Trade and innovation

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Abstract

Two central insights from the Schumpeterian approach to innovation and growth are that the pace of innovation is endogenously determined by the expectation of future profits and that growth is inherently a process of creative destruction. As international trade is a key determinant of firm profitability and survival, it is natural to expect it to play a key role in shaping both incentives to innovate and the rate of creative destruction. In this paper, we review the theoretical and empirical literature on trade and innovation. We highlight four key mechanisms through which international trade affects endogenous innovation and growth:(i) market size; (ii) competition; (iii) comparative advantage; (iv) knowledge spillovers. Each of these mechanisms offers a potential source of dynamic welfare gains in addition to the static welfare gains from trade from conventional trade theory. Recent research has suggested that these dynamic welfare gains from trade can be substantial relative to their static counterparts. Discriminating between alternative mechanisms for these dynamic welfare gains and strengthening the evidence on their quantitative magnitude remain exciting areas of ongoing research.

Key words: innovation, growth, international trade
JEL codes: F1; F43; O3; O4

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1 Introduction

One of the central insights of recent research on innovation and growth is that the pace of innovation is endogenously determined by the expectation of future profits. As international trade is a key determinant of firm profitability, through both the size of the market and the extent of product market competition, it is natural to expect it to play a key role in shaping innovation and growth. In this paper, we review the theoretical and empirical literature on trade and innovation, focusing on insights from taking a Schumpeterian perspective. According to this view, growth occurs through a process of creative destruction, such that existing state of art technologies are progressively replaced by the next generation of technologies.[1] Through endogenising the rate of innovation, these theories open up an entirely new channel for potential welfare gains from trade. In addition to the conventional static welfare gains from trade, these theories point towards the possibility of dynamic welfare gains from increases in the rate of innovation and growth. Determining the magnitude of these dynamic welfare gains from trade, the relative importance of different possible mechanisms for them, and whether they involve a permanent change in economic growth (endogenous growth) or a temporary one along the transition path (semi-endogenous growth) remain exciting areas of ongoing research.

In the existing international trade literature, there is a good deal of consensus about the static welfare gains from trade, defined as the increase in the level of flow utility from country participation in international markets. Traditional theories of international trade following Ricardo (1817), Heckscher (1919) and Ohlin (1924) emphasize cross-country variation in the opportunity cost of production for different commodities as source of comparative advantage and welfare gains from trade. Specialization to exploit these differences in opportunity cost gives rise to inter-industry trade, as countries export in industries of comparative advantage and import in those of comparative disadvantage. New theories of international trade following Krugman (1979a), Helpman (1981) and Helpman and Krugman (1985) highlight product differentiation and increasing returns

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[1]For an earlier review of trade and technological change, see Grossman and Helpman (1995). For surveys of recent research on trade and innovation, see Shu and Steinwender (2018) and Akcigit and Melitz (2021). For syntheses of Schumpeterian growth theory in general, see Aghion and Howitt (1997) and Akcigit et al. (2014).

to scale, which can generate welfare gains from trade through both an expansion of product variety and reductions in production costs. The resulting specialization to realize these economies of scale generates intra-industry trade, in which countries simultaneously export and import similar products within the same industry. Finally, theories of heterogeneous firms in differentiated product markets following Melitz (2003) and Bernard et al. (2003) point towards the non-random selection of the most productive firms into international trade and the resulting intra-industry reallocations of resources. The most productive firms expand into enter export markets while increased competition induces the least productive firms to exit. This generates welfare gains through increased average industry productivity.

While theories of endogenous innovation and trade open up the possibility for dynamic welfare gains from trade, there is much less consensus about the existence and magnitude of such changes in countries' rates of innovation and growth. Four main mechanisms for these dynamic welfare gains from trade have been proposed. First, international trade expands the market size accessible to firms. To the extent that innovation involves fixed costs, this expansion of market size can raise the incentive to innovate, because these fixed costs can be spread over a larger number of units of production. Second, international trade increases product market competition as the producers from different countries enter one another's markets. To the extent that this increased product market competition reduces firm profits, this can depress the incentive to innovate, as in the classic trade-off in industrial organization between static and dynamic efficiency. However, an important contribution of the Schumpeterian approach has been to uncover a rich nexus of channels through which increased competition can have the opposite effect of raising the incentive to innovate, or generate a non-monotonic relationship between innovation and competition.

Third, international trade induces specialization according to comparative advantage, as in the conventional theories of trade discussed above. If sectors differ in their rates of innovation and growth, this specialization according to comparative advantage can affect aggregate rates of growth through a change in sectoral composition. However, the implications of this specialization

for welfare are more subtle, since output and consumption growth are not equal to one another in the open economy. Even if a country specializes in sectors with slow output growth, it can enjoy the fruits of its trade partners' more rapid output growth through an ongoing improvement in the international terms of trade. Fourth, international knowledge spillovers can directly affect countries' rates of economic growth, and international trade in goods itself can be a conduit through which ideas spread around the world. These knowledge spillovers can facilitate catch-up to the world technology frontier and can accelerate the rate of advancement of this world technology frontier. Trade can influence knowledge spillovers through changing both the set of firms selling in a market and the set of firms producing in a country. Knowledge spillovers may occur serendipitously, or as a result of either direct investment in knowledge acquisition, or more indirectly via imitation of more advanced products (leading to product cycle, in which products are first invented in some parts of the world, and then imitated in others).

In exploring these different mechanisms through which international trade can affect innovation and growth, we distinguish between three key classes of models of endogenous innovation. First, there are models of endogenous innovation through the expansion of product variety (horizontal differentiation), which build on the closed economy framework of Romer (1990), and include Rivera-Batiz and Romer (1991) and Grossman and Helpman (1991a). Second, there is the Schumpeterian approach of endogenous innovation through the improvement of product quality (vertical differentiation), including Aghion and Howitt (1992), Grossman and Helpman (1991c) and Grossman and Helpman (1991a). Third, more recently, models combining elements of both those approaches have been developed. In much of this recent literature, firms supply horizontally-differentiated varieties, but these varieties differ systematically from one another in terms of productivity or quality.[2]

Some economic forces are common to variety and quality-based models of endogenous innovation. In both approaches, innovations differ from conventional economic goods in two key respects. First, they are *non-rivalrous*, such that once an idea has been created, it can be used by

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[2]See Akcigit and Melitz (2021) for a more detailed review of this recent literature.

anyone at zero marginal cost. Second, they are *partially excludable*, such that intellectual property rights or intangible knowledge about the implementation of innovations enable researchers to appropriate at least some of the economic return from them. Furthermore, many of the forces that influence the future profits from innovation are common to both groups of models, including the roles of both market size and product market competition.

Other economic forces are quite different between variety and quality-based models of innovation. In particular, creative destruction features much more prominently in the Schumpeterian approach. Since products are vertically differentiated, all consumers agree about which product is preferred at given prices. Therefore, when innovation occurs, the existing state of the art technology is displaced. This property has a number of economic implications. First, creative destruction affects the incentives for innovation for incumbent and entrant firms. In the basic Schumpeterian model, the fact that the existing stream of profits is destroyed by innovation (the replacement effect of Arrow 1962), implies higher incentives for innovation by entrants who then displace incumbents. Second, creative destruction affects the the size and magnitude of the externalities from innovation, and hence the divergence between private and social rates of return. When making their endogenous investments in innovation, new entrants do not internalize the externality from the destruction of existing firms' profits. Third, the vertical nature of innovation has important implications for the relationship between incentives to innovate and product market competition. Depending on the distance between firms in technology space, increased product market competition can either depress incentives to innovate (through a discouragement effect) or enhance incentives to innovate (as firms try to escape competition).

