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On the Factor Content of Trade

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TEP Working Paper No. 0817

January 2018

Trinity Economics Papers
Department of Economics

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January 29, 2018

Abstract

Theories of international trade have severe difficulties in explaining why, despite i) substantial differences in factor-proportions across industries and ii) considerable cross-country differences in capital-labor ratios, the iii) capital intensity of U.S imports does not vary systematically across countries. We propose a simple explanation: standard trade theories disconnect assumptions about the productivity from other core model parameters. In a standard macroeconomic model, we show that appropriately accounting for the factor-bias of productivity, in conjunction with endogenous capital formation, eradicates the gains from factor-proportions trade and can thus reconcile the three aforementioned stylized facts.

JEL: F11, F14, F41, O47

Keywords: factor-proportions trade, Heckscher-Ohlin-Vanek, macroeconomic general equilibrium models, endogenous growth, biased productivity

*We thank Ron Davies, Panos Hatzipanayotou, Panagiotis Konstantinou, Ben Moll, Peter Neary, Kevin O'Rourke and participants at the SITT Conference on International Trade 2017 for helpful comments and suggestions.

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1 Introduction

Standard theories in international economics predict that open U.S. borders move the production location of labor-intensive goods to labor-abundant countries such as Mexico and China. While recent micro-level studies have tendered some support for this effect (Autor et al. (2014), Acemoglu et al. (2016), Pierce and Schott (2016)), the preponderance of evidence at the macro-level has not been favorable. As Figure 1 shows, the labor intensity of U.S. imports does not vary systematically across countries (Panels B, C and D). This lack of clear evidence is rather surprising given that a systematic variation across countries is a distinctive prediction of many theories with heterogeneous industries, including the neoclassical trade model.¹

In this paper we provide a simple explanation for this finding. Studying the neoclassical trade model that embodies the factor proportions trade (FPT) theory, we first provide overwhelming support for its *two* main assumptions. Namely, Figure 1 reveals both i) substantial differences in factor proportions across industries (panel A) and ii) vast discrepancies in capital-labor ratios across countries (Panels B, C and D). We then address the following question: given that the core assumptions of the FPT theory are true, why does its main prediction fail so badly?

Importantly, we emphasize that altering an often overlooked assumption in the literature eliminates the gains from FPT and thus rationalizes the empirical regularities. While trade economists usually set the elasticity of intermediate goods with different labor intensities to unity for tractability reasons, we make the more realistic assumption that intermediate goods with contrasting production characteristics are complements.² Following from this assumption of complementarity, we then set productivity to be higher in more labor intensive industries.

The consequences of changing the allocation of productivity in this manner can be illustrated using two real world examples. When China opens up to trade in the early 1980s, standard models imply substantial output composition shifts toward labor-intensive industries in the country and toward capital-intensive industries in the U.S.. Similarly, when NAFTA is introduced in 1994, production in Mexico should become more labor intensive while production in the U.S. should become more capital intensive. In contrast to such sizable structural breaks predicted by conventional models, the data display rather smooth transitions akin to the ones predicted by our model.

The mechanism that suppresses the gains from trade specialization in the FPT model can be explained by drawing on an important insight from endogenous growth theory. In the case of complementarity between different goods, an optimal production allocation necessitates that goods be produced in similar quantities. Accordingly, more resources must be allocated to those goods

¹Many theories in international trade imply that cross-country differences in capital-labor ratios should lead to pronounced trade specialization patterns. Although it is well known to trade economists that evidence in favor of this prediction is quite weak (Bowen et al. (1987), Trefler (1995), Davis and Weinstein (2001), Schott (2004), Trefler and Zhu (2010), Antràs (2016) and Feenstra (2016)), the reasons behind this outcome are not well understood. Indeed Trefler and Zhu (2010) and Caron et al. (2014) indicate that more in-depth knowledge is required in order to comprehend why this “missing trade” result arises.

²Empirically, we observe complementarity between capital and labor inputs (Antràs (2004), Chirinko (2008), Chirinko et al. (2011), Oberfield and Raval (2014), Herrendorf et al. (2015), Chirinko and Mallick (2016)). Thus, it is natural to assume complementarity between capital-intensive and labor-intensive intermediate goods used in production. As shown in Table 2 of this paper, labor- and capital-intensive goods largely overlap with durable and nondurable goods, which are known to be complements (Pakos (2011), Cashin (2016), Cashin and Unayama (2016)).

that are relatively difficult to produce. Within our framework, more productivity, capital and labor is allocated to less capital-intensive goods as these goods depend more on labor, the relatively scarce factor of production.

Due to the “induced bias of technical change” effect, the relative price of labor-intensive goods falls in proportion to the productivity level in each country such that relative prices across countries are equalized even in the absence of free trade (in autarky). Given the cross-country equalization of relative prices in autarky, the motives for trade specialization are eradicated. By contrast, in the standard FPT setup, there is a difference in relative prices across countries in autarky that translates into a comparative advantage when countries open up to trade. Thus, those countries with a lower relative price of capital-intensive goods start exporting these goods in exchange for labor-intensive goods. Similarly, countries with a higher relative price of capital-intensive goods start exporting labor-intensive goods and importing capital-intensive goods.

Our paper relates to two main literatures. First, we contribute to the literature that seeks to integrate trade dynamics into open economy macroeconomic frameworks. [Findlay \(1970\)](#), [Mussa \(1978\)](#), [Ventura \(1997\)](#), [Cunat and Maffezzoli \(2004\)](#), [Antràs and Caballero \(2009\)](#), [Bajona and Kehoe \(2010\)](#), [Jin \(2012\)](#), [Ju et al. \(2014\)](#), [Zymek \(2015\)](#) and [Jin and Li \(2017\)](#), amongst others, all integrate FPT-style assumptions into dynamic frameworks. One characteristic of these integrated macro-trade models is that they predict sizable structural breaks in the data. The breaks occur because these models imply pronounced trade specialization patterns that result from comparative advantage. Nevertheless, as [Figure 1](#) demonstrates, the empirical evidence for such predictions is rather weak.

A subset of studies, including [Kongsamut et al. \(2001\)](#), [Acemoglu \(2002\)](#), [Ngai and Pissarides \(2007\)](#) and [Acemoglu and Guerrieri \(2008\)](#) for instance, provide mechanisms that can reconcile industry heterogeneity with smooth aggregate economic outcomes in closed economy models. However, as implied, these models do not take into consideration trade specialization as a motive for output composition shifts. By reverting back to the insights of [Uzawa \(1961\)](#), [Acemoglu \(2002\)](#) and [Jones \(2005\)](#), we illustrate that labor-augmenting productivity can suppress incentives for FPT-style trade specialization and thus reconcile industry heterogeneity with stable aggregate outcomes in open economy models.³

Second, our paper contributes to the literature that studies the Heckscher-Ohlin-Vanek (HOV) theorem ([Vanek \(1968\)](#)). This theorem predicts that each country will be a net exporter of the goods and services that use most intensively its abundant factor of production. As [Davis and Weinstein \(2001\)](#) note in an important paper, and as alluded to earlier, this prediction is “spectacularly at odds with the data” although the theory itself is elegant and intuitive. We argue that capital abundance is endogenous to technical progress, with productivity being allocated in a way that overcomes factor scarcity. Consequently, factor abundance does not imply a comparative advantage in goods for countries that intensively use this factor.

Our study is complementary to those works attempting to explain this “missing trade” result. [Caron et al. \(2014\)](#) show that the introduction of nonhomothetic preferences in the context of a

³On the related issue of technical change over time, [Struck and Velic \(2017\)](#) show that labor-augmenting technological progress is empirically plausible.

HOV production structure can resolve this puzzle. Our analysis is also related to the work of [Struck and Velic \(2016\)](#) who, using a dynamic macroeconomic model, illustrate that the gains from intra-industry trade in labor- and capital-intensive goods suppress the gains from FPT-style specialization.

The remainder of the paper is structured as follows. Section 2 outlines the theory and explains the underlying mechanism of our model. In Section 3, we employ numerical simulations to illustrate the main results. Finally, Section 4 concludes.

