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Input Chains and Industrialization

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A key aspect of industrialization is the adoption of increasing-returns-to-scale, *industrial*, technologies. Two other well-documented aspects are that industrial technologies (ITs) are adopted throughout intermediate-input chains and that they use intermediate inputs intensively relative to the technologies they replace. These features of ITs combined imply that countries with access to similar technologies may have very different levels of industrialization and aggregate income, even if the degree of increasing returns to scale at the firm level is relatively small. Furthermore, a minor improvement in the productivity of ITs can trigger full-scale industrialization and a large increase in aggregate income.

1. INTRODUCTION

It is often maintained that many countries have achieved high levels of aggregate income through industrialization, and that the main aspect of industrialization is the widespread adoption of increasing-returns-to-scale, *industrial*, technologies. A prominent exposition of this view can be found in Murphy *et al.* (1989), who also present a theoretical examination of industrialization when industrial technologies (ITs) can only be adopted in final-goods production. An important by-product of their analysis is that this narrow view of industrialization cannot explain an increase in aggregate income greater than the productivity increase at the firm level. This theoretical upper bound makes it difficult to attribute high levels of aggregate income to industrialization as empirical evidence suggests that increasing returns at the firm level are relatively small.[1] Murphy *et al.*'s theoretical work also confirms Fleming's (1955) argument that the narrow view of industrialization alone cannot explain why a small improvement in ITs may trigger full-scale industrialization and a large increase in aggregate income. Nor can it explain why countries with access to similar technologies may have very different levels of industrialization and aggregate income.

Two other well-documented aspects of industrialization are that ITs are adopted throughout intermediate-input chains in the economy and that ITs use intermediate inputs intensively relative to the technologies they replace. For example, one of the empirical regularities found in Chenery *et al.* (1986)—the most detailed comparative study of industrialization available—is that intermediate inputs' share of the value of manufacturing production increases with industrialization. Their data show that this share tripled between 1956 and 1971 in Taiwan and rose rapidly with industrialization in Israel, Japan, and South Korea. Intermediate inputs' share of the value of total production also increased with industrialization in these countries. In Taiwan, it grew by approximately 1% annually and reached 61% in 1971. Chenery *et al.* also observe that, during their sample period, intermediate-input use in both Taiwan and South Korea became similar to the pattern in more industrialized Japan, where 100 dollars of final demand in 1970 generated more than 80 dollars in intermediate-input demand. Their empirical analysis yields that the increase in the intermediate-input intensity of production during industrialization is

1. See Bresnahan (1989) and Roberts and Tybout (1996). Relatively small increasing returns to scale at the firm level are one of the reasons why, starting with Marshall (1890) and Young (1928), external returns (technological or linked to the specialization of industries) have been advanced as an explanation for the large effect of industrialization on aggregate income.

mostly driven by changes in technology, although changes in the structure of final-goods demand also play a (minor) role. Furthermore, the data show that, during industrialization, productivity increases throughout input chains and that input–output matrices become much less sparse as sectors become more interdependent.

This paper presents a theory of industrialization when industrial, relatively intermediate-input intensive technologies can be adopted throughout input chains in the economy. One result emerging from the analysis is that, if ITs are very intermediate-input intensive, then industrialization will have large effects on aggregate income and productivity, even if the degree of increasing returns to scale at the firm level is relatively small. This is because ITs are adopted throughout input chains in the economy. The increase in aggregate productivity will therefore consist not only of the productivity increase in final-goods production, but also the compounded productivity increase in the production of intermediate inputs used to produce final goods, of intermediate inputs used to produce intermediate inputs to produce final goods and so on. Intermediate-input-intensive ITs and input chains therefore provide a simple way to reconcile large effects of industrialization on aggregate income with relatively small increasing returns to scale at the firm level.

Input chains also imply that, if ITs use intermediate inputs more intensively than the technologies they replace, then industrializing firms may raise aggregate income even if they make a loss. This aggregate-income externality arises because industrializing firms raise the profits of their intermediate-input suppliers and, through their suppliers' input demand, profits of their suppliers' suppliers and so on.

The main consequence of input chains for industrialization is that, if ITs are sufficiently more intermediate-input intensive than the technologies they replace, then minor differences in the productivity of ITs may translate into large differences in equilibrium levels of industrialization and aggregate income. Furthermore, a small improvement in the productivity of ITs may trigger full-scale industrialization and a large increase in aggregate income. Both results hold even if industrial firms coordinate the adoption of ITs.

The remainder of the paper is structured in the following way. Section 2 discusses the related literature, and Section 3 describes the model. Section 4 determines sectoral demand and Section 5 aggregate income. Section 6 discusses the relationship between the structure of the economy—especially the characteristics of the IT—and equilibrium industrialization and aggregate income. Section 7 shows that input chains imply that a new general-purpose technology (GPT) has large effects on aggregate productivity, even if it is only introduced in a small number of (upstream) sectors. Section 8 concludes with some remarks on economic policy.

2. RELATED LITERATURE

The discussion of the role of input chains for industrialization dates back to Fleming's (1955) criticism of Nurkse (1952) and Rosenstein-Rodan (1943). Nurkse and Rosenstein Rodan argue that the adoption of ITs in the production of final goods could increase aggregate income even if firms adopting these technologies were to make a loss. They also maintain that these effects on aggregate income could result in *horizontal* demand linkages among final-goods producers, creating the need for coordinated adoption of ITs—sometimes referred to as the *big push*—for industrialization to be profitable at the individual firm level. Fleming's point is that final-goods firms adopting ITs and making a loss will always subtract from, not add to, aggregate income under full-employment. Thus, if uncoordinated adoption of ITs were unprofitable at the individual firm level, then coordinated adoption would neither be profitable for individual firms nor socially desirable. Fleming goes on to argue, however, that this is because firms are assumed to only be linked through aggregate income and that *vertical* demand linkages that arise along input chains in the economy could prevent socially desirable adoption of ITs. Scitovsky (1954) and Hirschman (1958) make related points about how vertical demand linkages can create a vicious circle preventing the widespread adoption of ITs.[2]

A formal analysis of Fleming's argument about the role of horizontal demand linkages for the big push can be found in Murphy *et al.*'s (1989) analysis of industrialization. They first show that the narrow view of industrialization alone implies that equilibria are unique and socially efficient. Furthermore, they also demonstrate that the big push will not lead to equilibrium industrialization. Intuitively, this is because, if aggregate income is the only channel of linkages between firms, then an industrializing firm making a loss will necessarily decrease the potential profits of adopting increasing-returns-to-scale technologies in all other sectors. Hence, the big push would only result in losses in all sectors. Murphy *et al.* then extend their benchmark model by analyzing three mechanisms that give rise to two Pareto-rankable equilibria—one where all firms use the pre-industrial technology (PIT) and another where they use the IT—and therefore introduce a potential role for the big push. The mechanisms are the industrial wage-premium asserted by Rosenstein-Rodan (1943), an intertemporal mechanism based on the timing of investment and cash flow, and the possibility of a large infrastructure investment that reduces industrial firms' cost of production. One of the ways to think of the present paper is as proposing an empirically motivated, alternative mechanism for the big push. The main results of the analysis, however, do neither rely on the existence of multiple equilibria nor do they concern the big push. The key issue here is the effect of the characteristics of available ITs on equilibrium industrialization and aggregate income.

The role of vertical linkages for economic development has also been analyzed in Okuno-Fujiwara (1988) and Rodriguez-Clare (1996). They show how market structure and specialization in the intermediate-inputs sector can generate vertical linkages with the final-goods sector and result in multiple, Pareto-rankable equilibria because of coordination failure.[3] Their argument is that linkages arise because an increase in the demand for inputs may lower input-prices due to increased competition (Okuno-Fujiwara) or increase input efficiency due to increased specialization (Rodriguez-Clare). Neither input chains nor the intermediate-input intensity of ITs play any role in their analysis however. Most closely related to the present paper are Fafchamps and Helms (1996) and Gans (1997, 1998*a*,*b*). They discuss the role of input chains and the intermediate-input intensity of ITs for industrialization in open economies and in dynamic economies respectively, building on earlier versions of the present paper (Ciccone, 1993*a*,*b*).

3. MODEL

The model of industrialization has two key features. First, each good can be produced with a constant-returns-to-scale or an increasing-returns-to-scale technology. The adoption of increasing-returns-to-scale technologies is referred to as *industrialization*. Second, production of all goods but one with the increasing-returns-to-scale technology requires intermediate inputs. This gives rise to input chains: goods are produced with intermediate inputs that are themselves produced with intermediate inputs.

2. A by-product of the analysis in this paper is that vertical demand linkages do not necessarily create a vicious circle preventing the widespread adoption of ITs. For this to be the case, ITs must be more intermediate-input intensive than the technologies they replace.

3. See Matsuyama (1995) for a review of models of multiple equilibria in economic development. The economic geography literature also analyzes vertical linkages, see Venables (1995, 1996) and Puga and Venables (1996). Puga and Venables consider a numerical multi-sector model to analyze the geographic spread of industry induced by technological change. The approach and context is very different from this paper and the aforementioned industrialization literature however.

3.1. *Economic environment*

The commodities in the model are labour and a measure one of goods that can be consumed or used as inputs into production.