The remainder of this paper is structured as follows. In Section 2, we review the baseline Schumpeterian approach, and use this framework to discuss the different potential mechanisms through which trade can affect innovation. The remaining four sections of the paper consider each of the above four mechanisms in turn. In Section 3, we review the literature on trade, market size and innovation. In Section 4, we focus more specifically on the nexus between trade and Schumpeterian competition, and its consequences for innovation. In Section 5, we consider com-

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parative advantage as a channel through which trade affects aggregate innovation and growth. In Section 6, we examine mechanisms where knowledge spillovers play a key role in shaping the impact of trade on innovation. Section 7 summarizes our conclusions.

2 The Schumpeterian Approach

In this section, we introduce the baseline Schumpeterian approach to endogenous innovation and growth from Aghion and Howitt (1992). To highlight the key insights, we begin by considering a closed economy setting, before using this setting to highlight the potential mechanisms through which trade can affect innovation.

Preferences and Technology We consider the following economic environment. Time is continuous and we suppress the time subscript to simplify notation. The economy is populated by a continuous mass L of workers. Workers have linear intertemporal preferences, such that the interest rate is equal to the subjective rate of time discount (r). Each worker is endowed with one unit of labor that is supplied inelastically. Output of a single final good (y) is produced using intermediate inputs (x) according to the following production technology:

$$y = Ax^\alpha, \qquad 0 < \alpha < 1, \tag{1}$$

where A corresponds to the quality or productivity of intermediate inputs; we choose the final good as the numeraire, such that its price is equal to one.

Intermediate inputs are produced one-for-one with labor according to a linear technology, such that employment in intermediate production equals output of intermediate inputs (x). Labor market clearing implies that employment in intermediate input production plus employment in research (n) equals the economy's total supply of labor:

$$L = x + n. \tag{2}$$

Innovations are assumed to arrive randomly in the research sector, with a Poisson arrival rate λn, where λ parameterizes the productivity of research. Each innovation is assumed to

improve the quality or productivity of intermediate inputs by a constant proportion $\gamma > 1$, such that there is a productivity or quality ladder, with $A_{t+1} = \gamma A_t$, where t indexes innovations. An important feature of this specification is that each generation of researchers benefits from knowledge spillovers from previous generations, with each innovation standing on the shoulders of the previous state of the art technology. A firm that successfully innovates can monopolize the intermediate sector until replaced by the next innovator. We assume that innovations are drastic, such that final goods firms prefer to employ the state of the art intermediate input at the profit-maximizing monopoly price rather than the next best technology at its marginal cost of production.

Research Sector   Free entry into research implies that the wage in the intermediate sector (w_t) using technology t equals the probability of innovation (λ) times the value of the next technology $t + 1$ (V_{t+1}):

$$w_t = \lambda V_{t+1}. \tag{3}$$

The value of successful innovation (V_{t+1}) depends on the flow of profits from monopolizing the intermediate sector (π_{t+1}) and the probability of being subsequently replaced by the next best technology (λn_{t+1}) according to the following Bellman equation:

$$rV_{t+1} = \pi_{t+1} - \lambda n_{t+1} V_{t+1}. \tag{4}$$

In equilibrium, all research is undertaken by entrants rather than the incumbent monopolist of the current state of the art technology, because of the "replacement effect": The incremental increase in profits for the incumbent from developing the next generation of technology is smaller than the total profits gained by an entrant from displacing an incumbent. Aghion et al. (1997) and Aghion et al. (2001) extend this framework with multiple ladder rungs (resulting from "step-by-step" innovation outcomes). In this version, incumbents still have an incentive to innovate, but the highest innovation effort is still exerted in anticipation of replacing the incumbent at the top of the ladder.

Intermediate Sector At each point in time, the monopolist of the state of the art technology t chooses output (x) of intermediate inputs to maximize profits $(\pi_t(x))$:

$$x_t = \arg\max_x \{\pi_t(x) = p_t(x)x - w_t x\}, \tag{5}$$

where $p_t(x)$ is the price of the intermediate input. This price is determined from the downward-sloping demand curve from the final goods sector:

$$p_t(x) = A_t \alpha x^{\alpha-1}. \tag{6}$$

Profit maximization implies that the equilibrium price of the intermediate input is a constant mark-up over marginal cost:

$$p_t = \frac{1}{\alpha} w_t, \tag{7}$$

where this constant mark-up $(1/\alpha)$ reflects the fact that the producer of the state of art intermediate input faces a constant elasticity derived demand function (6). Equilibrium output and profits in the intermediate sector can be written as the following functions of the productivity-adjusted wage $(\omega_t \equiv w_t/A_t)$:

$$x_t = \left(\frac{\alpha^2}{w_t/A_t}\right)^{1/(1-\alpha)} = \left(\frac{\alpha^2}{\omega_t}\right)^{1/(1-\alpha)} \equiv \widetilde{x}(\omega_t), \tag{8}$$

$$\pi_t = \left(\frac{1-\alpha}{\alpha}\right) w_t x_t \equiv A_t \widetilde{\pi}(\omega_t).$$

General Equilibrium The general equilibrium of the model can be characterized by a no-arbitrage condition equating the returns to working in the intermediate and research sectors and the labor market clearing condition. From the free entry condition (3), the asset equation (4) and equilibrium profits (8), no-arbitrage between the intermediate and research sectors implies:

$$\omega_t = \lambda \frac{\gamma \widetilde{\pi}(\omega_{t+1})}{r + \lambda n_{t+1}}. \tag{9}$$

Labor market clearing (2), together with equilibrium intermediate production (8) implies:

$$L = n_t + \widetilde{x}(\omega_t). \tag{10}$$

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The no-arbitrage condition (9) and the labor market clearing condition (10) determine the equilibrium productivity-adjusted wage (ω_t) and research employment (n_t) for technology t as a function of expectations of the equilibrium productivity-adjusted wage (ω_{t+1}) and research employment (n_{t+1}) for technology $t+1$.

Steady-state Equilibrium In a steady-state equilibrium, there is a constant productivity-adjusted wage ($\omega_{t+1} = \omega_t = \omega$) and constant research employment ($n_t = n_{t+1} = n$). Combining the no-arbitrage condition (9) and the labor market clearing (10), steady-state equilibrium research employment solves the following relationship:

$$1 = \lambda \frac{\gamma^{\frac{1-\alpha}{\alpha}} (L - n)}{r + \lambda n}. \tag{11}$$

The economy's steady-state rate of output growth in turn depends on this equilibrium research employment (n), the productivity of research (λ), and the size of innovations (γ):

$$g = \lambda n \ln \gamma. \tag{12}$$

Introducing Trade and its Impact on Innovation and Growth This characterization of the closed economy equilibrium suggests four potential mechanisms for international trade to affect endogenous innovation and growth. First, the closed economy equilibrium features a scale effect, such that countries with a larger supply of labor (L) experience higher rates of innovation and output growth. To the extent that international trade operates like an increase in the supply of labor, this suggests a first mechanism for trade to affect innovation and growth through larger market size.

Second, the rate of innovation and output growth in the closed economy depends on the profits from successful innovation. In this baseline Schumpeterian specification with drastic innovation, the markup from successful innovation is completely determined by the parameter α. More generally, the profits from successful innovation depend on market structure and the degree of product market competition. To the extent that international trade affects market structure, this

points towards a second mechanism for trade to affect innovation and growth through product market competition.