2 Theory

Consider a world with two countries, Home (H) and Foreign (F), each populated by a representative consumer. Both countries produce two tradable intermediate goods in autarky whose demands are denoted by X_n where $n \in \{1, 2\}$. Each of these goods is produced with two inputs, capital (K) and labor (L). The two intermediate goods can be combined, with substitution elasticity θ , to form a final good Y . We develop two parallel models. Section 2.1 commences with a description of the industry structure that underpins both models. Next, section 2.2 presents a *baseline* FPT model that serves as the starting point of our analysis. Section 2.3 subsequently presents an *augmented* FPT model with labor augmenting productivity. Sections 2.4 and 2.5 present the consumer problem and market clearing conditions, respectively, that both models have in common. Section 2.6 outlines the equilibrium definitions across states of autarky and free trade. The key feature of both, *baseline* and *augmented*, FPT models is that the capital intensity differs across intermediate goods with $\alpha_1 > \alpha_2$.^{4,5}

2.1 Industry Structure

The final good Y^i used in country $i \in \{H, F\}$ is given by

$$Y^i \equiv \left[\gamma^{\frac{1}{\theta}} [X_1^i]^{1-\frac{1}{\theta}} + (1-\gamma)^{\frac{1}{\theta}} [X_2^i]^{1-\frac{1}{\theta}} \right]^{\frac{\theta}{\theta-1}} \quad (1)$$

⁴We note that our models comprise elements of both Ricardian and Heckscher-Ohlin frameworks, in the sense that they feature both productivity and factor proportion differences across countries. In international macroeconomics, it is difficult to disentangle these two features as the capital stock is normally endogenously determined, ultimately depending on the exogenously given level of productivity. Thus differences in capital stocks and investment across countries depend on cross-country productivity differentials.

⁵Our core analysis of autarky versus free trade outcomes under both *baseline* and *augmented* FPT models is conducted intratemporally. That is, we examine transitions from one zero-growth steady state (autarky) to another zero-growth steady state (free trade). Such an approach allows for a comparison with the classical Heckscher-Ohlin trade model which studies trade patterns along the cross section at a fixed point in time.

where γ denotes the share of intermediate good 1 in the final good. As the two intermediate goods represent goods with different production characteristics, they are most likely to be complements.⁶

The assumption of complementarity is central to our results as it later motivates the assumption of labor augmenting productivity in the *augmented* FPT model. In standard Heckscher-Ohlin models, the focus is usually not on the elasticity, which is typically set equal to unity (i.e. $\theta = 1$) in order to obtain an analytical solution (see e.g. [Allen and Arkolakis \(2016\)](#)).⁷ *In contrast, we stress that focusing on the elasticity is pivotal as complementarity between intermediate goods annihilates the gains from trade specialization by altering the distribution of productivity across sectors which equalizes the relative prices of intermediate goods across countries even in the absence of free trade (in autarky).*

Assumption 1: *The elasticity of substitution between the two tradable goods 1 and 2 reflects complementarity with $0 < \theta < 1$.*

Optimization leads to the intermediate goods demands

$$X_1^i = \gamma \left(\frac{P_1^i}{P^i} \right)^{-\theta} Y^i \quad \text{and} \quad X_2^i = (1 - \gamma) \left(\frac{P_2^i}{P^i} \right)^{-\theta} Y^i, \quad (2)$$

where P_n^i denotes the price of good n in country i . Thus, relative prices are given by

$$\left(\frac{X_1^i}{X_2^i} \frac{1 - \gamma}{\gamma} \right)^{-\frac{1}{\theta}} = \frac{P_1^i}{P_2^i} \quad (3)$$

and

$$\left(\frac{X_1^i}{X_1^i \frac{P_1^i}{P^i} + X_2^i \frac{P_2^i}{P^i}} \frac{1}{\gamma} \right)^{-\frac{1}{\theta}} = \frac{P_1^i}{P^i}, \quad (4)$$

where P^i denotes the aggregate price level. We next highlight the key differences between the standard Heckscher-Ohlin theory (the baseline FPT model) and an augmented FPT model with labor augmenting productivity.

2.2 The Baseline FPT Model

We first introduce the *baseline* FPT model. We set up this model in a spirit similar to that of [Allen and Arkolakis \(2016\)](#). A representative firm in the perfectly competitive intermediate sector

⁶This assumption is plausible because, as shown in Table 2, labor- and capital-intensive tradable goods largely overlap with durables and non-durables which are known to be complements (see e.g. [Pakos \(2011\)](#), [Cashin \(2016\)](#) and [Cashin and Unayama \(2016\)](#)). While [Ogaki and Reinhart \(1998\)](#) find an elasticity of substitution between durables and nondurables of greater than 1, [Pakos \(2011\)](#) illustrates that results like these may be biased upward due to the assumption of homothetic preferences. Adopting homothetic preferences over durables and nondurables, which are defined as luxuries and necessities respectively, durable consumption share growth over time that has been accompanied by a decline in durable prices is erroneously ascribed to the substitution effect as opposed to the income effect.

⁷Since the elasticity is less than one we cannot obtain an analytical expression for relative prices and therefore illustrate our main effect numerically below. In Appendix B, we provide the analytical solution in the case of the standard FPT model for which $\theta = 1$.

$n \in \{1, 2\}$ in country $i \in \{H, F\}$ produces Q_n^i units of good n using a combination of capital and labor inputs. Specifically, output is given by the Cobb-Douglas production function

$$Q_n^i = A^i [K_n^i]^{\alpha_n} [L_n^i]^{1-\alpha_n} \quad (5)$$

where A^i denotes country-specific total factor productivity and α_n is the capital intensity of sector n .

Assumption 2a: *Productivity is factor-neutral.*

Optimization with respect to capital and labor leads to the first-order conditions

$$r_n^i = P_n^i \alpha_n A^i [K_n^i]^{\alpha_n-1} [L_n^i]^{1-\alpha_n}, \quad (6)$$

and

$$w_n^i = P_n^i (1 - \alpha_n) A^i [K_n^i]^{\alpha_n} [L_n^i]^{-\alpha_n}, \quad (7)$$

where r_n^i and w_n^i denote the return to capital and wage rate of sector n in country i . After rearranging Eq. (6), we obtain

$$\frac{K_n^i}{L_n^i} = \left(\frac{r_n^i}{P_n^i \alpha_n A^i} \right)^{\frac{1}{\alpha_n-1}}. \quad (8)$$

We now parallel this subsection with a subsection on an augmented FPT model characterized by labor-augmenting productivity.

2.3 The Augmented FPT Model

We now introduce the *augmented* FPT model. We set up this model in a spirit similar to that of the closed economy models of heterogeneous industries put forward by [Acemoglu \(2002\)](#) and [Acemoglu and Guerrieri \(2008\)](#), amongst others. A representative firm in the perfectly competitive intermediate sector $n \in \{1, 2\}$ in country $i \in \{H, F\}$ produces Q_n^i units of good n using a combination of capital and labor inputs. Specifically, output is given by the Cobb-Douglas production function

$$Q_n^i = [K_n^i]^{\alpha_n} [A^i L_n^i]^{1-\alpha_n} \quad (9)$$

where A^i denotes country-specific labor productivity and α_n denotes the capital intensity of sector n . The assumption of country-specific productivity is supported by evidence indicating that the level of productivity varies strongly across countries (see for example [Hall and Jones \(1999\)](#)). The assumption that productivity is labor-augmenting can be endogenously derived in this class of models and follows directly from Assumption 1 as shown by [Uzawa \(1961\)](#).⁸

Assumption 2b: *Productivity is labor-augmenting.*

⁸We also refer the reader to [Acemoglu \(2002\)](#) and [Jones \(2005\)](#) on labor-augmenting productivity. In Appendix C, we briefly illustrate an endogenous growth foundation behind the assumption of labor-augmenting productivity in the class of models that we use.

Optimization with respect to capital and labor leads to the following first-order conditions

$$r_n^i = P_n^i \alpha_n A_i^{1-\alpha_n} [K_n^i]^{\alpha_n-1} [L_n^i]^{1-\alpha_n}, \quad (10)$$

$$w_n^i = P_n^i (1 - \alpha_n) A_i^{1-\alpha_n} [K_n^i]^{\alpha_n} [L_n^i]^{-\alpha_n}, \quad (11)$$

where, once again, r_n^i and w_n^i are the returns to capital and labor respectively in sector n of country i . After rearranging Eq. (10), we obtain

$$\frac{K_n^i}{L_n^i} = \left(\frac{r_n^i}{P_n^i \alpha_n A_i^{1-\alpha_n}} \right)^{\frac{1}{\alpha_n-1}}. \quad (12)$$

2.4 Consumers

The representative consumer of country i maximizes lifetime utility given the resource constraint by selecting aggregate consumption, C^i , and allocating capital and exogenously given labor across sectors. In particular, the problem is

$$\max_{C^i, L_n^i, K_n^i, I_n^i} U_0 = \sum_{t=0}^{\infty} \beta^t \frac{C_{i,t}^{1-\phi}}{1-\phi} \quad (13)$$

subject to the period-budget constraint

$$w_{1,t}^i L_{1,t}^i + r_{1,t}^i K_{1,t}^i + w_{2,t}^i L_{2,t}^i + r_{2,t}^i K_{2,t}^i = P_t^i C_t^i + P_t^i I_t^i \equiv P_t^i Y_t^i \quad (14)$$

where β is the discount factor, t is time, and I^i is aggregate expenditure on investment.⁹ The maximization problem is constrained by the consumers income and the market clearing conditions introduced in subsection 2.5 below. The consumer earns income from working in both sectors and providing capital to each sector. The constraint is binding such that consumer income must equal expenditure. In contrast to the standard Heckscher-Ohlin model, the final good can be used for both consumption and investment. Capital is endogenously accumulated in each sector with

$$K_{n,t+1}^i = (1 - \delta) K_{n,t}^i + I_{n,t}^i, \quad (15)$$

where, at any point in time, total investment equals the sum of sectoral investments, i.e. $\sum_n I_{n,t}^i = I_t^i$, and δ is the capital depreciation rate. In the zero growth steady state, any variable Z is constant over time, i.e. $Z_{t+1} = Z_t$. The following standard equations therefore hold,

$$K_n^i = \frac{I_n^i}{\delta}, \quad (16)$$

and

$$r^i = P^i \left(\frac{1}{\beta} - 1 + \delta \right). \quad (17)$$

We now present the market clearing conditions and remaining equations that both models (the baseline FPT model and the augmented FPT model) have in common.

