

# A Global View of Creative Destruction

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We formulate a two-country model of trade and creative destruction by domestic and foreign firms. In the model, trade liberalization quickens the pace of creative destruction and the flow of technology across countries. International idea flows are essential for understanding why country technologies do not drift apart and for matching two empirical facts. First, contracting firms are more likely to lose exports than domestic sales, whereas the opposite is true for expanding firms. Second, the product composition of a country's exports exhibits ample turnover. In our model, a country's comparative advantage is constantly shifting due to global creative destruction.

## I. Introduction

Studies by Bernard and Jensen (1999), Eaton and Kortum (2002), Melitz (2003), and others placed heterogeneous firms at the center of research

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on international trade. The first wave of follow-up research has focused mostly on models in which trade liberalization leads to a burst of reallocation and growth but no long-run effects on reallocation rates or growth rates.

A growing literature seeks to assess the growth effects of trade. Empirical studies include Bloom, Draca, and Van Reenen (2016) and Aghion et al. (2020). Modeling efforts build on the foundational work of Krugman (1979), Rivera-Batiz and Romer (1991), and Grossman and Helpman (1993). Recent modeling includes Alvarez, Buera, and Lucas (2017), Buera and Oberfield (2020), Akcigit, Ates, and Impullitti (2021), and Perla, Tonetti, and Waugh (2021). Papers with both models and empirics range from Eaton and Kortum (1999) to Arkolakis et al. (2018).

In this paper, we present a two-country model of the interaction of creative destruction and trade. In our model, innovating firms improve on existing technologies. When innovators take over the market for an existing product (creative destruction), export reallocation across countries can take place. Domestic firms can take over foreign markets for a product, and foreign firms can take over the domestic market. This is a two-economy version of the influential Klette and Kortum (2004) model of creative destruction, only with exogenous probabilities of innovation in each country in each year for simplicity.

We assume that innovators can build on the technology of products sold in their market or on the blueprints of local firms. When innovators build on the technology of sellers, which includes the country's imports, trade then facilitates the flow of ideas across countries. But we also consider a model in which ideas flow across countries independent of trade, as in Ramondo, Rodríguez-Clare, and Saborío-Rodríguez (2016) and others. In both versions of the model, the diffusion of ideas generates a constant reallocation of exports between the two countries and results in the two economies growing at the same rate in the long run.

We calibrate the model to fit manufacturing moments in the United States versus the rest of the Organization for Economic Cooperation and Development (OECD). We match total factor productivity (TFP) growth, relative value added per worker in the United States and the OECD, exports relative to all shipments (the trade share), and the sensitivity of trade to trade barriers (the trade elasticity). We also match employment in the United States versus the rest of the OECD. We infer higher innovation rates in the United States given its higher GDP per worker

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Institute for Economic Policy Research. Any opinions and conclusions expressed in this paper are those of the authors and do not necessarily represent the views of the Federal Reserve System or its staff or the US Census Bureau. All results have been reviewed by the US Census Bureau to ensure that no confidential information is disclosed. Code to reproduce the model simulations and empirical moments in this paper is available in the Harvard Dataverse: <https://doi.org/10.7910/DVN/TWAA4I>. This paper was edited by Ariel Burstein.

relative to the rest of the OECD. We pin down the dispersion of product quality of the innovation draws by fitting the dispersion in revenue per worker across manufacturing firms in the United States.

Given the estimated dispersion in product quality, we ask, How much do ideas need to flow across countries to fit a trade elasticity of 5? We estimate that spillovers must occur on most traded goods to match a trade elasticity of 5. Using our estimate of spillovers, we analyze the model's transition dynamics and steady-state response to changes in tariffs. Because ideas flow across countries due to trade, lower tariffs not only increase trade but also increase the long-run growth rate. Even taking into account the transition, the gains from trade relative to autarky from the boost in idea flows are equivalent to a permanent 31% increase in consumption in the United States. The rest of the OECD gains even more (75%) from idea flows because the United States is more innovative.

In the alternative version of the model wherein idea flows are independent of trade, cutting tariffs has no effect on the growth rate. In this alternative model, increasing the flow of ideas across countries increases the long-run growth rate and reduces trade. More idea flows lead to a narrower distribution of relative product quality across countries, thereby lowering the (standard) comparative advantage gains from trade. As in the baseline model, the rest of the OECD benefits more from idea flows than the United States because the United States is more innovative.

We also entertain the effect of trade liberalization in a model where idea flows across countries are severely limited. In this version, when a product is imported, learning is almost entirely from dormant domestic producers rather than from foreign sellers into the domestic market. As a result, the total gains from trade are much closer to the static gains. In this model, however, stochastic innovation causes country technologies to drift apart. Not only does the United States grow faster than the OECD, but comparative advantage becomes very strong across products. This implies a counterfactually low trade elasticity.

We further compare our model's predictions with exporting firm dynamics in the United States and a number of other countries (in particular, Chile, Colombia, China, and Indonesia). We find that contracting firms are much more likely to lose exports than domestic sales, consistent with creative destruction from foreign innovation. In contrast, expanding firms are much more likely to gain domestic sales than gain exports. This occurs in our model because domestic firms carrying out innovation on foreign firms find it easier to sell the product domestically than to overcome tariff barriers to exporting the product.

We also document ample turnover of exports across product categories, just as Hanson, Lind, and Muendler (2018) do. This is consistent with our model, in which comparative advantage is constantly shifting due to global creative destruction. We find that most of the adjustment in exports within

industries occurs on the extensive margin: a country gains exports in a sector primarily when new exporters enter, and declining export sectors reflect mainly firm exit from exporting. At the same time, there are many firms that exit from foreign markets in sectors where net exports increase and many firms that enter export markets in industries where net exports fall. These facts point to creative destruction rather than demand shocks facing all firms in an industry driving the turnover of exports across industries.

Our effort is most related to four recent papers. We build on Alvarez, Buera, and Lucas (2017) in having domestic firms learn from exporters into the domestic market. They analyze how this learning affects the distribution of comparative advantage and the growth rate from diffusion of an unbounded distribution of knowledge. Whereas they analyze a setting with 30 trading partners, we analyze two trading countries. They abstract from innovation, however, whereas we feature growth from the frequency of innovation, both at home and abroad.

Perla, Tonetti, and Waugh (2021) study the impact of trade on exit, entry, domestic technology diffusion, and growth in a model of symmetric countries.<sup>1</sup> Like us, they find large dynamic gains from trade. They derive analytical steady-state solutions in a model of many countries, whereas we simulate a two-country model calibrated to evidence on export reallocation across products and firms. Our focus is on innovation, idea flows across countries, and creative destruction, whereas their focus is on how trade interacts with domestic technology diffusion.

We follow Buera and Oberfield (2020) in studying international technology diffusion in a model with Bertrand competition. They endogenously obtain Fréchet distributions of productivity within countries, allowing them to characterize multilateral trade flows as in Bernard et al. (2003). They stress that the dynamic effects of trade could be small or even negative depending on whether firms learn from domestic producers or from sellers into the domestic market. Our focus is more empirical and quantitative, as we show that our model matches evidence on export dynamics at the firm and industry levels. We argue that these facts are consistent with knowledge flows across countries.

Like us, Akcigit, Ates, and Impullitti (2021) characterize the impact of tariffs on growth in a two-country model with technology spillovers. Theirs is a step-by-step innovation model, with escape-from-competition effects through which trade can induce more innovation. They analyze transition dynamics and optimal R&D subsidies. They emphasize the convergence of patenting rates in other advanced countries toward the patent rate in the United States in recent decades. In contrast, in our model and empirics we focus on how trade affects export reallocation at the firm and industry levels.

<sup>1</sup> Sampson (2016) is an earlier effort in the same vein as Perla, Tonetti, and Waugh (2021).

The rest of the paper is organized as follows. Section II lays out the details of our baseline model. Section III calibrates the model. Section IV shows how the model stacks up against nontargeted evidence on firm and industry export dynamics. In section V, we assess the gains from trade (and idea flows more generally) in our model. Section VI concludes.

## II. Baseline Model

This section presents a model of growth driven by creative destruction, where innovation can come from domestic or foreign firms.

### A. Static Equilibrium

The static part of our model is similar to Bernard et al. (2003) or to Dornbusch, Fischer, and Samuelson (1977) only with markup heterogeneity. Utility of the home country representative consumer is given by consumption of a continuum of varieties  $C_{jk}$  with measure one:

$$U = \int_0^1 \ln C_{jk} \, dj,$$

where  $j$  represents the index of the product and  $k$  represents the index of the relative productivity of the product in each time period. This utility function implies that consumers spend the same on each variety.<sup>2</sup>

Output of each variety is the product of labor and the quality of the blueprint for the product. We denote  $A_{jk}$  as the “best” blueprint for  $j$  among domestic firms;  $A_{jk}^*$  is the corresponding best blueprint for  $j$  among foreign firms. Furthermore, suppose we order products in each period so that the index  $k$  is decreasing in  $A_{jk}/A_{jk}^*$ . The index of the product  $j$  is fixed but the index of relative productivity  $k$  associated with a product potentially changes over time due to productivity growth (which we introduce in the next section). Given the definition of  $k$ , products  $k \in [0, x]$  are traded and produced at home,  $k \in [x, x^*]$  are nontraded, and  $k \in [x^*, 1]$  are traded and produced abroad. The cutoff products  $x$  and  $x^*$  are defined by

$$\frac{A_{jx}}{\tau} = \omega A_{jx}^*,$$

$$A_{jx^*} = \frac{\omega A_{jx^*}^*}{\tau},$$

where  $\omega$  denotes the relative wage (domestic relative to foreign) and  $\tau \geq 1$  represents the symmetric gross tariff rate. When  $\tau = 1$ ,  $x = x^*$  and all products are traded.