Household preferences over consumption goods are symmetric and the elasticity of substitution between different goods is unity

$$U = \int_0^1 \log c(m)dm. \tag{1}$$

There is a measure L of households in the economy. Each household is endowed with one unit of labour, which is supplied inelastically to the labour market.

All goods can be produced with two technologies: a constant-returns-to-scale, PIT and an increasing-returns-to-scale, IT. The PIT uses labour only and requires one unit of labour for each unit of output produced. Formally $y^P(m) - l^P(m)$ for all $m \in [0, 1]$ where $y^P(m)$ denotes production of good m and $l^P(m)$ the amount of labour used to produce good m with the PIT.

Production of good $m = 0$ with the IT also requires labour only. The IT is $y^I(0) = \max[(1/\theta)l^I(0) - f, 0]$ where $l^I(0)$ is the amount of labour used to produce good $m = 0$ with the IT and f is the fixed input requirement of industrial production. It will be assumed throughout that $0 < \theta < 1$ and $f > 0$. Hence, the IT for $m = 0$ is subject to increasing returns to scale and more efficient than the corresponding PIT at the margin once the fixed input requirement has been incurred.

Production of all goods $m > 0$ with the IT requires labour and goods i ranked strictly lower than m. The production function is

$$y^I(m) = \max[(1/\theta)x(m) - f, 0], \tag{2}$$

where $x(m)$ is a generalized input produced according to

$$\log x(m) = \log B + \beta \log z(m) + (1 - \beta)\log l^I(m), \qquad 0 < \beta < 1. \tag{3}$$

Intermediate inputs enter production with the IT through the intermediate-input composite $z(m)$, which is produced with all goods ranked lower than m using

$$\log z(m) = \log m + \frac{1}{m}\int_0^m \log x(i, m)di, \tag{4}$$

where $x(i, m)$ is the quantity of good i used as input in the industrial production of good m. The constant B in (4) is assumed to satisfy $\log B = -\beta \log \beta - (1 - \beta)\log(1 - \beta)$ to ensure that industrial firms producing goods $m > 0$ have the same marginal cost of production in equilibrium as the industrial firm producing good $m = 0$. The assumption that intermediate inputs are only used by the IT is made to simplify the exposition. It is straightforward to extend the model to the case where the PIT also requires intermediate inputs. This extension is discussed in the appendix. The main insight of the extension is that all the results proven for the model where only the IT uses intermediate inputs carry over as long as the IT uses intermediate inputs more intensively than the PIT.

The specification of the intermediate-input composite in (4) eliminates increasing returns to specialization as defined by Ethier (1982). Intuitively, increasing returns to specialization arise when the efficiency of production increases with the variety of intermediate inputs used. To see that the specification in (4) eliminates this possibility assume that all intermediate inputs can be purchased at the same price ($p = 1$). Given that inputs enter symmetrically into the production of intermediate-input composites, this implies that industrial firms minimize costs of production by using the same quantity of all upstream inputs. The output of intermediate-input composites in sector m (which uses a variety of inputs m) is therefore linked to intermediate-input expenditures

e by $z(m) = e$. Hence, the efficiency of intermediate-input production, measured as the ratio of output to expenditures on inputs, is independent of the measure of inputs m used in production.

The assumption in (3) and (4) that production of each good $m > 0$ with the IT requires all goods i ranked strictly lower than m results in a triangular input-requirement structure. This structure is chosen because it is the simplest way to generate input chains while avoiding circular input requirements.[4] Goods ranked lower than m will be referred to as goods produced upstream of m and goods ranked higher as goods produced downstream of m.

There is a continuum of firms with access to the PIT to produce each good. These firms will be referred to as pre-industrial firms. The IT to produce each good is available to only one firm, referred to as industrial firm, and each industrial firm produces one good only. Both pre-industrial and industrial firms take prices in intermediate-input markets and in the labour market as given. These assumptions imply that pre-industrial firms will sell at the marginal cost of production. Industrial firms will maximize profits by setting prices above the marginal cost of production.

Different goods will be thought of as produced in different sectors. Sectors where production is undertaken by industrial firms will be referred to as industrial sectors, and sectors where production is undertaken by pre-industrial firms will be referred to as pre-industrial sectors.

3.2. *Definition of equilibrium*

Equilibria in this economy are defined by prices, production levels, input demands, consumption demands, and industrialization decisions for each sector that satisfy the following conditions:

(I) The demand for consumption goods maximizes household utility given household income and the prices of all goods.

(II) The quantities of goods produced in pre-industrial sectors and the quantities of labour these sectors demand are profit-maximizing choices of pre-industrial firms given the wage and the prices of all goods.

(III) The prices of goods produced in industrial sectors and the quantities of inputs these sectors demand are profit-maximizing choices of industrial firms given the wage, upstream prices, downstream input-demand functions, and the consumption-demand functions.

(IV) Industrial firms in industrial sectors do not make losses and industrial firms in pre-industrial sectors would make losses if they were to produce.

(V) Quantities produced in each sector are equal to quantities demanded.

4. PRICES, PROFITS, AND SECTORAL DEMAND

Demand for each sector in the economy is the sum of consumption-good demand and intermediate-input demand. Intermediate-input demand for a given sector depends on how many downstream sectors have industrialized—and hence use intermediate inputs—as well as on the quantity of intermediate inputs demanded by each downstream industrial sector. To determine intermediate-input demand for each sector it is useful to first discuss the behaviour of prices and firms' industrialization decision.

4. Setting up the model following the differentiated-input business-cycle literature by assuming that each intermediate input uses all other intermediate inputs in production (see for example, Basu, 1995) would imply that, for any two intermediate inputs, the first input is required to produce the second and the second to produce the first. Production in such a model is a logical contradiction and it is therefore unclear what can be learnt from it.

4.1. *Equilibrium prices*

The assumptions about technology and preferences combined with the market structure imply that prices of all goods, whether they are produced in industrial or pre-industrial sectors, are identical in equilibrium.

Lemma 1. *Prices of all goods are identical in equilibrium. Moreover, choosing labour as numeraire implies that* $p^*(m) = 1$ *for* $m \in [0, 1]$ *where* $p(m)$ *is the price of good* m *and asterisks denote equilibrium values.*

Proof. The assumptions about technology and preferences in (1)–(4) imply that industrial firms face unit-elastic consumption-demand and input-demand functions. Hence, profit maximization by industrial firms implies that—if industrial firms produce at all—they will set the largest price at which they cannot be undercut by pre-industrial firms in the same sector (assuming that consumers and producers buy from industrial firms at equal prices). The largest price at which industrial firms cannot be undercut is the marginal cost of production of pre-industrial firms. Pre-industrial firms transform labour into output one-to-one, which implies that their marginal cost of production is equal to the wage rate w. Choosing labour as numeraire therefore yields that all industrial firms in industrial sectors will set a price equal to unity. The price of goods produced in perfectly competitive, pre-industrial sectors will be equal to the marginal cost of pre-industrial firms and hence also equal to unity. Thus, equilibrium prices are equal to unity in industrial and pre-industrial sectors. ||

4.2. *Profits and the industrialization decision*

The production of the generalized input $x(m)$ in (3) is subject to constant returns to scale. Hence, the average cost of producing the generalized input is equal to the marginal cost. The marginal cost $q(m)$ is a geometric average of the cost of producing one unit of the intermediate-input composite in (4),

$$\exp\left(\frac{1}{m}\int_0^m \log p(i)di\right), \tag{5}$$

and the wage w, with weights equal to β and $1 - \beta$ respectively,

$$\log q(m) = \beta\left(\frac{1}{m}\int_0^m \log p(i)di\right) + (1 - \beta)\log w. \tag{6}$$

The expression for the average cost of producing the generalized input in (6), combined with equilibrium prices $p^*(m) = 1$ for $m \in [0, 1]$ and the normalization $w = 1$, yields that the average cost of producing $x(m)$ is equal to unity in equilibrium. According to the IT in (2), industrial firms producing goods $m > 0$ require $\theta(y + f)$ units of the generalized input $x(m)$ to produce a quantity y. Hence, industrial firms' total cost of producing a quantity y of goods is $\theta(y + f)$, independently of the sector they produce in. Furthermore, (3) implies that it will be optimal for industrial firms to spend a fraction β of their total cost of production to purchase upstream intermediate inputs.

Combining industrial firms' costs of production with equilibrium prices yields their profits as a function of demand y,

$$\pi = (1 - \theta)y - \theta f. \tag{7}$$

Industrial firms adopt the IT if demand is large enough for profits to be positive.

The choice of labour as numeraire yields that the marginal cost of production of pre-industrial firms is unity. Industrial firms' marginal cost of production is $\theta < 1$. Hence, the

TABLE 1

Key parameters of the model

Parameter	Interpretation
$1 > \beta > 0$	• Intermediate-input intensity of IT
$\frac{1}{\theta} > 1$	• Relative productivity of IT • Price/marginal cost in sectors adopting the IT
$f > 0$	• Fixed input requirement of IT

marginal cost of production in pre-industrial sectors relative to industrial sectors is $1/\theta$. This ratio will be referred to as the relative marginal productivity of the IT. Furthermore, the price relative to the marginal cost of production in industrial sectors is also $1/\theta$. Table 1 summarizes the interpretation of the parameters of the IT.