Third, this baseline Schumpeterian model features a single final good sector. More generally, one could envision multiple final goods sectors that differ in the productivity of innovation (λ), the step size for each quality improvement (γ) and equilibrium investments in innovation (n). To the extent that international trade changes the composition of economic activity across sectors that differ in rates of innovation and growth, this highlights a third mechanism for trade to affect innovation and growth through specialization according to comparative advantage.

Fourth, a key feature of this closed economy specification is that there are knowledge spillovers, such that each generation of researchers builds on the discoveries of previous generations of researchers. In an open economy, these knowledge spillovers can occur not only domestically but also internationally, revealing a fourth mechanism for trade to affect innovation and growth through international knowledge spillovers. The magnitude of these knowledge spillovers is likely to depend on the extent to which there is duplication in research, whether a country is close to or far from the global technological frontier, and whether international knowledge spillovers occur through international trade in goods (embodied) or occur independently of those flows of goods (disembodied).

In this baseline Schumpeterian model, there is a single intermediate input producer of the state of art technology in equilibrium, because of the vertical differentiation of technology. Additionally, all innovation is undertaken by entrants rather than incumbent firms, because of the "replacement effect" discussed above. More generally, technologies can be both horizontally and vertically differentiated, such that a range of technologies operates in equilibrium, and incumbents can invest in innovation as well as entrants. In such setting, international trade can also affect innovation and growth is through reallocations of resources across heterogeneous producers. In much of the existing heterogeneous firm literature in international trade following Melitz (2003), these reallocations affect the level of productivity rather than innovation and growth. In dynamic models of innovation and producer heterogeneity, they can also affect endogenous rates

of innovation and growth through the four mechanisms discussed above.

Efficiency Models of endogenous innovation typically feature of number of externalities, such that the private rate of return to R&D differs from its social rate of return. Furthermore, these externalities in general differ between variety and quality-based models of endogenous innovation. First, researchers typically only appropriate part of the return to innovation, because they capture only the profits from the innovation and not the associated consumer surplus. This "appropriability effect" acts to reduce private investments in innovation relative to the socially-optimal level. Second, researchers typically do not take into account that their discovery can be used as an input into research by subsequent generations of researchers. This "knowledge spillovers" effect again works to reduce private investments in innovation relative to the socially-optimal level.

Third, in the standard Schumpeterian model of innovation discussed above, all innovation is undertaken by entrants rather than incumbents, because of the replacement effect. As a result, the current generation of researchers does not internalize the destruction of the flow of profits from the existing state of the art technology. This "business stealing" or "creative destruction" effect works to increase private investments in innovation relative to the socially-optimal level. Fourth, in these Schumpeterian models in which incumbents are replaced by new entrants, the private and social discount rates differ. The current generation of researchers internalizes the expected flow of profits from innovation over the interval of time until they are displaced by a subsequent generation of researchers, whereas the social planner internalizes that the increase in quality from the innovation persists forever. Again this "discounting effect" acts to reduce private investments in innovation relative to the socially-optimal level.

Even in the closed economy, these divergences between private and social rates of return to innovation can provide a rationale for policy interventions to either promote or retard investments in innovation. In the open economy, these domestic distortions can interact with trade frictions to influence the welfare gains from trade, as discussed further below. Akcigit et al. (2021) develop an open economy model of Schumpeterian growth that quantitatively examines

those interactions. We discuss this contribution in the following section.

3   Market Size, Trade and Innovation

The idea that market size is an important determinant of economic development dates back to at least Adam Smith. In the third chapter of the first book of the Wealth of Nations, Smith (1776) argued: "As it is the power of exchanging that gives occasion to the division of labour, so the extent of this division must always be limited by the extent of that power, or, in other words, by the extent of the market." We begin by discussing the role of market size in static models of international trade. We next turn to consider the impact of market size on innovation in dynamic trade models and the debate about scale effects. Finally, we close this section by considering the effect of market size on innovation in models of firm heterogeneity.

Market Size in Static Trade Models   In static models of international trade, this idea that market size influences the extent of specialization and the division of labor was formalized in Krugman (1979a, 1980). In the presence of horizontal product differentiation and increasing returns to scale from fixed production costs, each firm specializes in producing a distinct variety, and in the closed economy the measure of varieties produced depends on the size of the economy's labor force. In Krugman (1979a) with a variable elasticity of demand system and firms competing under conditions of monopolistic competition, the opening of international trade both expands the measure of varieties available to consumers and increases output of each variety, which increases average productivity, because of the economies of scale. Both forces imply welfare gains from trade, even for trade between countries with identical preferences and production technologies. In Krugman (1980), the assumption of constant elasticity of substitution (CES) preferences and monopolistic competition implies that there is no effect of the opening of trade on average firm size, and hence the sole source of welfare gains from trade is an expansion of the measure of varieties available to consumers.

Market Size in Dynamic Trade Models Whereas in these static trade models, the creation of new varieties requires firms to incur a fixed cost, in dynamic models of endogenous growth through the expansion of product variety, such as Romer (1990), the stock of varieties expands gradually over time through flow investments in research and development (R&D). These flow investments again have the feature of a fixed cost: Once the blueprint for a new variety has been created, it can be used at zero marginal cost, leaving only production costs to be incurred. As a result, basic models of endogenous innovation and growth feature a powerful scale effect, such that larger economies have higher rates of endogenous growth.

Whether or not these scale effects are consistent with the data has been a lively source of debate. An influential series of papers in Jones (1995a,b, 1999) argues that this prediction of scale effects is inconsistent with the empirical evidence. In particular, an implication of these scale effects is that an increase in resources devoted to R&D should lead to a proportionate increase in a country's long-run rate of economic growth. In contrast to this prediction, the number of scientists engaged in R&D in advanced countries grew dramatically in the second half of the twentieth century, but country growth rates either exhibited a constant mean or declined on average. Motivated by these empirical findings, Jones (1995a) develops a semi-endogenous growth model, in which endogenous innovation shapes the economy's rate of growth in the transition to steady-state, but the economy's long-run rate of growth is exogenously determined by population growth. Young (1993) also develops a model in which scale effects show up the level of economic activity through a proliferation of product variety but not in changes in the economy's long-run rate of growth. In practice, transition dynamics can be slow, and hence distinguishing between endogenous and semi-endogenous growth models empirically can be challenging. Furthermore, given these slow transition dynamics and discounting, whether policies affect the growth rate permanently or over a long transition period may be of relatively little consequence.

Although international trade expands market size and hence increases incentives to invest in innovation, its effect on the rate of growth is more subtle than an increase in an economy's supply of labor in the closed economy. The reason is that international trade also increases product

market competition between firms, which decreases incentives to invest in innovation in the simplest models of endogenous growth. Paralleling the result discussed above for static models of international trade, if the horizontal differentiation of varieties takes a constant elasticity of substitution (CES) form, these market access and competition effects exactly offset one another in models of endogenous growth through product variety. In particular, suppose that countries open to trade in goods alone, with no knowledge spillovers between them and no duplication in research. In these circumstances, trade raises the level of countries' welfare through the increased range of varieties available to consumers, but has no effect on countries' long-run rates of growth, because of the offsetting market size and competition effects, as shown in Rivera-Batiz and Romer (1991) and Grossman and Helpman (1991a). Instead, international openness affects countries' rates of growth in these models through international knowledge spillovers and the elimination of duplication in research. As for static models of international trade, this result is specific to CES preferences, and the impact of trade in goods alone would be more subtle for the general additive preferences considered by Krugman (1979a) and Zhelobodko et al. (2012).