⁹To make the two models comparable we assume a zero growth steady state. The equilibrium of this dynamic macroeconomic model therefore becomes static as in the standard Heckscher-Ohlin trade model.

2.5 Market Clearing

The clearing of factor markets implies that the sum of sectoral capital stocks and the sum of sectoral labor supplies yield the aggregate capital stock and labor supply. Formally,

$$L^i \equiv \sum_{n=1,2} L_n^i, \quad (18)$$

and

$$K^i \equiv \sum_{n=1,2} K_n^i. \quad (19)$$

The inter-industry mobility of labor and capital implies that each factor of production earns the same return across industries. Formally,

$$w_1^i = w_2^i, \quad (20)$$

and

$$r_1^i = r_2^i. \quad (21)$$

In autarky, domestic intermediate goods consumption must equal domestic intermediate goods supply,

$$X_n^i = Q_n^i \quad (22)$$

By contrast, under free trade, world intermediate goods consumption must equal world intermediate goods supply,

$$\sum_i X_n^i = \sum_i Q_n^i \quad (23)$$

where we assume domestic and foreign prices are equalized as a result of free trade i.e. $P_n^i = P_n^{-i}$. To close the free trade models, we assume that there is zero net trade, consistent with a long-run budget constraint. Formally,

$$\sum_{n=1,2} \frac{P_n}{P} X_n^i = \sum_{n=1,2} \frac{P_n}{P} Q_n^i. \quad (24)$$

2.6 Static Equilibrium

We solve a total of four models as we have two states of nature (autarky and free trade) as well as two model classes (baseline and augmented). We solve for the standard equilibrium with perfect competition, consumer and firm optimization, market clearing and zero net trade. To summarize, the equilibria of the two models in each state are defined by:

Autarky

The Baseline FPT Model

given parameters: $A^i, L^i, \alpha_1, \alpha_2, \theta$

variables: $X_1^i, X_2^i, K_1^i, K_2^i, L_1^i, L_2^i, P_1^i/P_2^i, P_1^i/P^i, P_2^i/P^i$

system of equations: Eq. (3); Eq. (4); Eq. (18); combined Eqs. (20) and (7); combined Eqs. (21) and (6); combined Eqs. (22) and (5) (one for each sector); combined Eqs. (8) and (17) (one for each sector).

The Augmented FPT Model

given parameters: $A^i, L^i, \alpha_1, \alpha_2, \theta$

variables: $X_1^i, X_2^i, K_1^i, K_2^i, L_1^i, L_2^i, P_1^i/P_2^i, P_1^i/P^i, P_2^i/P^i$

system of equations: Eq. (3); Eq. (4); Eq. (18); combined Eqs. (20) and (11); combined Eqs. (21) and (10); combined Eqs. (22) and (9) (one for each sector); combined Eqs. (12) and (17) (one for each sector).

Free Trade

The Baseline FPT Model

given parameters: $A^i, L^i, A^{-i}, L^{-i}, \alpha_1, \alpha_2, \theta$

variables: $X_1^i, X_2^i, K_1^i, K_2^i, L_1^i, L_2^i, P_1/P_2, P_1/P, P_2/P, X_1^{-i}, X_2^{-i}, K_1^{-i}, K_2^{-i}, L_1^{-i}, L_2^{-i}$

system of equations: 2x Eq. (3); 2x Eq. (4); 2x Eq. (18); 2x combined Eqs. (20) and (7); 2x combined Eqs. (21) and (6); combined Eqs. (23) and (5) (one for each sector); Eq. (24); 2x combined Eqs. (8) and (17).

The Augmented FPT Model

given parameters: $A^i, L^i, A^{-i}, L^{-i}, \alpha_1, \alpha_2, \theta$

variables: $X_1^i, X_2^i, K_1^i, K_2^i, L_1^i, L_2^i, P_1/P_2, P_1/P, P_2/P, X_1^{-i}, X_2^{-i}, K_1^{-i}, K_2^{-i}, L_1^{-i}, L_2^{-i}$

system of equations: 2x Eq. (3); 2x Eq. (4); 2x Eq. (18); 2x combined Eqs. (20) and (11); 2x combined Eqs. (21) and (10); combined Eqs. (23) and (9) (one for each sector); Eq. (24); 2x combined Eqs. (12) and (17).

When the intermediate goods elasticity is assumed to be below unity, we cannot derive our main effect analytically. We therefore illustrate the main effect numerically in the subsequent section.

3 Numerical Analysis

In this section we numerically explore the implications of our theoretical frameworks. We stipulate once again that the two models (baseline and augmented) are evaluated across states of autarky and free trade.

3.1 Parameter Calibration

In order to conduct the model simulations, we need to select parameter values. Table 1 displays the chosen values. Regarding the common set of parameters across models, we firstly set the capital intensities of intermediate goods 1 and 2, α_1 and α_2 , to 0.56 and 0.33 respectively. These values are consistent with the U.S. data estimates provided in Table 2. The table divides tradable manufacturing goods (i.e. industries) into two relatively stable fractions, a composite capital-intensive tradable good (1) and a composite labor-intensive tradable good (2). Consistent with Table 2 again, intermediate good 1's share in the final good, γ , is set equal to 0.5.

The elasticity of substitution between intermediate goods, θ , is assigned the value 0.1. Given the complementarity found empirically between capital and labor factor inputs in production (e.g.

Antràs (2004), Chirinko (2008), Chirinko et al. (2011), Oberfield and Raval (2014), Herrendorf et al. (2015) and Chirinko and Mallick (2016)), it is natural to assume complementarity between capital- and labor-intensive intermediate good inputs in final good production in our setup. As shown in Table 2, the consolidated capital- and labor-intensive goods largely overlap with durable and nondurable goods categories. Indeed, Cashin and Unayama (2016) find that durable and nondurable goods exhibit strong complementarity, with an estimated intratemporal elasticity of substitution that is less than 0.21. Others reaching similar conclusions include Pakos (2011) and Cashin (2016). More generally, intermediate goods featuring different production characteristics tend to be complements.

Based on the population sizes of the developed (Home) and developing (Foreign) country samples listed in Appendix A, we set $L_H = 1$ and $L_F = 5$. Caselli and Feyrer (2007) show, as does Table A in Appendix A, that significant discrepancies in capital-labor ratios exist across countries, with developed economies generally being characterized by higher ratios than developing economies. Thus, overall, one can view Home (i.e. the developed world) as being relatively capital-abundant, and Foreign (i.e. the developing world) as being relatively labor-abundant.

Next, we set $A_H = 4.5$ and $A_F = 1$ based on estimates from a Cobb-Douglas production function applied to our sample of countries. Moreover, this parameterization is broadly consistent with findings in the related literature suggesting significant discrepancies in cross-country productivity levels e.g. see Hall and Jones (1999) amongst others. We note that our productivity estimates are derived using a period-average economy-wide capital share of 0.33, roughly consistent with Gollin (2002) and Lawrence (2015) for example. However, very similar parameter values are obtained using the manufacturing sector capital intensity of 0.45 given in Table 2. Lastly, we assume a relatively standard value for the discount factor β of 0.97, while the capital depreciation rate is set equal to 0.05. As a robustness check, in Appendix D we provide results for the simulation exercise that follows under an alternative set of parameter values.

3.2 Simulation Results

Figure 2 numerically illustrates the effect of moving from a state of autarky to a state of free trade across the baseline and augmented FPT models respectively. Panels A and B of the figure illustrate the standard effect of opening up to trade in the baseline FPT model. In the state of autarky (time 1-5), panel A shows that labor-abundant Foreign has a higher relative price of capital-intensive good 1, P_1/P_2 , than capital-abundant Home. Liberalizing trade (time 6-10) induces strong specialization patterns across the two regions in this setting. Foreign begins to specialize in the labor-intensive good while Home begins to specialize in the capital-intensive good. Foreign exports the labor-intensive good to Home where its relative price is higher and imports the capital-intensive good from Home where that good's relative price is lower. At the same time, Home does the opposite. Panel A shows that the end result is an equalization of relative prices across Home and Foreign. Correspondingly, panel B demonstrates that, under free trade, the capital-intensity of exports minus the capital-intensity of imports is negative for Foreign, while positive for Home.