4.3. *Sectoral demand*

Denote aggregate income when the n, $0 \leq n \leq 1$ sectors furthest upstream have industrialized and the remaining sectors use the PIT with $Y(n)$. It will become clear later that, if a measure n of sectors industrialize in equilibrium, then it will always be the sectors furthest upstream because they face the largest demand and therefore earn the highest profits. Furthermore, denote total demand for good m when the n sectors furthest upstream have industrialized and the remaining sectors use the PIT with $y(m, n)$. Demand for good m and aggregate income are, of course, linked. The fact that equilibrium prices of all goods are equal to unity implies that households demand the same quantity $c(m) = Y(n)$ of all goods $m \in [0, 1]$. Also, the PIT does not use intermediate inputs and the assumption that the n sectors furthest upstream have industrialized and that the remaining sectors use the PIT therefore implies that goods m, $n \leq m \leq 1$ are not demanded as input in downstream sectors. This yields that goods produced in sectors downstream of n are demanded for consumption only and hence that the demand for these goods is given by

$$y(m, n) = Y(n), \qquad n \leq m \leq 1. \tag{8}$$

Determining the demand for goods m produced upstream of n ($m < n$) is less straightforward as these goods are also demanded as inputs in downstream industrial sectors. It turns out that the demand for these goods can be determined recursively as the only difference between the demand for good m, $m < n$ and the good just upstream of m is the quantity of the good just upstream demanded for production of good m.

To see this formally notice that (4) assumes that all goods upstream of m enter industrial production of good m symmetrically. Combined with the result that all goods cost the same in equilibrium, this implies that industrial sector m demands the same quantity of all upstream goods. Formally, $x(i, m, n) = v(m, n)$ for $i < m \leq n$ where $x(i, m, n)$ denotes demand for good i as input in the production of good m when only the n sectors furthest upstream have industrialized. This implies that each industrial sector downstream of m demands the same quantity of good m and the good just upstream of m. Symmetric preferences yield that consumers also demand the same quantity of good m and the good just upstream. The difference between the demand for good m and the good just upstream is therefore equal to $v(m, n)$, the quantity of the good just upstream demanded for production of good m.

The demand for each sector in the economy can be determined by linking the demand for each good m to the demand for inputs produced upstream of m. To do so, notice that the total cost of intermediate inputs used to produce good m with the IT when the n sectors furthest upstream have industrialized is $mv(m, n)$, as the price of all goods is equal to unity in equilibrium. Furthermore, (3) implies that industrial firms spend a fraction β of their total cost of production on intermediate inputs. Hence, total intermediate-input expenditures of industrial firms are $mv(m,n) = \beta\theta(y(m,n) + f)$. The demand for good $i < m$ as input in the production of good $m \leq n$ is therefore linked to total demand for good m by $v(m,n) = \beta\theta(y(m,n)+f)/m$. The result that the difference between the demand for good m and the good just upstream is equal to $v(m,n)$ combined with market clearing in each sector therefore yields that

$$\frac{\partial y(m,n)}{\partial m} = -\theta\beta\frac{y(m,n)+f}{m}, \qquad m < n. \tag{9}$$

Hence, demand is greater the further upstream the sector. This implies that industrial firms further upstream earn higher profits and therefore validates the initial conjecture that, if a measure n of sectors industrialize in equilibrium, then it will always be the sectors furthest upstream. Furthermore, (9) can be integrated subject to (8) to obtain the demand for the goods produced in each industrial sector,

$$y(m,n) = \left(\frac{n}{m}\right)^{\theta\beta} Y(n) + \left(\left(\frac{n}{m}\right)^{\theta\beta} - 1\right) f, \qquad m \leq n. \tag{10}$$

5. DETERMINANTS OF AGGREGATE INCOME

Demand for each sector in the economy can now be used to determine aggregate income and discuss how aggregate income and productivity depend on firms' industrialization decisions and on the characteristics of ITs.

5.1. *Aggregate income and productivity*

Sectoral demand in (10) combined with (7) determines profits in each industrial sector as a function of aggregate income. The sum of industrial firms' profits combined with labour income yields aggregate income $Y(n) = L + \int_0^n \pi(m,n)dm$. This aggregate income identity can be solved for aggregate income when only the n sectors furthest upstream have industrialized,

$$Y(n) = \frac{L - \lambda f n}{\lambda n + (1-n)}, \tag{11}$$

where

$$\lambda = \frac{1-\beta}{1/\theta - \beta}. \tag{12}$$

The next result proves that λ is the average amount of labour required to produce one additional unit of each good $m \in [0,n]$ for consumption when all sectors upstream of n use the IT; λ will be referred to as the *industrial labour requirement*.

Lemma 2. *Suppose that all sectors upstream of n produce with the IT. Then the average amount of labour necessary to produce one additional unit of each good upstream of n for consumption is equal to* λ.

Proof. Denote with $\hat{y}(m,n)$ the additional amount of good m necessary to produce one additional unit of each good upstream of n for consumption. Using the argument behind (9) yields that $\hat{y}(m,n)$ satisfies $\partial\hat{y}(m,n)/\partial m = -\theta\beta\hat{y}(m,n)/m$. Furthermore, using the argument behind (8) yields $\hat{y}(n,n) = 1$. Integrating these equations yields that $\hat{y}(m,n) = (n/m)^{-\theta\beta}$. The assumptions about the IT imply that each unit of output produced with the IT requires $\theta(1-\beta)$ units of labour. Hence, the total amount of labour necessary to produce one additional unit of each good upstream of n for consumption is $\theta(1-\beta)\int_0^n \hat{y}(m,n)dm = \lambda n$ and the average amount of labour is λ. ||

With this understanding of λ it becomes straightforward to interpret the expression for aggregate income in (11). The denominator is the average amount of labour required to produce one additional unit of each good for consumption if the n sectors furthest upstream produce with the IT and the $1-n$ sectors furthest downstream produce with the PIT (the amount of labour required for each unit of output produced in pre-industrial sectors is unity). The aggregate marginal productivity of labour in producing consumption goods is therefore

$$\text{Aggregate marginal productivity} = \frac{1}{\lambda n + (1-n)}. \tag{13}$$

Furthermore, $\lambda f n$ in (11) is the amount of labour required to produce the fixed input requirements for the n industrial sectors. Hence, aggregate income is equal to the labour available after production of the fixed input requirement for all industrial sectors multiplied by aggregate productivity.

5.2. *Determinants of the industrial labour requirement*

The two determinants of the industrial labour requirement can be readily identified from (12). First, the IT's relative productivity. Evidently, the greater $1/\theta$, the smaller the industrial labour requirement. Second, the IT's intermediate-input intensity. The greater β, the smaller the industrial labour requirement. This is because the IT is not only used in the production of consumption goods upstream of n, but also in the production of inputs to produce these goods, of inputs to produce these inputs and so on. Hence, the industrial labour requirement also reflects the compounded productivity increase in the production of inputs, which will be greater the more intensively intermediate inputs are used in industrial production.

To see the determinants of the industrial labour requirement at work in a simple example, suppose that there are only two sectors: an upstream sector and a downstream sector. Both sectors produce with the IT and have incurred the fixed cost. What is the average amount of labour necessary to produce one additional unit of both goods for consumption? The amount of labour and upstream good necessary to produce one additional unit of the downstream good are $(1-\beta)\theta$ and $\beta\theta$ respectively. The amount of labour necessary upstream to produce one additional unit of the upstream good for consumption and $\beta\theta$ units for downstream production is $\theta + \beta\theta^2$. Hence, the average amount of labour necessary to produce one additional unit of both goods for consumption is $\theta(1-(1-\theta)\beta/2)$, which is decreasing in $1/\theta$ and β.

5.3. *The impact of the IT on aggregate income*

It is evident that the increase in aggregate productivity and income implied by industrialization will be larger the greater the relative productivity of the IT. The effect of industrialization on aggregate productivity and income may, however, be large even if the productivity increase in sectors adopting the IT is relatively small. This will be the case if the IT uses intermediate inputs sufficiently intensively.

Lemma 3. *Aggregate income and productivity in an economy where all goods are produced with the IT increases with the IT's intermediate-input intensity. Furthermore, the difference in aggregate income and productivity between an economy where all goods are*

TABLE 2

Increase in aggregate productivity implied by industrialization

	Intermediate-input intensity of IT (β)			
Productivity-increase of IT ($1/\theta - 1$)	0	50%	60%	70%
20%	20%	40%	50%	70%
40%	40%	80%	100%	130%
80%	80%	160%	200%	270%

Notes: The aggregate productivity increase is $1/\lambda - 1$ where λ is defined in (12).

produced with the IT and one where all goods are produced with the PIT becomes arbitrarily large as the IT's intermediate-input intensity tends to unity.

Proof. The simplest way to establish this result is by using (11) to determine aggregate income and (13) to determine aggregate productivity when all sectors use the PIT and IT respectively. Equation (13) implies that aggregate productivity is unity if all sectors use the PIT and that aggregate productivity is $1/\lambda$ if all sectors use the IT. Aggregate income is equal to L if all sectors use the PIT and equal to $L/\lambda - f$ if all sectors use the IT. Hence, the effect of industrialization on aggregate productivity and income is larger the smaller the industrial labour requirement λ. Furthermore, the difference in aggregate income and productivity between the economy where all goods are produced with the IT and the one where all goods are produced with the PIT becomes arbitrarily large as $\lambda \to 0$. The definition of the industrial labour requirement in (12) and $1/\theta > 1$ yields that λ decreases with β and that $\lambda \to 0$ as $\beta \to 1$. ||

It is interesting to note that a higher intermediate-input intensity of the IT increases aggregate productivity but not productivity of industrial firms. The reason is that the price of intermediate inputs does not reflect their opportunity cost as upstream sectors are imperfectly competitive. Imperfect competition implies that productivity gains associated with an increase in the intermediate-input intensity of production are not passed on to intermediate-input buyers, leaving their productivity unchanged. An increase in the intermediate-input intensity of production therefore widens the gap between aggregate productivity and productivity at the firm level.

