The Dance of the Dynamics: The Interplay of Trade and Growth

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Abstract

We study the interaction of endogenous growth and Ricardian trade working solely through comparative advantage. The model is built on several facts about R&D and trade. Trade and growth affect each other in ways previously unexposed or unexplored. The model can explain and reconcile in a single framework several phenomena usually analyzed separately. Trade may raise or lower the growth rates of trading partners in any combination: both up, both down, or one up and one down, depending on parameter values. The mechanism at work is consistent with the data, in contrast to the previous literature. Trade leads to "effective technology transfer," with the growth rate looking as if a country adopted its partner's technology even though it does not. Economic growth can change the trading regime endogenously, moving trading partners incomplete to complete specialization (from the Ricardian corner to the Ricardian interior), which can explain why trade helps some countries catch up but leaves others behind. Trade may raise or lower social welfare. The model specifies the conditions under which each possible outcome occurs. The model has many testable implications. We perform three tests, which the model passes.

1 Introduction

This paper uses a "second-generation" fully endogenous growth model to study the interaction of Ricardian trade and economic growth. Standard static trade theory provides powerful results on the economic effects of trade through comparative advantage. One might expect similarly powerful implications of comparative advantage for economic growth. However, most studies of trade and growth do not address that issue but instead restrict attention to how trade facilitates technology transfer, as Feenstra (1996) noted long ago and as continues to this day (Alvarez, Buera, and Lucas 2012; Perla and Tonetti 2014; Sampson 2016). In that literature, any growth effects from trade arise from technology transfer, not from trade itself. The distinction is similar to that underlying the classic factor price equalization theorem. Mobility of factors can equalize factor prices, but trade in goods even with no international mobility of factors also can equalize factor prices. The issue we address here is how trade *per se* can affect growth even if there is no technology transfer. A small subset of the existing trade and growth literature does examine that issue, but literally all of it has used growth models that have been rejected by formal tests, which renders any conclusions about trade and growth invalid.[1] Second-generation endogenous growth theory (Peretto 1996, 1998c, 1999a; Dinopoulos and Thompson 1998; Howitt 1999) has received strong empirical support (e.g., Laincz and Peretto 2006; Ha and Howitt 2007; Madsen 2008, 2010; Ang and Madsen 2011), but it has not been applied to the study of how Ricardian trade and economic growth affect each other.[2] We develop a version of the 2nd-generation model that is consistent with several key facts from the IO and trade literature and show that combining it with Ricardian trade delivers a large number of results on trade and growth, a few of which confirm conclusions in the earlier literature but most of which either contradict previous results or are completely new. The model can explain a wide variety of observations in a single framework, offering a unified explanation of disparate phenomena that previously have been given unrelated explanations or not been explained at all.

Our investigation of trade and growth is motivated by two considerations. The first is simple intellectual curiosity. It is natural to see if 2nd-generation growth theory - which has been so fruitful in addressing other issues - can produce useful insights about the interaction of trade and growth. The second is that previous models of Ricardian trade and economic growth cannot explain salient features of the data. Two examples are the evidence on the growth effects trade and the persistent failure of sub-Saharan Africa to share in the world-wide increases in growth rates. Table 1 presents growth rate data for the world before and after the 1980 trade liberalization. Perhaps the most obvious question one can ask about trade and growth is whether trade promotes growth. The question may be obvious, but the answer is not. The first line of Table 1 shows that the world average growth rate was higher after liberalization than before, suggesting that trade enhances growth. The next two lines of the table muddy the picture considerably. They divide the world into the industrialized and non-industrialized countries. The growth rate for the two groups moved in opposite directions after trade liberalization, with the industrialized countries' growth rates falling and the non-industrialized countries' rates rising. It isn't just that some countries gained and other lost, but rather that there is a clear pattern to who the gainers and loser are. Advanced economies lost, and developing economies gained. Existing models of trade in a growth framework cannot explain that pattern. Virtually all predict that trade will raise the growth rates of all trading partners, and trade-induced reductions are impossible. An exception is Grossman and Helpman (1990), in which trade can reduce the growth rates of all trading partners but cannot lead to mixed results. Furthermore, Grossman and Helpman's mechanism for reducing growth rates did not operate during the time period in question. In Grossman and Helpman's story, trade can reduce world growth rates by inducing the country that is the R&D leader to shift resources from R&D to producing tradable goods. The resulting reduction in the leader's R&D activity reduces the rate of economic growth. That, however, cannot be the explanation for the events surrounding 1980. As Tables 2 and 3 show, the leading R&D countries did not experience a reduction in R&D resources. Indeed,

[1] Invalid but not necessarily wrong. The falsity of a premise invalidates the logic leading to the conclusion. The conclusion may be correct, but it remains unproven.

[2] "First-generation" endogenous growth theory is the version developed by Romer (1986, 1990), Grossman and Helpman (1991), and Aghion and Howitt (1992). Second-generation growth theory endogenizes firm size, which brings the theory into conformity with the data and leads to a large number of additional implications. A full discussion is beyond the scope of the present paper.

for most of them R&D activity increased after trade liberalization. These cross-country differences in the apparent effect of trade on growth have fueled much debate about whether or not trade is good for growth, exemplified by Sachs and Warner (1995) on one side and Rodriguez and Rodrik (2000) on the other. Turning to Africa, we see from Table 4 that the growth rate for Africa is positively correlated with the growth rates for the rest of the world but has remained substantially below the other growth rates for the entire time, even showing signs of divergence. Existing models cannot that behavior except perhaps as an extremely slow transition to a steady state with equal growth rates across countries. However, one thousand years is a sufficiently long time to be a candidate for steady state behavior, bringing into question the slow transition argument. As we show below, our model offers a coherent explanation for these and other facts.

We begin by extending the 2nd-generation endogenous growth model to include Ricardian trade. We build the model to be consistent with several sets of fundamental facts established by the industrial organization and trade literatures and then show that it can explain the foregoing issues and also others. We do *not* build the model deliberately to explain the foregoing issues concerning trade and growth, a procedure that would run the risk of being *ad hoc*. We discuss the relevant IO and trade facts when we introduce the parts of our model that are motivated by them. It is sufficient here to summarize their effects. The 2nd-generation approach endogenizes the firm's market size, which eliminates the artificial aggregate market size effects that are the source of the main empirical rejections of the 1st-generation model. The best known is the aggregate scale effect, which says counterfactually (Backus, Backus, and Kehoe 1992; Jones 1995; Gong, Greiner, and Semmer 2004 that the economy's growth rate is positively related to the economy's size. However, other inappropriate aggregate market size effects afflict both 1st-generation endogenous and semi-endogenous growth theory, as we explain. More important for our results are the IO facts on which firms do R&D and what kind of R&D they do. The interaction of the IO structure of R&D on the one hand and the specialization induced by comparative advantage on the other hand leads to many new results about how trade affects economic growth and *vice versa*. The model is consistent with all the data patterns just mentioned.

Our analytical framework stands apart from Melitz (2003) and Eaton and Kortum (2002), which are the two most prominent models of trade used today. Our model has a superficial similarity to Melitz (2003), for both emphasize aspects of the economy's IO structure and depend on them for their results, but the two approaches are quite different. The important element in Melitz (2003) is the cross-firm heterogeneity of total factor productivity (TFP). In contrast, our model focuses on the nature of R&D and which firms do it. Melitz heterogeneity has only transitory effects on economic growth in the 2nd-generation growth framework, consistent with recent empirical evidence (Harrison, Martin, and Nataraj 2013). Including Melitz-type aspects of the IO structure would greatly complicate the analysis without changing its major conclusions, so we exclude them. The Eaton and Kortum (2002) approach to trade is very rich, allowing analysis of many goods and many countries. Unfortunately, in our model that much dimensionality would render the analysis intractable, so we restrict attention to a 2-country, 2-good framework, taking a step back in the treatment of trade in order to take a step forward in the treatment of growth. We discuss both Melitz (2003) and Eaton and Kortum (2002) in more detail in the main text.

Our results fall into two groups: (1) the effects of trade on growth and (2) the effects of growth on trade. Many of the results in the first group differ from those in the earlier literature because of the different underlying IO structure of our model. Other results on trade's effect on growth are completely new. Nearly everything in the second group of results is new. We summarize the two sets of results here.

Trade affects economic growth by effectively allowing countries to substitute foreign R&D for their own, even though no actual substitution takes place. The mechanism by which that happens is that many traded goods have the fruit of R&D embodied in them in the form of quality improvements. Indeed, one of the IO facts underlying the specification of our model is that most private R&D is devoted to quality improvement. When the improved goods are factors of production (intermediate goods or physical capital), their higher quality makes their buyer more productive. Continual quality improvements thus drive continually increasing productivity and economic growth. Trade in the relevant factors of production allows the embodied quality improvements to be carried to other countries, which experience an increase in their productivity just as if they themselves had invented the quality improvements. In other words, trade allows "effective technology transfer," by which trading partners can increase their productivity as if they had imported their partner's technology even if no technology transfer ever actually occurs. Thus comparative advantage can increase economic growth through pure trade.

An important implication of our analysis is that trade may reduce rather than increase growth of one or both trading partners. That is because most private R&D is done by incumbent firms and specialization induced by Ricardian trade drives firms out of business. Comparative advantage determines which firms go out of business, but firms' efficiency at R&D determines their contribution to economic growth. As our analysis shows, comparative advantage and R&D efficiency are determined by unrelated forces. Consequently comparative advantage may shut down firms that are relatively good at R&D, thereby reducing the growth rate of one country even while it raises the growth rate of another. That possibility a kind of dynamic inefficiency, a negative externality arising from agents making today's trade decisions without accounting sufficiently for the effect of their decisions on tomorrow's productivity. This dynamic inefficiency is a novelty of our analysis. Our theory provides the conditions determining whether a trade-induced change in growth is positive or negative. It thus offers an explanation for the sometimes seemingly contradictory evidence on the relation between trade and growth and thus a reconciliation of long-running debate in the literature on trade's growth effects, e.g., Sachs and Warner (1995) and Rodriguez and Rodrik (2000) mentioned above.

Another novelty of our analysis is its complete characterization of the Ricardian corner solution, in which some trading partners specialize but others do not. Most trade literature ignores the corner case. In contrast, we analyze it fully and find it not only interesting but apparently descriptive of much of the world. The corner is often where countries are just after they open to trade, so behavior in the corner is central to understanding the dynamic adjustment path following trade liberalization. Also, the corner seems to be where certain perpetually backward countries reside, in particular sub-Saharan Africa.

Most previous work on trade and growth examines trade's effect on growth. Virtually none considers growth's effect on trade. Our framework allows exploration of that issue. We show that growth can move the world across trading regimes. The interior solution (the region of complete specialization) is dynamically stable. The entire region is a basin of attraction for the balanced growth path that lies within it. Once the world is completely specialized, it stays that way, barring of course an exogenous shock. The corner solution (the region of incomplete specialization) is saddle path stable, with the economy possibly moving to the interior, remaining on a knife-edge balanced growth path, or moving deeper into the corner with growth rates of the trading partners asymptotically approaching a constant difference. Economic growth can move the world economy *endogenously* from the corner solution to the interior solution. Movement in the opposite direction does not occur. As Eaton and Kortum (2012) have noted, one of the major reasons Ricardian theory was not used for empirical work was that it delivered different types of trading regimes that were walled off from each other, creating a "clumsy taxonomy." Given its static nature, standard Ricardian theory offered no explanation for the movement from one regime to another, whereas our theory does. To the best of our knowledge, there is nothing like that result in the previous literature.

Having a complete description of the transition dynamics allows a full analysis of the welfare effects of opening to trade. Because of the possible dynamic inefficiency, trade that is beneficial initially may not maximize social welfare.

The model delivers many testable implications. We test three to illustrate the wide range of issues to which the model applies and also to contrast it with models in the earlier literature: the relation between a country's growth rate and the change in its terms of trade, the effect of globalization on the growth rates of the world's R&D leaders and followers, and the evolution of the growth rate of slow-growth countries after globalization. Our model has implications for each test that differ from the predictions of earlier models. The tests fail to reject our model and do reject competitors.

Trade and growth are engaged in a dynamic dance, intricate and beautiful, in which the partners move together and react to each other. Let's see how they do it.

2 Model Structure

Our theory is not built to explain the empirical observations that motivate it, although it does that, but to conform with a set of other facts from the trade and IO literatures. We list those facts and then refer to them at the point in the model development where they are used.

2.1 Underlying Facts

The important facts underlying our model fall into two groups: those concerning the IO structure of the model and those concerning trade and its effects. It is beyond the scope of this paper to explain and document the facts in any detail. We give only an illustrative reference or two for the facts that are most important for our purposes. The interested reader can find a much more extensive discussion with a very long list of references in the working paper version of this article.

The IO facts are eight in number. (1) Both the number of firms and firms' market size are endogenous. (2) Technical progress is driven by R&D. (3) Firms in virtually every country in the world do R&D (World Bank 2016; US Patent & Trademark Office 2014).[3] (4) R&D by multinational firms' foreign affiliates is a small percentage of the firms' total R&D (e.g., about 9% for US firms; NSF 2010a). Virtually all of it is specific to the country where it is done and is not transferrable back to the parent companies' home countries (Hines 1994; Bilir and Morales 2016). (5) There are three broad classes of R&D: improvement in the quality of existing varieties of goods, reduction in the cost of producing existing varieties of goods, and expansion in the number of varieties of goods. (6) All three types of R&D are done mostly by incumbent firms (Appendix Table 4-3, NSF 2010a). In the US, about 70% of R&D is private, and over 90% of that is done by incumbents.[4] (7) Incumbents' R&D is devoted mostly to increasing the quality of their products, which means that it is not they but rather their buyer that reap any productivity gains of the R&D. About 40% of firms' R&D is for improving existing varieties of goods. Another 40% is for developing new products, most of which do not expand the variety of products the firm offers but rather replace existing products and so are another form of quality improvement. Overall, about 75% of incumbents' R&D is for quality improvement. Another 20% of incumbents' R&D is for reducing the cost of producing existing varieties of goods. The remaining 5% of incumbent R&D is for expanding the incumbent firm's variety of products (Mansfield 1968, Scherer 1984, Broda and Weinstein 2010). (8) The remaining private R&D is done by outsiders mostly to develop new varieties of goods. Very little outsider R&D is done to develop products that challenge incumbents' existing varieties. R&D thus results almost entirely in "creative accumulation" rather than "creative destruction."[5] Creative destruction, in the sense of firms driving rivals out of business, does occur, but it is almost entirely restricted to new industries that have not yet matured. It is responsible for only a small fraction of total technical progress. Garcia-Macia, Hsieh, and Klenow (2015) confirm the centrality of creative accumulation in an indirect and novel way. They calibrate a model and find that the resulting parameter estimates have two major implications: (i) most growth has come from innovation by incumbents rather than entrants and (ii) most growth has arisen from improvements to

[3] Aggregate R&D expenditure varies greatly across countries, with most being concentrated in 10 or 15 of the largest economies. However, as we see below, a major characteristic of the 2nd-generation growth approach is that growth depends on R&D expenditure per firm, not aggregate expenditure. For our model, aggregate expenditure and its cross-country concentration are irrelevant. We delve into these point in more detail below.