Market Size in Heterogeneous Firm Trade Models   Much of the recent literature on firm heterogeneity in international trade following Melitz (2003) has focused on models that are largely static. In these frameworks, trade affects the range of varieties available for consumption and reallocates resources across firms of heterogeneous productivity, but does not influence innovation and growth. In the open economy equilibrium of these models, only the most productive firms self-select into exporting, because of the fixed costs of serving export markets. Symmetric reductions in international trade costs induce within-industry reallocations, in which high-productivity exporters expand; intermediate productivity firms enter export markets; lower productivity firms that serve only the domestic market contract; and the lowest-productivity firms exit. Each of these responses reallocates resources within the industry towards more productive firms, raising average industry productivity.[3] More recently, a number of studies have incor-

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[3]For reviews of this literature on firm heterogeneity, see for example Bernard et al. (2007), Melitz and Trefler (2012), Melitz and Redding (2014) and Bernard et al. (2018). For research on selection into importing and Global

porated endogenous technology adoption or innovation into environments with heterogeneous producers, and we now turn to consider the implications of this heterogeneity for the impact of international trade on technology adoption, innovation and growth.

In models of firm heterogeneity and endogenous technology choice, market size effects also play an important role in determining whether a more advanced technology is adopted. Bustos (2011) considers a version of the Melitz (2003) model, in which heterogeneous firms make endogenous decisions over both whether to incur a fixed cost of exporting and whether to incur the fixed cost of adopting a more advanced technology.[4] A key prediction of the model is that the increase in firm revenues from exporting can induce firms to upgrade technology. Consistent with the predictions of the model, the effect of tariff reductions from MERCOSUR on technology upgrading by Argentinian firms is greatest for firms in the upper-middle range of the firm-size distribution. Costantini and Melitz (2008) develops a dynamic model of the decisions of heterogeneous firms to adopt a new technology that features transition dynamics in response to trade liberalization. In this framework, the distributional effects of trade liberalization across firms depend on whether trade liberalization is anticipated or unexpected, and whether it occurs gradually or all of a sudden. In particular, the anticipation of future trade liberalization, or a more gradual path of trade liberalization once implemented, can induce firms to innovate ahead of export market entry.

Further evidence of the importance of market size for incentives to innovate is provided by Lileeva and Trefler (2010) using the Canada-U.S. Free Trade Agreement. Canadian plants that were induced by the tariff cuts to start exporting or to export more increased their labor productivity, engaged in more product innovation, and had higher rates of adoption of manufacturing technology. Furthermore, the paper shows that the empirical finding that the productivity gains from exporting are largest for the plants that are initially small and less productive can be explained by allowing for two forms of heterogeneity: in productivity and the return to investment. The intuition can be seen by considering two firms that are initially just indifferent between either (i) exporting and investing and (ii) doing neither. The initially higher-productivity firm will

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Value Chains (GVCs), see Antràs et al. (2017) and Antràs and de Gortari (2020)

[4]This key tradeoff involving exports and technology adoption was first analyzed by Yeaple (2005)

perform well in export markets, and so its indifference must be due to low expected productivity gains from investing. In contrast, the initially lower-productivity firm will perform poorly in export markets, and hence its indifference must be due to large expected productivity gains from investment. As a result, when trade barriers fall, and both firms start to export and invest, the initially less productive firm will experience the greater productivity growth.

While all the previous three studies focus on technology adoption, Atkeson and Burstein (2010) develops a model of firm heterogeneity with both product innovation (the entry of new firms) and process innovation (investments to increase firm productivity). The model features endogenous decisions over exit, exporting, product innovation and process innovation. The paper decomposes the change in aggregate productivity from a reduction in trade costs into the direct effect (holding constant firms' exit, exporting, product innovation and process innovation decisions) and the indirect effect that arises from changes in firms' exit, exporting, process innovation and product innovation decisions. The free entry condition that equates the expected value of entry with the sunk entry cost disciplines the overall magnitude of this indirect effect. The paper finds that, in the steady-state, the magnitude of this indirect effect is not affected by the introduction of firm heterogeneity. Even though exporters respond to trade liberalization by raising their innovation rates relative to non-exporters (under heterogeneity) – those differences do not translate into higher aggregate productivity relative to a model where all firms export and share a common innovation rate. Impullitti and Licandro (2018) introduce oligopolistic competition into a similar dynamic framework. They find that the endogenous markups induced by this competition break that equivalence result highlighted by Atkeson and Burstein (2010), leading to a first-order impact of trade liberalization on welfare via firm selection with heterogeneous firms. Tougher selection reduces markups and triggers higher productivity growth. In a calibrated version of this model, Impullitti and Licandro (2018) find that those additional welfare gains are substantial: they are roughly doubled relative to a model without the firm-selection channel.[5]

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[5]Long et al. (2011) also incorporate oligopoly into a static model of trade and innovation. They find that the relative magnitude of the positive market size effect and negative competition effect critically depend on the level of the trade costs.

Using firm-level production, trade and patenting data, Aghion et al. (2020) provide theory and evidence on the role of market size and competition effects in influencing incentives for firms to invest in ongoing innovation. To disentangle the direction of causality between export demand and innovation, the paper constructs a firm-level export demand shock that captures demand conditions in a firm's export destinations but is exogenous to the firm's decisions. Using data for French manufacturing, the paper shows that French firms respond to exogenous growth shocks in their export destinations by patenting more, and that this response is entirely driven by the initially more productive firms. The paper shows that this pattern of results emerges naturally in a model of firm heterogeneity with endogenous innovation. The positive market demand shock induces all firms to innovate more because of the expansion in market size, but also increases market entry and product market competition, which discourages innovation by the less productive firms.

4   Product Market Competition, Trade and Innovation

As discussed in the previous section, the relative magnitude of market size and competition effects plays a key role in shaping the effect of international trade on rates of innovation and growth. In this section, we explore competition effects in further detail. We begin by discussing the negative effect of competition on innovation in conventional models of endogenous innovation and growth. We next discuss three novel mechanisms through which competition can have positive effects on innovation in Schumpeterian models.[6] Finally, we end this section by considering the empirical evidence on these mechanisms and discussing ongoing work on their role in shaping the effects of international trade in general equilibrium.

Competition Effects in Conventional Innovation Models   In conventional models of endogenous innovation, whether variety or quality-based, greater product market competition depresses the incentive to innovate by lowering the expected future profits from innovation, as in

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[6]For a review of the evidence on competition and productivity, see Holmes and Schmitz (2010).

the classic trade-off between static and dynamic efficiency under monopoly in Industrial Organization. In contrast to these theoretical predictions, there is empirical evidence that greater product market competition can in fact spur firms to greater innovative efforts. Using panel data for U.K. manufacturing companies, Nickell (1996) finds that increased product market competition leads to increased productivity, using both measures of domestic market competition and import penetration. A distinctive feature of Schumpeterian models of innovation through product quality is that they provide microfoundations for this idea that greater product market competition can enhance incentives to innovate. We next discuss three different mechanisms for this positive effect of competition on innovation in Schumpeterian models.