Similarly, panels C and D of Figure 2 show the impact of free trade on relative prices and production specialization across Home and Foreign in the augmented FPT model. This time, the

panels indicate that relative prices across countries remain equalized in states of both autarky and free trade and that FPT-style trade specialization does not take place upon opening up to trade. The discrepancy in simulation patterns across baseline and augmented FPT models arises as a result of the way productivity is incorporated. In particular, the combination of complementarity between intermediate goods, with the implication that productivity is labor-augmenting, and endogenous capital formation in the augmented FPT model acts to eliminate the gains from FPT-style trade specialization.

The intuition behind the lack of trade specialization as a result of the aforementioned ingredients is as follows. Firstly, the quite realistic assumption of complementarity between goods with different production characteristics implies that these goods should be produced in similar quantities at the optimum. Therefore, more resources must be devoted to goods that are more difficult to produce. Within our setup, more resources are directed toward the production of the good that uses more intensively the relatively scarce factor of production, namely, labor. The implication for productivity specifically is that it must be labor-augmenting or, put differently, biased toward relatively labor-intensive tasks.¹⁰ As resources are distributed in the same fashion in each country, relative prices across countries are equalized even in the absence of trade. Furthermore, the assumption of endogenous capital accumulation ensures that capital is amassed in proportion to the level of technology in each country, thereby maintaining the previous price equalization effect.

Since cross-country relative prices are equalized in autarky, no country has a comparative advantage in the production of any good. Consequently, there are no welfare improvement incentives for FPT-style trade specialization patterns under free trade. By contrast, in standard FPT models, there is an ex-ante difference in relative prices across countries. This discrepancy in prices provides the source for gains from trade, and thus motivates pronounced trade specialization in the class of FPT models.

4 Conclusion

Two-country models with heterogenous industries predict that gains from factor proportions trade (FPT) lead to a strong relation between capital-labor ratios and the capital-intensity of exports across countries. Yet, U.S. bilateral trade data indicate that this relation is rather weak. In this paper, we provide a simple explanation for this well known finding. We contend that appropriately accounting for the bias of productivity in conjunction with endogenizing the capital formation process completely alters the predictions of standard theories and subsequently allows us to rationalize the empirical evidence.

Our analysis demonstrates that changing a seemingly innocent assumption of the standard FPT theory triggers an important interaction that eliminates the gains from FPT-style trade specialization. The assumption pertains to the elasticity of substitution between intermediate goods which has implications for the bias of productivity. We rather realistically assume that intermediate goods with different production characteristics are complements. Within our framework, this ingredient

¹⁰The fundamental insight that technical progress is directed toward scarce goods and resources under complementarity is well known in the endogenous growth literature.

implies that more resources are allocated toward the good that uses labor more intensively, the relatively scarce factor of production. Thus, the implication for the distribution of productivity under complementarity is that it must be labor-augmenting. Under labor-augmenting productivity, relative prices across countries are equalized even in the absence of free trade.

Importantly, since relative prices are equalized in autarky, no country has a comparative advantage in producing any good. Therefore, under our assumption of complementarity, there are no incentives for FPT-style specialization patterns under free trade. In comparison, ex-ante cross-country relative price discrepancies are present in standard FPT models. Such differences generate gains from trade, and thus lead to predictions of pronounced trade specialization developments in the class of FPT models.

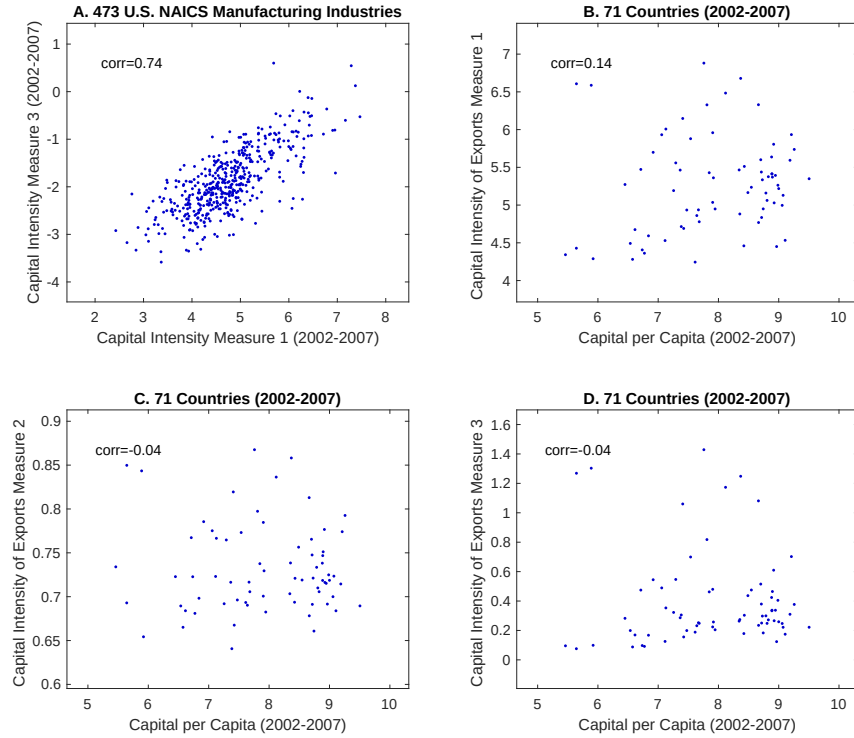
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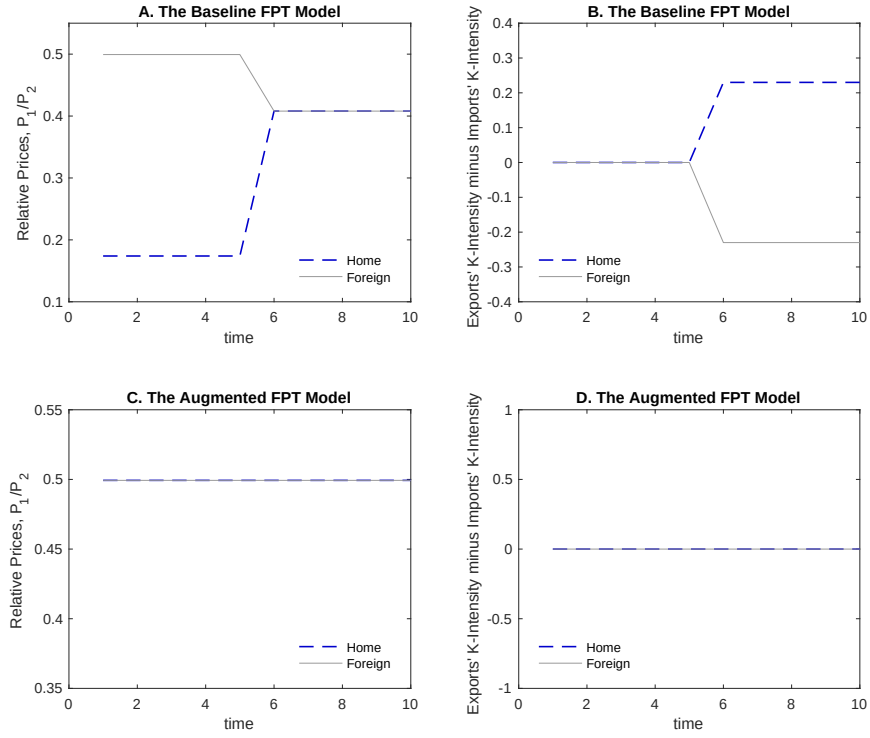
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Figure 1: U.S. NAICS Imports, Capital Intensity and Cross-Country Capital-Labor Ratios, 2002-2007



Notes: The cross-country data pertain to cross-section averages over the period 2002-2007. Panel A shows the relation between two different measures of the capital intensity across 473 NAICS U.S. Manufacturing Industries. Panels B, C and D show the relation between three export-weighted measures of industry capital intensity (i.e. measures of revealed comparative advantage (RCA)) and the capital-per-capita ratio (log investment per capita) across 71 developed and developing countries. Pearson correlations reported. Data construction details and list of countries employed are provided in Appendix A. Table A of Appendix A provides the RCA and capital-labor ratio statistics for each country.

Figure 2: Relative Prices and Specialization under Autarky and Free Trade



Notes: Time 1-5 shows the equilibrium in autarky. Time 6-10 shows the equilibrium under free trade. The top two Panels, A and B, show the equilibrium of the baseline FPT model. The bottom two Panels, C and D, show the equilibrium of the augmented FPT model.