[4] Very little government-funded R&D raises economic productivity. Much (60% in the US) is for national defense. Most of the rest is for "basic" research, which by definition is not expected to have any practical application in the near future (NSF 2010a, 2010b). Furthermore, government R&D crowds out private R&D, leading to a net *negative* estimated impact on economic growth. (OECD 2003).

[5] The concepts of creative destruction and creative accumulation both originate with Schumpeter (1912 and 1942, respectively). The former is by far the better known, but Schumpeter himself emphasized the latter in his later work. See Fontana, Nuvolari, Shimitzu, and Vezzulli (2012) for a brief history of the two terms.

existing varieties of goods rather than from creation of new varieties.

The trade facts are two. (9) About three-quarters of international trade is in factors of production, either physical capital or intermediate goods. (10) Firms and whole industries may shut down in the face of foreign competition.

The foregoing are the main facts on which our model is built. Of course they are not all the facts, which no single model can address, but conforming to them gives our model a structure distinctly different from any previous work on trade embedded in a growth framework. Failure to account fully for the relevant aspects of firm endogeneity in fact #1 is the main source of the empirical rejections of both 1st-generation fully endogenous growth theory and semi-endogenous growth theory. Fixing that deficiency not only eliminates the best-known empirical problems of the earlier approaches but also yields different results in other ways, as we show below. Fact #2 focuses attention on the centrality of R&D to technical progress, in contrast to mechanical self-fulfilling models of growth such as AK model and the CES model with a (counterfactually) high elasticity of substitution between capital and labor. We mention the rest of the facts as we come to the parts of the model that rely on them.

We turn now to the specification of the model.

2.2 Final Goods

A country can produce three types of goods: final, processed, and intermediate. (An equivalent specification with only two types of goods is discussed briefly below.) Intermediate goods are combined with labor to make processed goods. Processed goods are used to make final goods. Final goods are used for consumption, as an input for intermediate goods, and as an input into research and development. Endogenous growth models usually have only final goods and intermediate goods. We add the intervening processed goods sector to facilitate the discussion of trade. We explain each sector in turn.

In the final goods sector, identical competitive firms produce a single homogeneous good Y using two non-durable processed goods X_1 and X_2 as inputs in Cobb-Douglas production:

$$Y = X_1^{\epsilon} X_2^{1-\epsilon} \tag{1}$$

We take the final good as the numeraire, so $P_Y = 1$. The representative firm's profit is

$$\pi_Y = Y - P_{X_1} X_1 - P_{X_2} X_2 \tag{2}$$

where P_{X_1} and P_{X_2} are the prices of X_1 and X_2.

In this specification, labor does not appear as a direct factor of production in the final goods sector. However, it does enter indirectly, as we see shortly. Furthermore, under a mathematically equivalent specification of the model, it enters directly. We discuss these issues below.

2.3 Processed Goods

The processed goods sector comprises two industries, each producing a single homogeneous good X_i, $i \in \{1, 2\}$. Both industries are competitive in all markets. The representative firms in the two industries use non-durable intermediate goods G and labor l to produce their respective processed goods. Consider first the closed economy. We follow Aghion and Howitt (2005) and Peretto (2007) in specifying the processed goods production function for industry 1 as

$$X_1 = \int_0^{N_1} G_{1j}^{\lambda} \left(Z_{1j}^{\delta} Z_1^{\gamma} Z_2^{1-(\delta+\gamma)} l_{1j} \right)^{1-\lambda} dj, \quad 0 < \lambda, \gamma, \delta < 1 \tag{3}$$

with a symmetric equation for industry 2. Here G_{ij} is the amount of the intermediate good produced by firm j and used in industry i, Z_{ij} is the quality of good G_{ij}, $Z_i \equiv (1/N_i) \int_0^{N_i} Z_{ij} dj$ is the average quality of class-i intermediate goods (explained momentarily), l_{ij} is the amount of labor working with intermediate good G_{ij}, and N_i is the number of varieties of intermediate goods used in each industry. There are two classes of intermediate goods, $\{G_{1j}\}_{j=0}^{N_1}$ and $\{G_{2j}\}_{j=0}^{N_2}$, with one class providing inputs for the X_1 industry and the other class providing inputs for the X_2 industry. The sets of intermediate goods used by the X_1 and X_2 industries are disjoint and generally have different numbers of elements ($N_1 \neq N_2$). Each intermediate good's quality Z_{ij} is determined by the R&D that has been done by the firm that produces G_{ij}. Labor productivity depends on the quality Z of the intermediate good it works with. The values of the exponents γ and $\delta + \gamma$ determine whether there are knowledge spillovers across firms and across industries, respectively. When we allow international trade in intermediate goods, the cross-industry knowledge spillover will become a cross-country spillover. We thus can study the importance of this type of technology transfer for our results by varying the value of $\delta + \gamma$.

The quality Z_{ij} that is embodied in G_{ij} augments labor. Much quality improvement is of that type. The best-known example probably is the textile machines of the Industrial Revolution:

> "[W]ith the marvelously perfect and self-acting machinery of today no special skill is required on the part of the attendant. *The machinery itself supplies the intelligence.*"[Quoted by Clark (2007), emphasis added.]

Similar examples continue to this day, such as the computer chips in modern car engines that greatly reduce the skill needed to diagnose mechanical problems. We could include intermediate good-augmenting quality improvement, but that would add nothing important. Labor is the only non-reproducible factor of production, so technical progress must augment it for there to be perpetual growth. We therefore restrict attention to labor-augmenting quality improvement.

Two aspects of (3) require brief comment. First, there is no love of variety, which helps us in two ways: it isolates the effects of comparative advantage by eliminating an alternative motive for trade (*a la* Krugman, 1979, and Melitz, 2003) and, by preventing the marginal product of an intermediate good from going to infinity when the quantity of that intermediate goes to zero, it allows the traditional specialization of the standard Ricardian model, in which the comparatively disadvantaged industry shuts down (fact #10 in section 2.1). Second, (3) is unstable in the Nash sense. Intermediate goods are perfect substitutes in (3), so if one firm gets slightly ahead of the others in its level of technology, it takes over the market immediately, converting the model to one of monopoly. We avoid that outcome by following Aghion and Howitt (2005) and Peretto (1999b, 2007) in assuming that all firms start at the same level of technology and that new entrants enter at the industry average level. The economy then remains in the monopolistically competitive equilibrium because the model solution is symmetric and there are no random shocks to disrupt the equilibrium. The equilibrium is well-behaved dynamically, as we show below. Intra-industry behavior is not relevant to the issues we discuss, so Nash instability is not a problem for our analysis. We therefore sacrifice richness in one dimension of the economy's microeconomic behavior (aspects of intra-industry dynamics) to gain insight into other aspects (shut-down induced by international competition).[6]

As explained below, countries trade intermediate goods, so the processed goods production function must be modified to allow use of both domestic and foreign intermediate goods:

$$
\begin{aligned}
X_{H1} \quad = \quad & \int_0^{N_{H1}} \left(G_{H1j} - G_{H1j}^E\right)^\lambda \left[Z_{H1j}^\delta Z_{H1}^\gamma \left(\tilde{Z}_{H2}\right)^{1-(\delta+\gamma)} l_{H1H}\right]^{1-\lambda} dj \\
& + \int_0^{N_{F1}} \left(G_{F1k}^I\right)^\lambda \left[Z_{F1k}^\delta Z_{F1}^\gamma \left(\tilde{Z}_{H2}\right)^{1-(\delta+\gamma)} l_{H1F}\right]^{1-\lambda} dk
\end{aligned}
$$

[6] We sacrifice very little by using a Nash-unstable model that starts in the Nash equilibrium. Even in models that are Nash-stable, it is impossible to obtain the dynamic solution in closed form, so those always assume the economy starts in the Nash equilibrium, where it then stays because of the symmetry of the firm decisions. See Peretto (1996, 1998a, 1998b, 1998c, 1999a, 1999b) and Howitt (1999). Several of Peretto's papers have detailed discussions of the assumptions needed to produce Nash stability and symmetric equilibrium.

The subscripts H and F denote the Home and Foreign countries, respectively, G^E_{H1j} is the amount of G_{H1j} exported, and G^I_{F1k} is the amount of intermediate good G_{F1k} imported from Foreign. To keep the analysis tractable, we restrict a country either to export or to import all of one class of intermediates, so only one of G^E_{H1j} and G^I_{F1k} can be positive. We assume that $\tilde{Z}_{H2}$ takes the following form:

$$\tilde{Z}_{H2} = \begin{cases} Z_{H2} & \text{only Home-produced } G_2 \text{ used} \\ Z^{\eta}_{H2} Z^{1-\eta}_{F2} & \text{both Home- and Foreign-produced } G_2 \text{ used} \\ Z_{F2} & \text{only Foreign-produced } G_2 \text{ used} \end{cases}$$

where $0 < \eta < 1$.

Processed goods firms in industry 1 in Home choose the combination of intermediate goods 1 to buy from domestic firms and foreign firms to maximize profit. The solution is bang-bang with home firms buying only $G_{H1j} - G^E_{H1j}$ or only G^I_{F1k}, according to which has the lower *quality-adjusted* price: $P_{G_{H1}}/Z_{H1}^{(\delta+\gamma)(1-\lambda)/\lambda}$ or $P_{G_{F1}}/Z_{F1}^{(\delta+\gamma)(1-\lambda)/\lambda}$, respectively. The situation for producers of X_2 is similar, as is that of producers in Foreign.

2.4 Intermediate Goods

The intermediate goods sector is where most of the important action in the model occurs. It has two industries distinguished by which processed goods industry buys their products.

2.4.1 Incumbents

Each intermediate goods industry comprises a continuum of monopolistically competitive firms. A firm produces a single intermediate good G_{ij} unique to that firm and also undertakes R&D to improve the quality Z_{ij} of the good it produces (fact #6 in section 2.1). An increase in quality raises the demand for the good and so raises profit. We follow Peretto (1996, 1998b, 1998c) and assume that all quality-improving R&D is done by incumbents, in line with one of the IO facts discussed previously.

Production technologies, R&D technologies, and fixed costs are the same for all firms within an industry but differ across industries. Identical technologies and costs within an industry together with monopolistic competition yield a symmetric equilibrium *within* each industry but asymmetry *across* the industries. Asymmetry is unusual in endogenous growth models, and we regard it as one of the contributions of our analysis. Asymmetry provides a natural division among goods along which comparative advantage may operate. It also is a step toward a more realistic analysis than with complete symmetry.

All firms in industry i have a linear technology that converts A_i^{-1} units of the final good into one unit of intermediate good G_{ij} (i.e., the unit cost of G_{ij} is A_i)

$$G_{ij} = A_i^{-1} Y_{ij} \tag{4}$$

where Y_{ij} is the amount of the final good used by firm j in industry i. Spending one unit of the final good on R&D in industry i yields α_i units of quality improvement:

$$\dot{Z}_{ij} = \alpha_i R_{ij} \tag{5}$$

where R_{ij} is amount of the final good Y spent on R&D.[7] The firm obtains the resources for R from retained earnings.[8] As with the final goods sector, labor does not enter the intermediate good sector's

[7] We could add knowledge spillovers in the production of G and in R&D, but they would add no new insight in the model, only different channels for the main effects that the spillovers in the processed goods production functions already capture. Thus for simplicity we exclude them.

[8] It would be slightly more precise to distinguish between investment I and retained earnings R because in principle the two need not be the same. However, the requirements of general equilibrium will make them the same, so we keep the notation simple by imposing $I = R$.

production functions directly but does enter indirectly, explained in section 2.5.

Firms face a fixed operating cost ϕ_{ij} that depends on the average qualities Z_i and Z_k of the firm's own industry and the other industry, respectively. There are two channels of influence. First, the operating cost depends positively on own industry quality on the assumption that a more sophisticated industry requires more sophisticated inputs. We borrow a page from the adjustment cost literature and assume that fixed operating costs are convex in the level of industry sophistication. Second, operating costs are reduced by knowledge, which in our model is captured by quality. We suppose that both Z_i and Z_k help reduce costs. To keep the analysis tractable, we assume that all firms in a given industry have the same fixed cost function, which takes the analytically convenient form $\phi_{ij} = \theta_i Z_i^3 / Z_i Z_k = \theta_i Z_i^2 / Z_k$. The cubic term in the numerator captures the convexity of cost, and the two terms in the denominator capture the effect of knowledge in reducing costs. Dependence of cost on industry averages and not the firm's own quality level is not restrictive because the model's solution is symmetric within an industry with all firms having the same quality level and thus equal to the industry average.

The firm pays a dividend of

$$D_{ij} = G_{ij} \left(P_{G_{ij}} - A_i \right) - \phi_i - R_{ij} = \Pi_{ij} - \phi_i - R_{ij}$$

where $\Pi_{ij} = G_{ij} \left(P_{G_{ij}} - A_i \right)$ is profit gross of fixed operating cost. The value of the firm is the present discounted value $V_{ij}(t)$ of its dividends:[9]

$$V_{ij}(t) = \int_t^\infty D_{ij}(\tau) \, e^{-\int_t^\tau r(s)ds} \, d\tau \tag{6}$$

The firm chooses the paths of its product price $P_{G_{ij}}$ and its R&D expenditure R_{ij} to maximize its value subject to its demand function, R&D production function, and the average qualities, Z_1 and Z_2, which the firm takes as given.

Differentiating eq.(6) with respect to time gives the firm's rate of return to equity (i.e., entry):

$$r_{ij}^E = \frac{D_{ij}}{V_{ij}} + \frac{\dot{V}_{ij}}{V_{ij}} \tag{7}$$

which is the usual profit rate plus the capital gain rate.

Our model has no R&D for cost reduction. Cost reduction is one of the three main types of R&D (fact #5 in section 2.1), but it consumes a much smaller fraction of R&D expenditures than quality improvement (fact #7). Furthermore, it is isomorphic to quality improvement in our model and so would add nothing important to the analysis. We ignore it for simplicity.