Formally, the aggregate productivity increase implied by full industrialization $1/\lambda - 1$ is linked to the productivity increase in each industrial sector $1/\theta - 1$ by

$$1/\lambda - 1 = \frac{1}{1-\beta}(1/\theta - 1). \tag{14}$$

Hence, input chains ($0 < \beta < 1$) magnify the effect of the productivity increase in each industrial sector on aggregate productivity. For example, a 40% productivity increase in industrial sectors translates into a 100% aggregate productivity increase when the intermediate-input intensity is 60%. Table 2 gives an idea of the effects of full-scale industrialization on aggregate productivity for reasonable values of the intermediate-input intensity in industrial sectors. (For example, the average intermediate-input intensity of production in South Korea, Taiwan, and Japan is between 50 and 70% (Chenery *et al.*, 1986). The average intermediate-input intensity in the US during the early 1990s was around 60% (Bureau of Economic Analysis, 1996).)

5.4. *Aggregate productivity in finite chain economies*

So far the analysis has focused on economies with a continuum of goods and input chains of infinite length. It is natural to wonder whether aggregate productivity in finite chain

TABLE 3

Relative productivity with N sectors

Number of sectors	5	10	15	20	25
Productivity relative to continuum economy	90%	92%	93%	94%	95%

Notes: Relative productivity $R(N) = \lambda/\Lambda(N)$ is calculated using (12) and (15).

economies converges to aggregate productivity in the continuum economy as the number of sectors increases. Another interesting question is whether aggregate productivity in finite chain economies will be of a similar magnitude as that in the continuum economy even if the number of sectors is rather small. These issues are addressed next.

In an economy with a finite number of sectors the amount of labour necessary to produce one additional unit of good $N \geq 2$ when all sectors use the IT is $\Omega(N) = \theta(1-\beta)+\theta\beta\Lambda(N-1)$ where $\Lambda(N-1) = \sum_{J=1}^{N-1} \Omega(J)/(N-1)$ is the average amount of labour necessary to produce one additional unit of all goods upstream of N (the industrial labour requirement upstream of N) and $\Omega(1) = \theta$. Combining these equations yields that the industrial labour requirement as a function of N satisfies

$$\Lambda(N) = \left(\frac{1-\beta\theta}{N}\right)\lambda + \left(1 - \frac{1-\beta\theta}{N}\right)\Lambda(N-1) \tag{15}$$

for $N \geq 2$ and $\Lambda(1) = \theta$. Hence, if $\lambda < \Lambda(N-1)$, then $\lambda < \Lambda(N) < \Lambda(N-1)$. This fact combined with $\Lambda(1) = \theta > \lambda$ implies that the industrial labour requirement $\Lambda(N)$ decreases with the number of sectors and tends to the industrial labour requirement of the continuum economy λ as the number of sectors tends to infinity. Taking into account that aggregate productivity in finite chain economies is the inverse of the industrial labour requirement in (15) therefore yields that aggregate productivity in finite chain economies converges to aggregate productivity in the continuum economy as the number of sectors increases.

Table 3 calculates aggregate productivity in an economy with N sectors relative to aggregate productivity in the continuum economy, $R(N) = \lambda/\Lambda(N)$, assuming $1/\theta = 1{\cdot}4$ and $\beta = 0{\cdot}6$. It can be seen from the table that aggregate productivity in the economy with a finite number of sectors is similar to the continuum economy, even if the number of sectors is small and input chains are rather short. For example, in the economy with five sectors, where the largest input chain operates across five sectors and the average length of input chains is three, aggregate productivity is only 10% below the continuum economy. The gap shrinks to 5% in the economy with 25 sectors where the average input chain is of length 13.

5.5. *Industrialization multiplier and aggregate-income externalities*

How does industrialization affect aggregate income? To answer this question it is useful to use (11) to calculate industrialization's marginal effect on aggregate income,

$$Y'(n) = \frac{(1-\lambda)Y(n) - \lambda f}{\lambda n + (1-n)}. \tag{16}$$

The numerator of this expression—which will be referred to as the *direct impact of industrialization*—is equal to the amount of labour saved in the production of good n. To see this notice that $Y(n)$ is equal to the amount of labour required to produce $Y(n)$ units of the good n with the PIT. The amount of labour required directly (by the industrial firm in sector n) and indirectly (by upstream industrial firms producing required intermediate inputs) if good n is produced with the IT is $\lambda(Y(n)+f)$. Hence, the labour saved by the adoption of the IT in the production of good n is equal to $Y(n)-\lambda(Y(n)+f)=(1-\lambda)Y(n)-\lambda f$. Industrialization's marginal effect on aggregate income is therefore the amount of labour saved in the newly industrialized sector multiplied by the aggregate productivity of labour $1/(\lambda n+(1-n))$ in (13).

There is another useful interpretation of industrialization's marginal effect on aggregate income. The direct impact of industrialization is equal to industrialization's effect on the profits of all industrial firms holding consumption demand constant, while the aggregate productivity of labour captures the increase in aggregate income induced by the direct impact of industrialization on profits. This last effect will be referred to as the *industrialization multiplier*.

To see that the direct impact of industrialization is equal to industrialization's effect on the profits of all industrial firms holding consumption demand constant, recall that wages are normalized to unity. Hence, the amount of labour saved in the production of good n, $(1-\lambda)Y(n)-\lambda f$, is equal to the reduction of aggregate labour costs. This is in turn equal to the increase in aggregate profits if consumption demand is held constant.

The industrialization multiplier captures that the direct impact of industrialization on aggregate income increases demand for consumption goods, intermediate-input demand, profits, and eventually aggregate income. To derive the multiplier formally suppose that demand for all consumption goods increases exogenously by one unit, and define $\hat{y}(m,n)$ as the implied increase in demand for good m assuming that all sectors upstream of n have industrialized. Notice that $\hat{y}(n,n)=1$ as goods $m\geq n$ are demanded for consumption only. Furthermore, the argument behind (9) yields $\partial\hat{y}(m,n)/\partial m=-\theta\beta\hat{y}(m,n)/m$ and hence $\hat{y}(m,n)=(m/n)^{-\theta\beta}$. This increase in demand raises profits in each industrial sector by $(1-\theta)\hat{y}(m,n)$ and aggregate income by $(1-\theta)\int_0^n\hat{y}(m,n)dm=(1-\lambda)n$. As a result of the increase in aggregate income, demand for all consumption goods increases by $(1-\lambda)n$, which generates additional intermediate-input demand, profits, and aggregate income. The implied increase in aggregate income is $((1-\lambda)n)^2$, which generates more demand for consumption goods and so on. The industrialization multiplier, $\sum_{k=0}^{\infty}((1-\lambda)n)^k=(\lambda n+(1-n))^{-1}$, is the total increase in aggregate income generated by an exogenous one-unit increase in the demand for all consumption goods.

The potentially large aggregate-income effect of industrialization makes it especially interesting to ask if this effect is internalized by industrial firms. To answer this question it is useful to rewrite the direct impact of industrialization using (7)

$$\text{Direct impact}=\frac{(1-\beta)\pi(n,n)+\beta(1-\theta)Y(n)}{1-\theta\beta},\tag{17}$$

where

$$\pi(n,n)=(1-\theta)Y(n)-\theta f\tag{18}$$

denotes profits of the industrial firm producing furthest downstream. Hence, the adoption of the IT may have a positive effect on aggregate income even if the industrializing firm makes a loss, giving rise to a positive aggregate-income externality.[5] Intuitively, this will be the case when the industrializing firm's losses are smaller than the increase in upstream profits due to the increase in intermediate-input demand by the industrializing firm and its intermediate-input suppliers.

6. INDUSTRIALIZATION AND AGGREGATE INCOME IN EQUILIBRIUM

Before analyzing how the level of industrialization and aggregate income depend on the structural parameters of the economy, and especially the characteristics of the IT, it is necessary to characterize the industrialization equilibria.

5. Using (16) and (18) yields that this will be the case if $\lambda f/(1-\lambda)<Y(n)<\theta f/(1-\theta)$.

6.1. *Characterization of industrialization equilibria*

There are two types of locally stable equilibria: pre-industrial equilibria (PI equilibria) where all goods are produced with the PIT, and full-industrialization equilibria (FI equilibria) where all goods are produced with the IT. Intuitively, equilibria are locally stable if profits in industrial sectors neither increase with a small increase in the measure n of sectors adopting the IT nor decrease with a small decrease in the measure n of sectors adopting the IT.[6] Formally, an interior equilibrium ($0 < n^* < 1$) is locally stable if there exists a $\delta > 0$ such that $\pi(n^* - \varepsilon, n^* - \varepsilon) > 0$ and $\pi(n^* + \varepsilon, n^* + \varepsilon) < 0$ for all $0 \leq \varepsilon \leq \delta$. A FI equilibrium is locally stable if there exists a $\delta > 0$ such that $\pi(1 - \varepsilon, 1 - \varepsilon) > 0$ for all $\varepsilon \leq \delta$. And a PI equilibrium is locally stable if there exists a $\delta > 0$ such that $\pi(\varepsilon, \varepsilon) < 0$ for all $0 \leq \varepsilon \leq \delta$.