Table 1: Parameters

good 1's output share	$\gamma = 0.5$
elasticity of substitution	$\theta = 0.1$
capital intensities	$\alpha_1 = 0.56, \alpha_2 = 0.33$
labor endowments	$L_H = 1, L_F = 5$
productivity levels	$A_H = 4.5, A_F = 1$
discount factor	$\beta = 0.97$
capital depreciation	$\delta = 0.05$

Table 2: U.S. Bureau of Labor Statistics (BLS) Capital Shares of 3-digit Manufacturing Industries, 2002-2007 Averages

Industry	Durables	Title	NAICS	α_n	$P_n Y_n / PY$
1	No	Petroleum and Coal Products	324	0.88	6.96 %
1	No	Chemical Products	325	0.66	14.25 %
1	No	Food, Beverage, Tobacco	311,312	0.51	10.24 %
1	Yes	Primary Metals	331	0.43	3.32 %
1	No	Paper Products	322	0.41	3.35 %
1	Yes	Transportation Equipment	336	0.40	13.53 %
2	Yes	Computer, Electronics	334	0.40	12.36 %
2	Yes	Nonmetallic Mineral Products	327	0.39	2.85 %
2	No	Plastics and Rubber Products	326	0.36	3.88 %
2	Yes	Electrical Equip., Appliances, etc.	335	0.36	2.80 %
2	Yes	Miscellaneous Manufacturing	339	0.33	3.94 %
2	Yes	Machinery	333	0.31	6.77 %
2	Yes	Fabricated Metal Products	332	0.31	7.24 %
2	No	Printing, Related Activities	323	0.24	2.62 %
2	No	Textile Mills, Textile Product Mills	313,314	0.23	1.27 %
2	Yes	Furniture and Related Products	337	0.23	1.94 %
2	Yes	Wood Products	321	0.22	1.88 %
2	No	Apparel, Leather, Applied Products	315,316	0.18	0.80 %
	Yes	<i>Durables</i>		0.36	56.17 %
	No	<i>Non-Durables</i>		0.57	43.83 %
1		<i>Capital Intensive</i>		0.56	51.64 %
2		<i>Labor Intensive</i>		0.33	48.36 %
1, 2		<i>Manufacturing Sector</i>		0.45	100.00 %

Notes: α_n denotes the capital intensity of industry / goods category n . $P_n Y_n / PY$ denotes the output share of industry / goods category n in the total output of the manufacturing sector.

Appendices

A Data Details For Figure 1

A.1 Data Construction

Following [Struck and Velic \(2016\)](#), we obtain measures of inter-industry trade using bilateral international U.S. trade data. The U.S. trade dataset is constructed as follows. Firstly, we combine the U.S. 6-digit North American Industry Classification System (NAICS) trade data of [Schott \(2008\)](#) with Census trade data in order to produce the extended sample period 2002-2007. The raw dataset is then rectangularized by treating any missing values as zero import or export flows.

Subsequently, we match this dataset up with the NBER-CES Manufacturing Industry data ([Becker et al. \(2009\)](#)) which comprises subsectoral information on variables such as employment, payroll, investment, capital stock, and value added.¹¹ This completes the final dataset employed in the construction of the different indices of inter-industry trade.

Specifically, the degree of trade specialization in capital- and labor-intensive manufacturing industries across countries is captured by computing trade-weighted measures of revealed comparative advantage (RCA). More precisely, for country i at time t , we define revealed comparative advantage in capital-intensive goods as the trade-weighted capital intensity of exports

$$RCA_{i,t} = \sum_{z \in Z} \frac{x_{i,z,t}}{X_{i,t}} k_{z,t}$$

where $x_{i,z,t}$ denotes the exports of country i in industry $z \in Z$ to the U.S. in period t , $X_{i,t}$ represents the total exports of country i to the U.S. in period t , and $k_{z,t}$ is the capital intensity of industry z in period t . The trade-weighted nature of the measure implies that the index is insensitive to the digit level of the trade data. In addition, this measure of trade specialization can be derived directly from theory (see [Struck and Velic \(2016\)](#)). Our definition makes the standard assumption that industry factor intensities are the same across countries. The implication is that factor intensity can be consistently ranked using factor share data for just one country, namely the U.S..¹² U.S. capital intensity data is used due to its availability and attractiveness, given the size and diversity of the industrial economy.

Consistent with the literature, we put forward three different measures of capital intensity in order to ensure the robustness of our results. These include 1) the logarithm of the real capital stock per worker adopted from [Antràs \(2016\)](#), 2) the share of total capital compensation in value added adopted from [Romalis \(2004\)](#) and [Jin \(2012\)](#), and 3) the logarithm of the capital to labor expenditure ratio which provides the corresponding spending flows version of 1). Thus, the three RCA variables generated are

$$\text{Measure 1: } RCA_{i,t}^1 = \sum_{z \in Z} \frac{x_{i,z,t}}{X_{i,t}} \ln \left(\frac{\text{cap}}{\text{emp}} \right)_{z,t} \quad (\text{A.1a})$$

$$\text{Measure 2: } RCA_{i,t}^2 = \sum_{z \in Z} \frac{x_{i,z,t}}{X_{i,t}} \left(1 - \left(\frac{\text{pay}}{\text{vadd}} \right)_{z,t} \right) \quad (\text{A.1b})$$

$$\text{Measure 3: } RCA_{i,t}^3 = \sum_{z \in Z} \frac{x_{i,z,t}}{X_{i,t}} \ln \left(\frac{\text{invest}}{\text{pay}} \right)_{z,t} \quad (\text{A.1c})$$

where “cap” is the total real capital stock, “emp” is total employment, “pay” is total payroll, “vadd” is total value added, and “invest” is total capital expenditure.

Finally, we obtain information on aggregate investment, population and GDP from the World Bank’s World Development Indicators.

A.2 Country Sample

The 71 countries (U.S.’s bilateral trading partners) in our sample are selected using criteria adopted from [Lane and Milesi-Ferretti \(2012\)](#). First, we remove all economies with nominal GDP below \$20 billion in the year 2007 as small countries can experience high or outsized trade balance volatility. Second, we discard oil-dominated countries as their

¹¹Note that the NBER-CES Manufacturing data are available at the 6-digit NAICS level consisting of 473 industries. Once these data are paired with the corresponding trade data, we are left with 389 NAICS common manufacturing industries.

¹²Put differently, we assume no factor intensity reversals.

external trade dynamics are highly dictated by the price of petroleum. The exclusion of these countries eliminates extreme outlier observations that could potentially impede any meaningful analysis of the relation between macroeconomic outcomes and inter-industry trade dynamics. The final list of countries used is as follows¹³

Developed: Australia (AUS), Austria (AUT), Belgium (BEL), Canada (CAN), Denmark (DNK), Finland (FIN), France (FRA), Germany (DEU), Greece (GRC), Iceland (ISL), Ireland (IRL), Italy (ITA), Japan (JPN), Luxembourg (LUX), Netherlands (NLD), New Zealand (NZL), Norway (NOR), Portugal (PRT), Spain (ESP), Sweden (SWE), Switzerland (CHE), United Kingdom (GBR), United States (USA).

Developing: Argentina (ARG), Bangladesh (BGD), Belarus (BLR), Brazil (BRA), Bulgaria (BGR), Cameroon (CMR), Chile (CHL), China (Mainland) (CHN), Colombia (COL), Costa Rica (CRI), Croatia (HRV), Cyprus (CYP), Czech Republic (CZE), Dominican Republic (DOM), Egypt, Arab Rep. (EGY), El Salvador (SLV), Estonia (EST), Ghana (GHA), Guatemala (GTM), Hong Kong S.A.R. (HKG), Hungary (HUN), India (IND), Indonesia (IDN), Israel (ISR), Kenya (KEN), Korea Rep. (KOR), Latvia (LVA), Lebanon (LBN), Lithuania (LTU), Malaysia (MYS), Mexico (MEX), Morocco (MAR), Pakistan (PAK), Peru (PER), Philippines (PHL), Poland (POL), Russia (RUS), Serbia (SRB), Singapore (SGP), Slovak Republic (SVK), Slovenia (SVN), South Africa (ZAF), Sri Lanka (LKA), Thailand (THA), Tunisia (TUN), Turkey (TUR), Ukraine (UKR), Uruguay (URY), Vietnam (VNM).

Table A displays the average RCA and capital-labor ratio figures for each of the countries in our sample over the period 2002-2007.