2.4.2 Entrants

New entrants produce new varieties of goods, in accord with fact #8 in section (2.1). For simplicity, we refer only to entry, even though exit is always possible. We assume entry is costless.[10] That makes N_i a jumping variable rather than a state variable, thus reducing the dimensionality of the state space enough to make a closed-form solution possible, as will be clear when we solve the model.

[9] A firm has value even though there is no durable physical capital because the firm has monopoly rights to its variety of good and that good's quality. See Barro and Sala-i-Martin (Ch.6 & 7, 2004).

[10] With costly entry, even the closed economy has four state variables: Z_{H1}, Z_{H2}, N_{H1}, and N_{H2}, which is analytically intractable. Costless entry makes the variety numbers N_{Hj} jumping variables rather than state variables. It also makes shutdown instantaneous rather than gradual when trade opens. As we show below, either one or two of the N_{ij} $(i = H, F)$ jump to zero when there is trade. The corresponding Z_{ij} stop changing and drop out of the list of active state variables. We end up with either two or three active Z_{ij}, which is analytically tractable. See Peretto (2007) for discussion of costly entry in a closed-economy framework similar to ours.

Whenever the net present value of a new firm V differs from the entry cost of zero, new firms jump in or out to restore equality between the value of the firm and the entry cost. We thus have at all times

$$V_{ij} = 0 \tag{8}$$

and so also $\dot{V} = 0$, which together with eq. (7) imply

$$D_{ij} = 0 \tag{9}$$

As mentioned earlier, we follow Aghion and Howitt (2005) and Peretto (1999b, 2007) in assuming that all firms have the same level of technology initially and that new entrants arrive with the industry average level of technology. The model's equilibrium then is symmetric at all times within each industry, with all firms in an industry making the same decisions on pricing, production, and R&D expenditures.[11] Firms are alike in an industry but different across industries, with the firms in the two industries generally making different decisions on everything.

The zero profit condition (9) implies that firms pay no dividends but instead retain all earnings for investment in R&D. The household owners of the firm reap their return in the form of increasing consumption as R&D delivers higher quality and raises output. The current-value Hamiltonian for the intermediate good firm is

$$CVH_{ij} = \Pi_{ij} - \phi_i - R_{ij} + q_{ij}(\alpha_i R_{ij})$$

where q_{ij} is the costate variable. The Maximum Principle gives the necessary condition for the evolution of q_1, which we can write as

$$r_{ij}^{R\&D} = \frac{\partial \Pi_{ij}}{\partial Z_{ij}} \frac{1}{q_{ij}} + \frac{\dot{q_{ij}}}{q_{ij}} \tag{10}$$

This equation defines the rate of return to R&D (i.e., to quality innovation) r_{ij} as the percentage marginal revenue from R&D plus the capital gain (percentage change in the shadow price). As with intermediate goods prices, the expressions for the rates of return differ across the two industries.

2.5 Equivalent Industrial Structure

An equivalent specification of the model that aids some aspects of the intuition is obtained in two steps. First, dispense with the processed goods sector and embed (3) in (1). The final goods industry buys the intermediate goods directly and transforms them into its output using labor. Second, recognize that the specification of the intermediate sector's production functions is a "lab equipment model" (Rivera-Batiz and Romer 1991) in which only the final goods are inputs. That is equivalent to the production functions for the intermediate and final goods being the same up to their TFP constants. After embedding (3) in (1) we can substitute (1) into (4) and (5). We then have two sectors, one for final goods and one for intermediate goods, both of which use labor as an input. The alternative specification clarifies labor's importance to all parts of the economy.

2.6 Households

There is a representative household that supplies labor inelastically in a perfectly competitive market and buys corporate equity. We assume for simplicity that there is no population growth. Positive population growth would induce perpetual entry and variety expansion at the rate of population growth. However,

[11] Note that a strategy in which a firm with below-average quality leaves the market and then immediately re-enters with the average quality is not feasible. An incumbent who leaves loses all claim to the niche he vacates. That is the meaning of exit, after all. Upon re-entering the market, he would join the pool of other potential entrants vying for the vacated niche. There are an uncountable number of them, so the probability that the former incumbent will reclaim the vacated niche is zero, so the expected value of the strategy is zero, rendering it unprofitable. For a complete discussion of market equilibrium and its stability in these types of R&D models, see Peretto (1996, 1999b, 2007) and the references cited therein.

with no love of variety, the steady-state rate of variety expansion would produce no growth in income per person, and no important results would change.[12] The utility function is

$$U(t) = \int_t^\infty log(c)\, e^{-\rho t} \tag{11}$$

where c is consumption per person and ρ is the rate of time preference.

The only assets that the household can accumulate are firms that it owns. The household's lifetime budget constraint therefore is

$$0 = \int_0^\infty \left(\int_0^{N_1} D_{1j} dj + \int_0^{N_2} D_{2j} dj + wL - C \right) e^{-\int_t^\tau r(s)ds} dt \tag{12}$$

where C is aggregate consumption and L is labor supply. The intertemporal consumption plan that maximizes utility is given by the consumption Euler equation

$$r = \rho + \frac{\dot{C}}{C} \tag{13}$$

2.7 Trade

The trade part of the model is a standard Ricardian specification except that the unit costs that determine comparative advantage are adjusted by quality levels that change through quality-improving technical progress. That feature allows growth to affect trade and can lead to endogenous changes in the trading regime. We restrict attention to two country and two goods. The trade dimension of the model is thus more restricted than some contributions (Dornbusch, Fischer, and Samuelson, 1977; Eaton and Kortum, 2002; Shiozawa, 2007), but that restriction enables a much richer growth part of the model than has been attempted in the previous literature.

2.7.1 Assumptions and Overview

There are two countries, Home and Foreign. They have the same utility functions and the same production functions for Y, X_1, and X_2 but different production functions and fixed costs for the intermediate goods. The G-production functions have the same form in the two countries but different values for their productivity parameters A_1 and A_2, R&D productivities α_1 and α_2, and fixed operating costs ϕ_1 and ϕ_2.

Analytical tractability requires that we restrict the set of goods that can be traded. Most traded goods are intermediates (fact #9 in section 2.1), so we assume only those are traded.[13] The particular intermediate goods a country imports or exports are determined by comparative advantage, not imposed *a priori*. In that regard, the model differs from almost all the literature on growth with trade, in which the set of varieties each country can invent and produce is exogenously given and countries always trade all varieties they produce (e.g., Grossman and Helpman 1990 and 1991, Feenstra 1996, Acemoglu and Ventura 2002, Baldwin and Robert-Nicoud 2008). As we show below, the endogenous determination of the sets of imported and exported goods is important for the results on trade and growth.

Our two countries are "large" because intermediate goods producers are monopolistically competitive and set prices rather than take them as given. Both countries do R&D, in conformity with fact #3 in section 2.1. To avoid complications arising from strategic behavior, we suppose that neither country has a government that can act as an agent representing all its firms collectively. Each country comprises a multitude of agents who cannot form a cartel to act as monopolists or monopsonists. The focus of this paper is trade, so to keep the analysis simple and the results sharp, we suppose there is no foreign

[12] See Peretto and Connolly (2007).

[13] Allowing trade in both types of intermediate goods and also final goods is analytically intractable. In a companion paper (Kane, Ji, and Seater 2015) we study a model with only one intermediate goods industry whose output can be traded for final goods.

direct investment and no direct technology transfer by multinational firms.[14] Technology transfer can occur through knowledge spillovers as already discussed.

2.7.2 Comparative Advantage

Comparative advantage means that each country has a lower quality-adjusted relative price for one class of intermediate goods:

$$\frac{\mathbf{P_{G_{H1}}}}{\mathbf{Z_{H1}}^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}}} \leq \frac{\mathbf{P_{G_{F1}}}}{\mathbf{Z_{F1}}^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}}} \quad \textbf{and} \quad \frac{\mathbf{P_{G_{H2}}}}{\mathbf{Z_{H2}}^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}}} \geq \frac{\mathbf{P_{G_{F2}}}}{\mathbf{Z_{F2}}^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}}} \tag{14}$$

or the reverse. The direction of the inequalities determines which goods are exported and imported. The direction is inconsequential to our results, so we assume the ordering in (14), which means Home and Foreign have comparative advantages in goods 1 and 2, respectively.

The final good in Home is the numeraire: $P_{Y_H} \equiv 1$. The price of the final good in Foreign is P_{Y_F}. The price of the intermediate good equals the monopolistic markup over unit cost. These facts imply that the comparative advantage condition (14) is equivalent to

$$\frac{A_{H2}}{A_{F2}} \left(\frac{Z_{F2}}{Z_{H2}} \right)^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}} \geq P_{Y_F} \geq \frac{A_{H1}}{A_{F1}} \left(\frac{Z_{F1}}{Z_{H1}} \right)^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}} \tag{15}$$

The price P_{Y_F} must be in this closed interval because otherwise condition (14) would be violated and one country would want to buy both goods from the other, implying a market disequilibrium. If we ignore the quality ratios and look at the unit cost ratio only, inequality (15) is the standard trade condition for Ricardian model. In the standard Ricardian model, labor is the only factor of production for tradable goods, and the relative wage across countries must be inside an interval defined by the unit cost ratios. In our model, intermediate goods rather than final goods are traded, so the relevant interval is defined by the productivity ratios for intermediates. The difference between (15) and the standard expression is that (15) adjusts the productivity parameters (on which the monopolistic prices depend) by the quality of the respective goods.

2.8 Two Remarks on Model Structure

Our model differs in many ways from those previously used to study Ricardian trade and growth. The salient characteristics of our model are that (1) growth is driven by technical progress arising from proprietary R&D, (2) R&D activity is a choice that economic agents make, (3) there are two kinds of R&D, (4) quality-improving R&D is done by incumbent firms, (5) variety-expanding R&D is done by outsiders, (6) firms face fixed operating costs, and (7) trade is determined by comparative advantage. Each of these characteristics plays an important role in the results that follow. Previous models differ in at least one characteristic and usually several. For example, Grossman and Helpman (1990) and Baldwin and Robert-Nicoud (2008) have only variety expansion with no fixed operating costs.[15] However, variety expansion cannot be the source of long-run growth in income per person when fixed operating costs are present because those costs put a maximum on the number of varieties that can be sustained

[14] Bilir and Morales (2016) present evidence that the R&D by parent companies affects the productivity of their overseas affiliates, but not vice versa. That parent-to-affiliate effect has no bearing on the qualitative conclusions of our model except under the following (unbelievable) condition: a parent that shuts down in its home country continues R&D in that country and also continues producing in its foreign affiliate countries. We know of no example of such behavior. Even if there are one or two examples, it seems an exceedingly rare event. It thus seems safe to ignore it. Furthermore, in light of fact #4 in section 2.1, international technology transfer by multinationals is negligible, so it would have an insignificant quantitative impact even if we included it.

[15] Baldwin and Robert-Nicoud (2008) include several sunk costs but not fixed operating costs. The difference is crucial, as we explain below. Baldwin and Robert-Nicoud confuse matters by interchangeably referring to their sunk costs as fixed costs. See Tirole (1988) for a discussion of the difference between sunk and fixed costs in a dynamic setting.

(Peretto and Connolly, 2007).[16] Instead, growth can arise only from quality improvement (or its mathematically isomorphic twin, cost reduction). Redding (1999) and Eaton and Kortum (2001) have quality improvement (and no variety expansion) but assume it is either free (Redding) or carried out by an independent R&D sector (Eaton & Kortum) rather than by incumbent firms. As we show below, these and other differences in model structure lead to major differences in the results on the relation between trade and growth. The differences in model structures arise from our discarding various counterfactual assumptions used in the previous literature (see section 2.1 above). The differences in model implications are testable, and as we show below, our model can explain a wide variety of observations that the previous literature cannot, and it passes some new tests that we conduct.

Finally, our main results hold even if many of our assumptions are weakened. For example, we can have incumbents as well as outsiders invent new varieties, domestic outsiders challenge domestic insiders (i.e., traditional creative destruction), cost reduction as well as quality improvement, and population growth. We also can have a positive entry cost, but in that case we can obtain only the balanced growth path and not the transition dynamics.

3 Model Solution

We now solve the model. We postpone discussion of the solution's economic implications to section 4. Most derivations are relegated to a Mathematical Appendix available from the authors.

As with all models of this type, we consider a symmetric Nash equilibrium in open loop strategies, which implies a one-shot game. At the opening of play, firms commit to a time path, and the paths of economic structure and economic growth are simultaneously determined. Feedback strategies would be more realistic but are unsolvable with imperfect competition in a dynamic general equilibrium context. For a full discussion of the game-theoretic foundations of this kind of model, see Peretto (1996, 1999b) and their precursor, Dasgupta and Stiglitz (1980).

Intermediate goods prices $P_{G_{ij}}$ are constant markups over variable cost:

$$P_{G_{ij}} = \frac{A_i}{\lambda} \equiv P_{Gi} \tag{16}$$

The intermediate goods firm's Hamiltonian is linear in R&D expenditure, so the solution for investment expenditure R_{ij} is bang-bang with R_{ij} infinite, zero, or positive and finite depending on whether $1/\alpha$ is larger, smaller, or equal to the costate variable q_{ij}. We rule out both corners: $R_{ij} = \infty$ (i.e., $1/\alpha > q_{ij}$) because it is inconsistent with market equilibrium and $R_{ij} = 0$ (i.e., $1/\alpha < q_{ij}$) because it implies no economic growth, contrary to observation. We thus have the interior solution

$$\frac{1}{\alpha_i} = q_{ij} \tag{17}$$

The left side of eq. (17) is the same for all j, so all firms in industry i choose the same level of R&D, denoted R_i. Firms in a given industry have the same unit cost A_i and so charge the same price, by (16). They pay the same dividend and so have the same value, by (6). Because α_i is constant, we have $\dot{q}_{ij}/q_{ij} = 0$ in (10).