<sup>2</sup> Utility of the foreign consumer is analogously given by  $U^* = \int_0^1 \ln C_{jk}^* \, dj$ .

The owner of the best blueprint sets their quality-adjusted price to push their closest competitor out of the market (Bertrand competition), so the gross markup is the gap between the incumbent firm's marginal cost and the cost of its closest competitor—domestic or foreign.<sup>3</sup> The relative wage is pinned down by balanced trade:

$$I^* \cdot x = I \cdot (1 - x^*), \quad (1)$$

where  $I$  and  $I^*$  denote nominal GDP at home and abroad, respectively. The left-hand side of equation (1) represents the home country's exports, and the right-hand side represents the home country's imports. Nominal GDP in each country is given by

$$I = \frac{\bar{\mu}wL}{1 - [(1 - \tau)/\tau] \cdot (1 - x^*)},$$

$$I^* = \frac{\bar{\mu}^*w^*L^*}{1 - [(1 - \tau)/\tau] \cdot x},$$

where  $\bar{\mu}$  denotes the average gross markup,  $w$  represents the nominal wage, and  $L$  represents the labor supply at home.<sup>4</sup>

We can express the real (consumption) wage as a function of the distribution of the best blueprints, the markups, the cutoffs, the relative wage, and the tariff rate. The real wages at home  $W$  and in the foreign country  $W^*$  are given by

$$\ln W = \int_0^{x^*} \ln \left( \frac{A_{jk}}{\mu_{jk}} \right) dk + \int_{x^*}^1 \ln \left( \frac{A_{jk}^*}{\mu_{jk}^*} \cdot \frac{\omega}{\tau} \right) dk,$$

$$\ln W^* = \int_0^x \ln \left( \frac{A_{jk}}{\mu_{jk}} \cdot \frac{1}{\omega \tau} \right) dk + \int_x^1 \ln \left( \frac{A_{jk}^*}{\mu_{jk}^*} \right) dk.$$

The home country buys  $k \in [x^*, 1]$  from the foreign country, so the domestic real wage is increasing in the productivity of foreign firms on these products. Likewise, the foreign country purchases  $k \in [0, x]$  from the home country, so the foreign real wage increases with domestic firm productivity on these products.

<sup>3</sup> See table A1 for a summary of the markups implied by this model.

<sup>4</sup> Variables with an asterisk denote the foreign country. The average price-cost markup in the home country is  $1/\bar{\mu} \equiv [\int_0^{x^*} (1/\mu_{jk}) dk + (1/\tau) \cdot \int_0^x (1/\mu_{jk}^*) dk] / (x^* + x/\tau)$ , where  $\mu_{jk}^*$  denotes the markup of domestic firms on their exported products. The expression for the foreign firms' average markup is analogous. The expression for nominal income comes from equating nominal income to the revenue of local firms plus tariff revenue:  $I = \bar{\mu}wL + (\tau - 1)(I/\tau)(1 - x^*)$  and  $I^* = \bar{\mu}^*w^*L^* + (\tau - 1)(I^*/\tau) \cdot x$ .

### B. *Innovation*

We now introduce dynamics to the model. As in Klette and Kortum (2004), a firm is a portfolio of products. An entrant has one product, while incumbent firms potentially produce many varieties. Innovation takes the form of creative destruction. We posit exogenous probabilities of innovation for simplicity.<sup>5</sup> The probability of innovation is proportional to the number of products owned by a firm; a firm with two products is twice as likely to creatively destroy another firm's variety compared with a firm with one product. We assume that innovation builds on the existing quality of the product. Such knowledge externalities are routinely built into quality ladder models from Grossman and Helpman (1991) and Aghion and Howitt (1992) onward. See Coe, Helpman, and Hoffmaister (1997, 2009) and Ayerst et al. (2020) for evidence consistent with learning by importing.

We depart from Klette and Kortum (2004) by allowing a product made in one country to be creatively destroyed by a firm in another country. Table 1 summarizes the probabilities of innovation. The probability that a product is improved on by an incumbent domestic firm is represented by  $\lambda$ , while  $\eta$  represents the probability that the product is improved by an entering domestic firm. Analogously,  $\lambda^*$  represents the probability that the product will be improved by a foreign incumbent firm, and  $\eta^*$  represents the probability that a foreign entrant innovates on the best blueprint. In short, a given product can be improved on by a domestic incumbent firm, a domestic entrant, a foreign incumbent firm, or a foreign entrant.<sup>6</sup>

The improvement in product quality yielded by an innovation follows a Pareto distribution with shape parameter  $\theta$  and scale parameter equal to the existing quality level. The average percent improvement in quality is thus  $1/(\theta - 1) > 0$ .

### C. *Trade-Embodied Knowledge Flows*

We assume that innovators improve on the products sold in their market with probability  $\kappa$  and improve on the blueprints of local firms (including

<sup>5</sup> In an earlier version of this paper, we endogenized the probability of innovation as a function of research labor. The model's steady-state properties were very similar, even in response to trade liberalization. See Hsieh, Klenow, and Nath (2019). Cai, Li, and Santacreu (2021) also analyze the endogenous response of innovation rates to trade liberalization, although their focus is the endogenous reallocation of research resources across sectors in a multisector model.

<sup>6</sup> Since we assume a continuum of products, we do not distinguish between conditional vs. unconditional probabilities of innovation. Also, we could have modeled domestic innovations by incumbent firms as being on their own products as in Garcia-Macia, Hsieh, and Klenow (2019). The firm dynamics would differ in that case but not the implications for country growth and trade.

TABLE 1  
PROBABILITIES OF INNOVATION

	By Domestic Firms	By Foreign Firms
By incumbents	$\lambda$	$\lambda^*$
By entrants	$\eta$	$\eta^*$

NOTE.—This table shows the probability of innovation by domestic and foreign firms in the columns and the probability of innovation by incumbents and entrants in the rows. The average improvement in quality for each innovation is  $1/(\theta - 1)$ .

the last domestic firm to produce the product if it is currently imported) with probability  $1 - \kappa$ . When  $\kappa = 1$ , innovators build on the blueprint of imported products they draw. The other extreme is  $\kappa = 0$ , when innovators build on only the blueprints owned by local firms.<sup>7</sup> So  $\kappa = 1$  is the case with full idea spillovers from trade, and  $\kappa = 0$  is the case when ideas do not move across borders.

Table 2 summarizes the probability of creative destruction in the home market (top panel) and foreign market (bottom panel) by domestic firms (col. 1) and foreign firms (col. 2). The probability of creative destruction of products sold in the home market depends on whether the product is exported (row 1), nontraded (row 2), or imported (row 3). The first row shows the probability of innovation in the domestic market for an exported product. The probability that such a product is improved on by another domestic firm is  $\lambda + \eta$ . A domestic innovator will always replace the incumbent firm in this market.

A foreign firm improves on the domestic firm's blueprint of the same exported product with probability  $\kappa(\lambda^* + \eta^*)$  and improves on the blueprint of the current (or previous) foreign firm with probability  $(1 - \kappa)(\lambda^* + \eta^*)$ . Even when the quality of the foreign innovator of the exported product exceeds that of the incumbent domestic firm, however, it will not necessarily replace the domestic incumbent. Conditional on having a higher quality, the probability that the foreign innovator will replace the domestic incumbent depends on the relative wage and the trade cost between the two countries. Higher domestic wages increase the probability that a foreign innovator will be competitive enough to replace the domestic incumbent in the domestic market. Higher tariffs make the foreign innovator less competitive compared with the domestic incumbent.

The expected growth in the domestic real consumption wage is the product of the rate of creative destruction from domestic and foreign firms and the increases in product quality (conditional on the product

<sup>7</sup> When  $\kappa = 0$ , growth rates diverge across countries.

TABLE 2  
PROBABILITY OF CREATIVE DESTRUCTION

	Domestic Firm (1)	Foreign Firm (2)
Home market:		
Exported by home	$\lambda + \eta$	$(\lambda^* + \eta^*) \left[ \kappa \left( \frac{\omega}{\tau} \right)_m^\theta + (1 - \kappa) \left( \frac{\omega A_{jk}^*}{\tau A_{jk}} \right)_m^\theta \right]$
Nontraded	$\lambda + \eta$	$(\lambda^* + \eta^*) \left( \frac{\omega A_{jk}^*}{\tau A_{jk}} \right)_m^\theta$
Imported by home	$(\lambda + \eta) \left[ \kappa \left( \frac{\tau}{\omega} \right)_m^\theta + (1 - \kappa) \left( \frac{\tau A_{jk}}{\omega A_{jk}^*} \right)_m^\theta \right]$	$\lambda^* + \eta^*$
Foreign market:		
Exported by home	$\lambda + \eta$	$(\lambda^* + \eta^*) \left[ \kappa (\omega \tau)_m^\theta + (1 - \kappa) \left( \frac{\omega \tau A_{jk}^*}{A_{jk}} \right)_m^\theta \right]$
Nontraded	$(\lambda + \eta) \left( \frac{A_{jk}}{\omega \tau A_{jk}^*} \right)_m^\theta$	$\lambda^* + \eta^*$
Imported by home	$(\lambda + \eta) \left[ \kappa \left( \frac{1}{\tau \omega} \right)_m^\theta + (1 - \kappa) \left( \frac{A_{jk}}{\tau \omega A_{jk}^*} \right)_m^\theta \right]$	$\lambda^* + \eta^*$

NOTE.— $x_m^\theta \equiv \min[x^\theta, 1]$ ;  $\kappa$  represents the probability that the innovator improves on the products sold in its market;  $1 - \kappa$  represents the probability that the innovator improves on the blueprint of local firms;  $\lambda + \eta$  represents the probability of innovation from domestic firms; and  $\lambda^* + \eta^*$  represents the probability of innovation from foreign firms. All probabilities listed are unconditional.