Schumpeterian Models of Step-by-Step Innovation   Aghion et al. (2001) develops a model of endogenous growth with "step-by-step" innovation, in which technological laggards must first catch up with the leading-edge technology before battling for technological leadership in the future. Such a specification changes the incremental incentives that firms face when deciding on their innovative investments. In particular, when firms are "neck-and-neck" with similar levels of technology, each firm may have a strong incentive to innovate to "escape competition." In contrast, if a firm is far behind the technological frontier, increased product market competition may reduce the incremental return to innovation, because the firm has to first catch up with the leader before advancing the frontier, leading to a "discouragement effect." Therefore, the effect of competition on the overall aggregate rate of innovation can be subtle and potentially non-monotonic, because it depends on the entire probability distribution of firms across alternative states of technology, which is itself endogenous to the intensity of product market competition.

Schumpeterian Models of Agency Concerns   Aghion et al. (1999) develops a model of agency concerns, in which increased product market competition affects the incentives for technology adoption by non-profit maximizing managers. In particular, the paper considers a setting in which managers enjoy private benefits of control and face private costs of technology adoption, but only appropriate some of the monetary returns from technology adoption, because the firm is

dependent on outside finance. In such a setting, if the private benefits of remaining solvent are sufficiently large, a deterioration of profitability from an increase in product market competition can raise managers' incentives to adopt new technologies. This allows the firm to remain solvent and the manager to continue to benefit from the private benefits of control. Therefore, agency considerations from a separation of ownership and control can provide another route through which increased product market competition can spur greater innovative efforts. Within this framework, debt contracts can provide an alternative mechanism to discipline managers to exert effort in order to continue to enjoy the private benefits of control.

Schumpeterian Models of Research and Development   Aghion and Howitt (1996) considers a richer specification of technology and innovation that provides another channel through which greater product market competition can raise innovation and growth. In the basic quality ladder model of growth, technology is one-dimensional, such that each generation of technology improves on the previous state of the art technology by a proportion $\gamma > 1$. In contrast, Aghion and Howitt (1996), allows technology to be multi-dimensional by drawing a distinction between "research" and "development." Research produces fundamental knowledge, which by itself may not be useful, but which opens up windows of opportunity, which are modeled as new product lines. In contrast, "development" generates secondary knowledge, which allows these opportunities to be realized, by filling up the new product lines. In this specification, more competition between new and old product lines, as parameterized by increased substitutability between them, can induce developers to switch from old to new product lines more rapidly, thereby leading to more research and a higher rate of growth.[7]

Empirical Evidence   Although Schumpeterian models highlight these three different channels through which increased product market competition can raise incentives to innovation, there is scope for more empirical research to discriminate between these three mechanisms. In an

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[7]Such models of multi-dimensional technological change create the potential for path dependence, hysteresis and technological lock-in, in which historical patterns of technological development can influence long-run levels of economic activity, as in Brezis et al. (1993) and Redding (2002).

influential empirical study, Aghion et al. (2005) provides evidence of an inverted-U-shaped relationship between competition and innovation using company accounts data on a panel of firms listed on the London Stock Exchange. This inverted U-shaped relationship is rationalized using a model of "step-by-step" innovation along the lines discussed above, in which competition encourages neck-and-neck firms to innovate, but discourages laggard firms from innovating. Together these two effects generate the inverted U-shaped relationship. When competition is low, a larger equilibrium fraction of sectors involve neck-and-neck competition, so that overall the escape competition effect dominates, and greater product market competition increases incentives to innovate. In contrast, when competition is high, a large fraction of sectors have innovation being performed by laggard firms, so that the discouragement effect is more powerful, and greater product market competition decreases incentives to innovate. Additionally, two other properties of the data provide further support for the mechanisms in the model. First, the average technological distance between leaders and followers increases with competition, and second, the inverted U-shape is steeper when industries are more neck-and-neck.

International Trade and the Schumpeterian Mechanisms   International trade provides a natural empirical setting for examining the consequences of increased competition on innovation. As we previously discussed, international trade in general induces changes to both the market size and competition channels for innovation. However, asymmetric changes that predominantly affect import competition provide a way of assessing the competition channel for the domestic incumbent firms. Aghion et al. (2004) and Aghion et al. (2009) examine the impact of increased foreign competition on the innovation activities and outcomes of U.K. firms. They find that sectors in the U.K. that were more exposed to increased foreign competition exhibited higher rates of productivity growth – thus highlighting the importance of the escape competition channel. When restricting the measure of competition more narrowly to "greenfield" foreign entry (FDI), they find evidence supporting both the escape competition as well as the discouragement channel – leading to an inverted-U relationship between competition and innovation similar to Aghion

et al. (2005).

Another large asymmetric import competition shock that has hit advanced economies has been the so called "China Shock", following its entry into the WTO in 2001. Autor et al. (2020) examine the impact on the innovation response of U.S. firms, and find evidence mostly supporting the discouragement channel: U.S. firms in sectors most impacted by the increase in Chinese import competition respond by reducing R&D expenditures and new patent introductions. On the other hand, Bloom et al. (2016) find that increased Chinese competition induced European firms to increase their rates of innovation, highlighting the escape competition channel. Returning to the case of U.S., Hombert and Matray (2018) find evidence for both the discouragement and escape competition channels. More specifically, they find that this escape competition channel works through firm investments in more differentiated products. Yang et al. (2021) also find similar evidence for Canadian firms; and Fieler and Harrison (2018) find that this type of escape competition directed at product differentiation is also exhibited by Chinese firms who face increased competition by foreign firms entering the Chinese market following its accession to the WTO.[8]

Aghion et al. (2021b) offer a different explanation for the evidence of both positive and negative innovation responses to increased Chinese competition: They show that there are two very distinct components to this increased competition that induced adjustments in opposite directions for French firms exposed to Chinese exports. One component is horizontal: the exposed firms produce a good that competes with similar imported Chinese goods. The other component is vertical: the exposed firms use intermediate goods similar to the imported Chinese goods. Aghion et al. (2021b) find that the horizontal component of the China shock induces a strong negative innovation response for the affected French firms, whereas the response to the vertical component is positive.

On the theoretical side, there has been relatively little research introducing these Schumpete-

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[8]Bombardini et al. (2017) find that a positive escape competition innovation response is exhibited by relatively more productive Chinese firms. In a broader sample of 27 emerging markets, Gorodnichenko et al. (2010) find evidence supporting mainly the escape competition response.

rian mechanisms into general equilibrium models of international trade – even though international trade plays a key role in shaping product market competition. In a notable exception, Akcigit et al. (2021) develops a general equilibrium model of step-by-step innovation and trade, which is used to study the welfare implications of country trade and innovation policies. A R&D tax credit is found to generate substantial welfare gains over medium and long horizons. The optimal value of this tax credit is decreasing in the level of trade openness. They also find that protectionist policies can generate welfare gains in the short-run by shielding domestic firms from foreign competition. But they subsequently engender substantially larger losses in the long-run because they distort innovation incentives, leading to slower growth.

5 Comparative Advantage, Trade and Innovation

In models of endogenous innovation and trade, comparative advantage plays an important role, both in shaping the effects of economic growth, and in determining the pace of innovation and growth. We first discuss how comparative advantage influences the effects of economic growth in the open economy. We next consider comparative advantage as determinant of innovation and growth. Finally, we consider potential implications for public policy in the open economy.

Comparative Advantage and the Effects of Economic Growth   In the open economy, comparative advantage plays a key role in shaping the effects of economic growth. Matsuyama (1992) and Uy et al. (2012) show that the effect of sectoral productivity growth on structural transformation and economic development hinges critically on whether the economy is closed or open to international trade. In a closed economy, higher productivity growth in agriculture induces structural transformation away from that sector in the presence of inelastic demand between sectors, as in classic model of unbalanced growth of Baumol (1967). In contrast, in an open economy, higher productivity growth in agriculture can have the opposite effect reallocating employment towards that sector through specialization according to comparative advantage.