3.1 Complete Specialization

When condition (15) holds with strict inequality, both countries completely specialize in the class of goods in which they have a comparative advantage. The final goods industry is competitive with Cobb-Douglas production, so the final good producer in Home pays compensation $(1 - \epsilon)\lambda Y_H$ to the

[16] With population growth, the number of varieties can expand at the same rate as the population, so output can grow through variety expansion but output per capita cannot. See Peretto and Connolly (2007). All our results then go through for output per capita instead of output.

producers of intermediate industry 2, which are Foreign firms. Similarly, the final good industry in Foreign pays compensation $\epsilon\lambda P_{Y_F} Y_F$ to the intermediate producers of industry 1, which are Home firms. Trade balance requires $1 \cdot Y_H (1-\epsilon)\lambda = P_{Y_F} \cdot Y_F \epsilon\lambda$ (recall that $1 = P_{Y_H}$, the numeraire), which after some substitution and rearrangement can be written as $P_{Y_F} = [(1-\epsilon) L_H / \epsilon L_F]^{1-\lambda}$. The right side numerator is the total amount of Home's labor force using intermediate goods produced in Foreign, and the denominator has the converse meaning. Substituting for P_{Y_F} yields the condition for complete specialization:

$$\frac{A_{H2}}{A_{F2}} \left(\frac{Z_{F2}}{Z_{H2}} \right)^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}} > \left[\frac{(1-\epsilon) L_H}{\epsilon L_F} \right]^{1-\lambda} > \frac{A_{H1}}{A_{F1}} \left(\frac{Z_{F1}}{Z_{H1}} \right)^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}} \tag{18}$$

where $(1-\epsilon) L_H$ is the fraction of Home's labor force that uses the Foreign-produced intermediate and ϵL_F to the fraction of Foreign's labor force that uses the Home-produced intermediate. This condition means that each country is "technologically big enough" to satisfy its trading partner's demands, as will become clearer when we discuss incomplete specialization.

Complete specialization is equivalent to an integrated economy with G_1 produced by the technologies from Home and G_2 produced by the technologies from Foreign. Under complete specialization, the home and foreign countries abandon intermediate goods industries 2 and 1, respectively. Once production of an intermediate good has stopped, R&D to improve its quality also stops because R&D is done in-house by the producing firms, which now have shut down. As a result, Z_{H2} and Z_{F1} stop growing, but Z_{H1} and Z_{F2} continue to grow. That widens the price interval within which complete specialization occurs, so if the world economy starts in a state of complete specialization, it stays there forever. Complete specialization is locally dynamically stable.[17]

The numbers of firms in each country (and thus in each intermediate goods industry) are

$$N_{H1} = \Omega_{N1}^{H} \left\{ \left[A_1^{\epsilon} A_2^{(1-\epsilon)} \right]^{-\lambda/(1-\lambda)} L_H \right\} \tag{19}$$

$$N_{F2} = \Omega_{N2}^{F} \left\{ \left[A_1^{\epsilon} A_2^{(1-\epsilon)} \right]^{-\lambda/(1-\lambda)} L_F \right\} \tag{20}$$

where the Ω_{N1}^{k} are positive constants independent of A_1 and A_2. The internal symmetry of each industry leads all firms in an industry to assign the same amount of labor to each intermediate input:

$$l_{H1} = L_H / N_{H1} \tag{21}$$

$$l_{F2} = L_F / N_{F2} \tag{22}$$

The rates of return to R&D for the firms in the two intermediate goods industries are

$$r_{H1} = \Omega_{r1}^{H} \left\{ \left[A_1^{\epsilon} A_2^{(1-\epsilon)} \right]^{-\lambda/(1-\lambda)} l_{H1} \right\} \tag{23}$$

$$r_{F2} = \Omega_{r2}^{F} \left\{ \left[A_1^{\epsilon} A_2^{(1-\epsilon)} \right]^{-\lambda/(1-\lambda)} l_{F2} \right\} \tag{24}$$

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Two game-theoretic aspects of analysis require brief mention. First, firms in the country with superior R&D ability may want to continue doing R&D even if they are out-competed now by their foreign competitors because eventually they would increase their quality enough to obtain a comparative advantage. To do that, however, they would have to borrow the funds to pay for the R&D because, with no sales, they have no earnings to retain. Monopolistic competition and the zero profit condition (8) make it impossible for firms ever to have excess funds to repay their debts, rendering the strategy infeasible. Second, there is no strategic behavior in this model. Firms do not condition their R&D behavior on what other firms are doing. In an oligopoly setting, strategic behavior would be possible. Unfortunately, it is not known how to solve an oligopoly model of endogenous growth when strategic behavior is present, even for a closed economy. See Peretto (1996).

where Ω_{r1}^H and Ω_{r2}^F are positive constants independent of A_1 and A_2. Substituting into (23)-(24) from (19)-(22), expanding the four Ω coefficients, and doing some algebra shows that the two rates of return are equal, as capital market equilibrium requires.

Equations (23)-(24) show the characteristic that distinguishes the 2nd-generation framework from both the semi-endogenous and 1st-generation endogenous growth models: rates of return depend on market size *per firm*, not aggregate market size. That distinction leads to major differences in the 2nd-generation growth results compared to those of the alternative approaches. It arises from the interaction of the two kinds of R&D , variety expansion and quality improvement. In explaining the economics at work, we restrict attention to industry 1, which operates in Home. The situation for industry is symmetric. The relevant measure of firm i's market size is the demand for its product G_i, which is proportional to the term in braces in (23). The term comprises the number of workers l_i that the processed goods sector assigns to use G_i multiplied by the number of units of G_i each worker uses, proportional to the transformed Cobb-Douglas combination of the unit costs A_1 and A_2. The unit cost term appears because lower unit costs mean lower prices for the intermediate goods and thus greater demand, all else equal. If we hold fixed the number of intermediate firms, an increase in the labor force L or a reduction in unit costs A_1 and A_2 raises demand for the firm's product and so also raises its rate of return to quality-improving R&D. The rate of return's positive dependence on L is the standard aggregate scale effect, and the positive dependence on the unit costs is a price effect. In general equilibrium, the number of firms does not stay fixed. The higher rate of return induces entry of new firms (i.e., new varieties) to the point where the rate of return is brought back to its original value, as can be seen by substituting (19) and (21) into (23). Entry cancels both the scale effect and the price effect on the growth rate.

In 1st-generation growth models, there is only one kind of R&D, either quality improvement or variety expansion, so the foregoing interaction cannot occur. In those models, either the number of firms is fixed (quality ladder models) or each intermediate good is assumed to be used by the entire labor force L (variety expansion models). In both cases, the equilibrium rate of return depends on both L and the unit costs combination.[18] Mechanical *ad hoc* adjustment, such as dividing output by L, eliminate the scale effect but leave the price effect intact. Semi-endogenous growth models are variants of 1st-generation models that eliminate the scale effect by restricting a parameter in the R&D production function but again leave the price effect intact. Rates of return still depend on inappropriate aggregate variables. The 2nd-generation model is the only approach to endogenous growth that eliminates all inappropriate aggregate market size effects. See Peretto (1998c, 1999), Dinopoulos and Thompson (1998, 1999), and Howitt (1999) for further discussion.

The distinction between firm market size and aggregate market size is the hallmark of the 2nd-generation approach. It reflects deep microeconomic behavior and is central to the differences between our model and the previous literature on trade and growth, as explained below. It is why R&D expenditure per firm rather than aggregate R&D expenditure that matters for economic growth, why the cross-country concentration of aggregate R&D expenditure is irrelevant to our results, and why small countries such as Belgium, Finland, and Israel that have small total R&D expenditures but large fractions of R&D expenditure relative to GDP manage to garner large numbers of patent awards (World Bank 2016; US Patent and Trademark Office 2014).

[18] Clearly seen from the rate of return solutions in chapters 6 and 7 of Barro and Sala-i-Martin (2004). In both cases the equilibrium rate of return is $r = B^{1/(1-\beta)}LR$, where B is TFP (analogous to A^{-1} in our model), β is labor's exponent in the Cobb-Douglas aggregate production function, L is aggregate labor, and R is other terms.

3.1.1 Level Effect

Opening the world to trade has an immediate impact on the trading countries' income levels. Home's final output under autarky and trade are

$$Y_H^{Autarky} = \kappa_H^{'} \left[\left(\frac{Z_{H1}^{\delta+\gamma}}{P_{G_{H1}}^{\frac{\lambda}{1-\lambda}}} \right) Z_{H2}^{1-(\delta+\gamma)} \epsilon \right]^{\epsilon} \left[\left(\frac{Z_{H2}^{\delta+\gamma}}{P_{G_{H2}}^{\frac{\lambda}{1-\lambda}}} \right) Z_{H1}^{1-(\delta+\gamma)} (1-\epsilon) \right]^{1-\epsilon} L_H \tag{25}$$

$$Y_H^{Trade} = \kappa_H^{'} \left[\left(\frac{Z_{H1}^{\delta+\gamma}}{P_{G_{H1}}^{\frac{\lambda}{1-\lambda}}} \right) Z_{F2}^{1-(\delta+\gamma)} \epsilon \right]^{\epsilon} \left[\left(\frac{Z_{F2}^{\delta+\gamma}}{P_{G_{F2}}^{\frac{\lambda}{1-\lambda}}} \right) Z_{H1}^{1-(\delta+\gamma)} (1-\epsilon) \right]^{1-\epsilon} L_H \tag{26}$$

where $\kappa_H^{'}$ is a constant. The first term in brackets is the contribution from X_{H1} to Y_H, and the second term in brackets is the contribution from $X_{H2.}$ to Y_H. Trade affects the initial level of final output through two channels: a direct impact and an externality. The direct impact is the standard gain from trade through comparative advantage. Foreign has the lower quality-adjusted price for good 2, $P_{G_{F2}}^{\lambda/(1-\lambda)}/Z_{F2}^{\delta+\gamma}$, so Home gets more output by substituting the imported G_{F2} for the domestically produced G_{H2}. The externality arises from the knowledge spillover to industry 1 through $Z_{F2}^{1-(\delta+\gamma)}$ in (26). The externality is present if $\delta + \gamma < 1$. If it is present, it can be positive or negative depending on whether $Z_{F2} \gtreqless Z_{H2}$, respectively. The externality operates across different industries in the two countries and so can be positive in one country and negative in the other.

3.1.2 Balanced Growth Rate

Under autarky, each country's balanced growth rate is

$$(g_k^*)^{Autarky} = \frac{\delta}{1-\delta} \sqrt{\alpha_{k1}\theta_{k1}\alpha_{k2}\theta_{k2}} - \frac{1}{1-\delta}\rho \tag{27}$$

where $k \in \{H, F\}$. On the balanced growth path, the growth rates of Z_1 and Z_2 are equal and the ratio Z_1/Z_2 is constant, so we have

$$g^\star = \frac{\dot{Z}_1}{Z_1} = \frac{\dot{Z}_2}{Z_2} = \frac{\dot{Y}}{Y} = \frac{\dot{C}}{C} = \frac{\dot{X}_1}{X_1} = \frac{\dot{X}_2}{X_2} = \frac{\dot{G}_1}{G_1} = \frac{\dot{G}_2}{G_2} = \frac{\dot{w}}{w} \tag{28}$$

Under complete specialization the balanced growth rates are equal and have the same structure as under autarky but with some of the parameters replaced by the trading partner's parameters:

$$(g_H^\star)^{Trade} = g_F^\star = \frac{\delta}{1-\delta} \sqrt{\alpha_{H1}\theta_{H1}\alpha_{F2}\theta_{F2}} - \frac{1}{1-\delta}\rho \tag{29}$$

Equality of the individual growth rates means we also have a world balanced growth rate.

As with any 2nd-generation fully endogenous growth model, there is no aggregate market size effect: the growth rate does not depend on either the scale of the economy L or the unit cost parameters A_1 and A_2. The absence of those effects arises from their absence from the rates of return, explained in section 3.1 above, and underlies many of our results, explained in section 4 below.

3.1.3 Transition Dynamics

When the two countries satisfy the condition for complete specialization but are not on the balanced growth path, the growth rates of their incomes are still equal:

$$g = \frac{\dot{Y}_i}{Y_i} = \Gamma \frac{\dot{Z}_{H1}}{Z_{H1}} + (1-\Gamma) \frac{\dot{Z}_{F2}}{Z_{F2}}; \; where \; i = H, F \tag{30}$$

where the constant $\Gamma \equiv [1 - (\delta + \gamma)] + \epsilon [2(\delta + \gamma) - 1]$. The intuition is straightforward. When the two countries are completely specialized, each does R&D to improve the qualities of one of the two sets of intermediate goods. Each country imports the good that it does not produce. Consequently, each country uses the same sets of intermediate goods, one made at home and one made abroad, and so enjoys the same quality improvements. As a result, their growth rates are the same weighted average of the growth rates of the two qualities Z_{H1} and Z_{F2}. The next section shows that this property does not hold in the case of incomplete specialization.

The following differential equation governs the transition dynamics of the relative quality levels under complete specialization:

$$(Z_{H1}\dot{/}Z_{F2}) = -\alpha_{H1}\theta_{H1}(\frac{Z_{H1}}{Z_{F2}})^2 + \alpha_{F2}\theta_{F2} \tag{31}$$

The positive root $\sqrt{\alpha_{F2}\theta_{F2}/\alpha_{H1}\theta_{H1}}$ is stable, and the economy converges monotonically to its balanced growth path. Growth rates change along the transition path as they approach the balanced growth rate, but the growth rates of income in the two countries always equal each other when the countries are completely specialized.

3.2 Incomplete Specialization

Balance of trade requires that the relative price $P_{Y_F}/P_{Y_H} = P_{Y_F}/1$ be inside the closed interval given in condition (15). Condition (18) shows that when the quantity $\left[(1-\epsilon)\, L_H/\epsilon L_F\right]^{1-\lambda}$ is inside that interval, P_{Y_F} equals it. However, there is no reason that $\left[(1-\epsilon)\, L_H/\epsilon L_F\right]^{1-\lambda}$ need be inside the interval. If it isn't, then P_{Y_F} cannot equal it and will be at the boundary closest to it. We then have a corner solution with one of the two countries completely specialized, producing only one class of intermediates and trading for the other, and the other country incompletely specialized, producing both types of intermediate goods. The incomplete specialization case has been given little attention in the literature, typically receiving no more than a few quick words acknowledging its existence. In fact, the behavior of the economy under incomplete specialization is quite different than under complete specialization and can explain aspects of the data that are inconsistent with the solution under complete specialization. To our knowledge, the analysis that follows is the first to examine the dynamics of the world economy when some countries do not completely specialize. Some of the results we obtain have no parallel in the previous literature.

Which country specializes depends on which boundary P_Y hits. The results are completely symmetric in the two possible cases, so without loss of generality we assume the following condition, which guarantees that Foreign specializes and Home does not:

$$\left[\frac{(1-\epsilon)\, L_H}{\epsilon L_F}\right]^{1-\lambda} > \frac{A_{H2}}{A_{F2}}\left(\frac{Z_{F2}}{Z_{H2}}\right)^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}} > \frac{A_{H1}}{A_{F1}}\left(\frac{Z_{F1}}{Z_{H1}}\right)^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}} \tag{32}$$

Intuitively, P_{Y_F} "tries" to equal $\left[(1-\epsilon)\, L_H/\epsilon L_F\right]^{1-\lambda}$and so hits the upper bound of the interval. We can see what that implies by rearranging terms:

$$\frac{A_{H2}}{A_{H1}}\left(\frac{Z_{H1}}{Z_{H2}}\right)^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}} = P_{Y_F} > \frac{A_{F2}}{A_{F1}}\left(\frac{Z_{F1}}{Z_{F2}}\right)^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}}$$

The expressions at the left and right extremes are the relative prices of the two classes of intermediate goods that would prevail under autarky in Home and Foreign, respectively. When P_{Y_F} equals the left term, the world price equals the autarkic Home price, indicating that Home derives no price advantage from importing either good from abroad. In contrast, P_{Y_F} is larger than the autarkic Foreign price, so Foreign still finds it advantageous to specialize in intermediate good 2 and import good 1. In effect, Foreign is not "technologically big enough" to satisfy Home's requirement for class-2 intermediates.

