Agglomeration in Economic Development." *Journal of the Japanese and International Economies* 10, no. 4(1996): 440-64.
- Romer, P. M. "Endogenous Technological Change." *Journal of Political Economy* 98, no. 5(1990): S71-102.
- Rosenberg, N. *Inside the black box : technology and economics*. Cambridge [Cambridgeshire] ; New York: Cambridge University Press, 1982.
- Sachs, J. "Helping the World's Poorest." *Economist*, no. Aug 14(1999).
- Sachs, J. "A new map of the world." *Economist*, no. Jun 24(2000).
- Sagasti, F. R., J. J. Salomon, and C. Sachs-Jeantet. *The uncertain quest : science, technology and development*. Tokyo ; New York: United Nations University Press, 1994.
- Schmutzler, A. A. S. C. Z. "The New Economic Geography." *Journal of Economic Surveys* v13, no. n4 (September 1999)(1999): 355-79.

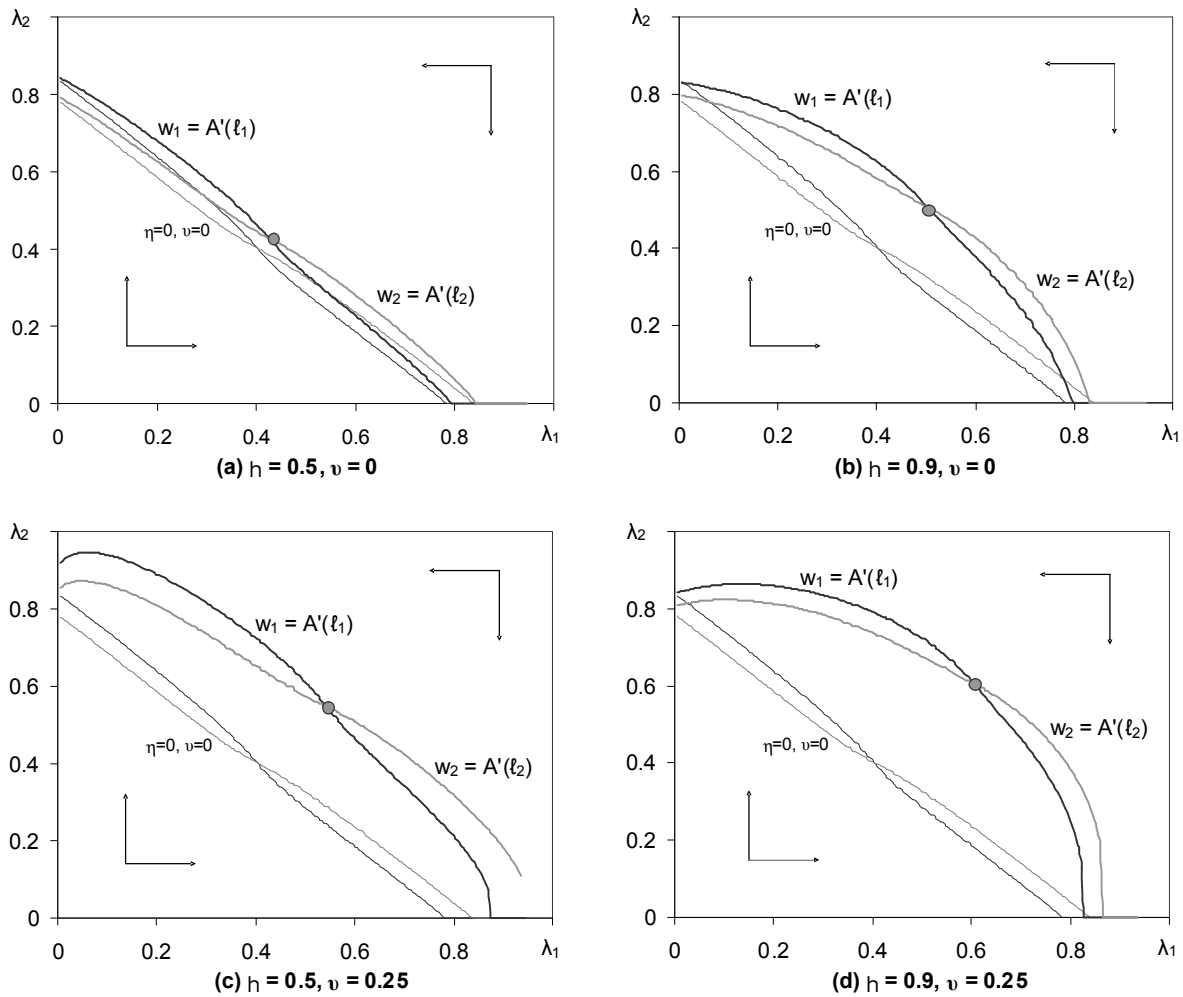


Figure 1 Manufacturing labor shares and wage curves, $T = 2.2$