B Analytical Solution: Case of $\theta = 1$

To illustrate the main mechanism analytically, we rely on the special case that the intermediate goods elasticity θ equals unity. This assumption turns Eq. (3) into

$$\frac{X_2^i}{X_1^i} \frac{\gamma}{1-\gamma} = \frac{P_1^i}{P_2^i}. \quad (\text{B.1})$$

The price index simplifies to a Cobb-Douglas function,

$$P^i = P_{1,i}^\gamma P_{2,i}^{1-\gamma}. \quad (\text{B.2})$$

In the *baseline FPT* model, combining wage equalization, $w_n^i = w_{-n}^i$, with wages, Eq. (7), and the capital-labor ratio, Eq. (8), yields

$$\frac{P_n^i}{P_{-n}^i} = \frac{1-\alpha_{-n}}{1-\alpha_n} \frac{A_i}{A_i} \frac{\left(\frac{r^i}{\alpha_{-n} P_{-n}^i A^i}\right)^{\frac{\alpha_{-n}}{\alpha_{-n}-1}}}{\left(\frac{r^i}{\alpha_n P_n^i A^i}\right)^{\frac{\alpha_n}{\alpha_n-1}}}. \quad (\text{B.3})$$

Substituting in the steady state condition for capital returns, Eq. (17), and the price index, Eq. (B.2), leads to an expression that highlights the link between relative prices and the country's level of development, A_i :

$$\frac{P_{1,i}^{1+(1-\gamma)\frac{\alpha_1}{1-\alpha_1}+\gamma\frac{\alpha_2}{1-\alpha_2}}}{P_{2,i}^{1+(1-\gamma)\frac{\alpha_1}{1-\alpha_1}+\gamma\frac{\alpha_2}{1-\alpha_2}}} = \frac{A_i^{\frac{1}{1-\alpha_2}}}{A_i^{\frac{1}{1-\alpha_1}}} \frac{1-\alpha_2}{1-\alpha_1} \frac{\left(\frac{(\frac{1}{\beta}-1+\delta)}{\alpha_2}\right)^{\frac{\alpha_2}{\alpha_2-1}}}{\left(\frac{(\frac{1}{\beta}-1+\delta)}{\alpha_1}\right)^{\frac{\alpha_1}{\alpha_1-1}}}. \quad (\text{B.4})$$

In particular, this expression shows that the relative price of the labor-intensive good increases with the level of development.

Proposition 1. In the *baseline FPT* model, the country with the higher level of development has a higher relative price for the labor-intensive good (in autarky). Conversely, the country with the lower level of development has the higher relative price for the capital-intensive good (in autarky). ■

We next turn our focus to the *augmented FPT* model. To find an expression for relative prices in this model, we follow the previous procedure, however this time using instead the capital-labor ratio from Eq.(12) and wages from

¹³Data availability also governs our country sample size.

Table A: Revealed Comparative Advantage (RCA) and Cross-Country Capital-Labor Ratios, 2002-2007 Averages

country	RCA^1	RCA^2	RCA^3	capital labor	country	RCA^1	RCA^2	RCA^3	capital labor	country	RCA^1	RCA^2	RCA^3	capital labor
ARG	5.88	0.77	0.70	7.54	GBR	5.44	0.75	0.38	8.71	NOR	5.93	0.77	0.70	9.21
AUS	5.00	0.70	0.25	9.06	GHA	6.61	0.85	1.27	5.64	NZL	4.77	0.68	0.23	8.67
AUT	5.22	0.72	0.26	9.00	GRC	5.60	0.77	0.52	8.70	PAK	4.29	0.65	0.10	5.92
BEL	5.37	0.75	0.46	8.90	GTM	4.41	0.72	0.10	6.74	PER	5.93	0.78	0.49	7.06
BGD	4.43	0.69	0.08	5.64	HKG	4.45	0.69	0.12	8.96	PHL	5.27	0.72	0.28	6.45
BGR	5.43	0.74	0.46	7.85	HRV	4.88	0.74	0.27	8.35	POL	4.95	0.68	0.20	7.94
BLR	6.88	0.87	1.43	7.76	HUN	5.47	0.70	0.26	8.34	PRT	5.24	0.72	0.48	8.55
BRA	5.19	0.69	0.32	7.26	IDN	4.67	0.68	0.17	6.62	RUS	6.33	0.80	0.82	7.81
CAN	5.39	0.72	0.34	8.95	IND	4.49	0.69	0.20	6.54	SGP	5.59	0.71	0.31	9.19
CHE	5.13	0.72	0.22	9.07	IRL	5.74	0.79	0.38	9.26	SLV	4.59	0.70	0.17	6.84
CHL	5.96	0.78	0.48	7.90	ISL	4.53	0.68	0.17	9.11	SRB	4.86	0.69	0.23	7.64
CHN	4.69	0.67	0.16	7.42	ISR	4.46	0.69	0.18	8.42	SVK	5.51	0.72	0.30	8.43
CMR	6.59	0.84	1.30	5.89	ITA	4.84	0.69	0.25	8.72	SVN	5.06	0.71	0.25	8.81
COL	5.56	0.76	0.55	7.29	JPN	5.38	0.71	0.27	8.83	SWE	5.41	0.75	0.34	8.89
CRI	4.94	0.72	0.25	7.67	KEN	4.34	0.73	0.10	5.46	THA	4.93	0.70	0.20	7.47
CYP	5.17	0.76	0.44	8.49	KOR	5.41	0.72	0.33	8.89	TUN	6.15	0.82	1.06	7.41
CZE	4.95	0.66	0.18	8.74	LBN	4.24	0.69	0.19	7.61	TUR	4.78	0.71	0.25	7.68
DEU	5.33	0.72	0.30	8.73	LKA	4.36	0.68	0.09	6.77	UKR	6.01	0.77	0.35	7.13
DNK	5.03	0.72	0.27	8.92	LTU	6.48	0.84	1.17	8.12	URY	4.72	0.64	0.31	7.38
DOM	4.53	0.72	0.13	7.11	LUX	5.35	0.69	0.22	9.50	USA				9.16
EGY	5.47	0.77	0.47	6.71	LVA	6.68	0.86	1.25	8.37	VNM	4.28	0.67	0.09	6.57
ESP	5.26	0.72	0.40	8.99	MAR	5.70	0.79	0.54	6.92	ZAF	5.46	0.72	0.29	7.36
EST	6.33	0.81	1.08	8.66	MEX	5.04	0.70	0.22	7.90					
FIN	5.64	0.74	0.42	8.88	MYS	5.36	0.73	0.26	7.92					
FRA	5.16	0.73	0.30	8.79	NLD	5.81	0.78	0.61	8.92					

Notes: The capital-labor ratio is given by the log of investment per capita ratio.

Eq. (11). The equivalent of the previous expression for relative prices, Eq. (B.4), in the *augmented FPT* model is given by

$$\frac{P_{1,i}^{1+(1-\gamma)\frac{\alpha_1}{1-\alpha_1}+\gamma\frac{\alpha_2}{1-\alpha_2}}}{P_{2,i}^{1+(1-\gamma)\frac{\alpha_1}{1-\alpha_1}+\gamma\frac{\alpha_2}{1-\alpha_2}}} = \frac{1-\alpha_2}{1-\alpha_1} \frac{\left(\frac{(\frac{1}{\beta}-1+\delta)}{\alpha_2}\right)^{\frac{\alpha_2}{\alpha_2-1}}}{\left(\frac{(\frac{1}{\beta}-1+\delta)}{\alpha_1}\right)^{\frac{\alpha_1}{\alpha_1-1}}}. \quad (\text{B.5})$$

This expression shows that the relative price of the labor-intensive good does *not* depend on the level of development. Thus, in the *augmented FPT* model, a country with a lower level of development has no comparative advantage in labor-intensive goods. Conversely, a country with a higher level of development has no comparative advantage in capital-intensive goods.

Proposition 2. In the *augmented FPT* model, a country with a higher level of development has the same relative price as the country with a lower level of development (in autarky). ■

C Extended Model with Endogenous Bias of Technical Change [NOT FOR PUBLICATION]

In a closed economy model based on Acemoglu and Guerrieri (2006, 2008) we highlight an endogenous growth foundation behind Assumption 2b. Consider an economy in which aggregate output is a composite of the output of two intermediate industries $n = 1, 2$. The output of the intermediate industries can be combined to form a final good that can be used for consumption, investment and research. The intermediate industries differ in their labor intensity. In each industry n , there are $M_{n,t}$ symmetric firms $i \in [0, M_{n,t}]$ at time t . The number of infinitely living consumers grows at an exogenously given constant rate, n .