Recall that $(1-\epsilon)\, L_H/\epsilon L_F$ is the ratio of the fraction of Home's labor force that uses the Foreign-produced intermediate to the fraction of Foreign's labor force that uses the Home-produced intermediate. It can be large for two reasons. First, Home's population can be large relative to that of Foreign. That is a straightforward relative size effect. Foreign is simply too small to meet the demands of Home, so Home continues producing intermediate good 2. This is not a scale effect. Increasing the size of the two countries' populations equiproportionally leaves everything unchanged, whereas shifting population from one country to another can move the world from the interior of the critical interval to the boundary (or vice versa) even if world population as a whole is unchanged. What matters is the relative sizes of Home and Foreign, not their absolute sizes. Second, the elasticities ϵ and $1-\epsilon$ are the weights of the intermediate goods in final good production. If intermediate good 2 gets a heavy weight (i.e., $1-\epsilon$ is high), the more of it Home wants.

3.2.1 Level Effect

The level effect on output of opening to trade is essentially the same as under complete specialization, so we do not discuss it.

3.2.2 Balanced Growth Rate

The two countries' balanced growth rate under incomplete specialization is

$$g^{Trade*} = \frac{\delta}{1-\delta}\sqrt{\alpha_{H1}\theta_{H1}\left(\alpha_{H2}\theta_{H2}\right)^{\eta}\left(\alpha_{F2}\theta_{F2}\right)^{1-\eta}} - \frac{\rho}{1-\delta} \tag{33}$$

The interesting new element is that now growth depends on three sets of growth and fixed cost parameters, reflecting the fact that three industries rather than just two are active. In particular, Home's R&D ability in class-2 intermediates enters the growth rate of Foreign even though Foreign does not import that good. The reason is that Z_{H2} affects the accumulation of Z_{H1} which is embodied in the G_{H1} good that Foreign does import.

3.2.3 Transition Dynamics

The balanced growth path under incomplete specialization is only saddle-path stable, so the transition dynamics are especially interesting. To the best of our knowledge, some of the results we obtain are completely new and also, as we explain in section 6, of considerable practical significance.

As with complete specialization, the Home and Foreign growth rates of income along the transition path are weighted averages of the quality growth rates:

$$\frac{\dot{Y}_H^{Trade}}{Y_H^{Trade}} = \Gamma\frac{\dot{Z}_{H1}}{Z_{H1}} + \left\{\eta\epsilon\left[1-(\delta+\gamma)\right] + (\delta+\gamma)(1-\epsilon)\right\}\frac{\dot{Z}_{H2}}{Z_{H2}} + \left\{(1-\eta)\left[1-(\delta+\gamma)\right]\epsilon\right\}\frac{\dot{Z}_{F2}}{Z_{F2}} \tag{34}$$

$$\frac{\dot{Y}_F^{Trade}}{Y_F^{Trade}} = \Gamma\frac{\dot{Z}_{H1}}{Z_{H1}} - (\delta+\gamma)\,\epsilon\frac{\dot{Z}_{H2}}{Z_{H2}} + \left\{\left[1-(\delta+\gamma)\right]\epsilon+\delta\right\}\frac{\dot{Z}_{F2}}{Z_{F2}} \tag{35}$$

where Γ is the same constant as in (30). Comparing these growth rates with those under complete specialization given in (30) reveals two notable differences. First, as with the balanced growth rate, both countries' transitional growth rates are weighted averages of the three quality growth rates $\dot{Z}_{H1}/Z_{H1}$, $\dot{Z}_{H2}/Z_{H2}$, and $\dot{Z}_{F2}/Z_{F2}$, rather than just $\dot{Z}_{H1}/Z_{H1}$ and $\dot{Z}_{F2}/Z_{F2}$ that appear in (30). Second, and much more important, the two countries' income growth rates now differ from each other whenever the growth rates of Z_{H2} and Z_{F2} differ:

$$\frac{\dot{Y}_H^{Trade}}{Y_H^{Trade}} - \frac{\dot{Y}_F^{Trade}}{Y_F^{Trade}} = \left\{\eta\epsilon\left[1-(\delta+\gamma)\right]+(\delta+\gamma)\right\}\left(\frac{\dot{Z}_{H2}}{Z_{H2}} - \frac{\dot{Z}_{F2}}{Z_{F2}}\right) \tag{36}$$

where $\eta\epsilon\left[1-(\delta+\gamma)\right]+(\delta+\gamma) > 0$. This result contrasts with almost all the previous literature, which restricts attention to the region of complete specialization and so obtains equal growth rates for trading partners (e.g., Taylor 1993, Acemoglu & Ventura 2002). In fact, actual growth rates of trading partners often differ substantially. We explain below how incomplete specialization can explain other important characteristics of the data.

To study the transition behavior of the incompletely-specialized world economy we analyze the ratios $u \equiv Z_{H1}/Z_{H2}$, $v \equiv Z_{H1}/Z_{F2}$, and $w \equiv Z_{H2}/Z_{F2}$. Because $v = u \cdot w$, the evolution of the world economy is described by the evolution of just u and w. The equilibrium loci $\dot{u} = 0$ and $\dot{w} = 0$ are

$$u = -\left(\frac{1-\eta}{2}\frac{u^\star}{w^\star}\right) w + (3-\eta)\, u^\star \tag{37}$$

$$w = w^\star \tag{38}$$

where $u*$ and $w*$ are the steady state values. Figure 1 shows the phase diagram. The crucial variable turns out to be w. There are three cases. (1) If the initial value of w equals w^*, w is on its equilibrium locus and does not change, and u converges to $u^\star$. The world economy converges to a saddle-path stable balanced growth rate with perpetual incomplete specialization. (2) If initial w is less than $w^\star$, then $\dot{w} < 0$. At some finite time, w falls below a critical value, the economy crosses into the region of complete specialization, and the dynamics change accordingly.[19] Also, $\dot{w} < 0$ requires that Z_{F2} grows faster than Z_{H2}, which in turn requires from (36) that Y_F grows faster than Y_H. (3) If initial w exceeds $w^\star$, then $\dot{w} > 0$. The world economy remains incompletely specialized forever, and the difference between the two countries' growth rates converges to a constant:

$$\left(\frac{\dot{Y_H}}{Y_H} - \frac{\dot{Y_F}}{Y_F}\right) \to \left(\delta + \frac{\delta^2}{\eta\epsilon\,[1-(\delta+\gamma)]+\gamma}\right)\alpha_{H2}\theta_{H2}\frac{1}{u^\star}$$

Home's growth rate is perpetually above Foreign's, and the difference is bounded away from zero. The world goes asymptotically to a state in which Foreign constitutes a vanishing fraction of world output.[20]

Our analysis considerably extends Ventura (1997), who shows in a partial equilibrium analysis driven by a scale effect that trade can move a small open economy from low growth to high growth. We obtain that result in a framework of dynamic general equilibrium without a scale effect and adds a complete description of the world's transition dynamics. Ventura's main result survives and is strengthened.

4 Interpretations, Implications, and Comparisons

In this section we discuss the foregoing results, including extensive comparisons with the existing literature. We first discuss the economics underlying the model's mechanics, and then we delve into the results that flow from those.

4.1 Model Mechanics

The intuition behind our model's mechanics is quite simple. Comparative advantage, given by (14), determines three critical patterns: the trading pattern (which goods each country exports and imports), the specialization pattern (which goods each country produces), and the R&D pattern (which kinds of R&D each country does). Trade induces at least one country and possibly both to specialize production completely. The specialization pattern in production is intimately tied to the specialization pattern in

[19] This change of regime requires a slight modification of the game structure. Previously we assumed that firms have an infinite horizon. That would not be true of firms that shut down. For our mathematics to be correct, we must assume an element of bounded rationality: at the beginning of the game agents do not recognize that trade will cause shut-down, so then the boundary is reached, the game is (unexpectedly) replayed using the economy's state at that time as the initial conditions. A game of full information would introduce extra dynamics in that all firms would make adjustments around the switching time. Those dynamics would render the model unsolvable. Compromises of this sort are unavoidable with games in a dynamic setting, as explained in Dasgupta and Stiglitz (1980).

[20] Our analysis is consistent with and extends that of Ventura (1997). Ventura shows in a partial equilibrium analysis driven by a scale effect that trade can move a small open economy from low growth to high growth. Our model extends his analysis to a complete framework of dynamic general equilibrium without a scale effect, showing that Ventura's main result survives and adding a complete description of the world's transition dynamics.

R&D. Long-run growth is driven by quality-improving R&D, which only incumbent firms do. When industries shut down because of trade (which, after all, is what specialization means in a Ricardian model), their R&D operations also shut down. That affects the world's average growth rate by changing the world's average R&D efficiency. The change in the R&D pattern feeds back on comparative advantage by changing the path of the goods' quality levels and thus those goods relative quality-adjusted prices. The change in comparative advantage may move trading partners from a corner solution where one country specializes its production completely and one does not specialize to the interior where both countries specialize completely. As the world moves along its transition path, growth rates change until a steady state is reached. Simple as the model's intuition is, it is substantially different from that behind all previous work on trade and growth. The novelty of the approach is two-fold: the treatment of comparative advantage and the treatment of the economy's IO structure.

Dependence of the trading pattern on comparative advantage may seem an obvious property for a trade model to have. Nonetheless, it is absent from many previous models of trade and growth, which assume instead that countries are endowed with non-intersecting sets of goods that they produce and trade (the Armington assumption). Grossman and Helpman (1990), Acemoglu and Ventura (2002), and Baldwin and Robert-Nicoud (2008) are but a few examples. In such models, trade alters neither the set of goods a country produces and trades or the type of R&D it does. Furthermore, economic growth has no effect on comparative advantage. Treating the trading and R&D patterns on the one hand and comparative advantage on the other hand as independent of each other misses important channels through which trade and growth interact.

The IO structure of our model differs from that of its predecessors in several ways, but the two most important differences are that our model has two types of R&D (quality improvement and variety expansion) rather than just one and in our model quality improvement is done by incumbents rather than outsiders. Having two kinds of R&D in progress at the same time eliminates inappropriate aggregate market size effects, as explained in section 3.1 above. Having incumbent firms responsible for quality improvement ties the pattern of R&D to trade in a way that is missing in the approaches typically found in the 1st-generation and semi-endogenous growth literature and that leads to profoundly different implications for the interaction of trade and growth.

With these basics in hand, we can delve into the interaction of trade and growth.

4.2 How Trade Affects Growth

We begin with three properties of the growth rate solutions (29),(31), (33), (34), and (35): (1) growth is driven entirely by quality improvement, with no parameters or variables pertaining to variety expansion appearing in any of the growth solutions, (2) growth depends on the efficiency α_{ij} of improving the quality of intermediate goods and the fixed cost parameters θ_{ij} associated with running an intermediate goods firm but does not depend on the current quality levels Z_{ij} or the unit cost A_{ij} of producing intermediate goods, and (3) technology transfer has no effect on balanced growth and only quantitative, not qualitative, effects on transitional growth.

The absence of variety expansion from the growth solutions is a consequence of fixed operating cost. An economy can have no more firms (i.e., varieties) than the number that would absorb total output just to pay fixed operating costs, and of course the equilibrium number of firms is less than that. Variety expansion thus cannot continue forever and so cannot be a source of steady state growth.[21] In our model, variety expansion does not affect transitional growth, either, because entry cost is zero. That means the number of firms jumps instantly to its equilibrium value, as in Krugman (1979). If entry costs were positive, the equilibrium number of firms would be reached gradually rather than instantaneously, and variety expansion would affect the transition dynamics. As mentioned earlier, the transition dy-

[21] As mentioned earlier, with population growth we must modify this statement to say that variety expansion cannot be a source of growth in income per capita.

namics would be analytically intractable because of the curse of dimensionality.[22] Even though variety expansion does not appear in the growth solutions, it has an indirect effect on growth by regulating the number of firms and eliminating inappropriate market size effects, as explained previously in section 3.

The presence of α_{ij} and the absence of A_{ij} and Z_{ij} are consequences of the economy's industrial structure. Growth arises from quality improvement, which reduces the economy's unit cost of production A_{ij}/Z_{ij}. The current level of unit cost is irrelevant. In contrast, the current level of R&D efficiency α_{ij} is relevant because it determines the amount of technical progress obtained per unit of R&D input. The dependence of the growth rate on fixed operating costs is more subtle. It reflects the deep IO issues at play and shows the importance of including fixed operating cost in the analysis. The growth rate depends *positively* on fixed operating costs. Why should an increase in the cost of doing business raise the growth rate? The reason is that the equilibrium number of intermediate goods firms (i.e., the number of varieties N_1 and N_2) depends negatively on fixed operating costs. Higher costs reduce the number of firms, which means a higher rate of return to R&D given by (23) for the extant firms. Recall that the crucial concept in a 2nd-generation growth model is activity per firm. In particular, R&D per firm determines the rate of technical progress and thus the rate of growth of the economy. There is more R&D per firm when there are fewer firms, and fixed operating costs reduce the number of firms.[23] This result is important for understanding the full effect of trade on growth, as we see momentarily.

Finally, technology transfer, captured in our model by knowledge spillovers, is irrelevant to our main results. Knowledge spillovers occur if $1-(\delta+\gamma)>0$ and are absent if $1-(\delta+\gamma)=0$. The term $1-(\delta+\gamma)$ does not appear in the steady state growth rates (27) and (33), so those are unaffected by knowledge spillovers. The term does appear in the transition equations (30), (34), and(35), so the transition dynamics do depend on knowledge spillovers. However, only the magnitudes of some coefficients, never their signs, are affected. Transition paths thus depend quantitatively but not qualitatively on knowledge spillovers. Indeed, the *only* qualitative effect of knowledge spillovers is on the sign of trade's impact on the initial level of income, shown in (26). The level effect is a minor aspect of our analysis, which focuses on growth. Comparative advantage, not technology transfer, drives our results. Other channels of technology transfer not included in our model, such as foreign direct investment and multinational firms, may affect growth rates. The point here is that our main results hold even if we exclude all forms of technology transfer and so are not consequences of technology transfer. Our model is thus fundamentally different from the large fraction of the previous literature on trade and growth in which, as mentioned in the Introduction, trade's only effect on growth is facilitation of technology transfer.