Proposition 1. *There are two types of locally stable equilibria, PI equilibria and FI equilibria. A PI equilibrium exists if and only if*

$$f > \frac{(1-\theta)L}{\theta}, \tag{19}$$

and a FI equilibrium exists if and only if

$$f < \left(\frac{1-\theta\beta}{1-\beta}\right)\frac{(1-\theta)L}{\theta}.^{7} \tag{20}$$

Proof. A PI equilibrium exists if and only if no industrial firm would make a strictly positive profit from adopting the IT when all sectors produce with the PIT. Making use of the definition of $\pi(n, n)$ in (18), this is equivalent to $\pi(0, 0) \leq 0$. This last inequality is based on the fact that, if all goods are produced with the PIT, then the industrial firm in sector $m > 0$ makes the same profit or loss from adopting the IT than the industrial firm furthest upstream. It follows from (11) and (18) that $\pi(n, n)$ is continuous in n. Hence, $\pi(0, 0) < 0$ implies that there exists a $\delta > 0$ such that $\pi(\varepsilon, \varepsilon) < 0$ for all $0 \leq \varepsilon \leq \delta$ and therefore that the PI equilibrium is locally stable. Furthermore, (16) and (17) imply that $Y'(0) > 0$ if $\pi(0, 0) = 0$. Hence, (18) implies that $\partial\pi(n, n)/\partial n$ evaluated at $n = 0$ is strictly positive and that the PI equilibrium is locally unstable if $\pi(0, 0) = 0$. A locally stable PI equilibrium therefore exists if and only if $\pi(0, 0) < 0$. This last inequality combined with (11) and (18) yields (19). A FI equilibrium exists if and only if no industrial firm makes a loss when all sectors produce with the IT. Notice that, if $\pi(1, 1) \geq 0$, then the industrial firm furthest downstream does not make a loss if all sectors produce with the IT. Furthermore, all industrial firms further upstream face greater demand and therefore earn strictly higher profits than the industrial firm furthest downstream. Hence, no industrial firm makes a loss if and only if $\pi(1, 1) \geq 0$. Continuity of $\pi(n, n)$ in n implies that the FI equilibrium will be locally stable if $\pi(1, 1) > 0$. Moreover, (16) and (17) imply that $Y'(1) > 0$ if $\pi(1, 1) = 0$. Hence, (18) implies that $\partial\pi(n, n)/\partial n$ evaluated at $n = 1$ is strictly positive and that the FI equilibrium is locally unstable if $\pi(1, 1) = 0$. A locally stable FI equilibrium therefore exists if and only if $\pi(1, 1) > 0$. This last inequality combined with (11) and (18) yields (20). To see that all interior equilibria are locally unstable notice that, if $\pi(n^*, n^*) = 0$ for $n^* \in (0, 1)$, then (16) and (17) imply $Y'(n^*) > 0$. Hence, (18) implies that $\partial\pi(n, n)/\partial n$ evaluated at n^* is strictly positive and that all interior equilibria are locally unstable. ||

6. See Krugman (1991) for more on this concept of local stability.

7. Equation (20) implies that there is a scale effect as a sufficiently large population translates into full-scale industrialization. As pointed out by a referee, this scale effect would disappear however if the fixed cost required for adoption of the IT was proportional to population.

Clearly, aggregate marginal productivity will be greater in any FI equilibrium than in a PI equilibrium since ITs are assumed to be more productive at the margin than PITs. It turns out that aggregate income in any FI equilibrium is also greater than aggregate income in a PI equilibrium, despite the fact that labour is in part used to produce the fixed input requirement in the FI equilibrium.

Lemma 4. *Aggregate productivity and income are greater in the FI equilibrium than in the PI equilibrium.*

Proof. Aggregate productivity in the PI equilibrium is unity and in the FI equilibrium is $1/\lambda > 1$ using (13). Furthermore, (11) yields that aggregate income in the FI equilibrium is $L/\lambda - f$ and that aggregate income in the PI equilibrium is L. Notice that the condition for the FI equilibrium to exist in (20) can be rewritten as $L/\lambda - f > \theta L/\lambda$, which implies $L/\lambda - f > L$ as $\theta > \lambda$. Hence, aggregate income in the FI equilibrium is greater than in the PI equilibrium. ||

It can be shown using (19) that aggregate income in the FI equilibrium relative to the PI equilibrium satisfies $\theta/\lambda \leq Y(1)/Y(0) \leq 1/\lambda$. Hence, aggregate income in the FI equilibrium will be at least $\theta/\lambda > 1$ times the aggregate income in the PI equilibrium. The increase in aggregate income associated with full-scale industrialization will therefore be similar to the increase in aggregate productivity if the productivity increase in industrial sectors is small.

Notice that the conditions for the existence of a locally stable PI equilibrium and a locally stable FI equilibrium overlap if and only if the IT uses intermediate inputs, $\beta > 0$. This implies that there exists an open set of structural parameters where the locally stable PI equilibrium and FI equilibrium co-exist. When these equilibria co-exist, then it is possible for industrial firms to raise their profits by coordinating adoption of the IT if the economy is in a PI equilibrium (industrial firms only make a profit in the FI equilibrium; they do not produce in the PI equilibrium).[8] Lemma 4 implies that coordinating industrialization among industrial firms would not only increase profits of industrial firms but also aggregate income and productivity.

6.2. *Economic structure and equilibrium industrialization*

Proposition 2 summarizes the main result about industrialization.

Proposition 2. *Minor differences in structural parameters may be associated with large differences in equilibrium levels of industrialization, aggregate productivity, and aggregate income if the IT is sufficiently intermediate-input intensive. This will be the case even if industrial firms coordinate their industrialization decisions.*

Proof. Denote the set of all structural parameters $\sigma = (L, f, \theta, \beta)$ that satisfy $L > 0$, $f > 0$, $0 < \theta < 1$, $0 < \beta < 1$ with Σ, and the subset of structural parameters that satisfy $(1-\theta)(1-\theta\beta)L = \theta(1-\beta)f$ with Ω. Notice that all $\omega \in \Omega$ satisfy (19). Furthermore, denote the ith element of σ, ω with σ^i, ω^i respectively, and the set of all structural parameters $\sigma \in \Sigma$ that satisfy $\max\{|\sigma^i - \omega^i| : i = 1, \ldots, 4\} \leq \varepsilon/2$ for $\varepsilon > 0$ and $\omega \in \Omega$ with $B(\varepsilon, \omega)$. By construction, the structural parameters in $B(\varepsilon, \omega)$ are close to each other in the sense that the maximum distance between any two structural parameters does not exceed ε. Furthermore, $B(\varepsilon, \omega)$ contains structural parameters that satisfy (20) as well as structural parameters that satisfy (19) but not (20). Lemma 4 therefore implies that $B(\varepsilon, \omega)$ contains structural parameters for

8. This also implies that the share of profits in income will be greater in the FI equilibrium than in the PI equilibrium.

which there is a unique PI equilibrium and structural parameters for which there is a FI equilibrium. Lemma 4 yields that aggregate productivity and income is greater in the FI equilibrium than in the PI equilibrium. Finally, Lemma 3 implies that the difference in aggregate productivity and income between these equilibria becomes arbitrarily large for all sequences of ωs that imply $\beta \to 1$. The argument remains unchanged if industrial firms coordinate their decision to adopt the IT. The only difference is that in this case the equilibrium is unique (there will be a FI equilibrium if and only if (20) holds, and a PI equilibrium if and only if (20) does not hold). ‖

To understand this result, it is useful to first assume that there are no input chains ($\beta = 0$). This case corresponds to the benchmark model of industrialization in Murphy *et al.* (1989).[9] Their results therefore imply that, if there are no input chains, then the FI equilibrium will exist if and only if full industrialization aggregate income exceeds aggregate income when all sectors adopt the PIT. Intuitively, this is because the private marginal cost of production θ is equal to the social marginal cost of production λ in this case. If there are input chains ($1 > \beta > 0$) however, then the private marginal cost of production θ is strictly greater than the social marginal cost of production λ. Hence, full-industrialization aggregate income must be strictly greater than aggregate income when all sectors adopt the PIT for industrial firms to make a profit from the adoption of the IT.

The results so far have been developed assuming that the PIT does not use intermediate inputs. It is straightforward to extend the model to the case where the PIT uses intermediate inputs. The appendix discusses the extended model and demonstrates that Proposition 2 holds as long at the IT uses intermediate inputs strictly more intensively that the PIT. When the intermediate-input intensity of the IT is smaller or equal than the intermediate-input intensity of the PIT, however, then the industrialization equilibrium is unique and aggregate income becomes a continuous function of structural parameters. Hence, countries with access to similar technologies will in this case have similar levels of aggregate income despite input chains.

6.3. *The role of the IT*

Figure 1 uses (19) and (20) to relate the existence of PI equilibria and FI equilibria to the IT's intermediate-input intensity β and the inverse of its relative productivity θ. Notice that the equilibrium is unique for most values of θ as long as β is small. In particular, there will be a unique FI equilibrium when the productivity increase in industrial sectors is large and a unique PI equilibrium when the productivity increase in industrial sectors is small. As β increases, the region with unique equilibria shrinks and the region with multiple equilibria expands.