being replaced) associated with innovation on three types of products (exported, nontraded, and imported) sold in the domestic market:

$$\begin{aligned}
 g = & \underbrace{(\lambda + \eta) x^* \phi_{k \in [0, x^*]}^*}_{\text{domestic innovation on exports and nontraded products}} \\
 & + \underbrace{(\lambda + \eta) (1 - x^*) \left[ \kappa \left( \frac{\tau}{\omega} \right)_m^\theta \phi_{k \in [x^*, 1]} + (1 - \kappa) \int_{x^*}^1 \left( \frac{\tau}{\omega} \frac{A_{jk}}{A_{jk}^*} \right)_m^\theta \phi_{k \in [x^*, 1]} dk \right]}_{\text{domestic innovation on imported products}} \\
 & + \underbrace{(\lambda^* + \eta^*) x \left[ \kappa \left( \frac{\omega}{\tau} \right)_m^\theta \phi_{k \in [0, x]}^* + (1 - \kappa) \int_0^x \left( \frac{\omega}{\tau} \frac{A_{jk}^*}{A_{jk}} \right)_m^\theta \phi_{k \in [0, x]}^* dk \right]}_{\text{foreign innovation on exported products}} \\
 & + \underbrace{(\lambda^* + \eta^*) (x^* - x) \int_x^{x^*} \left( \frac{\omega}{\tau} \frac{A_{jk}^*}{A_{jk}} \right)_m^\theta \phi_{k \in [x, x^*]}^* dk}_{\text{foreign innovation on nontraded products}} \\
 & + \underbrace{(\lambda^* + \eta^*) (1 - x^*) \phi_{k \in [x^*, 1]}^*}_{\text{foreign innovation on imported products}},
 \end{aligned} \tag{2}$$

where  $\phi_{k \in [a, b]}$  denotes the average improvement in quality from innovation by domestic firms on products  $k \in [a, b]$  and  $\phi_{k \in [a, b]}^*$  denotes the average improvement in product quality from innovation by foreign firms on products  $k \in [a, b]$ .<sup>8</sup> The expected growth rate of the foreign real consumption wage is similarly the product of the probability of innovation from rows 4–6 of table 2 and the corresponding improvements in quality.

The first two lines in equation (2) show the growth contribution of innovation by domestic firms, where the first line is the contribution of domestic innovation on products made by domestic firms ( $k \in [0, x^*]$ ) and the second line is the contribution of domestic innovation on imported products ( $k \in [x^*, 1]$ ). Note that the spillover parameter  $\kappa$  matters only when domestic firms innovate on an imported product. Specifically, conditional on innovating on an imported product, the expected improvement in quality is a weighted average of expected quality improvement when the domestic firms builds on the quality of the foreign producer and the expected improvement from building on the best (dormant) domestic producer, where the weights are given by the probability  $\kappa$  of drawing on foreign versus domestic technologies.

The last three lines in equation (2) show the contribution of foreign innovation. Specifically, the third line is the contribution of foreign innovation on the home country's exports ( $k \in [0, x]$ ), the fourth line is the contribution of foreign innovation on nontraded varieties ( $k \in [x, x^*]$ ), and the fifth line is the contribution of foreign innovation on the home country's imports ( $k \in [x^*, 1]$ ). Again, here the spillover parameter  $\kappa$  matters only when the foreign producer attempts to innovate on an exported product.

More generally, the growth rates in the two countries also depend on the probabilities of innovation in the two countries, the step size ( $\theta$ ), the trade cost ( $\tau$ ), the relative wage ( $\omega$ ), and the share of products exported by each country ( $x$  and  $1 - x^*$ ). The relative wage and the share of products made by each country are pinned down by balanced trade and the distribution of relative technologies  $A_{jk}/A_{jk}^*$ , where the latter is endogenous to innovation.

To illustrate how quality advances as each country builds on the innovations of the other country, it is useful to consider the case of completely free trade ( $\tau = 1$ ) and full cross-border spillovers ( $\kappa = 1$ ). In this case all products are traded, so the probability that a domestic firm creatively destroys another firm is given by

$$\begin{aligned} \text{domestic creative destruction rate} &= (\lambda + \eta) \cdot x^* \\ &+ (\lambda + \eta)(1/\omega)_m^\theta \cdot (1 - x^*). \end{aligned}$$

<sup>8</sup> Table A2 shows the average improvement in quality from foreign and domestic innovation on each type of product as a function of the step size,  $\theta$ , and the frequency of knowledge spillovers,  $\kappa$ .

The first term is the probability that a domestic firm replaces a product made by another domestic firm, and the second term is the probability that a domestic firm replaces a variety produced by a foreign firm. The corresponding rate of creative destruction by a foreign firm under free trade ( $\tau = 1$ ) is

$$\begin{aligned} \text{foreign creative destruction rate} &= (\lambda^* + \eta^*) \cdot (1 - x^*) \\ &\quad + (\lambda^* + \eta^*)(\omega)_m^\theta \cdot x^*. \end{aligned}$$

Ceteris paribus, higher  $\omega$  (home wage relative to foreign wage) lowers the rate of creative destruction of domestic firms and raises that of foreign firms. In steady state, the equilibrium relative wage equates the rate of creative destruction by domestic firms to that of foreign firms. So, if domestic firms are more innovative, domestic wages are higher, but the creative destruction rate of domestic firms is the same as for foreign firms in steady state.

It is also helpful to contrast autarky and free trade when the two countries are symmetric in size and in their innovation probabilities in the full idea spillover case ( $\kappa = 1$ ). In this special case, the relative wage  $\omega = 1$  and the growth expressions become simply

$$\begin{aligned} \text{autarky growth rate} &= (\lambda + \eta) \frac{1}{\theta - 1}, \\ \text{frictionless growth rate} &= 2 \cdot (\lambda + \eta) \frac{1}{\theta - 1}. \end{aligned}$$

In autarky, each country benefits only from domestic innovation. With frictionless trade, each country benefits from both domestic and foreign innovation. The doubling of growth under free trade compared with autarky underscores the scale effect generating dynamic gains from trade in this model.

#### *D. Knowledge Spillovers and Effect of Changes in Trade Costs*

We now show the importance of the spillover parameter  $\kappa$ . Table 3 shows the importance of the spillover parameter  $\kappa$  for the evolution of the quality distribution. The table shows the expected value of  $A_j$  and  $A_j^*$  in a future period  $t + 1$  as a function of  $A_j$  and  $A_j^*$  in the current period  $t$  for the three types of products in period  $t$  (those exported by the home country, nontraded, and imported by the home country, all in period  $t$ ).<sup>9</sup> For

<sup>9</sup> We omit the index of relative productivity  $k$  because  $k$  of a given product in period  $t$  will not be the same in period  $t + 1$ .

TABLE 3  
LAW OF MOTION FOR THE QUALITY DISTRIBUTION

	Domestic Quality in $t + 1$ ( $\mathbb{E}_t A_j(t + 1)$ ) (1)	Foreign Quality in $t + 1$ ( $\mathbb{E}_t A_j^*(t + 1)$ ) (2)
Exported by home in $t$	$A_j(t)\{1 + \frac{\lambda + \eta}{\theta - 1}\}$	$A_j^*(t)(1 - \kappa)\{1 + \frac{\lambda^* + \eta^*}{\theta - 1}\}$ $+ A_j(t)\kappa\{1 + \frac{\lambda^* + \eta^*}{\theta - 1}\}$
Nontraded in $t$	$A_j(t)\{1 + \frac{\lambda + \eta}{\theta - 1}\}$	$A_j^*(t)\{1 + \frac{\lambda^* + \eta^*}{\theta - 1}\}$
Imported by home in $t$	$A_j(t)(1 - \kappa)\{1 + \frac{\lambda + \eta}{\theta - 1}\}$ $+ A_j^*(t)\kappa\{1 + \frac{\lambda + \eta}{\theta - 1}\}$	$A_j^*(t)\{1 + \frac{\lambda^* + \eta^*}{\theta - 1}\}$

NOTE.—This table shows the expected value in period  $t + 1$  of domestic (col. 1) and foreign (col. 2) quality for products that are exported by the home country in period  $t$  (row 1), nontraded in period  $t$  (row 2), and imported by the home country in period  $t$  (row 3).

products in period  $t$  made in each country, the expected quality in the next period is only a function of local quality, regardless of the value of  $\kappa$ . However, for the products that are traded, the degree of spillovers determines whether future quality draws on the local quality or on quality in the other country. When  $\kappa$  is close to zero, the quality of a traded product in  $t + 1$  depends on only the quality of the same product in period  $t$  in the same country. That is, the evolution of the quality distribution of a traded product is exactly the same as that of a product that is produced in each country, in that future quality depends only on local quality. As a consequence, when  $\kappa$  is close to zero, technologies of the two countries diverge.

Alternatively, when  $\kappa$  is far above zero, the quality of products that are traded builds on the quality of the same product in the other country. Specifically, at the extreme when  $\kappa = 1$ , the expected quality of the (dormant) domestic producer of a product that is imported at time  $t$  is a function only of the quality of the foreign producer. Likewise, the expected quality of the (dormant) foreign producer of a product that is exported by the home country at time  $t$  depends only on the domestic quality of the same product. As a consequence, when  $\kappa$  is far above zero, technologies of the two countries are tethered together, and this is more so when a larger share of products are traded.