4.2.1 Complete Specialization

Comparing the autarkic growth rate in (27) with the open economy growth rate under complete specialization in (29), we see that trade results in the replacement of Home's good-2 growth efficiency and fixed cost parameters α_{H2} and θ_{H2} by Foreign's corresponding values. That outcome is the consequence of the interaction of comparative advantage and the economy's industrial structure. Under trade, Home stops producing good 2 and buys it from Foreign. All quality improvement for type-2 goods then is done in Foreign.[24] The fruit of Foreign's R&D effort is embodied in the goods that Home imports and that augment Home's labor, so Foreign becomes responsible for the part of Home's growth arising from quality improvement of good 2. A symmetric situation prevails in Foreign with respect to type-1 goods. An important aspect of these growth rates is that they look the same as if each country had adopted its trading partner's R&D technology for the imported good even it does not actually do that. In other words, trade by itself can produce an *effective* technology transfer even if no type of technology transfer occurs, a result reminiscent of factor-price equalization, according to which factor prices move as if factors shift across borders even if they actually stay put.

[22] See Peretto and Connolly (2007) for a complete of transition dynamics in a closed economy, which has few enough state variables to be analytically tractable when entry costs are positive.

[23] See Peretto (1999b) for more discussion of this point.

[24] Recall from fact #4 in section 2.1 that introducing multinational firms would not change this conclusion.

Effective technology transfer delivers a considerable generalization of Acemoglu and Ventura's (2002) conclusion that trade ultimately stabilizes the world income distribution even though individual countries' growth rates are inherently different. Acemoglu and Ventura assume, like us, that only intermediate goods are traded, not final goods. Their model differs from ours in having no R&D and a trading pattern fixed by an Armington assumption rather than by comparative advantage. The Armington assumption imposes complete specialization, so Acemoglu and Ventura's analysis takes place in what is equivalent to the interior of our model, i.e., the region of complete specialization. In the absence of trade, countries' growth rates are permanently different because their technologies are different. Acemoglu and Ventura's important result is that trade equalizes growth rates asymptotically even though countries' technologies remain different. Changes in the terms of trade ultimately bring all growth rates of trading countries to the same steady-state value. On the transition path, however, growth rates generally differ, so the world income distribution changes until the steady state is reached. Our results show that, when trade and R&D are endogenized, effective technology transfer equalizes growth rates everywhere in the region of complete specialization, not just on the balanced growth path. We thus get stabilization of the world income distribution whenever countries are in the region of complete specialization. Our dynamic analysis in section 3.2.3 shows that if the world ever leaves the region of incomplete specialization and becomes completely specialized, it does so in finite time, so stabilization of the world income distribution also can happen in finite time. However, an aspect of our analysis that is very different from Acemoglu and Ventura's is that the world may remain in the region of incomplete specialization forever with countries having permanently different growth rates and a world income distribution that never stabilizes. We discuss that possibility in section 4.2.4 below.

Effective technology transfer also has interesting empirical implications. Together with our earlier result on the possibility of negative spillovers, it can explain some rather puzzling findings in the empirical literature. Several studies report that "forward spillovers" (in which the country importing a good learns from the country supplying it) are negative,[25] a result difficult to interpret in terms of technology transfer. Why would a country choose to adopt a technology that is inferior to what it already has? The answer may be that the importing country makes no such choice but instead imports the inferior technology inadvertently as a joint product bundled with the intermediate goods it buys for other reasons. Effective technology transfer also suggests the need for a reconsideration of existing estimates of how much genuine technology transfer takes place. Several studies, starting with Coe and Helpman (1995), find that a country that trades with technologically advanced partners has a higher growth rate than a country that trades with less advanced partners. The usual conclusion drawn is that trade facilitates technology transfer. Our analysis suggests that conclusion may be unwarranted because the observed effects of trade may reflect effective rather than actual technology transfer. In principle, all the estimated technology transfer may be effective rather than genuine. The only way to sort out the contributions of the two types of technology transfer would be to include both in the estimation.

Another implication of (27) and (30) is that under complete specialization trade equalizes growth rates no matter which country is endowed with more resources (labor, in our model). This result is in sharp contrast to Grossman and Helpman's (1991, Chapter 7) model in which the growth rate is higher in the country with more of the productive resource. The reason for the difference is that here a firm's market size is determined endogenously whereas in Grossman and Helpman it is exogenous. Similarly, entry and the concomitant absence of an inappropriate market size effect guarantee that the larger country does not take over world R&D, in contrast to Grossman and Helpman (1991, Chapter 9). Even in the extreme case 3 of incomplete specialization discussed at the end of section 3.2.3, where the two countries' growth rates fail to converge, the lagging country's growth rate remains constant and the difference between it and the leader's growth rate goes asymptotically to a constant. Comparative advantage guarantees that each country will produce something, and profit maximization guarantees that the firms doing the production also will do R&D to improve quality. It thus never happens that one country takes over world R&D. Our result conforms with fact #3 in section 2.1, that virtually every

[25] See Koymen and Sayek (2010) and the large number of papers cited there.

country does R&D, whereas Grossman and Helpman's does not.

4.2.2 Growth and Dynamic Inefficiency

One of the most important implications of the growth rate solutions (29),(31), (33), and (35) is that trade can raise or lower the growth rate of either country. Comparative advantage determines trade, R&D determines growth, but comparative advantage and growth depend on disjoint sets of parameters and variables. Comparative advantage is determined by relative quality-adjusted prices. Substituting the solutions for those gives the inequalities in (15), which depend on the output unit cost parameters A_{ij} and the current quality levels Z_{ij} but not the R&D efficiency parameters α_{ij} or the fixed cost parameters θ_{ij}. In contrast, relative quality-adjusted prices have no bearing on R&D efficiency, which is determined by α_{ij} and θ_{ij}, as we can see from (29),(31), (33), and (35). Nothing guarantees that a country having a comparative advantage in a good also is more efficient than its trading partner in improving the quality of that good. A country's firms may little ability to improve quality that already may be low, but if the costs of production are sufficiently low, the country will have a comparative advantage in those goods anyway (exemplified again by the proverbial Walmart goods from China). That country's goods take over the market and drive out of business their foreign competitors, which may be better at quality-improving R&D. Furthermore, there is no necessary connection between the two industries' R&D efficiencies relative to those of its foreign competitors. Any pattern is possible: both domestic industries may be strong in R&D, both may be weak in it, or one may be strong and the other weak. Any pattern is compatible with any pattern of comparative advantage. Trade thus may raise or lower a country's growth rate, and it may affect the two countries' growth rates in the same way or in opposite ways. Two examples of comparative advantage leading to lower world R&D activity are the furniture and shipbuilding industries in the United States, both of which recently have been largely taken over by low-cost firms in foreign countries that generally also have lower R&D ability than the United States.

Redding (1999) and Grossman and Helpman (1990) also obtain the result that trade can lower growth but for reasons quite different from those at work here and consequently with different testable implications than our theory. Our result arises from the interplay of comparative advantage and R&D, with comparative advantage leading some firms to shut down and so shifting the pattern of R&D across countries through the decisions of maximizing economic agents. Redding (1999) has neither firms nor R&D, just two aggregate production functions, each with an exogenous source of technical progress that always operate.[26] The only element of endogenous growth in the model is that each economy chooses its allocation of labor across the two production functions and thus chooses the weights to give each type of exogenous growth. Trade can reduce growth by shifting production to the sectors that are more efficient at production, and those may be the sectors with lower rates of exogenous technical progress. Grossman and Helpman's (1990) model is one of technology transfer, not Ricardian trade. R&D is performed by an independent R&D sector not tied in any way to the firms that produce goods and that always operates. The knowledge that the R&D sector creates is freely available to the entire world with no proprietary element. Comparative advantage is defined in an unusual way, not as the relative price of tradable goods but rather as the relative efficiency of trading partners' R&D sectors. So defined, it does not determine the mix of goods that are traded, which is given exogenously by an Armington assumption. Instead, it simply defines which country is more efficient at R&D. Opening such economies to trade can reduce growth if Home is more efficient than Foreign at R&D (i.e., Home has a "comparative advantage" in R&D) and Foreign has a taste for Home's goods that increases the total demand for Home's goods. In that case, Home shifts labor from the R&D sector to the production sector, thus reducing its and the world's total output of technical progress. Both Redding's and Grossman and Helpman's models are inconsistent with several of the facts in section 2.1. They also are inconsistent with known evidence. Redding's growth rates are unaffected by R&D, contrary to the large body of evidence that R&D in fact is essential for growth. The rate of technical progress in each of Redding's sectors is proportional to that sector's output and does not respond to changes in fiscal policy, regulation, patent laws, or foreign aid,

[26] Redding calls the sources of exogenous growth learning by doing, but as Romer (1990) has noted, learning by doing is really a type of exogenous growth.

all of which have been shown by many studies to affect R&D activity.[27] Grossman and Helpman can get a reduction in growth only by shifting resources out of R&D activity in the world's leading research countries. As mentioned in the Introduction, the evidence in Tables 2 and 3 contradicts that implication.

The possibility that trade reduces growth arises from a kind of dynamic inefficiency. Processed-goods firms care about the quality-adjusted price they pay for intermediate goods today. Any effect their current purchasing decisions have on tomorrow's prices is an intertemporal externality that they ignore. This dynamic inefficiency is different from Diamond's (1965) version. Diamond's inefficiency is an *intergenerational externality*, arising from the current generation ignoring the costs that today's investment decisions impose on future generations. The dynamic inefficiency in the present model is completely different. It does not result from intergenerational considerations because there is only one infinitely-lived generation in the model. Rather, it is a *cross-functional externality.* Traders ignore the effects of their purchasing decisions on the R&D activity of the firms making the products that the traders decide to buy.

Intermediate-good firms can do nothing to prevent being driven out of business even if they are aware that they are better at R&D than their foreign rivals and would be able to offer a lower quality-adjusted price in the future. They have no sales and therefore no revenue today, so to continue their R&D they would have to borrow now and repay in the future once they regain dominance in the market. That course of action is not open to them. To borrow now they must generate sufficient excess profit in the future to repay the loan. However, being monopolistic competitors, they never have that much monopoly profit. Under monopolistic competition, entry guarantees that monopoly profit is only large enough to compensate the cost of entry. Nothing is left over, repayment of past loans is impossible, so the loans are never made.

4.2.3 Melitz heterogeneity and Eaton-Kortum multiplicity

The growth rate solutions show why little is lost in omitting Melitz-type heterogeneity from the model. Melitz (2003) introduces cross-firm heterogeneity in the efficiency of production, which corresponds to the inverse of our unit cost A_{ij}. In Melitz (2003) opening to trade winnows out the less efficient firms, leaving the average world value of unit cost lower (equivalently, productivity higher) than under autarky. In a 1st-generation growth model, a change in average unit cost affects the growth rate through the market size effect discussed in section 3.1, so introducing Melitz heterogeneity into such a model alters trade's effect on growth, as Baldwin and Robert-Nicoud (2008) show. In contrast, Melitz heterogeneity would have no growth effect in our model. The unit cost parameters A_{ij} do not enter our growth solutions because the market size effect through which they operate in a 1st-generation model is absent here, as explained in section 3.1. If we had a positive cost of entry, Melitz heterogeneity would affect transitional growth because output rises as average TFP rises. With positive entry cost, the number of firms does not jump immediately to its new steady state value but instead makes the transition over some period of time. However, once the transition is complete, there would be no enduring effect on growth. Our framework thus suggests an explanation for the empirical finding by Harrison, Martin, and Nataraj (2013) that Melitz heterogeneity has only transitional growth effects.

Eaton and Kortum (2002) introduce a very rich model of trade in which there are many countries and many tradable goods. As explained earlier, including that richness here would render the model analytically intractable. We therefore can say little on how trade and growth would interact in a model that combines the 2nd-generation approach to growth with Eaton and Kortum's model of trade. Eaton and Kortum (2001) themselves have extended their trade model to include semi-endogenous growth driven by quality improvement. Their conclusion is stark and radically different from ours: trade has no effect on growth. However, their model suffers from the standard limitations of the semi-endogenous approach (a fixed number of varieties with its inevitable aggregate market size effects, an independent R&D sector with its separation of innovation from trade-induced shutdown, population growth necessary for economic growth). Also, their result seems to depend on some properties of the model that do not

[27] See our working paper for a long list of references.

generalize to other growth assumptions, for Naito (2015) shows that in a model that combines the Eaton-Kortum trade model with the Acemoglu and Ventura (2002) growth model, trade liberalization does affect the growth rate. We suspect that combining Eaton-Kortum trade with 2nd-generation growth would deliver similar results to those we have obtained from our 2-country, 2-good model for the same reasons. However, definite conclusions await a successful combination of the two approaches.

4.2.4 Incomplete Specialization

In the region of on incomplete specialization, Home is too "technologically large", as defined precisely by condition (32), for Foreign to supply all of Home's demand for type-2 intermediate goods. Home continues to produce type-2 goods even though it also imports them from Foreign. The world has three active R&D operations rather than just two, and growth rates are combinations of the appropriate three sets of parameters. The region of incomplete specialization is divided into three sub-regions. (I) In one sub-region, Home grows more slowly than Foreign, which catches up to Home. At the point of catch-up, the world crosses into the region of complete specialization, the two countries' growth rates become equal, and the dynamics of complete specialization take over. Recall that the entire region of complete specialization is a basin of attraction for the the balanced growth path inside that region, so once the world is completely specialized, it stays that way. (II) In another sub-region, Home grows faster than Foreign, the world remains incompletely specialized forever, and the two countries' growth rates go asymptotically to a constant difference. (III) The third sub-region is the knife-edge division between the other two sub-regions, comprising a saddle-path stable balanced growth rate and the saddle-path stable transition to it. The two countries' growth rates are the same.

In sub-regions I and II, the two countries' growth rates are unequal. Sub-region I is similar to that part of Acemoglu and Ventura's (2002) phase space that is not the world balanced growth path. Growth rates are unequal, the world income distribution is changing, but the world is converging to equal growth rates. In our model, the world reaches equality of growth rates in finite time rather than just asymptotically as in Acemoglu and Ventura. Sub-region II is unlike anything in Acemoglu and Ventura's analysis. The world does not converge to equal growth rates, but instead converges to a constant difference of growth rates with the "large" country - Home - having the higher rate. Even though Foreign lags behind Home, it does gain from trade with Home. Its growth rate is higher than under autarky, but isn't enough higher to match Home's rate. Foreign's income grows faster than it did under autarky, but its share of world income vanishes asymptotically. The world distribution of income never stabilizes. Consequently, our general conclusion differs from Acemoglu and Ventura's: trade need not stabilize the world income distribution, even asymptotically.