More generally, comparative advantage and international trade are important in determin-

ing the relative price implications of economic growth. For example, Ventura (1997) develops a Ramsey model of capital accumulation in which rates of economic growth decline with capital accumulation in the closed economy, because of the conventional force of diminishing marginal returns to capital accumulation. In contrast, in the open economy, countries can continue to grow rapidly without any decline in the rate of return to capital accumulation, as long as their endowments remain within the factor price equalization set. This framework thus provides a neoclassical rationalization of "economic miracles" such as the rapid economic growth of South Korea from 1960 onwards. In Acemoglu and Ventura (2002), international trade leads to a stable world income distribution even in the absence of diminishing marginal returns to capital accumulation. This is because specialization and trade introduce de facto diminishing returns, as countries that accumulate capital faster than average experience declining export prices, thereby depressing the rate of return to capital and discouraging further accumulation.

Comparative Advantage as a Determinant of Economic Growth   We now turn to comparative advantage as a determinant of economic growth. If sectors differ in terms of rates of innovation and growth, specialization across these sectors according to comparative advantage naturally affects aggregate economic growth through a composition effect. Therefore, specialization according to comparative advantage not only generates static welfare gains as in neoclassical trade theories, but also has dynamic welfare effects through the rate of economic growth. As part of a broader analysis of human capital accumulation and economic growth, Lucas (1988) develops a two-sector model in which the two sectors differ in terms of their rates of learning by doing. Depending on patterns of comparative advantage, the opening of international trade can lead an economy to specialize in the sector with a lower rate of learning by doing, slowing its aggregate rate of economic growth. Relatedly, Young (1991) develops a Ricardian model with a continuum of goods, in which learning by doing in each good is bounded. When a less developed country trades with a developed country with a higher level of technology, it specializes in lower-technology goods, in which more of the potential for learning by doing has already been exhausted. As a re-

sult, the less-developed country experiences static welfare gains from specialization according to comparative advantage but dynamic welfare losses, as specialization in these lower-technology goods reduces its rate of growth relative to the closed economy. In Lucas (1993), spillovers of such learning by doing across goods are shown to provide an alternative explanation for "economic miracles," such as the rapid economic growth of South Korea from 1960 onwards.

While the previous three papers focus on learning by doing, Grossman and Helpman (1990, 1991a) develop R&D-based models of endogenous innovation, in which specialization according to comparative advantage can again affect aggregate economic growth. Consider an environment with two countries, two production sectors (low and high technology) and one factor of production (labor). In the low-technology sector, a homogeneous good is produced using a constant returns to scale technology under conditions of perfect competition. In the high-technology sector, horizontally-differentiated goods are produced under conditions of monopolistic competition. In addition to these two production sectors, there is a research sector that produces designs for new horizontally-differentiated varieties for the high-technology sector. Therefore, the low-technology sector is technological stagnant, whereas there is endogenous innovation from an expansion of product variety in the high-technology sector. To focus on the role of these endogenous investments in technological capabilities, the two countries are assumed to be identical in all respects, except for the initial stock of technological knowledge (captured by the initial mass of blueprints for varieties in the high-technology sector).[9]

In this environment, the effect of international trade on economic growth and welfare depends critically on whether knowledge spillovers are international or national in scope. With international knowledge spillovers, research firms in both countries have access to the same stock of knowledge, as determined by the worldwide stock of designs for differentiated varieties in the high-technology sector. In this case, there is a continuum of equilibrium trajectories that are consistent with given initial conditions in the two countries. All of those lead to different steady-state patterns of production and trade. The two countries' rates of growth of output differ across

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[9]For Ricardian models of international trade that incorporate Schumpeterian models of innovation, see Scott Taylor (1992), Scott Taylor (1994) and Somale (2021).

these steady-state equilibria because they involve different patterns of specialization between the low and high-technology sectors. However, the two countries' rates of growth of consumption and welfare are equal and identical across all of these steady-state equilibria. Even if one country experiences a slower rate of output growth than the other because it specializes in the low-technology sector, it nonetheless experiences the same rate of consumption growth as its trade partner, because it enjoys a terms of trade gain from the higher rate of output growth in its trade partner. Therefore, this prediction highlights the importance of distinguishing between output and consumption growth in the open economy, and the role of the international terms of trade in shaping the incidence of productivity growth between countries in the open economy.

With national knowledge spillovers, research firms in each country have access to different stocks of knowledge, as determined by the national stock of designs for differentiated varieties in the high-technology sector. In this case, initial conditions in the form of the initial stock of designs in each country play a central role in determining steady-state patterns of production and trade. In general, several different types of steady-state equilibria are possible, with different patterns of specialization across sectors and with different trajectories for relative wages in the two countries. However, a key property of the model with national knowledge spillovers is that it becomes possible for an initial technological lead in research to become self-perpetuating (hysteresis). Furthermore, in some of these steady-state equilibria, relative wages and welfare can differ between the two countries. The country with the higher initial stock of designs for differentiated varieties is characterized by a higher steady-state level of wages and welfare. In these circumstances, there is a potential for an R&D subsidy in the initially more technologically backward country to be welfare improving, depending on the assumptions regarding retaliation by its trade partner.

Comparative Advantage and Public Policy Interventions   This property that national public policy interventions can, in some circumstances, be welfare improving is a common characteristics of models of comparative advantage and endogenous technological change. Krugman

([1987](#)) considers a Ricardian model of a continuum of goods following [Dornbusch et al.](#) ([1977](#)), in which learning by doing is specific to each sector. In this environment, comparative advantage evolves endogenously over time, because current patterns of comparative advantage determine current production and the rate of learning by doing, which in turn determines future patterns of comparative advantage. As a result, temporary shocks, such as real exchange rate appreciations or protectionist trade policies, can have permanent effects on long-run patterns of comparative advantage and trade.

[Redding](#) ([1999](#)) explores the idea that developing countries may face a trade-off between specialization according to existing comparative advantage (in low-technology goods), and entering sectors in which they currently lack a comparative advantage, but may acquire such a comparative advantage in the future as a result of the potential for productivity growth (in high-technology goods). Learning by doing occurs as an externality at the industry level and hence is not internalized by individual firms when making their production decisions. As a result, specialization according to current comparative advantage under free trade can be welfare reducing. Furthermore, public policy intervention to promote specialization in the high-technology sector can be welfare improving, not only for the country undertaking the intervention, but more surprisingly also for its trade partner.

[Melitz](#) ([2005](#)) develops a welfare-maximizing model of infant industry protection, in which the domestic infant industry is competitive and experiences dynamic learning effects that are external to firms. The competitive foreign industry is mature and produces a good that is an imperfect substitute for the domestic good. A government planner can protect the infant industry using domestic production subsidies, tariffs, or quotas in order to maximize domestic welfare over time. As protection is not always optimal (although the domestic industry experiences a learning externality), the paper shows how the decision to protect the industry should depend on the industry's learning potential, the shape of the learning curve, and the degree of substitutability between domestic and foreign goods.