Figure 1 illustrates the implication of the spillover parameter  $\kappa$  and trade costs  $\tau$  for the technology gap between the two countries. The left panel shows distribution across products of quality in the home relative to the foreign country ( $A_j/A_j^*$ ) in a steady state with high tariffs ( $\tau = 4$ ) versus in a steady state with low tariffs ( $\tau = 1.5$ ) for the full spillover case

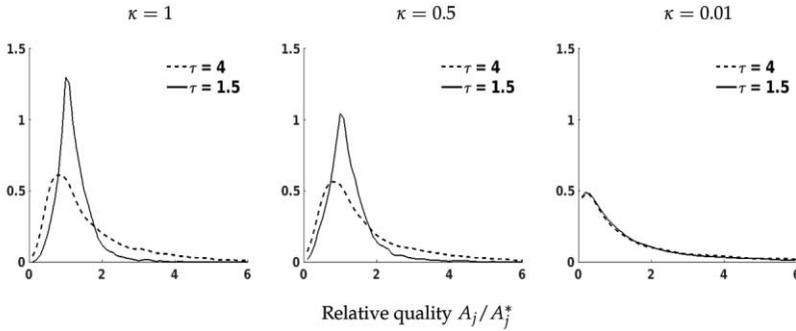


FIG. 1.—Effect of tariffs on relative quality dispersion. As in figure 2, simulations are run for symmetric countries of equal size, with  $\theta = 7$  and the probability of innovation ( $\lambda + \eta$  for the home and  $\lambda^* + \eta^*$  for the foreign country) set to 0.12 in each country. All parameters except  $\tau$  are held constant across the counterfactuals displayed.

( $\kappa = 1$ ). When ideas are embodied in trade, lower tariffs narrow the dispersion of relative quality, as ideas flow more quickly across countries with more trade. The right panel of figure 1 shows the distribution of relative product quality in a high-tariff ( $\tau = 4$ ) steady state versus a low-tariff ( $\tau = 1.5$ ) steady state for the limited spillover case ( $\kappa = 0.01$ ). In this case, lower tariffs have no noticeable effect on the dispersion of relative quality, as more trade does not lead to more idea flows across countries. Therefore, the strength of comparative advantage is virtually unaffected by trade costs.

Figure 2 illustrates the importance of the spillover parameter  $\kappa$  for the effect of changes in trade costs in the model. The figure shows the growth rate, the trade share, and the local trade elasticity across steady states with different trade costs for models where  $\kappa = 1$ ,  $\kappa = 0.5$ , and  $\kappa = 0.01$ , respectively.<sup>10</sup> The plot does not include the polar case of zero spillovers ( $\kappa = 0$ ), because in that case there is no steady state in terms of the trade shares and the local trade elasticity. The two countries' TFP paths diverge in the absence of spillovers, as their long-run TFP growth rates differ when  $\kappa = 0$ .

The left panel of figure 2 shows the effect of trade costs on the common long-run growth rate of the two economies. The higher the value of  $\kappa$ , the more sensitive growth is to tariffs. When fewer goods are traded, countries are less frequently building on each other's innovations and more frequently building on their own innovations. Changes in trade costs have no discernible effect on the growth rate when spillovers are minimal ( $\kappa = 0.01$ ). When ideas barely flow across countries from the exchange of goods, limiting trade has little effect on the growth rate.

<sup>10</sup> The numbers in the figure are for illustrative purposes only. We discuss the precise calibration of the model in a later section.

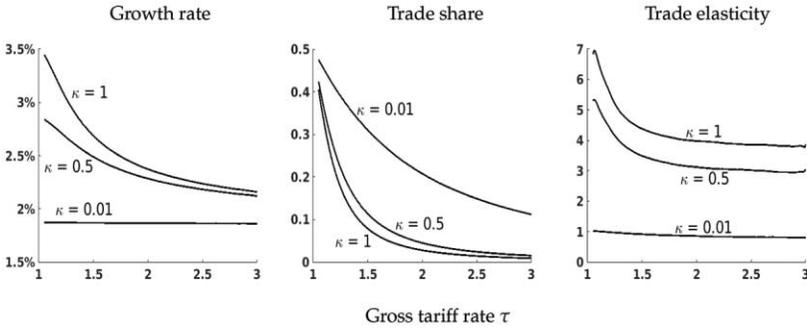


FIG. 2.—Effect of tariffs with varying levels of knowledge spillovers. Simulations are run for symmetric countries of equal size, with  $\theta = 7$  and probabilities of innovation ( $\lambda + \eta$  for the home country and  $\lambda^* + \eta^*$  for the foreign country) set to 0.12 in each country. All parameters except  $\tau$  are held constant across the range of counterfactuals displayed.

The middle panel in figure 2 shows that higher tariffs lower the trade share for all values of  $\kappa$ . But the trade share is more sensitive to tariffs for higher values of  $\kappa$ . As seen in figure 1, when  $\kappa$  is high, knowledge flows keep country technologies tethered together. Figure 2 shows that the convergence of technologies due to knowledge spillovers weakens comparative advantage and makes trade more sensitive to tariffs.

The right panel in figure 2 shows how the local trade elasticity responds to the trade cost. By the local trade elasticity we mean the change in the log of the import share from a local change (10 percentage point reduction) in the log trade cost. It is local in that it is evaluated in a given year starting from the initial steady-state distribution of relative quality across the two countries that exists before the tariff change.<sup>11</sup> When spillovers are severely limited ( $\kappa = 0.01$ ), relative qualities between the two countries drift apart because each country innovates largely on its own products. As a result, comparative advantage is strong and the trade elasticity is low for all tariff levels. When ideas flow more easily across countries with trade, however, higher tariffs hinder the flow of ideas and strengthen the degree of comparative advantage.<sup>12</sup> Thus, higher tariffs impede trade and idea flows and lower the trade elasticity when  $\kappa = 0.5$  or  $\kappa = 1$ .

In the empirical section of this paper, we use the insight that the degree of cross-country knowledge spillovers affects the trade elasticity to infer the value of  $\kappa$ . That is, we ask (roughly), given an estimate of the rate of innovation and the trade cost, what must be the magnitude of cross-border knowledge spillovers necessary to generate the comparative advantage implied by the trade elasticity measured in the data?

<sup>11</sup> Formally, we calculate the local trade elasticity as  $\{\log[(\text{imports}/\text{domestic sales})(\tau)] - \log[(\text{imports}/\text{domestic sales})(\tau - 0.1)]\} / [\log(\tau - 0.1) - \log(\tau)]$ .

<sup>12</sup> This result is also in Alvarez, Buera, and Lucas (2017).

*E. Disembodied Idea Flows*

In our baseline model, foreign innovators learn about domestic technologies through trade. We now consider a model in which the flow of ideas across borders is not related to trade. Consider the products  $k \in [0, 1]$  sorted by the highest to lowest ratio of domestic productivity to foreign productivity,  $A_{jk}/A_{jk}^*$ . Suppose that foreign innovators draw with probability  $z$  on a random domestic product from  $k \in [0, z]$  and with probability  $1 - z$  on a random foreign product from  $k \in [z, 1]$ . Also suppose that domestic innovators innovate with probability  $z^*$  on a random foreign product from  $k \in [1 - z^*, 1]$  and with probability  $1 - z^*$  on a random domestic product from  $k \in [0, 1 - z^*]$ . Spillovers from the domestic to foreign innovators are thus increasing in  $z$ , and spillovers from foreign blueprints to domestic innovators are increasing in  $z^*$ . We call this a “disembodied spillover” model since the knowledge spillovers are not related to trade.

In this disembodied spillover model, creative destruction from foreign innovators takes place when the foreign innovators target a domestic variety. Likewise, a foreign variety is creatively destroyed when a domestic innovator targets a foreign variety. Moreover, the steady state of the disembodied spillover model is equivalent to that of our baseline model where idea flows are fully embodied in trade ( $\kappa = 1$ ) if  $z = x$  and  $z^* = x^*$ , where  $x$  and  $x^*$  represent the fraction of products exported by the domestic and the foreign country, respectively.

The two models differ in that trade is essential to spillovers in our baseline model and unrelated to idea flows in this disembodied spillover model. In the former, the key parameters that determine the extent of spillovers are  $\kappa$  and the trade cost  $\tau$ . In the latter, the key parameters that govern spillovers are the spillover thresholds  $z$  and  $z^*$ . Figure 3 illustrates the effect of the spillover threshold by showing the growth rate, trade

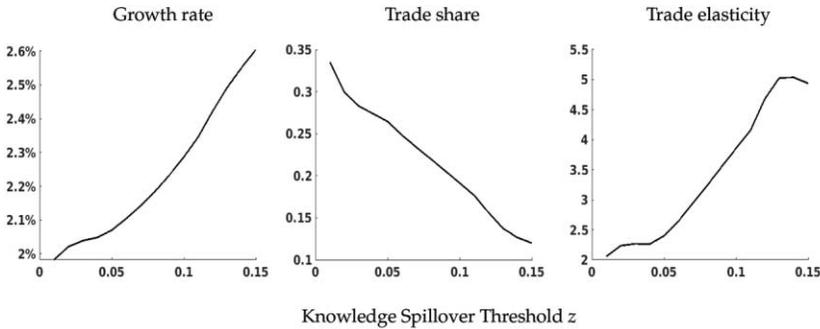


FIG. 3.—Effect of spillover threshold with disembodied knowledge flows. Simulations are run for symmetric countries of equal size, with  $\theta = 7$  and innovation probabilities ( $\lambda + \eta$  for the home country and  $\lambda^* + \eta^*$  for the foreign country) set to 0.12 in each country. All parameters except  $z$  are held constant across the range of counterfactuals displayed.

share, and trade elasticity in steady states with different values of the spillover threshold for foreign innovators  $z$ . Remember that the spillover of domestic ideas to foreign innovators increases as  $z$  rises. The growth rate rises as ideas flow more quickly from the domestic to foreign innovators with a higher  $z$ . Alternatively, the trade share falls and the trade elasticity rises as foreign qualities hug the domestic ones more closely in response to higher  $z$ , blunting the degree of comparative advantage.