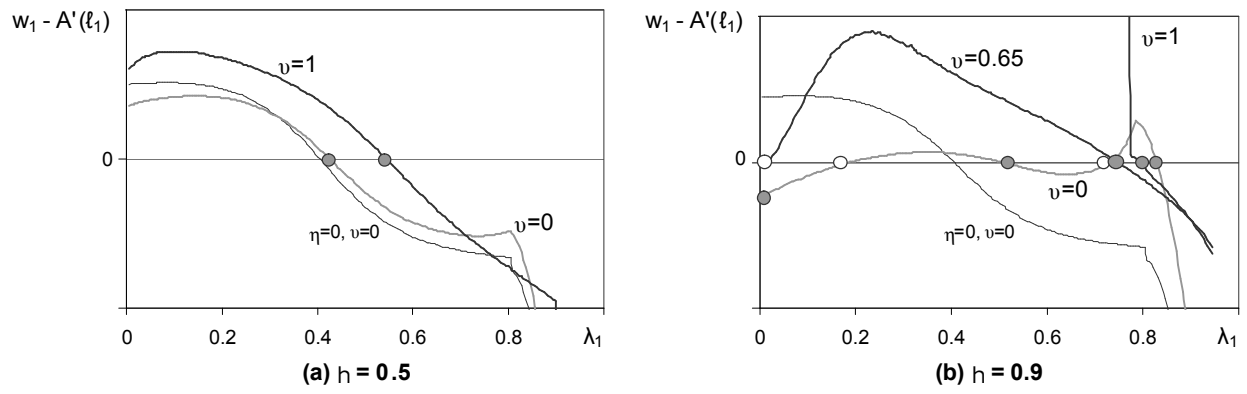


Figure 2 Wage gap between sectors M and A in region 1, $T=1.6$

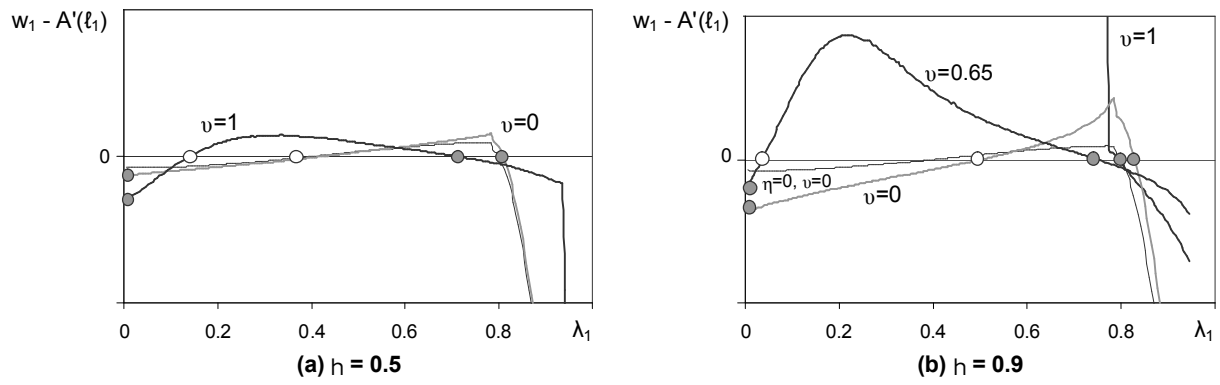


Figure 3 Wage gap between sectors M and A in region 1, $T=1.1$

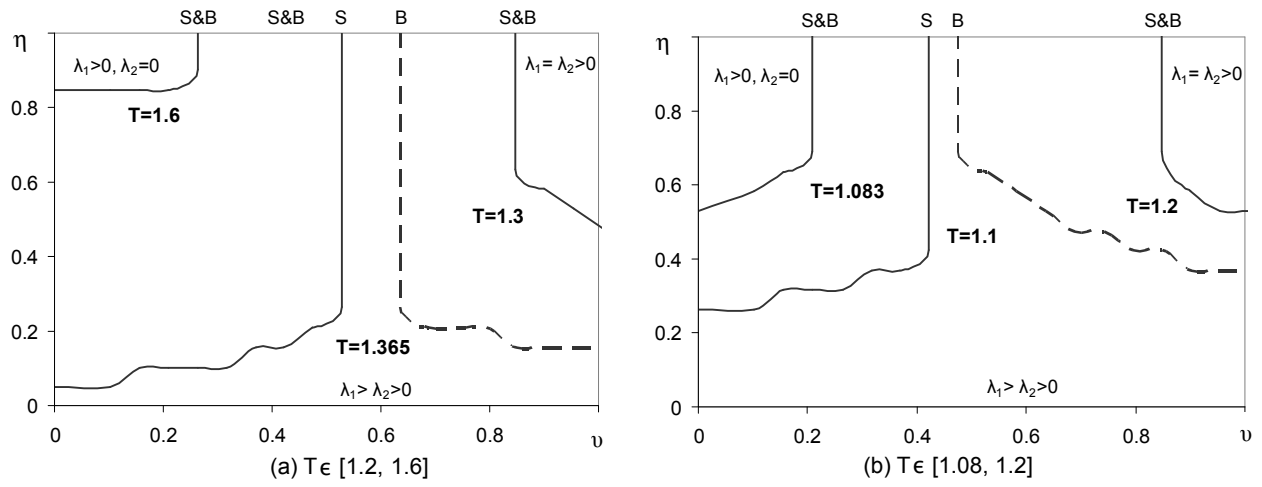


Figure 4 “Sustain” (S) and “Break” (B) curves in θ - v space

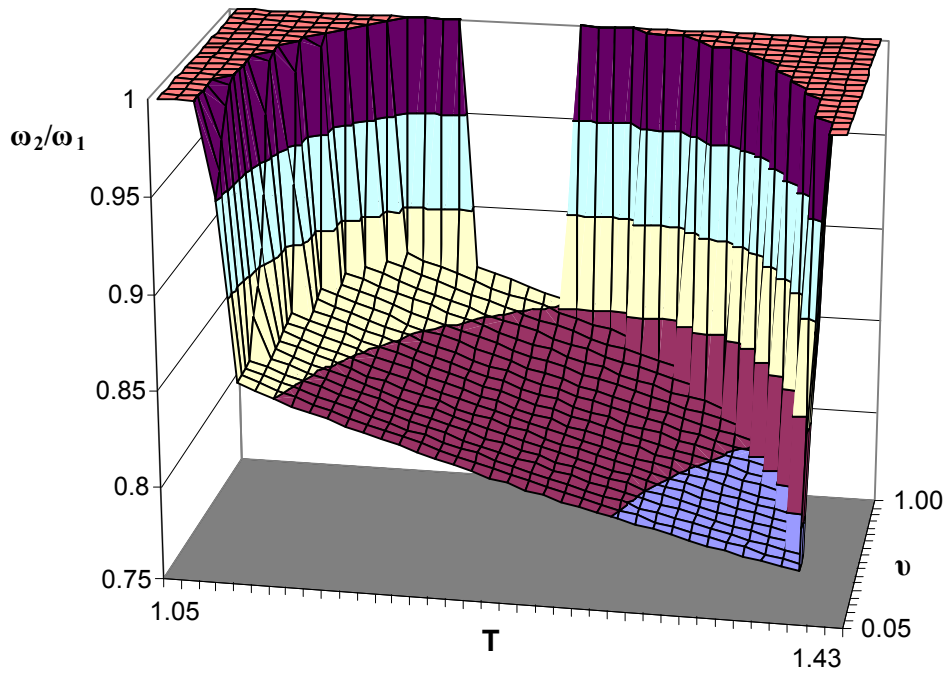


Figure 5 Real wage inequality in v - T space ($\theta=0.5$)