Figure 1 can be used to illustrate that minor differences in the productivity of the IT may be associated with large differences in equilibrium levels of industrialization and aggregate income. For example, one economy may have access to an IT that implies uniqueness of the FI equilibrium. Another economy with access to an IT that is only slightly less productive may be in the PI equilibrium. If the IT is sufficiently intermediate-input intensive, then the difference in the level of industrialization between the two economies will translate into a large difference in aggregate income. For example, suppose that the IT used in the industrialized economy is 80% more productive than the PIT and that the intermediate-input intensity of industrial production is 60%. Then aggregate income in the industrialized economy will be almost 2·2 times aggregate income in the pre-industrial economy. (This calculation combines that aggregate income in the FI equilibrium relative to the PI equilibrium is $Y(1)/Y(0) = 1/\lambda - f/L$ and that (19) does not hold if the FI equilibrium is unique. The latter yields the upper bound $(1-\theta)/\theta$ on f/L.

9. Equilibria are both unique and socially efficient in their benchmark model.

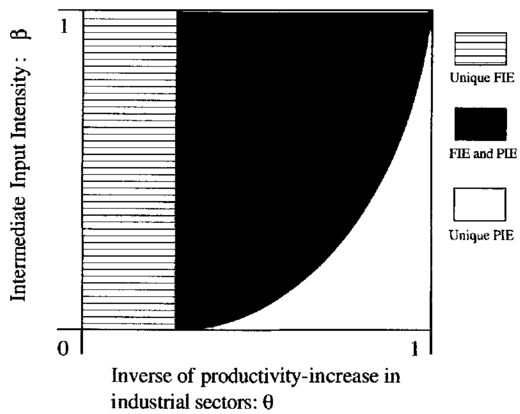

FIGURE 1

FI and PI equilibria. Notes: PIE (PI equilibrium) and FIE (FI equilibrium) denote values of θ and β such that (19) and (20) hold respectively

This upper bound can be used to find the lower bound $1/\lambda - (1-\theta)/\theta$ on aggregate income in the FI equilibrium relative to the PI equilibrium.)

Furthermore, it can also be seen from Figure 1 that a small improvement in the productivity of the IT may lead to a large increase in aggregate income. For example, consider a pre-industrial economy in the region where the FI equilibrium and the PI equilibrium co-exist. Suppose that an improvement in the productivity of the IT takes this economy into the region with a unique FI equilibrium. This will lead to an increase in aggregate income even if the technological improvement is small and the implied increase in aggregate income will be large if the IT is sufficiently intermediate-input intensive.

So far it has been assumed that industrial firms do not coordinate their industrialization decisions. This implies that the economy may be trapped into a PI equilibrium because of coordination failure. If industrial firms coordinate the adoption of the IT, then the economy will achieve full industrialization if and only if industrial firms make a positive profits by simultaneously adopting the IT. Hence, there will be a FI equilibrium if and only if (20) holds. Figure 2 plots the equilibrium level of aggregate income against the inverse of IT's relative productivity in the case of coordinated industrialization. It can be seen that there is a critical point where a minor improvement in the productivity of the IT implies a relatively large increase in aggregate income (accompanied by full-scale industrialization). The increase in aggregate income at the critical point will be large if the IT is sufficiently intermediate-input intensive. To see this notice that the critical point $\hat{\theta}$ is defined by (20) with equality. Hence, $\hat{\theta} \to 1$ as $\beta \to 1$. Furthermore, aggregate income when all sectors produce with the IT evaluated at the critical point is $\hat{\theta} f/(1-\hat{\theta})$. The increase in aggregate income at the critical point will therefore become arbitrarily large as the IT's intermediate-input intensity tends to unity.

So far the focus has been on the role of the IT's relative productivity for industrialization and aggregate income. The parameter f determining the fixed cost required for adoption of the IT plays an equally important and similar role however. For example, a minor drop in the fixed cost may trigger full-scale industrialization and a large increase in aggregate income. To see this suppose that industrial firms coordinate their industrialization decision and hence that the economy achieves a FI equilibrium if and only if (20) holds. This implies that, if the fixed cost required for the adoption of the IT falls below the critical level $\hat{f} = (1-\theta)L/\lambda$, then the economy goes from the PI equilibrium to the FI equilibrium. Aggregate income will increase as

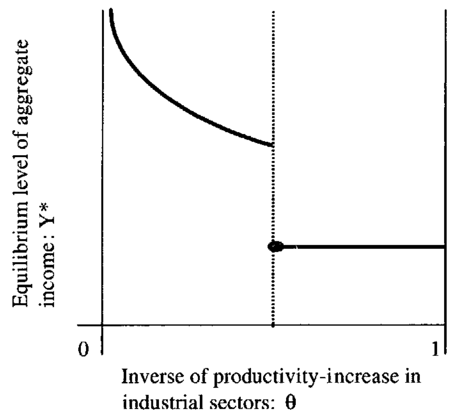

FIGURE 2

Aggregate income and industrial productivity. Notes: the figure assumes that the economy achieves full industrialization whenever a FI equilibrium exists

a result, and the increase in aggregate income will be large if the IT is sufficiently intermediate-input intensive. To see this notice that aggregate income when all sectors produce with the IT evaluated at the critical point is $\theta L/\lambda$ and that $\lambda \to 0$ as the IT's intermediate-input intensity tends to unity.

7. INPUT CHAINS, GENERAL PURPOSE TECHNOLOGIES, AND PRODUCTIVITY

Input chains imply that technological improvements affecting many sectors simultaneously—a new GPT for example—will have large effects on aggregate productivity if the IT is sufficiently intermediate-input intensive. For example, suppose that an economy is in the FI equilibrium, that the intermediate-input intensity of the IT is 60%, and that a new GPT lowers the IT's marginal general-input requirement from $\theta = 0{\cdot}9$ to $\theta_N = 0{\cdot}82$. This amounts to a 10% productivity increase in sectors that adopt the new technology. Making use of (13) yields that, if the new technology is adopted in all sectors of the economy, then the increase in aggregate productivity will be 22%.

Furthermore, the increase in aggregate productivity implied by a new GPT may be large even if it is only adopted by a small fraction of sectors, as long as the adopting sectors are those furthest upstream. This result can be established formally with the help of the next proposition.

Proposition 3. *Suppose that the economy is in the FI equilibrium and that industrial sectors upstream of $u \in [0, 1]$ produce with a more efficient IT than firms downstream of u. In particular, the marginal generalized-input requirement downstream of u is θ while it is $\theta_N < \theta$ upstream of u. Then the average amount of labour required to produce one additional unit of each good for consumption is*

$$\lambda(u) = \lambda_N u^{1-\theta\beta} + \lambda(1 - u^{1-\theta\beta}) \tag{21}$$

where $\lambda_N = \theta_N(1-\beta)/(1-\theta_N\beta)$.

Proof. Denote with $\hat{y}(m, u)$ the additional production of good m necessary to produce one additional unit of each good $m \in [0, 1]$ for consumption. Using the argument behind (9) yields that $\hat{y}(m, u)$ satisfies $\partial\hat{y}(m, u)/\partial m = -\theta\beta\hat{y}(m, u)/m$ if $m > u$ and $\partial\hat{y}(m, u)/\partial m =$

$-\theta_N \beta \hat{y}(m,u)/m$ if $m \leq u$. Furthermore, using the argument behind (8) yields $\hat{y}(1,u) = 1$. Integrating these equations implies that $\hat{y}(m,u) = m^{-\theta\beta}$ for $m > u$ and $\hat{y}(m,u) = u^{(\theta_N - \theta)\beta} m^{-\theta_N \beta}$ if $m \leq u$. The assumptions about the IT imply that each unit of output requires $\theta(1-\beta)$ units of labour. Hence, the average amount of labour to produce one additional unit of each good $m \in [0,1]$ for consumption is $\theta(1-\beta)\int_0^1 \hat{y}(m,u)dm = \lambda(1-u^{1-\theta\beta}) + \lambda_N u^{1-\theta\beta}$. ‖

Evidently, the average amount of labour required to produce one additional unit of all goods for consumption decreases and aggregate marginal productivity $\rho(u) = 1/\lambda(u)$ increases as the new, more efficient IT is introduced in upstream sectors. Furthermore, aggregate productivity is a concave function of u with $\rho'(0) = \infty$. Hence, the increase in aggregate productivity is especially large when the more efficient technology is first introduced upstream.

TABLE 4

Increase in aggregate productivity

Upstream sectors adopting new IT	0%	2%	4%	6%	10%	20%
Aggregate productivity-increase	0%	5·9%	7·1%	8·6%	10·8%	14·9%

Notes: calculations use (21) and $\beta = 0{\cdot}6$, $\theta = 0{\cdot}9$, and $\theta_N = 0{\cdot}82$.