C.1 Firms

We now illustrate that labor-augmenting technical change can be an endogenous outcome in this class of models. The final good Y_t in the economy is obtained by combining intermediate goods quantities $X_{1,t}$ and $X_{2,t}$ with an elasticity of substitution ϵ . Formally, we have

$$Y_t \equiv \left[\gamma^{\frac{1}{\epsilon}} [X_{1,t}]^{1-\frac{1}{\epsilon}} + (1-\gamma)^{\frac{1}{\epsilon}} [X_{2,t}]^{1-\frac{1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}. \quad (\text{C.1})$$

Suppose that the output of each industry is produced by a continuum of monopolistically competitive firms,

$$X_{n,t} = \left[\int_{i=0}^{M_{n,t}} y_{n,i,t}^{\frac{\phi-1}{\phi}} di \right]^{\frac{\phi}{\phi-1}}, \quad (\text{C.2})$$

where $y_{i,n,t}$ is the output of firm i in industry n ; $\phi > 1$ denotes the firm elasticity of substitution; $M_{n,t}$ is the number of firms in industry n at time t . A firm i in industry n produces output using a constant elasticity of substitution production technology,

$$y_{n,i,t} = k_{n,i,t}^{\alpha_n} l_{n,i,t}^{1-\alpha_n} \quad (\text{C.3})$$

where $k_{n,i,t}$ is the capital stock that firm i in industry n uses for production; $l_{n,i,t}$ is the amount of labor used by a firm; $M_{n,t}$ is still the number of varieties in industry n . Each firm maximizes profits $\pi_{n,i,t}$

$$\pi_{n,i,t} = p_{n,i,t} y_{n,i,t} - w_{n,i,t} l_{n,i,t} - r_{n,i,t} k_{n,i,t}. \quad (\text{C.4})$$

where $p_{n,i,t}$ is the price of firm i in industry n ; $w_{n,i,t}$ is the price of labor; $r_{n,i,t}$ is the price of capital. The profit of firm i in industry n can be expressed as a function of industry output,

$$\pi_{n,i,t} = \frac{1}{\phi} P_{n,t} \frac{X_{n,t}}{M_{n,t}}. \quad (\text{C.5})$$

At the industry level, production can be expressed as in the standard setup, that is,

$$X_{n,t} = M_{n,t}^{\frac{1}{\phi-1}} K_{n,t}^{\alpha_n} L_{n,t}^{1-\alpha_n} \equiv A_{n,t} K_{n,t}^{\alpha_n} L_{n,t}^{1-\alpha_n}. \quad (\text{C.6})$$

Research production takes the form of¹⁴

$$\frac{\dot{M}_1}{M_1} = b_1 \frac{Z_1}{Y} \quad \text{and} \quad \frac{\dot{M}_2}{M_2} = b_2 \frac{Z_2}{Y}, \quad (\text{C.7})$$

where Z_n denotes the research expenditure in industry. Assuming that the value function is differentiable in time, the net present discounted value of profits of monopolist i starting at time t is given by

$$V_{n,i,t} = \frac{\pi_{n,i,t} + \dot{V}_{n,i,t}}{r_t}. \quad (\text{C.8})$$

One unit spent on research in industry 1 leads to $b_1 M_1/Y$ units of new monopolists. One unit spent on research in industry 2 leads to $b_2 M_2/Y$ units of new monopolists. Free entry into research then implies that the profits from new monopolists equals the research expenditures (assuming research expenditure is positive):

$$V_{1,i} = \frac{Y}{b_1 M_1} \quad \text{and} \quad V_{2,i} = \frac{Y}{b_2 M_2}, \quad (\text{C.9})$$

which hold as equalities as long as research expenditure is positive.

C.2 Consumers

The number of workers in the economy grows at an exogenously given rate,

$$L_t = e^{nt} L_0. \quad (\text{C.10})$$

All workers have identical preferences over the aggregate consumption good. These preferences can be represented as the utility function of a single consumer:

$$\int_0^\infty e^{-(\rho-n)t} \frac{c_t^{1-\theta} - 1}{1-\theta} dt, \quad (\text{C.11})$$

where c_t denotes the per-capita level of real consumption; ρ denotes the time preference parameter; θ is the inverse of the inter temporal elasticity of substitution. Labor is inelastically supplied. The representative consumer faces the following budget constraint

$$\dot{K}_1 + \dot{K}_2 + C + Z_1 + Z_2 = w_1 L_1 + w_2 L_2 + r_1 K_1 + r_2 K_2 + \Pi, \quad (\text{C.12})$$

where X_1 and X_2 denote the research expenditures in industries 1 and 2, respectively; $C_t = L_t c_t$ is aggregate real consumption; $\dot{K}_n$ is the change in the sector n 's capital stock; w_n is the wage rate; r_n is the return to capital; Π denote the economy's profits. The wealth of the consumer, W , is the sum of the aggregate capital stock and the value of the firms in the two industries and is given by

$$W_t = K_t + V_{1,t} + V_{2,t}, \quad (\text{C.13})$$

where $K = \sum_n K_n$; the no-ponzi condition therefore takes the form of

$$\lim_{t \rightarrow \infty} \left\{ W_t \times \exp \left[- \int_{s=0}^t (r(s) - n) ds \right] \right\} \geq 0. \quad (\text{C.14})$$

The growth rate of consumption is given by

$$\frac{\dot{c}}{c} = \frac{1}{\theta} \left(\frac{r_t}{P_t} - \rho \right). \quad (\text{C.15})$$

Thus, per-capita consumption growth is constant, as long as $\frac{r_t}{P_t}$ is constant.

C.3 Market Clearing

All factor markets are competitive, thus, capital and labor markets clear,

$$\begin{aligned} L_t &= L_{1,t} + L_{2,t} \equiv \int_{i=0}^{M_{1,t}} l_{1,i,t} di + \int_{i=0}^{M_{2,t}} l_{2,i,t} di, \\ K_t &= K_{1,t} + K_{2,t} \equiv \int_{i=0}^{M_{1,t}} k_{1,i,t} di + \int_{i=0}^{M_{2,t}} k_{2,i,t} di. \end{aligned} \quad (\text{C.16})$$

¹⁴In [Acemoglu and Guerrieri \(2006\)](#), research production takes a different functional form. As a result, they obtain non-balanced growth.

The sum of firm profits in the two industries equal aggregate profits

$$\Pi_t = \Pi_{1,t} + \Pi_{2,t} \equiv \int_{i=0}^{M_{1,t}} \pi_{1,i,t} di + \int_{i=0}^{M_{2,t}} \pi_{2,i,t} di. \quad (\text{C.17})$$

Since firms within industries are symmetric, industry output can be expressed as the output of firm i premultiplied by an indicator of the quantity of firms in the industry

$$Y_t = X_{1,t} + X_{2,t} \equiv y_{1,i,t} M_{1,t}^{\frac{\phi}{\phi-1}} + y_{2,i,t} M_{2,t}^{\frac{\phi}{\phi-1}}. \quad (\text{C.18})$$

Because the key derivation details of this model are contained in [Acemoglu and Guerrieri \(2006\)](#), we skip the equilibrium definition and mainly focus on how to restore balanced growth in this framework.

C.4 Long-Run Behavior

Profits of the intermediate monopolist are given by

$$\pi_{n,i,t} = p_{n,i,t} y_{n,i,t} - w_{n,i,t} l_{n,i,t} - r_{n,i,t} k_{n,i,t} \quad \text{or} \quad \pi_{n,i,t} = p_{n,i,t} y_{n,i,t} - \frac{1}{\psi} y_{n,i,t} \quad (\text{C.19})$$

where $1/\psi$ denotes the marginal costs. Substituting into the previous equation the demand for intermediate goods, $y_{n,i,t} = \left(\frac{p_{n,i,t}}{P_{n,t}}\right)^{-\phi} Y_{n,t}$, and maximizing with respect to prices, $p_{n,i,t}$, yields

$$\frac{\partial \pi_{n,i,t}}{\partial p_{n,i,t}} = 0 \quad \Leftrightarrow \quad p_{n,i,t} = \frac{\phi}{\phi-1} \frac{1}{\psi}. \quad (\text{C.20})$$

Profit maximization with respect to, $k_{n,i,t}, l_{n,i,t}$ yields

$$w_{n,i,t} = \frac{\phi-1}{\phi} (1-\alpha) p_{n,i,t} \frac{y_{n,i,t}}{l_{n,i,t}} \quad \text{and} \quad r_{n,i,t} = \frac{\phi-1}{\phi} \alpha p_{n,i,t} \frac{y_{n,i,t}}{k_{n,i,t}} \quad (\text{C.21})$$

where $r_{n,i}$ is the return to capital and $w_{n,i}$ is the wage. Assuming no frictions implies that factor returns equalize across firms, i.e. that $w_{n,i} = w_{n,j}$ and $r_{n,i} = r_{n,j}$. Substituting Eq. (C.20) back into profits leads

$$\pi_{n,i,t} = \frac{1}{\phi} p_{n,i,t} y_{n,i,t} \quad (\text{C.22})$$

The economy has a simple representation at the industry level. Industry labor and capital are given by

$$\int_{i=0}^{M_{n,t}} l_{n,i,t} di = L_{n,t} \quad \text{and} \quad \int_{i=0}^{M_{n,t}} k_{n,i,t} di = K_{n,t}. \quad (\text{C.23})$$