Notice that the growth rate is negatively correlated with the trade share in the disembodied spillover model, whereas the correlation was positive in our baseline model where spillovers were embodied in trade flows. In both models, the growth rate rises and technology differences between the two countries narrow as ideas flow more frequently across countries. The narrowing of technology differences in the model comes from more trade in the trade-embodied spillover model. In contrast, trade has no effect on spillovers in the disembodied model. As a result, the dispersion of relative quality is not a function of trade costs in the disembodied spillover model.

Before we move to calibrating our model to look at its quantitative implications, it is worth stressing that it contains many strong assumptions that could be relaxed in future work. These include that the probability of innovation applies equally to produced and imported products, and the step size is the same for all innovations in both countries. Moreover, one could add idiosyncratic process efficiency shocks and fixed costs of exporting à la Melitz (2003). Future work could relax these assumptions and add these features.

### III. Model Calibration

Our baseline model involves eight parameters: the shape  $\theta$  of the Pareto distribution of innovation draws, two innovation rates (for incumbents  $\lambda$  and entrants  $\eta$ ) in each country, the tariff rate  $\tau$ , the spillover parameter  $\kappa$ , and relative employment in the home versus foreign country. We infer the value of these parameters from the seven data moments listed in table 4. We do not separately identify the probability of innovation for foreign entrants versus foreign incumbents but rather assume that this breaks down in the same way the US ratio breaks down. As mentioned, the United States is “home” and the rest of the OECD is “foreign.”

We back out  $\theta$  from the standard deviation of the log of labor productivity (revenue per worker) across firms. The higher the value of  $\theta$ , the smaller the variance in the innovation step size and the smaller the dispersion in labor productivity across firms. In the US manufacturing data, the standard deviation of the log of value added per worker across firms is 0.108.

For a given  $\theta$  and relative employment  $L/L^*$ , the innovation probabilities and the tariff rate ( $\tau$ ) jointly determine the growth rate, the trade

TABLE 4  
DATA MOMENTS USED FOR CALIBRATION

Data Moment	Source (1)	Value (2)	Model Fit (3)
Standard deviation log value added per worker	US census of manufacturing	.108	.104
TFP growth rate	Bureau of Labor Statistics data for US manufacturing	3.01%	3.01%
Value added per worker, home/foreign	KLEMS (capital, labor, energy, materials, services) data for US and OECD manufacturing	1.29	1.29
Employment share of entrants (age $\leq 5$ )	US census of manufacturing	14.4%	14.4%
Export share of revenues (home)	US census of manufacturing	10.2%	10.2%
Trade elasticity	Head and Mayer 2014	5	4.82
Employment, home/foreign	KLEMS for US and OECD manufacturing	.389	.389

share, and the relative wage. We target a growth rate of 3%, relative employment (US/OECD) of 0.389, a US trade share of 10%, and a relative wage (US/OECD) of 1.29. We use the employment share of new firms in US manufacturing (14.4% in the data) to pin down the ratio of innovation by entrants versus incumbents, which we assume is the same in the two countries.

Finally, we back out the crucial spillover parameter  $\kappa$  by targeting a trade elasticity of 5, in line with estimates in Head and Mayer (2014). Figure 2 showed that the trade elasticity increases with the degree of spillovers  $\kappa$  because the technology gaps between the two countries narrow when ideas flow more freely across countries. We ask, given the dispersion of the quality step size necessary to fit the dispersion of labor productivity in the US data, how much do ideas have to move across borders such that the dispersion of technology gaps across the two countries generates a trade elasticity of 5?

To characterize the model quantitatively, we take a discrete number of products and simulate the innovations on each variety.<sup>13</sup> Innovation draws are randomly assigned to an existing incumbent or a new entrant. The relative wage is found that balances trade between the two countries in each year. We simulate for several hundred years until the economy settles down to a steady state, at which point we calculate moments. We utilize a simulated annealing procedure to search for the parameter values that match the data moments.<sup>14</sup>

<sup>13</sup> As explained further in sec. IV, we run the simulation with approximately 21,000 products to match the relative volume of exports across the 264 US manufacturing industries. Note that the simulated moments in table 4 are not affected by the number of products in the simulation.

<sup>14</sup> Appendix section B provides more details on the solution procedure.

TABLE 5  
MODEL PARAMETER ESTIMATES

VARIABLE	DESCRIPTION (1)	VALUE	
		$\sigma = 1$ (2)	$\sigma = 3$ (3)
$\theta$	Shape parameter of innovation draws	7.11	4.51
$\lambda$	Home innovation rate from incumbents	12.1%	6.6%
$\eta$	Home innovation rate from entrants	2.6%	2.6%
$\lambda^* + \eta^*$	Foreign innovation rate from incumbents + entrants	13.1%	7.7%
$\tau$	Gross tariff rate	1.54	1.56
$\kappa$	Proportion of trade-embodied spillovers	.938	.683

The resulting calibrated parameter values are shown in table 5. The US combined innovation rate for incumbents and entrants is about  $\lambda + \eta = 15\%$ , and the OECD combined innovation rate is roughly  $\lambda^* + \eta^* = 13\%$ . The US innovation rate has to be higher to explain the 29% higher real wage (real value added per worker) in the United States than in the rest of the OECD. The value of the shape parameter for innovation draws,  $\theta$ , that matches the dispersion of labor productivity across firms is around 7.

The value of the spillover parameter,  $\kappa$ , that comes closest to hitting the trade elasticity target is 0.94. This implies that our model needs to incorporate spillovers on most traded goods to match the targeted trade elasticity. It is worth noting that we have omitted any spillover on nontraded goods that could also tether productivities together and reduce the strength of comparative advantage across countries. But the key point remains: given the stochastically evolving product-level technologies in our model, idea flows are essential to keep country technologies from drifting so far apart that comparative advantage becomes too strong and the trade elasticity too low.<sup>15</sup> Finally, conditional on the innovation rates, the shape parameter, the spillover parameter, and the relative size of the two economies, fitting the US trade share pins down a tariff rate of about 54%.<sup>16</sup>

One feature of our model that might be troubling is that, in principle, knowledge can be forgotten. In particular, because the wage in the rest of the OECD is below that in the United States, an inferior quality in the

<sup>15</sup> Static models in the spirit of Eaton and Kortum (2002) and Melitz (2003) can of course simply impose a trade elasticity of 5, as the trade elasticity is governed by an exogenous Pareto or Fréchet shape parameter in these models. In our model, in contrast, the distribution of productivity evolves dynamically in response to innovation draws. These stochastic innovation draws are a force for divergence that is absent from the static models.

<sup>16</sup> Eaton and Kortum (2002) and others infer high trade costs to explain bilateral trade flows.

former could potentially take over the market from a superior quality in the latter. Subsequent innovation in the United States would then build on the inferior quality imported from the rest of the OECD. It turns out that this does not happen in steady state at our calibrated parameter values because trade costs are higher than wage differences, so that only superior products from the rest of the OECD can take over the US market.

Column 3 in table 5 shows the parameter estimates when we relax the assumption of Cobb-Douglas preferences. Specifically, we assume that  $\sigma = 3$  and reestimate the model to fit the same data moments in table 4. Compared with the baseline model, the innovation probabilities and the spillover parameter  $\kappa$  are lower in the model with  $\sigma = 3$ . A given improvement in quality has a larger effect on growth rates in the model where  $\sigma = 3$ , so the probabilities of innovation are correspondingly lower to fit the same aggregate growth rate. As for the lower spillover parameter  $\kappa$ , a given dispersion of relative productivity has a larger effect on the trade elasticity when  $\sigma = 3$ . Therefore, a lower dispersion of relative productivity can fit the same trade elasticity of 5, which implies that knowledge spillovers are also correspondingly smaller (about 68% of innovation builds on imported products rather than the last domestic product produced, as opposed to 94% in the Cobb-Douglas case).

#### IV. Indirect Evidence of Idea Flows

In this section, we contrast the implications of our calibrated model with strong idea flows ( $\kappa$  close to one) to a model wherein idea flows are severely limited ( $\kappa$  close to zero).<sup>17</sup> First, we show that a model with more restricted idea flows cannot come close to generating a trade elasticity of 5. Second, we use data on manufacturing plants in the United States and several other countries to establish that exports decline by more than domestic sales among contracting exporters and grow by less than domestic sales among expanding exporters. Third, we document that the same manufacturing data exhibit a great deal of excess export reallocation across manufacturing industries. We show that the calibration with strong idea flows can replicate these two features of the data, whereas those calibrations with much more limited flows cannot.

##### A. *The Trade Elasticity*

As mentioned, the best fit of our model generates a trade elasticity of 4.82 with a spillover parameter  $\kappa$  of 0.94. The trade elasticity depends on the strength of comparative advantage, which is itself a function of

<sup>17</sup> We could simply decrease the  $z$  and  $z^*$  thresholds in the disembodied model to have the identical steady-state effects as lowering the degree of spillovers  $\kappa$ . We therefore focus only on  $\kappa = 1$  vs.  $\kappa = 0$  in this section.