To get a sense of the magnitudes involved it is useful to return to the example where the intermediate-input intensity of the IT is 60% and the new IT lowers the marginal general-input requirement from $\theta = 0{\cdot}9$ to $\theta_N = 0{\cdot}82$ (i.e. increase productivity at the firm level by 10%). Recall that if all sectors adopt the new technology, then the aggregate productivity increase is 22% in this case. The aggregate productivity increase as a function of the fraction of upstream sectors adopting the new IT is given in Table 4. It can be seen from the table that the new technology will raise aggregate productivity by 5·9%—more than a quarter of the aggregate productivity increase implied by adoption in all sectors—even if it is adopted by only 2% of all sectors, as long as the adopting sectors are those furthest upstream. If the upstream sectors adopting the new technology amount to 10% of all sectors, then the aggregate productivity increase is almost 50% of the aggregate productivity increase implied by full adoption. For comparison, in a model without input chains a GPT increasing sectoral productivity by 10% would increase aggregate productivity by 0·2% if it were adopted by 2% of all sectors and by 1% if it were adopted by 10% of all sectors.

8. CONCLUDING REMARKS

Two well-documented aspects of industrialization are that ITs are adopted throughout intermediate-input chains in the economy and that they use intermediate inputs intensively relative to the technologies they replace. This paper incorporates both of these aspects into a theory of industrialization. One result emerging from the analysis is that, if ITs are very intermediate-input intensive, then industrialization will have large effects on aggregate income and productivity even if the degree of increasing returns to scale at the firm level is relatively small. Intermediate-input-intensive ITs and input chains therefore provide a simple way to reconcile large effects of industrialization on aggregate income with empirically plausible increasing returns to scale at the firm level. The main consequence of input chains for industrialization is that, if ITs are sufficiently more intermediate-input intensive than the technologies they replace, then minor differences in the productivity of ITs may translate into large differences in equilibrium levels of industrialization and aggregate income. Furthermore, small improvements in the productivity of ITs may trigger full-scale industrialization and a large increase in aggregate income.

Input chains and relatively intermediate-input-intensive ITs also imply that economies may be inefficiently stuck in PI equilibria even if firms coordinate the adoption of ITs. Economic policy can play a role in achieving efficient industrialization in this case as well as in the case where the economy is trapped in the PI equilibrium because of coordination failure.

In the case of coordination failure, economic policy can subsidize the adoption of the IT to achieve the critical mass of upstream industrial sectors necessary for industrialization to be profitable. This critical mass is implicitly defined by the lowest level of industrialization n' such that $\pi(n, n) > 0$ for all $n > n'$ and can be determined explicitly as $n' = (\theta - (1-\theta)L/f)/(\theta - \lambda) \in (0, 1)$ using (18)–(20).[10] It is straightforward to show that the critical mass of industrial firms necessary for adoption of the IT to be profitable is decreasing in the IT's intermediate-input intensity. Hence, the greater the IT's intermediate-input intensity, the smaller the number of sectors that need to be subsidized.

To see the role of economic policy for efficient industrialization when industrial firms coordinate the adoption of the IT, notice that coordination implies that the economy will achieve full industrialization if and only if $\pi(1, 1) = (1-\theta)Y(1) - \theta f > 0$. This condition can be rewritten as $Y(1) > (\theta/\lambda)L$ making use of (11). The private marginal cost of production of industrial firms exceeds the social marginal cost of production, $\theta > \lambda$, and industrial firms may therefore not coordinate on the adoption of the IT although this would be socially efficient. Efficiency requires industrialization if and only if aggregate income when all sectors use the IT exceeds aggregate income when all sectors use the PIT, i.e. $Y(1) > L$. Economic policy can ensure socially efficient industrialization by subsidizing intermediate-input purchases to the point where the cost to buyers is equal to the social marginal cost of production. This involves a subsidy $s = \theta - \lambda$ per unit of inputs bought. Such a subsidy implies that industrial firms will coordinate on the adoption of the IT if and only if $\pi(1, 1) = (1 - (\theta - s))Y(1) - (\theta - s)f > 0$. Making use of (11) therefore yields that the economy will achieve full industrialization if and only if $Y(1) > L$. Hence, the subsidy implies that the economy will industrialize if and only if industrialization is socially efficient.

APPENDIX

Model where the PIT uses intermediate inputs

The PIT for the good furthest upstream ($m = 0$) uses labour only and requires one unit of labour for each unit of output produced. The PIT for goods further upstream ($0 \le m \le 1$) is

$$\log y^P(m) = \log A + \alpha \log z^P(m) + (1-\alpha)\log l^P(m), \qquad 0 < \alpha \le 1, \tag{A.1}$$

where $z^P(m)$ is the quantity of intermediate-input composites used in the production of good m with the PIT and $l^P(m)$ is the quantity of labour used in the production of good m with the PIT. It will be assumed that $\log A = -\alpha\log\alpha - (1-\alpha)\log(1-\alpha)$ to ensure that pre-industrial firms producing goods $m > 0$ have the same marginal cost of production in equilibrium as pre-industrial firms producing good $m = 0$. The specification of the PIT in (A.1) implies that the marginal cost and the average cost of production of pre-industrial firms in sector $m > 0$, $q^P(m)$, is

$$\log q^P(m) = \alpha\left(\frac{1}{m}\int_0^m \log p(i)di\right) + (1-\alpha)\log w. \tag{A.2}$$

Hence, the marginal and average cost of production of pre-industrial firms in sector m is simply a geometric average of the cost of one unit of the intermediate-input composite and the cost of labour. The weights are equal to the elasticities of output with respect to the intermediate-input composite and labour respectively.

All assumptions regarding market structure, including that pre-industrial firms are price-takers, will be maintained. The principal difference between the model here and the one in the main section is that pre-industrial firms now also have to choose intermediate inputs optimally when planning production.

10. The critical mass n' is equal to the unique locally unstable equilibrium.

Definition of equilibrium and equilibrium prices

Equilibria are defined as in the main text with the addition that the inputs demanded by the firms in pre-industrial sectors must be cost-minimizing choices of pre-industrial firms.

To determine equilibrium prices, notice that (A.1) and (1)–(4) in the main text imply that price-setting industrial firms face unit-elastic consumption-demand and input-demand functions. Hence, profit maximization by industrial firms implies that, if industrial firms produce at all, then they will set the largest price at which they cannot be undercut by pre-industrial firms in the same sector. The largest price at which industrial firms cannot be undercut is the marginal cost of production of pre-industrial firms. Pre-industrial firms' marginal cost of production can be determined recursively, starting with pre-industrial firms in the sector furthest upstream. These firms require one unit of labour for each unit of output and their marginal cost is therefore equal to the wage, which is normalized to unity. As a result, the industrial firm furthest upstream will set its price equal to unity if it produces, $p^I(0) = 1$. Now consider pre-industrial firms just downstream of sector $m = 0$. Their marginal cost of production in (A.2) is unity. The corresponding industrial firm will therefore set its price equal to unity if it produces. Applying the same argument to firms further downstream yields $q^P(m) = 1$ in all sectors and $p^I(m) = 1$ in all industrial sectors. Hence, equilibrium prices are equal to unity in all sectors.

Aggregate income and aggregate-income externalities

Now that pre-industrial sectors also demand intermediate inputs, upstream sectors face even greater demand relative to downstream sectors. Hence, if a measure n of sectors industrializes in equilibrium, then it will still be the sectors furthest upstream because they earn the highest profits.

Demand for each good is derived as in the main text. The main difference is that (9) is replaced by

$$\frac{\partial y(m,n)}{\partial m} = \begin{cases} -\theta\beta(y(m,n)+f)/m & \text{if } m < n \\ -\alpha y(m,n)/m & \text{if } m \geq n \end{cases} \tag{A.3}$$

where it has been assumed that all sectors upstream of n use the IT and all sectors downstream of n the PIT. The expression $\alpha y(m,n)/m$ captures the intermediate-input demand of pre-industrial sectors. Equation (8) in the main text is replaced by $y(1,n) = Y(n)$, as only the good furthest downstream is not used as an input in any other sector (goods $m, n < m < 1$, are used as inputs in pre-industrial sectors). Using the argument in the main text to determine aggregate income yields the following expression:

$$Y(n) = \frac{L - \lambda f n}{1 - n^{1-\alpha} + \lambda n^{1-\alpha}} \tag{A.4}$$

where the definition and interpretation of λ is unchanged (λ is defined in (12) in the main text). Notice that $\alpha > 0$ implies that, compared to the case where the PIT does not use intermediate inputs in (11), greater weight is put on the industrial labour requirement in the denominator. Hence, the industrialization multiplier will be greater in the case where the PIT uses intermediate inputs than in the case where it uses labour only (the multiplier is actually monotonically increasing in the intermediate-input share of the PIT). This is because some of the inputs of pre-industrial sectors are now produced with the IT. Aggregate income in the FI equilibrium $L/\lambda - f$ is, of course, unaffected by the PIT requiring intermediate inputs.