Figure 6 Iso-inequality curves in v - T space for $\omega_2/\omega_1=0.85$ ($\theta=0.5$)

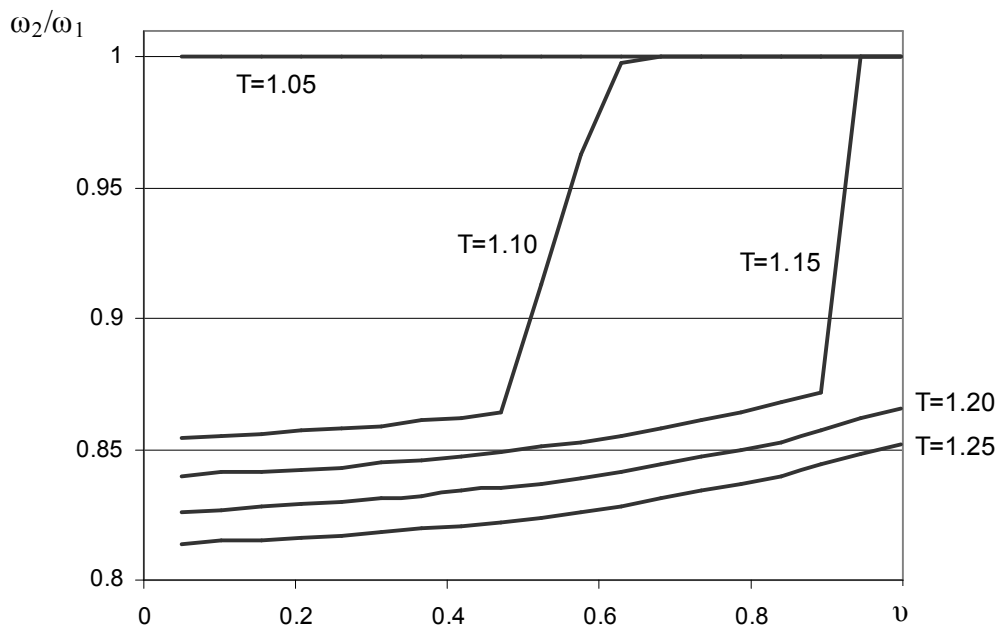


Figure 7 Real wage inequality cross-sections in v -space ($\theta=0.5$)

Table 1 Summary of agglomeration and dispersion forces

	Standard CPVL Model, No technical progress ($L_1=L_2=1$)	Exogenous technical progress ($L_1=L_2=L>1$)	Endogenous technical progress ($L_1=L_1(\lambda_1,\lambda_2)>0$, $L_2=L_2(\lambda_1,\lambda_2)>0$)
1. Agglomeration Forces (tending to increase δ_1)			
(a) Forward linkage	As λ_1 increases, there is a reduction in the cost of intermediate goods and therefore in G_1 , which tends to increase equilibrium wages in the short-term as seen in the G_1 term on the left side of the wage equation in (21).	Amplified	Amplified
(b) Backward linkage	As λ_1 increases, expenditures on manufactures, E_1 , increases (equation (22)), which shifts up firms' demand curves for intermediate goods and drives up manufacturing wages as seen in the E_1 term on the right side of equation (21).	Amplified	Amplified: Whenever spillovers are non-local ($\nu>0$), L_2 increases with λ_1 , which increases E_2 and drives w_1 yet higher.
2. Dispersion Forces (tending to decrease δ_1)			
(a) MPL in A	With the strictly concave agricultural production function specified in (8), an increase in λ_1 , and the corresponding decrease in agricultural labor, increases the marginal product of labor in agriculture.	Amplified	Diminished: As λ_1 increases, productivity and wages in both sectors increase.
(b) Product market competition	As λ_1 increases, so too does the supply of varieties, which reduces G_1 , shifts the firms' demand curves downward, and drives manufacturing wages downward as seen in the G_1 term on the right side of equation (21).	Amplified	Amplified: Whenever spillovers are non-local ($\nu>0$), L_2 increases with λ_1 , which reduces G_2 and drives w_1 yet lower.