4.2.5 Growth and the Terms of Trade

Acemoglu and Ventura's (2002) model of trade and growth predicts that level of a country's economic growth rate is positively related to the rate of change of its terms of trade (the price of exports relative to the price of imports). Our model has the very different prediction that there is no systematic relation between growth rates and changes in the terms of trade.

In our model, Home's terms of trade are the relative quality-adjusted prices:

$$TOT \equiv \left(\frac{P_{GH1}}{Z_{H1}^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}}} \right) \left(\frac{P_{GF2}}{Z_{F2}^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}}} \right)^{-1} = \frac{P_{GH1}}{P_{GF2}} \left(\frac{Z_{F2}}{Z_{H1}} \right)^{\frac{(\delta+\gamma)(1-\lambda)}{\lambda}} \tag{39}$$

Prices are constant mark-ups over cost, so the terms of trade rise or fall as Z_{H1} grows slower or faster than Z_{F2}. Equation (31) shows that within the region of complete specialization the two quality levels Z_{H1} and Z_{F2} do not grow at the same rate anywhere off the balanced growth path, so the terms of trade change as the world approaches the balanced growth path. However, there is no necessary relation between the growth rate and the change in the terms of trade. For example, suppose in the transition growth equation (30) that $\Gamma = 0.5$, the growth rate g_{H1} of Z_{H1} is 0.02, and the growth rate g_{F2} of Z_{F2}

is 0.4. Then the two countries' growth rate is 0.3, and the terms of trade are rising because $g_{F2} > g_{H1}$. Now suppose instead that g_{H1} is 0.04 and g_{F2} is 0.02. Then the two countries' growth rate again is 0.03, but the terms of trade are falling. The same growth rate can be associated with rising or falling terms of trade. The conclusion under incomplete specialization is the same. Recall from section3.2.3 that $u \equiv Z_{H1}/Z_{H2}$, $v \equiv Z_{H1}/Z_{F2}$, and $w \equiv Z_{H2}/Z_{F2}$. From (39), the evolution of v determines the evolution of the terms of trade. From the definitions we have $v = uw$. Figure 1 shows that u and w move in opposite directions, leaving the change in v ambiguous. By suitable choice of parameter values, one can make v rise or fall to the left of w^* and fall or rise to the right of w^*. To the left of w^* the growth rate of the specialized country is high relative to that of its unspecialized partner, and to the right of w^* it is relatively low. So rising or falling terms of trade can be associated with a high or low growth rate. Again, there is no necessary relation between growth rates and changes in terms of trade.

4.3 How Growth Affects Trade

Economic growth has one effect on trade, but it is an important one: growth can move the world across trading regimes *endogenously.* Explaining how the world can move across trading regimes (complete and incomplete specialization) brings the two regimes together into a unified treatment, whereas in the traditional static Ricardian literature they are distinct cases that must be treated separately. Our model thus overcomes what Eaton and Kortum (2012) appropriately call a "clumsy taxonomy."

Our analysis shows two things about endogenous movement across the trading regimes. First, the world can go only from incomplete to complete specialization. Endogenous movement in the other direction never occurs. Second, if the world is in the region of incomplete specialization, growth *may* push the world into the region of complete specialization, but it also may push the world farther into the region of incomplete specialization. The latter result is not possible in most of the previous literature because the region of incomplete specialization is ignored. Which result prevails depends on parameter values and the starting value of the cross-country quality ratio $w \equiv Z_{H2}/Z_{F2}$. The case where the world moves from incomplete to complete specialization arise when the country is "technologically small" grows faster than its "large" trading partner, which means that Z_{F2} grows faster than Z_{H2}. As time passes, the middle term of the comparative advantage inequality (32) grows and eventually exceeds the left-most term, converting (32) into (18). Foreign's quality has grown so much that Home abandons its own production of type-2 goods and relies entirely on imports from Foreign. The world has become completely specialized. When Z_{F2} does not grow faster than Z_{H2}, the comparative advantage condition (32) never coverts to (18), and the world remains incompletely specialized forever.

To the best of our knowledge, these results on the world economy's dynamic behavior under incomplete specialization are completely new.

5 Welfare

Our model gives a complete solution for the economy's transition dynamics, so we can do a welfare analysis of autarky versus trade. Trade has the same qualitative effects on welfare whether specialization is complete or incomplete, so here we restrict attention to complete specialization, which is simpler.

The welfare effects of trade are most easily seen by examining the ratio of flow utility after trade to before trade:

$$\log\frac{u_H^T(t)}{u_H^A(t)} = \log\frac{Y_H^T(t)}{Y_H^T} = \log Y_H^T(t) - \log Y_H^A \tag{40}$$
$$= (1-\epsilon)\log\left[\frac{Z_{F2}^{\delta+\gamma}(0)}{P_{G_{F2}}^{\frac{\lambda}{1-\lambda}}} - \frac{Z_{H2}^{\delta+\gamma}(0)}{P_{G_{J2}}^{\frac{\lambda}{1-\lambda}}}\right] + \epsilon(1-\delta-\gamma)\left[\log Z_{F2}(0) - Z_{H2}(0)\right]$$
$$+\left\{\Gamma\int_o^\infty \left[g_{H1}^T(s) - g_{H1}^A\right]ds + (1-\Gamma)\int_o^\infty \left[g_{F2}^T(s) - g_{H2}^A\right]ds\right\}$$

where Γ is the same combination of underlying parameters defined previously. The first term captures the standard static welfare gain from trade and is always positive because comparative advantage guarantees that foreign class-2 intermediates are cheaper in terms of quality-adjusted price at the moment that trade happens. The second term also is a static term that reflects the externality due to the quality spillover across industries within Home. Its sign is ambiguous, depending on whether the imported good's quality is higher or lower than the domestic good it replaces. The last term is very different from the first two and is a new result emerging from our theory. It is a purely dynamic effect, capturing the change in the economy's growth rate caused by trade. The third term has an ambiguous sign because the growth rates $g_1^T(s)$ and $g_2^T(s)$ prevailing under trade can be either higher or lower than the balanced growth rate under autarky g_H^A. Even if the first two terms in equation (40) are positive, a sufficiently negative third term will mean that trade reduces welfare. In principle it is possible to evaluate the welfare gain by calibrating the model, though that is far beyond the scope of the present effort. There may be some practical difficulties in performing the calibration because quality levels are hard to observe.

In summary, then, trade may increase or decrease welfare on impact, may increase or decrease it over time, and may result in any combination of those possibilities across the two trading partners. Which effect emerges depends on the relative R&D efficiencies of the two countries and on the structure of knowledge spillovers. Dynamic considerations therefore introduce the possibility of *immiserising trade*, a term we use somewhat hesitantly. It is deliberately reminiscent of Bhagwati's (1958) immiserising growth, which by choice of words emphasizes a possible bad outcome from something (i.e., growth) usually considered to be unquestionably good. Our result on trade and welfare has that same character. However, our mechanism is completely different from Bhagwati's, having nothing to do with elasticities of demand and everything to do with knowledge externalities and R&D efficiencies.

6 Reconciliations and Tests

We have a lot of possibilities: complete or incomplete specialization, the world staying incompletely specialized forever or moving to the interior, growth rates that are converge across countries or that stay permanently apart, and trade liberalization raising or lowering growth in any combination across the two countries. The plethora of possibilities does not mean the model has nothing to say. Quite the contrary. The model gives specific conditions under which each possibility arises, and those conditions are testable. The model thus is not vacuous but rather is very rich in terms of both theory and empirical implications.

It is far beyond the scope of this paper to perform extensive estimation of the model, so we restrict attention to a few simple tests. The tests are of two types. First are "reconciliations" in which we show that our model is consistent with the known relations in the data discussed on the Introduction. Recall that we used none of that evidence in building our model, so comparison of it with our model's predictions are valid tests of the model. Second we present three new tests that are both simple and formal and that examine very different aspects of the model.

6.1 Reconciliations

According to our theory, trade's effects on growth can be quite different from one country to another. Consequently, it may be very misleading to estimate "the" effect of trade on growth by looking at trade's effect on world growth. Our theory predicts that a if country good at R&D but with high quality-adjusted prices begins trading with another country with the opposite characteristics, the growth rate will fall in the first country and rise in the second. The data in Table 1 are consistent with that prediction. Recall that Table 1 reports growth rates for the industrialized and non-industrialized countries for the years before and after the spate of globalization that occurred around 1980. The data constitute an event study of trade's effect on growth. Eaton and Kortum (1999) report that most of the world's R&D is done in a few industrialized countries. Those countries also have high prices compared to many non-industrialized countries. Our model predicts that opening the world to trade should see growth rates fall in the industrialized R&D leaders and fall in the non-industrialized R&D laggards. That is exactly the pattern in Table 1. The growth rates for the industrialized countries fell by 1.7 percentage points and for the non-industrialized countries rose by 0.5 percentage points. The growth rate for the world as a whole rose by 0.2 percentage points. There has been a prominent debate over whether trade is good or bad for growth (e.g., Sachs and Warner 1995, Rodriguez and Rodrik 2000). Our theory offers a reconciliation of the two sides in the trade-growth debate and suggests that both sides make valid points.

When trading partners are incompletely specialized, their growth rates generally differ. Consider that part of the region of incomplete specialization in which the trading partners move toward complete specialization. Behavior there is consistent with the growth history of Asia *vis-a-vis* the West over the last hundred years or so. Table 4 reports the growth rates for several world regions. Define "the West" as the union of the Table's categories "Total Western Europe" and "United States," and define "Asia" as "Total Asia (excluding Japan)" and "Japan." A century ago, the West would have been the "technologically large" Home country in our analysis and Asia would have been the "technologically small" Foreign country. Once significant trade between the two regions began, Asia's growth rate rose above the West's but then began to approach it as the two groups of countries neared the region of complete specialization, with Japan being closer than the rest of Asia and perhaps already across the boundary.

Consider now the part of the region of incomplete specialization in which growth rates converge to a constant difference. That case seems to correspond to Africa *vis-a-vis* the rest of the world. Table 4 shows that Africa's growth rate has lagged behind that of Western Europe for the last 1,000 years, which seems about as good an approximation to the infinite horizon as one can expect to find in Earthly economic data. Our theory is not a complete explanation for Africa's lag because the gap between the growth rates of the West and Africa has increased over time rather than converged to a constant. However, that shortcoming may result from a problem with virtually all the endogenous growth literature. World economic history does not show an asymptotic approach to a balanced growth path but rather if anything a divergence, at least over the last 1,000 years. Most existing growth theories generally cannot explain such behavior, with the possible exception of Peretto (2012). The increasing gap between African and other growth rates may be a manifestation of the growth in growth rates with Africa lagging behind.

Putting together behavior in the various regions of the phase space offers a straightforward explanation for Quah's (1997) "twin peaks" in the world income distribution. A thousand years ago, countries of the world had much the same growth rates, barely greater than zero, so the world income distribution was approximately stable. Since then, growth rates in most of the world have increased for a number of reasons (Clark, 2007; Maddison, 2001), but some regions have experienced faster growth than others. Also, some regions whose growth rates initially lagged behind the leaders' rates later caught up, whereas other regions continued to lag. Our theory offers a possible explanation for the behavior of the catch-ups, who would be the countries (e.g., those in East Asia) that upon opening to trade found themselves in that part of thee region of incomplete specialization that leads to complete specialization, where growth rates are equal. Other countries (those in Africa) found themselves in that part of the region of incomplete specialization that leads deeper into that region, with growth rates permanently below those of the leaders. The original stable world income distribution thus bifurcated into two groups of rich and poor countries. Recall that in our model quality improvement and cost reduction (productivity improvement) are isomorphic, so our explanation of the twin peaks in the world income distribution is consistent with Feyrer's (2008) finding that the twin peaks arise from twin peaks in productivity, not in availability of physical or human capital.

Our theory is consistent with the data in Tables 2 and 3 on the behavior of R&D resources in the leading R&D countries before and after the burst of trade liberalization around 1980. Even though the leaders' growth rates declined with globalization, their commitment of resources to R&D did not decline and in fact rose. Our model can explain that combination of facts simply enough. Trade induced some industries in the leader countries to shut down. They were replaced in the world by firms elsewhere in the world, where R&D is less productive. In the leader countries, R&D resources just shifted over to the industries that remained active.

6.2 Three Tests

For our new tests, need cross-country data on growth rates of real output per person and the terms of trade. We measure growth rate of income as the growth rate of real income per worker from the Penn World Table 2011. Terms of trade are defined as the ratio of a trade-weighted average of export prices over a similar average of import prices. Data are from several sources: (a) the World Bank's World Tables of Economic and Social Indicators, (b) the World Bank's World Tables, (c) UNCTAD STAT, and (d) IHS Global Insight Data. The overall sample comprises 89 countries spanning the years 1950-2009, but the data for very few countries cover the full time period. Most countries fall into one of four groups: 1950-2009, 1950-2008, 1960-2008, and 1970-2008. Several countries have other initial years and a few have other terminal years.

We begin by testing our model's implication of no systematic relation between the growth rate and the change in the terms of trade. We regressed countries' average growth rates of real income per worker on their growth rates of the terms of trade. Table 5 reports the results. There is no evidence whatsoever of a statistically or economically significant relation between the growth rates of the terms of trade and real income per worker. The coefficient on the growth rate of the terms of trade is 0.012 with a standard error of 0.066, a p-value of 0.86, and an adjusted R^2 of -0.011. These results support our theory.

Our next test is a refinement of Bhalla's (2002) calculation of what the 1980 globalization did to the group average growth rates for the industrialized and non-industrialize countries. Instead of looking at the average growth rate for industrialized and non-industrialized countries, we look at how many advanced and laggard economies had an increase or decrease in their growth rates in the wake of the 1980s trade liberalization. Advanced economies already were trading extensively with each other before 1980. The 1980 globalization was primarily about less advanced economies opening to trade with the advanced economies. Given that the less advanced economies typically do far less R&D than the leaders, our theory leads us to expect a fall in the advanced economies' growth rates and a rise in the laggards' growth rates after trade opens. A simple indicator of being advanced is membership in the OECD. Our sample of 89 countries contains 29 OECD members and 60 non-members. We averaged each country's annual growth rates for the years up to and including 1980 and also for the years after 1980. We then compared the average growth rates before and after 1980 for each country. Table 6 shows the results. Only 1 OECD member out of 29, or 3.5%, had an increase in its growth rate after globalization, whereas 15 out of 60, or 25%, of non-members had an increase. The results are essentially identical if we use Bhalla's definition of developed countries, which divides our sample into 24 developed and 65 undeveloped countries. For the 24 developed countries, none had an increase in its growth rate, whereas 16 out of 65 undeveloped countries had a decrease. This pattern is consistent with our theory.