In these previous three papers, learning by doing is modelled as occurring serendipitously

through an externality. In contrast, in R&D-based models of innovation and growth, agents investing in R&D internalize the future profits to be derived from successful innovation. Nevertheless, there is in general a difference between private and social rates of return in these R&D-based models, as discussed above. This domestic distortion can interact with trade frictions to influence the welfare gains from trade and provide a rationale for public policy interventions, as discussed for the open economy models of R&D-based innovation in Grossman and Helpman (1990, 1991a). In these open economy models, there is typically a difference between the decisions of national social planners and those of a world social planner, and the case for intervention for a national social planner typically depends heavily on whether or not retaliation occurs.

6 Knowledge Spillovers, Trade and Innovation

Another key mechanism through which the international economy affects domestic economic activity is international knowledge spillovers. These international knowledge spillovers directly affect rates of innovation and growth, because they determine the growth rate of the world technological frontier, and promote catch-up or convergence to this world technology frontier. As discussed in the previous section, these knowledge spillovers can also play an important role shaping the effects of international trade in goods, depending for example on whether they are national or international in scope. These knowledge spillovers can occur serendipitously, and independently from the flow of goods (e.g. through research publications); they can be promoted through flows of goods (as in the reverse-engineering of products); or they can be the result of investments: in knowledge acquisition directly, or in imitation (as in models of the product life-cycle). In the remainder of this section, we first review models of innovation and technology diffusion. We next examine the role of international trade as a conduit for knowledge spillovers. Finally, we consider models of the product cycle.

Innovation and Technology Diffusion Eaton and Kortum (1999) develops a quantitative model of the invention of new technologies and their diffusion across countries. In equilibrium,

all countries grow at the same steady-state rate, with each country's productivity ranking determined by how rapidly it adopts ideas. Research effort is determined by the economic return to idea generation at home and abroad. Patents affect the return to ideas. The decision to patent an invention depends on the cost of patenting in a country and the expected value of patent protection in that country. Using data on international patenting, productivity, and research, the paper shows how to infer the direction and magnitude of the international diffusion of technology. Using data from the five leading research economies, the paper finds that the world lies about two-thirds of the way from the extreme of technological autarky to free trade in ideas – in the sense that research performed abroad is about two-thirds as potent as domestic research. As a result, the United States and Japan together drive around two-thirds of the growth in each of the countries in the sample.

Acemoglu et al. (2006) develop a model in which firms undertake both innovation and adoption of technologies from the world technology frontier. The selection of high-skill managers and firms is more important for innovation than for adoption. As the economy approaches the frontier, selection becomes more important. Countries at early stages of development pursue an investment-based strategy, which relies on existing firms and managers to maximize investment but sacrifices selection. Closer to the world technology frontier, economies switch to an innovation-based strategy with short-term relationships, younger firms, less investment, and better selection of firms and managers. The paper shows that relatively backward economies may switch out of the investment-based strategy too soon. Therefore, policy interventions to encourage the investment-based strategy, such as limits on product market competition or investment subsidies, can be beneficial. However, these policies can have long-run costs, because they make it more likely that a society will be trapped in the investment-based strategy and fail to converge to the world technology frontier.

Trade as a Conduit for Knowledge Spillovers   Using data on 21 OECD countries plus Israel during the period 1971-1990, Coe and Helpman (1995) provides empirical evidence on the role of

international trade as a conduit for knowledge spillovers.[10] For each country, a domestic knowledge stock is created using cumulative domestic R&D expenditure. Similarly, a foreign knowledge stock is created using foreign cumulative R&D expenditure, weighted by bilateral import shares. Using a panel data regression specification, domestic total factor productivity growth is found to be statistically significantly related to both domestic and foreign R&D knowledge stocks. More open countries with higher shares of imports in GDP are found to benefit more strongly from foreign R&D capital stock than more closed countries. For some of the smaller countries, foreign R&D capital stocks are more important as sources of domestic productivity growth than domestic R&D capital stocks. The rates of return to both domestic and foreign R&D are high, with an average rate of return from investment in R&D of 123 percent in G7 countries and 85 percent in the remaining 15 countries. Around one quarter of the total benefits of R&D investment in a G7 country are found to accrue to its trade partners through international knowledge spillovers. In subsequent work, Coe et al. (2009) find that domestic institutions are an important determinant of the rate of return to R&D. Countries where the ease of doing business and the quality of tertiary education systems are relatively high tend to benefit more from their own R&D efforts, from international R&D spillovers, and from human capital formation.[11]

Aghion et al. (2021a) find strong evidence for this knowledge spillover channel via international trade links. They find that a French firm's entry into a new export market induces (after a few years lag) a substantial innovation response in that export market. This innovation response takes the form of new patents that refer back to the technology developed by the French exporter, measured as a citation link from the new patent to the patents held by the French exporter.

Creative Destruction Hsieh et al. (2020) develop a Schumpeterian model of innovation, trade and growth that builds on the closed economy model of Klette and Kortum (2004). Innovation is undertaken by both incumbent and entrants in a domestic and foreign economy. Creative destruction occurs when innovators take over the market for an existing product. This creative

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[10]For a review of the literature on international technology spillovers, see Keller (2004).
[11]For evidence on the role of R&D and human capital as sources of absorptive capacity that facilitate catch up to the technological frontier, see Griffith et al. (2004).

destruction can occur both domestically and internationally, where domestic firms take over foreign markets for a product, or foreign firms take over the domestic market for a product. The arrival rates of innovation both at home and abroad are treated as exogenous and calibrated to match moments in the data. In the baseline version of the model, innovators build on the technology of sellers in a market, such that international trade in goods facilitates the flow of ideas. The diffusion of ideas between the two countries generates a constant reallocation of products and implies that the two economies grow at the same rate in the long-run. In the baseline version of the model, in which flows of goods facilitate idea diffusion, lower tariffs boost trade and the long-run rate of export reallocation as well as growth. For the calibrated parameters of the model, these dynamic welfare gains from trade are larger than the conventional static welfare gains.

Dynamic Selection   Sampson (2016) develops a dynamic model of heterogeneous firm selection that features elements of both variety and quality-based models of growth. Firms supply horizontally differentiated varieties, but these varieties differ in terms of productivity or quality. As in the existing literature on firm heterogeneity following Melitz (2003), firms pay a sunk entry cost in order to draw a productivity from a distribution. However, the key new feature of the model is that the distribution from which this productivity is drawn upon entry depends on the productivity distribution of incumbent firms. This captures a learning spillover from incumbents to entrants across the entire distribution of productivity. Because only a subset of relatively more productive entrants produce (and transition to incumbent status), the productivity distribution shifts upward over time. This dynamic selection process induces technology diffusion that in turn generates endogenous growth without scale effects. On the balanced growth path, the lower bound of the support of the productivity distribution increases over time. The free entry condition implies that trade liberalization must increase the dynamic selection rate to offset the increase in profits from new export opportunities. As a result, trade integration raises long-run growth. This dynamic selection is a new source of welfare gains from trade that is driven by producer heterogeneity. For the calibrated parameters of the model, these dynamic welfare gains

from trade are around three times larger than the conventional static welfare gains from trade.

Endogenous Technology Adoption   Perla et al. (2021) develops an alternative dynamic model of heterogenous firm selection in which incumbent firms (rather than entrants) choose whether to invest in upgrading technology. As in Melitz (2003), firms supply differentiated varieties under conditions of monopolistic competition with free entry. Firms choose whether to incur a fixed cost in order to export. Firms also choose to either upgrade their technology or to continue to produce with their existing technology. The productivity of the existing technology evolves stochastically according to a geometric Brownian motion. If a firm decides to upgrade its technology, it pays a fixed cost in return for a random productivity draw from the equilibrium distribution of firms that produce in the domestic economy. This upgrading process is interpreted as technology diffusion, because firms upgrade by adopting technologies already used elsewhere. A firm's incentive to upgrade depends on the expected benefit of a new productivity draw and the opportunity cost of taking that draw. In equilibrium, lower productivity firms find it profitable to upgrade technology, because they have both lower opportunity costs and higher expected benefits of a new productivity draw.