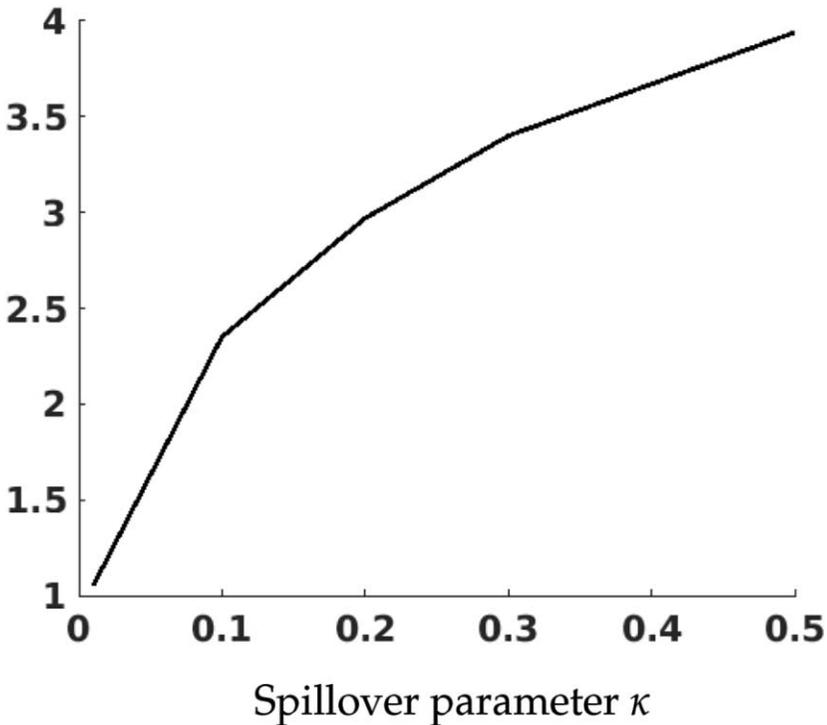


FIG. 4.—Effect of spillover parameter  $\kappa$  on the trade elasticity in the steady state. We fix  $\kappa$  and calculate the model parameters to match the data moments in table 4 except for the trade elasticity and trade share.

the extent to which ideas flow across borders. Figure 4 shows how limiting the extent of idea spillovers lowers the trade elasticity. Here, instead of estimating  $\kappa$ , we assume a lower value of  $\kappa$  and reestimate all the parameters of the model to fit the other target moments in table 4, except for the trade elasticity and trade share. Figure 4 shows that the trade elasticity falls as we impose a lower spillover parameter  $\kappa$ . The dispersion of relative quality and the strength of comparative advantage increases as idea spillovers become more limited. At the extreme where  $\kappa$  is almost zero, the trade elasticity is almost one.<sup>18</sup>

#### *B. Domestic Sales Growth versus Export Growth for Exporting Firms*

A second fact that helps discriminate between a model with strong spillovers and one with only weak spillovers is the growth rate of exports versus

<sup>18</sup> The evidence in fig. 4 also suggests that if we had targeted a lower trade elasticity (less than 5), then our estimate of  $\kappa$  would also likely be lower than our estimate of 0.94.

TABLE 6  
GROWTH RATE OF EXPORTS AND DOMESTIC REVENUES OF EXPORTING FIRMS

	CONTRACTING EXPORTERS		EXPANDING EXPORTERS	
	Exports (1)	Domestic Sales (2)	Exports (3)	Domestic Sales (4)
United States	-.840	-.408	-.422	.383
China	-1.469	-1.227	-.003	.449
Chile	-1.255	-1.083	.041	.291
Indonesia	-1.608	-.684	-.704	.905
Colombia	-1.230	-1.001	.007	.290

NOTE.—This table uses a sample of firms with positive exports at the beginning of each 5-year period and shows the average growth rates of exports and domestic sales of exporters over 5-year periods. Growth rate is measured as the change in exports or domestic sales of the firm over a 5-year period divided by the average of exports or domestic sales of the firm at the beginning and end of each 5-year period. Growth rate is  $-2$  for firms that exit from exporting or domestic sales. Contracting firms are defined as firms where total sales decrease, and expanding firms are defined as firms where total sales increase over each 5-year period. The growth rate of total sales (across all firms) is normalized to zero over each 5-year period. Growth rates are calculated over 5-year periods from 1987 to 2017 for the United States, 1995 to 2007 for Chile, 1998 to 2007 for China, 1990 to 1999 for Indonesia, and 1981 to 1989 for Colombia from the micro data of the manufacturing censuses of these countries.

domestic sales of exporting firms. Table 6 presents these growth rates over 5 years from the firm-level manufacturing censuses of the United States, China, Chile, Indonesia, and Colombia.<sup>19</sup> The sample is restricted to exporting firms at the beginning of each 5-year period, and we normalize the growth rate of total sales (domestic sales plus exports) to zero on average by subtracting the growth rate of aggregate sales of exporting firms in each 5-year period. We further group firms into ones where total (normalized) sales increase over 5 years and ones where total sales decrease over 5 years. For each sample, we then calculate the growth rate of a firm's exports between year  $t$  and  $t + 5$  as the ratio of the change in the firm's exports over the 5 years to average exports of the firm at the beginning and end of the 5-year period:

$$2 \cdot \frac{\text{export}_{i,t+5} - \text{export}_{i,t}}{\text{export}_{i,t+5} + \text{export}_{i,t}},$$

where  $\text{export}_{i,t}$  denotes firm  $i$ 's exports at time  $t$ . The growth rate of a firm's domestic sales is calculated similarly. The growth rate of exports (domestic sales) of a firm that exits exporting (domestic sales) is thus  $-2$ . Because the sample consists of firms exporting at the beginning

<sup>19</sup> The data are the firm-level manufacturing censuses from 1987 to 2017 for the United States, 1995 to 2007 for Chile, 1998 to 2007 for China, 1990 to 1999 for Indonesia, and 1981 to 1989 for Colombia.

of the period, entry into exporting in each 5-year period is not part of the calculations.

Table 6 shows the average growth rate of domestic sales and exports of contracting firms in columns 1 and 2 and expanding firms in columns 3 and 4.<sup>20</sup> The key message we take from table 6 is the asymmetry between contracting versus expanding firms in the growth rate of exports versus domestic sales. In all five countries, export sales fall among firms whose total sales decline over the 5-year period, and the average decline in exports is larger than the average decline in domestic sales. The opposite pattern holds among exporters whose total sales increase over the 5-year period. Among expanding firms, domestic sales increase as one might expect, but export growth of the same firms is either negative (in China, the United States, and Indonesia) or essentially zero (in Chile and Colombia).

Table 7 shows what our baseline model with strong idea flows predicts for the ratio of the growth rate of exports to domestic sales for expanding versus contracting firms.<sup>21</sup> The ratio of the growth rate of exports to domestic sales for contracting firms is 1.92 in the model calibrated to fit the US moments in table 4 compared with 2.06 in the US data. The spillover of ideas is crucial to this prediction. The spillover of ideas across borders means that foreign firms can innovate on the products of a domestic firm. When this happens, the domestic firm loses its product in the foreign market but not necessarily in the domestic market, because it is protected in the domestic market by the trade cost. As a consequence, when a firm shrinks in the model with spillovers, it is more likely that it loses the export market than the domestic market, and thus exports tend to fall more than domestic sales.

The model can also replicate the fact that, conditional on expanding, the expected growth rate of export sales is lower compared with domestic sales and even negative in the United States. The ratio of the growth rate of exports to domestic sales is  $-0.58$  among expanding exporters in the model with idea spillovers (table 7, row 2); the same moment in the US data is  $-1.1$ . Again, this prediction comes from creative destruction across borders due to the spillover of ideas. When a domestic firm innovates on a foreign firm's product, it is more likely to replace the foreign

<sup>20</sup> Table 6 shows the average growth rates over 5-year periods from 1987 to 2017 for the United States, 1995 to 2007 for Chile, 1998 to 2007 for China, 1990 to 1999 for Indonesia, and 1981 to 1989 for Colombia.

<sup>21</sup> In the model, firms are a collection of products. As in Klette and Kortum (2004), the distribution of the number of products per firm in our model is determined endogenously by the innovation rate of incumbents vs. entrants. In our baseline model, the number of products for the average firm is 2.4 and the standard deviation of the number of products per firm is 2.5. Firms expand and contract in the model as they gain and lose products.

TABLE 7  
GROWTH RATE OF EXPORTS RELATIVE TO DOMESTIC SALES  
IN THE UNITED STATES

	US DATA (1)	MODEL	
		$\kappa = .94$ (2)	$\kappa = .01$ (3)
Contracting exporters	2.06	1.92	1.13
Expanding exporters	-1.10	-.58	.89

NOTE.—This table shows the ratio of the growth rate of exports to domestic sales among contracting exporters (row 1) and expanding exporters (row 2) for the United States in the data (col. 1) and in the model calibrated to fit the US moments (cols. 2, 3). Contracting exporters are ones where total sales fall over 5 years, and expanding exporters are ones where total sales increase over 5 years. The parameters of the model in col. 2 are estimated to fit the data moments in table 4. The limited spillover version of the model in col. 3 assumes that  $\kappa = 0.01$  and estimates the model parameters to fit the same data moments, except for the trade elasticity.

firm in the domestic market than in the foreign market. The reason is because the tariff helps the domestic innovator—the foreign incumbent has to pay the tariff while the domestic innovator does not.

Column 3 in table 7 shows that a model with severely limited idea spillovers cannot generate the two facts. Here we show the prediction of a model where we impose a spillover parameter of  $\kappa = 0.01$  and reestimate the other parameters to fit the same target moments in table 4, except for the trade elasticity and trade share. In the model with limited idea spillovers, the growth rate of domestic sales is similar to the growth rate of exports. This is true for expanding as well as contracting firms. The reason is the absence of cross-border creative destruction in the limited spillover model. When spillovers are limited, foreign firms do not improve on a domestic firm's blueprint and domestic firms do not improve on a foreign firm's product. So a domestic firm shrinks primarily when another domestic firm improves on its product, and it expands when it improves on the product of another domestic firm. Thus, when a firm shrinks, it loses its product in both the foreign and the domestic market, and when it expands it gains the product in the domestic and the foreign market. This prediction of the model with limited cross-border creative destruction is clearly at odds with the evidence in table 6.