Substituting aggregate capital and labor into back into the combined Eqs. (C.6) and (C.2), we obtain a simple expression for industry output

$$X_{n,t} = \left[\int_{i=0}^{M_{n,t}} [k_{n,i,t}^{\alpha_n} l_{n,i,t}^{1-\alpha_n}]^{\frac{\phi-1}{\phi}} di \right]^{\frac{\phi}{\phi-1}} = M_{n,t}^{\frac{1}{\phi-1}} K_{n,t}^{\alpha_n} L_{n,t}^{1-\alpha_n} = A_{n,t} K_{n,t}^{\alpha_n} L_{n,t}^{1-\alpha_n}. \quad (\text{C.24})$$

where $M_{n,t}^{\frac{1}{\phi-1}} = A_{n,t}$. Using firm output as a function of industry output, $y_{n,i,t} = X_{n,t} / M_{n,t}^{\frac{\phi}{\phi-1}}$, relative prices, $p_{n,i,t} = P_{n,t} M_{n,t}^{\frac{1}{\phi-1}}$, and factor aggregation, $L_{n,t} / M_{n,t} = l_{n,i,t}$ and $K_{n,t} / M_{n,t} = k_{n,i,t}$, in combination with Eq. (C.21), industry factor returns can be expressed as

$$w_{n,t} = \frac{\phi-1}{\phi} (1-\alpha) P_{n,t} \frac{X_{n,t}}{L_{n,t}} \quad \text{and} \quad r_{n,t} = \frac{\phi-1}{\phi} \alpha P_{n,t} \frac{X_{n,t}}{K_{n,t}}. \quad (\text{C.25})$$

To study the long-run behavior, we rewrite the model in growth rates. We differentiate the key equations (C.24), (C.25), as well as equation (C.9) of the model above with respect to time. The system of equations we obtain is

$$\frac{\dot{X}_1}{X_1} = \frac{\dot{A}_1}{A_1} + \alpha_1 \frac{\dot{K}_1}{K_1} + (1-\alpha_1) \frac{\dot{L}_1}{L_1} \quad \text{and} \quad \frac{\dot{X}_2}{X_2} = \frac{\dot{A}_2}{A_2} + \alpha_2 \frac{\dot{K}_2}{K_2} + (1-\alpha_2) \frac{\dot{L}_2}{L_2}, \quad (\text{C.26})$$

$$\frac{\epsilon-1}{\epsilon} \frac{\dot{X}_1}{X_1} + \frac{1-\epsilon}{\epsilon} \frac{\dot{X}}{X} = 0 \quad \text{and} \quad \frac{\epsilon-1}{\epsilon} \frac{\dot{X}_2}{X_2} + \frac{1-\epsilon}{\epsilon} \frac{\dot{X}}{X} = 0, \quad (\text{C.27})$$

$$\frac{\dot{L}_1}{L_1} - \frac{\dot{L}_2}{L_2} = -\frac{1}{\epsilon} \left(\frac{\dot{X}_1}{X_1} - \frac{\dot{X}}{X} \right) + \frac{\dot{X}_1}{X_1} + \frac{1}{\epsilon} \left(\frac{\dot{X}_2}{X_2} - \frac{\dot{X}}{X} \right) - \frac{\dot{X}_2}{X_2}, \quad (\text{C.28})$$

$$\frac{\dot{r}_1}{r_1} - \frac{\dot{P}}{P} = -\frac{1}{\epsilon} \left(\frac{\dot{X}_1}{X_1} - \frac{\dot{X}}{X} \right) + \frac{\dot{X}_1}{X_1} - \frac{\dot{K}_1}{K_1} \quad \text{and} \quad \frac{\dot{r}_2}{r_2} - \frac{\dot{P}}{P} = -\frac{1}{\epsilon} \left(\frac{\dot{X}_2}{X_2} - \frac{\dot{X}}{X} \right) + \frac{\dot{X}_2}{X_2} - \frac{\dot{K}_2}{K_2}. \quad (\text{C.29})$$

Eq. (C.27) directly implies that $\dot{X}_2/X_2 = \dot{X}_1/X_1 = \dot{X}/X$. Given this result, and, assuming constant consumption growth, the real interest rate is constant, i.e. $\dot{r}_n/r_n - \dot{P}/P = 0$, Eq. (C.29) implies that $\dot{K}_2/K_2 = \dot{K}_1/K_1 = \dot{X}/X$. Eq. (C.28) then implies $\dot{L}_1/L_1 = \dot{L}_2/L_2 = \dot{L}/L$. Therefore,

$$\frac{1 - \alpha_1}{1 - \alpha_2} = \frac{\dot{A}_1/A_1}{\dot{A}_2/A_2}. \quad (\text{C.30})$$

This result for relative productivity growth is also implied by Assumption 2b. To see this, take the time derivative of the production function from Eq. (9)

$$\frac{\dot{Q}_1}{Q_1} = (1 - \alpha_1) \frac{\dot{A}}{A} + \alpha_1 \frac{\dot{K}_1}{K_1} + (1 - \alpha_1) \frac{\dot{L}_1}{L_1} \quad \text{and} \quad \frac{\dot{Q}_2}{Q_2} = (1 - \alpha_2) \frac{\dot{A}}{A} + \alpha_2 \frac{\dot{K}_2}{K_2} + (1 - \alpha_2) \frac{\dot{L}_2}{L_2}, \quad (\text{C.31})$$

Solving for relative productivity growth shows that the above result implies a production function with labor-augmenting technical change

$$\frac{\dot{A}_1/A_1}{\dot{A}_2/A_2} = \frac{(1 - \alpha_1)\dot{A}/A}{(1 - \alpha_2)\dot{A}/A}. \quad (\text{C.32})$$

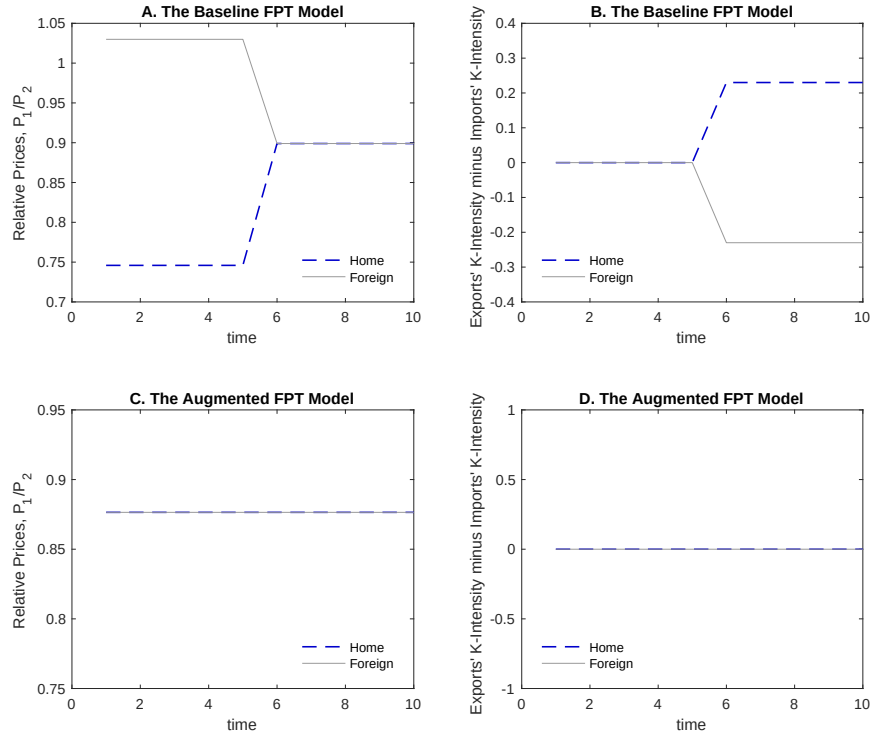
D Robustness of Simulations

Figure C illustrates the robustness of our simulation results under the alternative set of parameter values displayed in Table C.

Table C: Alternative Parameter Values

good 1's output share	$\gamma = 0.6$
elasticity of substitution	$\theta = 0.8$
capital intensities	$\alpha_1 = 0.42, \alpha_2 = 0.19$
labor endowments	$L_H = 1, L_F = 2$
productivity levels	$A_H = 2, A_F = 1$
discount factor	$\beta = 0.9$
capital depreciation	$\delta = 0.1$

Figure C: Relative Price and Specialization Patterns under Autarky and Free Trade Using Alternative Parameter Values



Notes: See Table C for the alternative parameter values employed. Time 1-5 shows the equilibrium in autarky. Time 6-10 shows the equilibrium under free trade. The top two Panels, A and B, show the equilibrium of the baseline FPT model. The bottom two Panels, C and D, show the equilibrium of the augmented FPT model.