Reductions in iceberg trade costs increase the rate of technology adoption and economic growth because they widen the ratio of profits between the average and the marginal adopting firm. As trade costs decline, low-productivity firms that serve only the domestic market contract, as foreign competition reduces their profits. In contrast, high productivity firms expand and export, increasing their profits. For low-productivity firms, this reallocation process both reduces the opportunity cost and increases the benefit of a new technology. Therefore, trade liberalization leads to more frequent firm technology adoption, which in turn raises the economy's aggregate rate of growth. In equilibrium, the privately-optimal rate of technology adoption is lower than the socially-optimal rate of technology adoption, because firms only appropriate part of the return from technology adoption. As a result the acceleration of technology adoption induced by trade liberalization generates dynamic welfare gains from trade that are again large relative to

the conventional static welfare gains from trade.

Knowledge Spillovers Buera and Oberfield (2020) develops a quantitative model of innovation and technology diffusion between heterogeneous producers. Innovation and diffusion are modelled as a process involving the combination of new ideas with insights from other industries and countries. In a first specification, insights are draw from those that sell goods to a country, following Alvarez et al. (2013). In a second specification, insights are drawn from technologies used domestically, as in Sampson (2016) and Perla et al. (2021). Openness to trade affects the quality of the insights drawn by producers because it determines the set of sellers to a country and the set of technologies used domestically. Starting from autarky, opening to trade results in a higher temporary growth rate, and a permanently higher level of the stock of knowledge, as producers are exposed to more productive ideas.

The overall welfare gains from trade can be decomposed into static and dynamic components. The static component consists of the gains from increased specialization and comparative advantage. The dynamic component consists of the gains that operate through the flow of ideas. The magnitude of the dynamic welfare gains from trade relative to its static counterpart depends on the rate of diffusion of ideas (the relative importance of insights from others) and whether insights are drawn from those that sell goods to a country or from the technologies used domestically. For the preferred calibration of the model, both the overall welfare gains from trade and the fraction of productivity growth explained by changes in trade costs are more than double those in a model without technology diffusion.

Product Cycle An influential idea in international trade dating back at least to Vernon (1966) is the idea of the product cycle. According to this view, products are typically first produced where they are invented in developed countries. As products mature, they become more standardized, and can be produced in countries at lower levels of development. Eventually, products become completely standardized and can be produced in the lowest cost location in less-developed countries. As a result of this product cycle, the developed country where the product is invented

transitions from being an exporter of the product in the early stages of its lifecycle to being an importer of the product in the late stages of its lifecycle.

This product cycle was first formalized in a general equilibrium model of international trade in Krugman (1979b). The world consists of two countries: an innovating North and a non-innovating South. Innovation is modelled as the exogenous rate of arrival of new products, which at first can only be produced in the North. Imitation also occurs at an exogenous rate, after which these products can be produced in the South. This lag in technological diffusion gives rise to international trade, with the North exporting new products and importing old products. In equilibrium, the North enjoys higher per capita income, because of the quasi-rents from the Northern monopoly of new products. The North must continually innovate, not only to maintain its relative income per capita, but also to maintain its real income in absolute terms.

In Krugman (1979b), the rates of arrival of innovation and imitation are exogenous. Using a Schumpeterian approach Segerstrom et al. (1990) develops a general equilibrium model of the product cycle, in which innovation is the result of endogenous investments in innovation. Again using a Schumpeterian approach, Grossman and Helpman (1991b) considers a richer specification in which the rates of both innovation and imitation are endogenous.[12] In the steady-state equilibrium of the model, the average rates of imitation and innovation are constant, as are the fraction of products manufactured in the North and the South, the North-South terms of trade, and the average length of the product cycle. The model features a rich set of interactions between innovation policies in the two countries. In particular, subsidies to innovation in the North can either cause the steady-state rate at which products flow from the North to the South to decline or increase, depending on the magnitude of the productivity advantage Northern innovators enjoy over the next best technology.

Extending this model of endogenous product cycles, Helpman (1993) explores the welfare implications of stricter intellectual property rights protection (IPR). On the one hand, proponents of stricter IPR argue that it encourages innovation in advanced countries from which all regions

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[12]For a model in which a product cycle emerges endogenously as a result of contractural incompleteness, see Antràs (2005).

of the world benefit. On the other hand, critics of stricter IPR argue that it only strengthens the monopoly power of companies based in developed countries to the detriment of less-developed countries. One of the key results of the paper is to show that stricter IPR necessarily reduces welfare in the South for economies that begin in steady-state. In contrast, the effect of stricter IPR on welfare in the North depends on the rate of imitation. For sufficiently small rates of imitation, stricter IPR necessarily reduces welfare in the North. Although this stricter IPR raises rates of innovation in the North, its also increases monopoly power, which reduces consumer welfare through higher prices.

7 Conclusions

Research on endogenous innovation and growth has delivered fundamental new insights about the nature of economic growth and the role played by international trade. In the Schumpeterian approach, the pace of innovation is endogenously determined by the expectation of future profits, and growth is inherently a process of creative destruction. As international trade is a key determinant of both firm profitability and survival, it is natural to expect it to play a key role in shaping incentives to innovate and the rate of creative destruction. In this paper, we review the theoretical and empirical literature on trade and innovation.

In the existing international trade literature, there is a good deal of consensus about the static welfare gains from trade, defined as the increase in the level of flow utility from country participation in international markets. Traditional theories of international trade emphasize variation in the opportunity cost of production across countries and sectors. New theories of international trade incorporate product differentiation and increasing returns to scale. More recent models of heterogeneous firms in differentiated product markets point towards within-industry reallocations of resources across firms of different productivity.

In contrast, theories of endogenous innovation and growth open up the possibility for dynamic welfare gains from trade, through changes in the rate of growth. However, there is much less consensus about the existence and magnitude of these dynamic welfare gains, the mecha-

nisms through which they occur, and whether they correspond to permanent differences in long-run growth (endogenous growth) or differences in growth along the transition to steady-state (semi-endogenous growth).

Four main mechanisms for these dynamic welfare gains from trade have been proposed. First, international trade expands the market size accessible to firms, thereby raising the incentive to incur the fixed costs of innovation. Second, international trade increases product market competition. While this heightened competition reduces the incentive to innovate in conventional economic theory, Schumpeterian models have highlighted channels through which it may instead raise the incentive to innovate, including in particular the motive to "escape competition." Third, international trade induces specialization according to comparative advantage, which can change aggregate rates of innovation and growth through changes in sectoral competition. Fourth, international knowledge spillovers can directly affect countries' rates of economic growth, and international trade in goods itself can influence technology diffusion, where knowledge spillovers can depend on either the set of firms selling in a market or the set of firms producing in a market.

While there is a commonly-used framework for quantifying the welfare gains from trade in a class of trade models that uses observed domestic trade shares and estimates of the elasticity of trade flows with respect to trade costs, the quantification of these dynamic welfare gains from trade is much more dependent on model structure. Going forward, discriminating between alternative mechanisms for dynamic welfare gains from trade and developing robust approaches to quantifying their magnitude remain exciting areas for further research.

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