### C. *Export Reallocation across Industries*

Our third fact is about excess export reallocation. We aggregate the firm-level data up to the industry level to calculate the aggregate rate of export reallocation across industries in a manner akin to how Davis, Haltiwanger, and Schuh (1996) calculate job-reallocation rates across firms. We first net

out aggregate export growth by scaling each firm's exports in year  $t + 5$  by the gross growth rate of aggregate exports in the country from year  $t$  to  $t + 5$ . This normalization nets out aggregate changes in nominal exports, due to both real growth and changing export prices.

We calculate excess export reallocation across industries by summing up the increases in exports in those industries showing an increase in exports over a given 5-year period. We get the excess export reallocation rate by dividing this by aggregate exports at the beginning of the period:<sup>22</sup>

$$\frac{\sum_{j \in +} (\text{export}_{j,t+5} - \text{export}_{j,t})}{\text{aggregate export}_t},$$

where  $j \in +$  denotes the set of industries with increasing exports and  $\text{export}_{j,t}$  denotes total exports of industry  $j$  at time  $t$ . We present the excess export creation rate across industries in table 8 (col. 1). It is sizable in all five countries, ranging from 16.7% for the United States to 41% for Indonesia. We are not the first to emphasize such dynamically evolving export patterns in the data—see Hanson, Lind, and Muendler (2018).

To compare the model with the data in terms of export reallocation across industries, we need to take a stand on the number of products in each industry. We assume that the smallest industry has one product and that the number of products in an industry increases at the exponential rate  $\epsilon$  as one goes from the smallest to the largest industries in terms of exports. We then choose the total number of products in the model and  $\epsilon$  to match two numbers in the US firm data: the number of industries and the ratio of the 75th to 25th percentile industry exports. There are 264 consistently defined industries in the US manufacturing census between 1987 and 2017. The 75/25 ratio of these industries is a factor of 27.6 for US exports. We fit these two data moments with 21,000 products and  $\epsilon = 2.35$ .

Table 9 shows that the model calibrated to fit the US moments in table 4 predicts an export reallocation rate across industries of 10.9% in the United States. Since our estimate of  $\kappa$  implies that spillovers occur over most traded goods, industries expand their exports when firms creatively destroy the products of firms located in other countries, and industries shrink their exports when their exports are innovated on and replaced by foreign firms. Again, creative destruction that takes place across borders is crucial to this prediction.

<sup>22</sup> We can also calculate the excess export destruction rate by adding the *decrease* in exports in all industries showing a decline in exports over the 5-year period and similarly dividing by aggregate exports at the beginning of the period. Given our normalization that the growth of total exports over the 5-year period is zero, however, the export destruction rate is the same as the export creation rate.

TABLE 8  
EXCESS EXPORT REALLOCATION BETWEEN AND WITHIN INDUSTRIES

	BETWEEN INDUSTRIES (1)	WITHIN CONTRACTING INDUSTRIES		WITHIN EXPANDING INDUSTRIES	
		Creation (2)	Destruction (3)	Creation (4)	Destruction (5)
United States	.167	.182	-.349	.340	-.173
China	.260	.268	-.529	.510	-.251
Chile	.222	.135	-.357	.443	-.221
Indonesia	.410	.196	-.606	.595	-.187
Colombia	.295	.083	-.378	.302	-.158

NOTE.—This table shows export creation and destruction rates between industries (col. 1) and within industries (cols. 2–5) over 5-year periods. Between-industry export creation is the sum of change in exports of expanding industries over a 5-year period divided by total exports (across all industries) at the beginning of each period. Total growth rate of exports is normalized to zero for each 5-year period, so the export creation rate between industries is equal to the export destruction rate between industries. Within-industry export creation is the sum of the change in exports of firms with expanding exports and exports of new exporting firms within each 5-year period for firms in contracting or expanding industries, all divided by total exports (across all industries) at the beginning of the 5-year period. Within-industry export destruction rate is the sum of the change of exports of firms with decreased exports in each industry plus exports at the beginning of the period of firms that stop exporting by the end of the period for firms in contracting or expanding industries, all divided by total exports (across all industries) at the beginning of the period. Export creation and destruction rates are calculated over 5-year periods from 1987 to 2017 for the United States, 1995 to 2007 for Chile, 1998 to 2007 for China, 1990 to 1999 for Indonesia, and 1981 to 1989 for Colombia.

The excess export reallocation rate in the model that assumes limited idea flows is much lower, at 3.1%. When idea flows are limited, firms innovate on products of other firms in the same country. If the product happens to be exported, the innovating firm gains an export but the incumbent firm loses an export. There is no net gain in exports at the industry level because higher exports of the innovating firm are offset by the export loss of the incumbent firm. There is a modest amount of

TABLE 9  
EXCESS EXPORT REALLOCATION ACROSS INDUSTRIES IN THE UNITED STATES

	US DATA (1)	MODEL	
		$\kappa = .94$ (2)	$\kappa = .01$ (3)
Export creation and destruction rate	.149	.109	.031

NOTE.—This table shows the export creation and destruction rate at the industry level for the United States over a 5-year period, where the growth rate of total exports (across all industries) is normalized to zero. The model parameters in col. 2 are estimated to fit the US data moments in table 4. The limited spillover version of the model in col. 3 assumes that  $\kappa = 0.01$  and estimates the model parameters to fit the same data moments, except for the trade elasticity.

excess export reallocation in the model with severely limited idea spillovers when an innovator improves on a nontraded product and the quality improvement is large enough such that the previously nontraded product becomes exported.

To restate, the excess export churn that we observe across industries can be explained by a model with cross-border creative destruction, whereas a model with limited idea flows is not consistent with this basic fact. An alternative explanation for this excess export churn, however, is that there is volatility of export demand. Industries with increasing exports could be hit by positive demand shocks, and industries with decreasing exports could be hit by negative demand shocks. That is, export reallocation could reflect demand shocks rather than innovation and global creative destruction.

We can shed some light on the demand shock explanation by measuring export churn at the firm level instead of at the industry level. If export churn at the industry level is driven by industry export demand shocks, then we would expect to see exports increase among all exporting firms in industries where exports rise. Likewise, exports should fall in all firms in the declining export sectors.

Table 8 provides export creation and destruction rates at the firm level for contracting export sectors (cols. 2, 3) and expanding export sectors (cols. 4, 5). We calculate the firm-level export creation rate in contracting industries by adding up the increase in exports in all firms with increasing exports (including entrants) in the industries that are contracting over the 5-year period. We then divide this number by aggregate exports at the beginning of the period. The export destruction rate in contracting industries is the sum of the decline in exports among all firms with declining exports (including firms that exit exporting) in contracting industries over the 5-year period divided by total exports at the beginning of the period. The export creation and destruction rates for industries with expanding exports are calculated similarly. By construction, the sum of the firm-level export creation and destruction rates in the contracting industries (sum of cols. 2 and 3 in table 8) is equal to the export destruction rate at the industry level. Likewise, the sum of the firm-level creation and destruction rates in expanding industries (sum of cols. 4 and 5 in table 8) is equal to the export creation rate at the industry level.

The basic pattern is that export creation and destruction rates at the firm level are much higher than at the industry level. In industries where net exports fall, there are still many firms where exports increase. Likewise, many firms lose their exports in industries where total exports are rising. This basic fact is consistent with our model where the within-industry export churn is driven by creative destruction across firms. It is not consistent with the view that the excess export churn at the industry

TABLE 10  
EXTENSIVE MARGIN SHARE OF EXPORT CREATION AND DESTRUCTION

	EXTENSIVE MARGIN SHARE OF:	
	Export Destruction in Contracting Industries (%) (1)	Export Creation in Expanding Industries (%) (2)
United States	57.5	57.8
China	69.4	90.6
Chile	47.1	73.1
Indonesia	72.9	84.0
Colombia	35.6	67.1

NOTE.—This table shows the share of gross export destruction within contracting industries due to exit from exporting (col. 1) and the share of gross export creation within expanding industries from entry into exporting (col. 2). Gross export creation in expanding industries is the sum of the change in exports of firms with expanding exports and exports of new exporting firms within each 5-year period for firms in expanding industries; gross export destruction in contracting industries is the sum of the change of exports of firms with decreased exports in each industry plus exports at the beginning of the period of firms that stop exporting by the end of the period for firms in contracting. Extensive margin shares are calculated over 5-year periods from 1987 to 2017 for the United States, 1995 to 2007 for Chile, 1998 to 2007 for China, 1990 to 1999 for Indonesia, and 1981 to 1989 for Colombia.

level is driven by industry-wide export demand shocks, as such shocks will not generate the excess export churn within industries.

Finally, table 10 shows the importance of entry and exit in the turnover of products across industries. Column 1 shows the share of gross export destruction in contracting industries due to firms that exit from foreign markets, and column 2 shows the share of gross export creation in expanding industries from new exporters. The evidence shows that most of the expansion of exports within expanding industries occurs through new exporters. Likewise, most of the decline of exports within declining industries comes from firms that exit from foreign markets. This evidence also points to creative destruction rather than demand shocks that face incumbents and exiters/entrants equally as the force behind the gross creation and destruction of exports.

## V. Gains from Trade and Idea Flows

In this section, we calculate the welfare gains from trade and idea flows in the model with the baseline parameter values in table 5. In this model, in which idea flows are embodied in trade, the gross tariff rate  $\tau$  is the key parameter that determines the extent to which ideas flow between countries. A decrease in  $\tau$  results in both static gains from trade and dynamic gains from more idea flows.