Our final test evaluates competing predictions from our model and that of Howitt and Mayer-Foulkes (2005). Howitt and Mayer-Foulkes examine the growth effects of costly technology transfer within an endogenous growth framework with no trade or embodied technology. In world equilibrium, countries divide into two groups: (1HM) those whose growth rates converge to the same value and (2HM) those whose growth rates stagnate to a low level that is unaffected by openness. Our results are similar to some extent. We also have two super-groups of countries: (1JS) those that are either in the region of complete specialization already or are in that part of the region of incomplete specialization that leads to complete specialization and (2JS) those in the other part of the region of incomplete specialization in which growth rates converge to a constant difference. Behavior in groups 2HM and 2JS is different, however. In our model, the only pairs of trading partners that can be in group 2JS are those for which the "large" country is the R&D leader in both industries. Because of that, the "small" country's growth rate always rises in response to trade. We test this difference between the two approaches by dividing our countries into three groups and examining their growth rates. First, we assign countries to three growth groups: High (countries with growth rates more than 1 percentage point above the world average growth rate), Low (countries with growth rates more than one percentage point below the world average growth rate, and Medium (all other countries). We then compare the initial five-year average growth rates for the Low countries with those same countries' average growth rates for the terminal five years in the sample period. According to Howitt and Mayer-Foulkes, the growth rates for the Low countries should show no benefit from trade. According to our theory, growth rates for the Low countries should rise after opening to trade. There are 20 countries in the Low group. Of those, 19 had growth rates that were higher in the terminal five years than in the initial five years. Only 1 country had a lower growth rate. These results favor our theory over that of Howitt & Meyer-Foulkes.

7 Conclusion

We have studied the interaction of trade and growth in the context of an endogenous growth model built to be consistent with several important facts about the nature of technical progress and its effect on economic growth, the industrial organizational structure of the economy, and the nature of international trade. The analysis shows that trade and growth affect each other in ways not previously revealed or even explored, and the interaction of an endogenous industrial structure with aggregate general equilibrium dynamics is crucial for understanding the two types of effects. Subtleties of the IO structure, though perhaps seemingly trivial, turn out to be of first-order importance. Which firms do R&D and what kind of R&D they do is pivotal to our results. The model offers a single framework for understanding a wide variety of phenomena that perviously have been given unconnected explanations. The model thus offers unification of both theory and evidence. On the theory side, it ties together trade, growth, and IO, each of which affects the other two. On the empirical side, it offers a reconciliation of theory with observations that previously had proven difficult to explain, and it passes some "horserace" tests between it and alternative models.

In building our model, we naturally have made some compromises, the most important being no Melitz heterogeneity, no trade in final goods, and only two countries and two goods. As we explained in the main text, introducing Melitz heterogeneity would not affect the main results, but it would add a realistic dimension to the model. Introducing trade in final goods would enrich the analysis and might add some new conclusions. We address trade in final goods in a companion paper with only one type of tradable intermediate good (Kane, Ji, and Seater 2015). Some results differ from those obtained here in ways that give further insight into how trade and growth interact, suggesting that a model that combines the two approaches might be fruitful. The most ambitious extension would be to combine our model of growth with Eaton and Kortum's (2002) model of trade, with its rich structure of many countries and many goods. In all these cases, the curse of dimensionality looms large, making analysis difficult. All would be worthwhile topics for further research.

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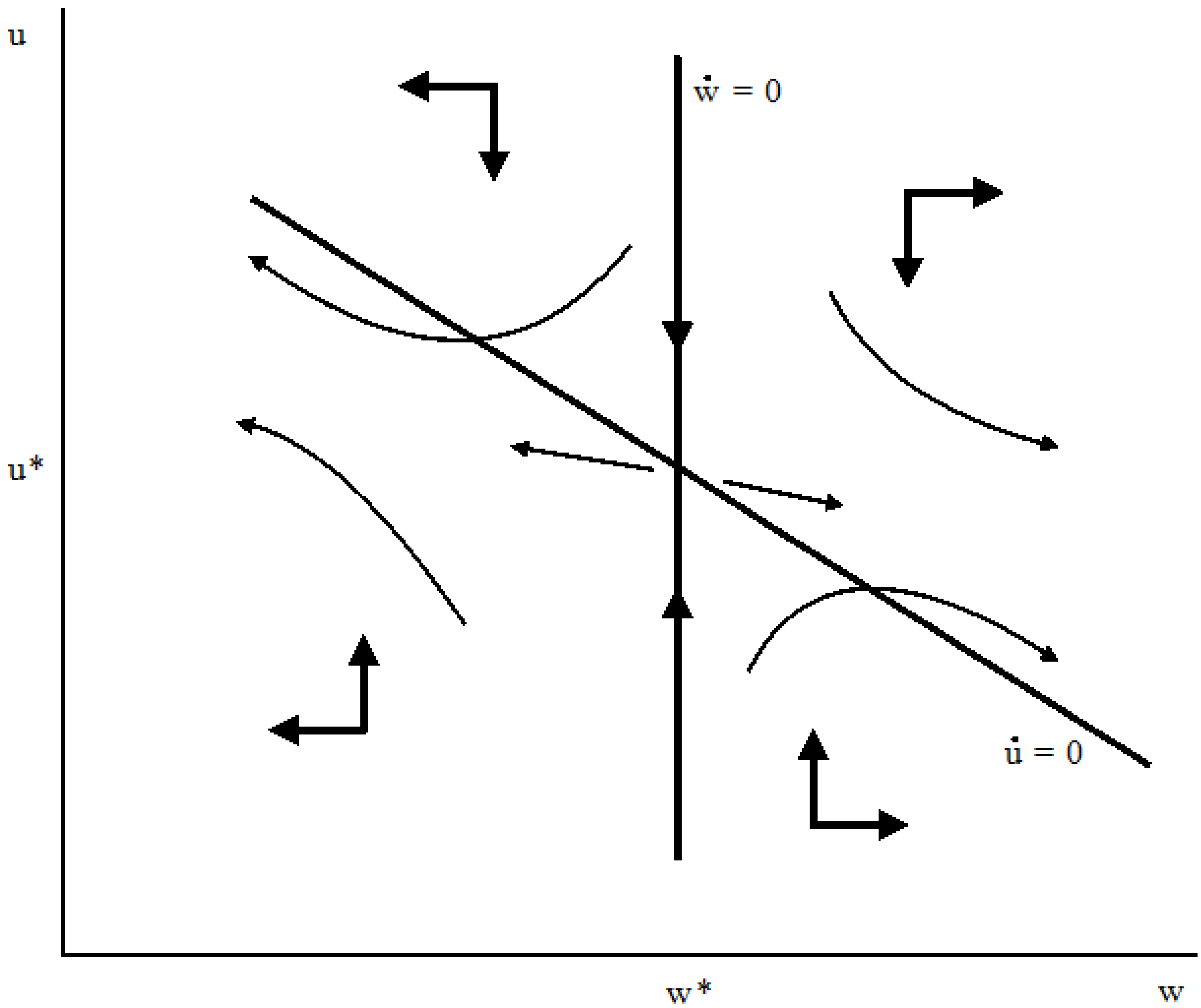

Figure 1: Phase diagram, incomplete specialization

Table 1
Globalization & Growth
(annualized per capita growth rates, percentage points)

	Years		
Region	1960-1980	1980-2000	Change
World	2.5	2.7	0.2
Industrialized	3.3	1.6	-1.7
Non-industrialized	2.3	2.8	0.5

Source: Bhalla (2002), Table 2.1

Table 2
R&D Expenditures

Total, billions of 1982 dollars							**R&D/GDP, percent**				
Year	France	W. Ger.	Japan	UK	US		France	W. Ger.	Japan	UK	US
1961	3.2	NA	3.9	8.1	45.8		1.4	NA	1.4	2.5	2.7
1962	3.6	4.2	4.4	NA	48.2		1.5	1.2	1.5	NA	2.7
1963	4.0	4.9	4.9	NA	52.6		1.6	1.4	1.5	NA	2.8
1964	5.0	5.8	5.5	8.4	57.2		1.8	1.6	1.5	2.3	2.9
1965	5.8	6.7	6.1	NA	59.4		2.0	1.7	1.6	NA	2.8
1966	6.3	7.3	6.6	8.8	62.6		2.1	1.8	1.5	2.3	2.8
1967	6.8	7.9	7.6	8.9	64.4		2.2	2.0	1.6	2.3	2.8
1968	7.0	8.4	9.0	9.1	65.5		2.1	2.0	1.7	2.2	2.8
1969	7.1	8.3	10.5	9.4	64.7		2.0	1.8	1.7	2.3	2.7
1970	7.1	9.9	12.4	NA	62.4		1.9	2.1	1.9	NA	2.6
1971	7.4	10.9	13.3	NA	60.4		1.9	2.2	1.9	NA	2.4
1972	7.7	11.4	14.7	9.3	61.4		1.9	2.2	1.9	2.1	2.3
1973	7.7	11.3	16.1	NA	62.4		1.8	2.1	2.0	NA	2.3
1974	8.1	11.5	16.4	NA	61.5		1.8	2.1	2.0	NA	2.2
1975	8.1	11.9	16.7	10.1	59.9		1.8	2.2	2.0	2.1	2.2
1976	8.4	12.1	17.3	NA	62.1		1.8	2.1	2.0	NA	2.2
1977	8.6	12.4	18.0	NA	63.7		1.8	2.1	2.0	NA	2.1
1978	8.9	13.3	19.1	11.1	66.8		1.8	2.2	2.0	2.2	2.1
1979	9.4	15.0	21.0	NA	70.1		1.8	2.4	2.1	NA	2.2
1980	9.8	15.3	23.1	NA	73.2		1.8	2.4	2.2	NA	2.3
1981	19.8	15.9	25.5	12.2	76.6		2.0	2.5	2.3	2.4	2.4
1982	11.5	16.3	27.4	NA	79.4		2.1	2.6	2.4	NA	2.5
1983	11.9	16.4	29.9	11.9	84.0		2.1	2.6	2.6	2.2	2.6
1984	12.6	16.9	32.4	NA	90.7		2.1	2.6	2.6	NA	2.6
1985	13.1	18.5	36.1	12.9	97.0		2.3	2.8	2.8	2.3	2.7
1986	13.6	18.6	36.6	13.8	98.6		2.3	2.7	2.8	2.4	2.7
1987	13.7	19.4	39.1	NA	100.8		2.3	2.8	2.9	NA	2.6

Source: NSF Science & Engineering Indicators 1989, Table 4-19.

Table 3
Scientists & Engineers Engaged in R&D

Millions							**Per 10,000 in the labor force**				
Year	France	W. Ger.	Japan	UK	US		France	W.Ger.	Japan	UK	US
1965	4.3	6.1	11.8	5.0	49.4		21.0	22.6	24.6	19.6	64.7
1966	6.0	6.0	12.9	NA	NA		29.2	22.3	26.4	NA	NA
1967	5.2	6.4	13.9	NA	NA		25.3	24.4	27.8	NA	NA
1968	5.5	6.8	15.7	5.3	55.0		26.2	25.9	31.1	20.8	67.9
1969	5.7	7.5	15.7	NA	55.3		27.1	28.2	30.8	NA	66.6
1970	5.8	8.3	17.2	NA	54.4		27.3	30.8	33.4	NA	64.1
1971	6.0	9.0	19.4	NA	52.3		27.9	33.4	37.5	NA	60.6
1972	6.1	9.6	19.8	7.7	51.5		28.2	35.6	38.1	30.4	58.0
1973	6.3	10.1	22.6	NA	51.4		28.5	37.1	42.5	NA	56.4
1974	6.4	10.3	23.8	NA	52.1		28.8	37.8	44.9	NA	55.6
1975	6.5	10.4	25.5	8.1	52.8		29.2	38.6	47.9	31.1	55.3
1976	6.7	10.4	26.0	NA	53.5		29.6	39.2	48.4	NA	54.7
1977	6.8	11.1	27.2	NA	56.1		29.7	41.8	49.9	NA	55.7
1978	7.1	11.4	27.3	8.8	58.7		30.7	42.7	49.4	33.3	56.5
1979	7.3	11.7	28.2	NA	61.5		31.4	43.4	50.4	NA	57.7
1980	7.5	12.1	30.3	NA	65.1		32.1	44.3	53.6	NA	60.0
1981	8.5	12.5	31.7	9.6	68.3		36.3	45.5	55.6	35.8	61.9
1982	9.0	12.8	33.0	NA	70.3		37.9	46.4	57.1	NA	62.8
1983	9.3	13.1	34.2	9.4	72.2		39.1	47.4	58.1	35.4	63.8
1984	9.8	13.7	37.0	9.6	74.6		41.1	49.6	62.4	35.5	64.7
1985	10.1	14.4	38.1	9.8	77.2		42.3	51.6	63.9	35.5	65.9
1986	10.5	14.7	40.6	9.9	79.1		43.8	52.3	67.4	35.5	66.2

Source: NSF Science & Engineering Indicators 1989, Table 3-19.

Table 4
Rates of Growth of GDP per Capita
(annual average compound growth rates, percentage points)

Region	*Years* 1000-1500	1500-1820	1820-70	1870–1913	1913-50	1950-73	1973-98
Western Europe	0.13	0.15	0.95	1.32	0.76	4.08	1.78
United States		0.36	1.34	1.82	1.61	2.45	1.99
Japan	0.03	0.09	0.19	1.48	0.89	8.05	2.34
Asia excluding Japan	0.05	0.00	-0.11	0.38	-0.02	2.92	3.54
Africa	-0.01	0.01	0.12	0.64	1.02	2.07	0.01

Source: Maddison (2001), Table B-22.

Table 5
Relation between growth rates of income and of the terms of trade

Dependent variable	Growth rate of income per worker			
Variable	Coefficient	Standard error	t-statistic	p-value
Constant	0.019754	0.001250	15.79736	0.0000
Growth rate of terms of trade	0.011614	0.066080	0.175759	0.8609
Adjusted R-squared	-0.011135			

Table 6
Globalization and Growth Rates

	Change in growth rate	
	Rise	Fall
Member OECD	1	28
Non-member OECD	15	45
Developed	0	24
Underdeveloped	16	49