Profits of the industrial firm furthest downstream when the n sectors furthest upstream have industrialized are

$$\pi(n,n) = (1-\theta)y(n,n) - \theta f, \tag{A.5}$$

where $y(n,n)$, the demand for the good produced in sector n when the n sectors furthest upstream have industrialized, can be obtained by using the lower part of the bracket in (A.3) together with $Y(1,n) = Y(n)$

$$y(n,n) = Y(n)n^{-\alpha}. \tag{A.6}$$

Notice that the more intermediate-input intensive the PIT, the greater $y(n,n)$ for a given value of aggregate income $Y(n)$. The marginal effect of industrialization on aggregate income can be obtained by differentiating (A.4)

$$Y'(n) = \frac{(1-\alpha)(1-\lambda)y(n,n) - \lambda f}{\lambda n^{1-\alpha} + (1 - n^{1-\alpha})} \tag{A.7}$$

with the interpretation given in the main text (after equation (16)). The numerator of (A.7) can be rewritten in terms of the profits of the industrial firm furthest downstream $\pi(n,n)$,

$$\text{Direct impact} = \lambda\pi(n,n)/\theta + (1-\lambda)(\beta-\alpha)y(n,n). \tag{A.8}$$

This implies that for industrialization to increase aggregate income even if the industrializing firm makes a loss, $\pi(n,n) < 0$, the IT has to use intermediate inputs more intensively than the PIT. Hence, $\beta > \alpha$ is a necessary condition for positive aggregate-income externalities. (If the IT uses intermediate inputs less intensively than the PIT, then there may be a negative aggregate-income externality as aggregate income may fall despite the fact that the industrial firm in the marginal industrial sector makes a strictly positive profit.)

Equilibrium industrialization

It follows directly from (A.5) and (A.6) that $\alpha > 0$ implies that $\pi(0, 0) > 0$. Hence, the industrial firm furthest upstream will find it profitable to adopt the IT even if all other sectors use the PIT. Intuitively, this is because the input demand of pre-industrial firms implies that demand for the good produced furthest upstream will always be large enough for adoption of the IT to be profitable. As a result, there is no PI equilibrium if $\alpha > 0$.

The PI equilibrium is replaced by a low-industrialization equilibrium (LI equilibrium) where all goods upstream of some sector $n^* \in (0, 1)$ are produced with the IT and all goods downstream are produced with the PIT. Using the expression for profits of the industrial firm furthest downstream in (A.5), a LI equilibrium is defined by $\pi(\hat{n}, \hat{n}) = 0$ and $0 < \hat{n} < 1$. The condition for the existence of a FI equilibrium in (20) remains, of course, unchanged.

The two main results about equilibrium industrialization when the PIT uses intermediate inputs are summarized next.

Proposition A1. *If the IT uses intermediate inputs less intensively than the PIT, $\alpha \leq \beta$, then the equilibrium is unique and aggregate income is a continuous function of structural parameters.*

Proof. It follows from (A.7) and (A.8) that $\beta \leq \alpha$ implies that, if the industrial firm furthest downstream makes a loss, then further industrialization necessarily decreases aggregate income. This, combined with the fact that the demand for the industrial firm furthest downstream is $Y(n)n^{-\alpha}$, yields that further industrialization is necessarily unprofitable. Formally, this implies that, if $\pi(n, n) < 0$ for some $0 < n < 1$, then $\pi(m, m) < 0$ for all $m > n$. It is therefore natural to consider the following three cases separately to prove uniqueness of the industrialization equilibrium. First, $\pi(n, n) > 0$ for all $n \in (0, 1)$, which implies that there is a unique FI equilibrium. Second, that $\pi(n, n)$ becomes strictly negative for some $n \in (0, 1)$. In this case, there is a unique LI equilibrium because $\pi(n, n)$, once strictly negative, remains so as n increases. The third possibility is that $\pi(n, n) \geq 0$ for all $n \in (0, 1)$ and $\pi(n, n) = 0$ for some $n \in (0, 1)$. In this case, there would be multiple equilibria, a locally stable FI equilibrium and a locally unstable LI equilibrium. To see that this is impossible notice that (A.4)–(A.6) imply that $\pi(n, n) = 0$ if and only if $v(n) = 0$ where

$$v(n) = (1-\theta)Ln^{-\alpha} + (\theta - \lambda) f n^{1-\alpha} - \theta f. \tag{A.9}$$

Moreover, $\pi(n, n) > 0$ ($\pi(n, n) < 0$) if $v(n) > 0$ ($v(n) < 0$). Hence, there will be a locally unstable, unique LI equilibrium if and only if $v(n) = 0$ for some $n \in (0, 1)$ and $v(n) \geq 0$ for all n. Furthermore, there will be a FI equilibrium if and only if $v(1) \geq 0$. Notice that $v(n)$ is U shaped and strictly convex. Defining $n^* = \operatorname{argmin} v(n)$ therefore yields that the FI equilibrium and the locally unstable LI equilibrium will co-exist if and only if $0 < n^* < 1$ and $v(n^*) = 0$. Straightforward algebra establishes that $n^* = (\alpha(1-\theta)L)/((1-\alpha)(\theta-\lambda)f) = (\alpha(1-\theta\beta)L)/((1-\alpha)\theta\beta f)$ where the second equality makes use of the definition of λ in (12). Moreover, $v(n^*) = (n^*)^{1-\alpha}[(1-\theta)\beta/((1-\theta\beta)\alpha)]\theta f - \theta f$. Notice that the term in square brackets will be strictly smaller than unity if $\beta \leq \alpha$. Hence, $0 < n^* < 1$ implies that $v(n^*) < 0$, which yields that the FI equilibrium and the locally unstable LI equilibrium will never co-exist.

To prove the second part of the proposition notice that the LI equilibrium and FI equilibrium depend continuously on the structural parameters of the model. Hence, for there to be a discontinuity, there must be structural parameters where a small perturbation causes a "jump" from the LI equilibrium to the FI equilibrium or *vice versa*. For this to be the case either (a) or (b) must hold:

(a) That $v(n^*) = 0$ and $0 < n^* < 1$. In this case, there is a LI equilibrium and a small perturbation of the parameters such that $v(n^*) > 0$ would cause the LI equilibrium to disappear and hence the equilibrium might "jump" from low industrialization to full industrialization. But $v(n^*) = 0$ and $0 < n^* < 1$ combined with strict convexity of $v(n)$ imply $v(1) > 0$ and hence that there would also be a FI equilibrium. This is impossible as it has already been proven that the equilibrium is unique.

(b) That $v(1) = 0$. In this case, there is a FI equilibrium and a small perturbation of structural parameters such that $v(1) < 0$ will cause the FI equilibrium to disappear. If $n^* \geq 1$, then the equilibrium will go continuously from a FI equilibrium to a unique LI equilibrium as $v(n)$ depends continuously on the parameters and is U shaped. Hence, there is no "jump" in this case. If $v(1) = 0$ and $n^* < 1$, then the U shape of $v(n)$ would imply that the equilibrium "jumps" from a FI equilibrium to a LI equilibrium defined by $v(\hat{n}) = 0$ and $0 < \hat{n} < 1$. But $v(1) = 0$ and $n^* < 1$ can never be satisfied simultaneously as these conditions combined with the U shape of $v(n)$ would imply that the FI equilibrium and the LI equilibrium co-exist and it has already been proven that the equilibrium is unique. ||

Proposition A2. *If $\beta > \alpha$, then there is a set of structural parameters for which there will be two locally stable equilibria.*

Proof. Recall that (A.4)–(A.6) imply that $\pi(n, n) = 0$ if and only if $v(n) = 0$ where $v(n)$ is defined in (A.9). Moreover, $\pi(n, n) > 0$ ($\pi(n, n) < 0$) if $v(n) > 0$ ($v(n) < 0$). These results combined with the U shape and strict convexity of $v(n)$ imply that there will be at most one locally stable LI equilibrium. This yields that for there to be multiple locally stable equilibria, the locally stable LI equilibrium and the FI equilibrium must co-exist. For this to be the case the following conditions must be satisfied: $v(1) > 0$, $v(n^*) < 0$, and $0 < n^* < 1$ where $n^* = (\alpha(1-\theta\beta)L)/((1-\alpha)\theta\beta f)$ and $v(n^*) = (n^*)^{1-\alpha}[(1-\theta)\beta/((1-\theta\beta)\alpha)]\theta f - \theta f$. In this case the FI equilibrium will co-exist with the locally stable LI equilibrium defined by $v(\hat{n}) = 0, 0 < \hat{n} < 1$, and $v'(\hat{n}) < 0$ (there will also be a locally unstable LI equilibrium where $v'(\hat{n}) > 0$). A sufficient condition for the FI equilibrium and the locally stable LI equilibrium to co-exist is therefore that $n^* = (\alpha(1-\theta\beta)L)/((1-\alpha)\theta\beta f) < 1$ and that $(1-\theta)\beta/((1-\theta\beta)\alpha) < 1$. ||

When there are two locally stable equilibria, profits of the industrial firm furthest downstream are strictly greater in the FI equilibrium than the LI equilibrium. This follows directly from the definition of the LI equilibrium ($\pi(\hat{n}, \hat{n}) = 0$ and $0 < \hat{n} < 1$) and the definition of the locally stable FI equilibrium ($\pi(1, 1) > 0$). Combining this result with the definition of $\pi(n, n)$ in (A.5) and the demand for the industrial firm furthest downstream in (A.6) yields $\pi(n, n) = (1-\theta)Y(n)n^{-\alpha} - \theta f$ and hence that $Y(\hat{n})\hat{n}^{-\alpha}$ is strictly smaller than $Y(1)$ in a FI equilibrium. Aggregate income is therefore strictly greater in the FI equilibrium than the LI equilibrium. Combined with the fact that industrial sectors use intermediate inputs more intensively than pre-industrial sectors, this yields that profits in each industrial sector are greater in the FI equilibrium than the LI equilibrium. These results imply that Proposition 2 in the main text carries over to the case where PITs require intermediate inputs as long as their intermediate-input intensity is below the intermediate-input intensity of ITs.

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