Table 11 shows the welfare gains from reducing tariffs in the model with trade-embodied idea flows. We calculate the gains as the equivalent

TABLE 11  
GAINS FROM TRADE WITH TRADE-EMBODIED IDEA FLOWS

	50% REDUCTION IN ( $\tau - 1$ )		RELATIVE TO AUTARKY	
	United States (%) (1)	OECD (%) (2)	United States (%) (3)	OECD (%) (4)
Static gains	6.2	3.6	26.7	20.7
Dynamic gains	12.6	20.3	31.1	75.0
Static + dynamic gains	18.8	23.9	54.8	95.7

NOTE.—Entries show the permanent increase in consumption that yields the equivalent variation in utility as reducing tariffs from 1.54 to 1.25 (cols. 1, 2) or reducing tariffs from 4 to 1.54 (cols. 3, 4). The aggregate trade share at  $\tau = 4$  is about 0.4%. We use a discount rate of 1.9% and log utility.

variation in consumption (permanent percentage change) with log utility and a discount rate of 1.9% to match a real interest rate of 5% given the TFP growth rate of 3%. In this model, there are two sources of gains from trade: the standard static gains from exploiting comparative advantage and the dynamic gains from more idea flows. Columns 1 and 2 show these effects when tariffs are lowered from  $\tau = 1.54$  to  $\tau = 1.27$ . Columns 3 and 4 show the gains from moving from near autarky, where the trade share is only around 0.4%, to the baseline, where the trade share is 10.2%.

The first row in table 11 shows the static welfare gains from reducing tariffs. We calculate the static gains as the equivalent permanent gain in consumption from reducing  $\tau$  while keeping both idea flows and the distribution of productivity in the two countries fixed. The static gains from cutting tariffs in half are 6.2% for the United States and 3.6% for the rest of the OECD. The corresponding static gains from moving from autarky to our baseline tariff (implying a trade share of 10.2%) is 26.7% for the United States and 20.7% for the rest of the OECD. The second row in table 11 shows that the dynamic gains are at least as large as the static gains in all cases. The dynamic gains are even larger for the rest of the OECD than for the United States. Because the rest of the OECD is less innovative, it gains more ideas than it gives.

For comparison, the static gain for the United States implied by the Arkolakis, Costinot, and Rodríguez-Clare (2012) formula is 1.1% from moving from autarky and 3% from cutting tariffs in half (starting from  $\tau = 1.54$ ).<sup>23</sup> Clearly, our baseline model does not fall into the Arkolakis, Costinot, and Rodríguez-Clare (2012) class in which the trade elasticity is a constant parameter. In our model, trade facilitates the flow of ideas

<sup>23</sup> The Arkolakis, Costinot, and Rodríguez-Clare (2012) formula for welfare gains relative to autarky is  $(1 - \text{trade share})^{-1/(\text{trade elasticity})}$ . We use a trade elasticity of 5 based on the survey by Head and Mayer (2014).

across countries. As a result, the distribution of product quality and the comparative advantage gains from trade vary endogenously with tariffs. Recall figure 1, which plotted the distribution of relative quality across products for the United States versus the rest of the OECD. The relative quality distribution was markedly more dispersed near autarky because relative quality drifted apart when ideas did not flow as quickly between countries. As a result, the trade elasticity was only 3 near autarky, whereas it is 5 under the baseline tariff of  $\tau = 1.54$  in our model.

In addition, when going from near autarky to  $\tau = 1.54$ , the trade share initially leaps from 0.4% to 28% in our model. This is shown in the left panel of figure 5. The trade share on impact overshoots the new steady-state trade share of 10.2% precisely because of dispersed relative qualities near autarky. Applying the Arkolakis, Costinot, and Rodríguez-Clare (2012) formula to the trade share on impact, the Arkolakis, Costinot, and Rodríguez-Clare (2012) static gains are 9.8% for the United States, compared with 3.5% with a trade share of only 10.2%. As qualities converge toward each other over time in response to higher trade flows, the trade share eventually settles down to 10.2% and the trade elasticity gradually rises from about 3.8 to 4.8 (the latter is shown in the right panel in fig. 5).

Because cutting tariffs increases idea flows across countries in our baseline model, it speeds up the common steady-state growth rate in the two economies. Specifically, moving away from autarky where the trade share is about 0.4% ( $\tau \approx 4$ ) to the baseline with a trade share of 10.2% ( $\tau = 1.54$ ) boosts the steady-state growth rate by 0.62 percentage points. This is the source of the large dynamic gains in our baseline model. Similarly, in

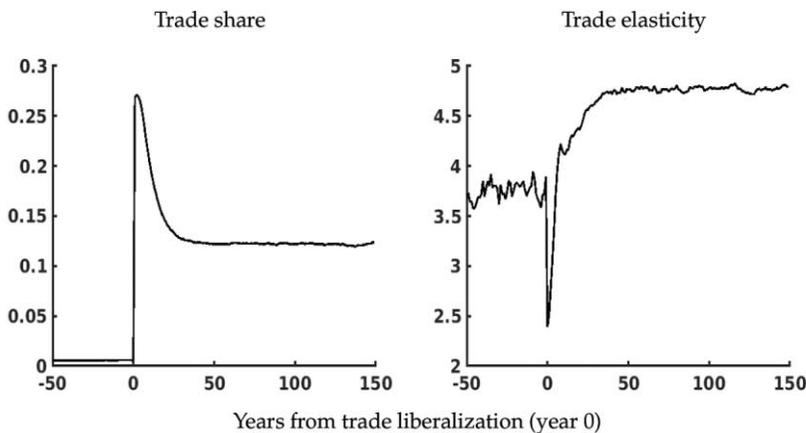


FIG. 5.—Response of trade share and trade elasticity to a one-time reduction of trade cost from near autarky to  $\tau = 1.54$ .

TABLE 12  
GAINS FROM TRADE AND IDEA FLOWS—DISEMBODIED SPILLOVER MODEL

	RELATIVE TO TRADE AUTARKY		RELATIVE TO IDEAS AUTARKY	
	United States (%) (1)	OECD (%) (2)	United States (%) (3)	OECD (%) (4)
Static gains	11.0	8.4	0	0
Dynamic gains	0	0	59.0	84.5

NOTE.—Entries give the equivalent variation change in the present discounted value of consumption in the disembodied spillover version of the model as a result of reducing tariffs from 4 to 1.54 (cols. 1, 2) or moving  $z$  and  $z^*$  inward from 0.01 and 0.99 to their baseline values of  $z = 0.147$  and  $z^* = 0.922$  (cols. 3, 4). The aggregate trade share at  $\tau = 4$  is about 0.4%. We use a discount rate of 1.9% and log utility.

the version of the model with  $\sigma = 3$ , moving from near autarky to the baseline trade share boosts steady-state growth by about 0.55 percentage points. The growth effects of trade are somewhat smaller under this parameterization because the estimated  $\kappa$  is smaller, implying fewer knowledge spillovers across countries. However, this effect is partially offset by the lower estimated  $\theta$  in the  $\sigma = 3$  case, which implies that the step size of each innovation is greater.

We are far from alone in finding large dynamic gains from trade, though our exact model and mechanisms differ from our predecessors. Sampson (2016) finds that growth is 15 basis points higher with trade than under autarky, lower than our 62 basis points. Alvarez, Buera, and Lucas (2017) obtain at least a doubling of world output from eliminating all trade costs. Buera and Oberfield (2020) calculate that about one-fifth of global growth arises due to trade, which is remarkably close to our estimate. Perla, Tonetti, and Waugh (2021) estimate that a 10% reduction in trade costs raises consumption-equivalent welfare by 11% and the long-run growth rate by 24 basis points.

In the alternative model with disembodied idea flows, the parameters  $z$  and  $z^*$  govern the spillover of ideas across countries.<sup>24</sup> For fixed  $z$  and  $z^*$ , tariffs have muted effects on welfare. Columns 1 and 2 of table 12 show the effect of moving from trade autarky to the baseline of  $\tau = 1.54$ . Here there are only the static gains from exploiting fixed comparative advantage. The static gains are 11.0% for the United States and 8.4% for the rest of the OECD in this disembodied model.

Columns 3 and 4 of table 12 show the effect of moving from (near) ideas autarky, where  $z$  and  $z^*$  are about 0.01 and 0.99 to their baseline values of  $z = 0.148$  and  $z^* = 0.922$ .<sup>25</sup> Here, moving away from ideas autarky

<sup>24</sup> Recall that these are the thresholds governing which products foreign firms learn from the United States ( $0, z$ ) and which products US firms learn from abroad ( $z^*, 1$ ).

<sup>25</sup> Recall that the steady state of the disembodied model with  $z = 0.148$  and  $z^* = 0.922$  is equivalent to that in the model where idea flows are embodied in trade and  $\tau = 1.54$ .

creates no static gains from trade for the simple reason that tariffs do not change, but it has a large effect on the flow of ideas across countries and thus on the growth rate. The dynamic gains from moving away from ideas autarky are 59% for the United States and 84.5% for the rest of the OECD. Again, the gains are larger for the rest of the world because the United States is more innovative. This table underscores that large dynamic gains can be reaped from idea flows, whether those are facilitated by trade or occur in a disembodied fashion.

## VI. Conclusion

We constructed a two-country model of creative destruction, trade, and growth. In the model, foreign and domestic firms take over each other's markets more frequently when ideas flow more easily across countries. This stimulates growth in the long run under exogenous innovation rates. We find that such dynamic gains from idea flows are at least as large as the usual static gains from trade.

We provided several strands of evidence consistent with idea flows across trading economies. First, idea flows are necessary to obtain realistic trade elasticities (and the underlying degree of comparative advantage that drives them). Second, idea flows can explain why country export composition changes across industries over time. Third, global creative destruction can explain why contracting firms are more likely to lose exports than domestic sales and why expanding firms are more likely to gain domestic sales than export markets. Fourth and finally, creative destruction can account for the dominant role of entering and exiting exporters in industry-level export growth. We document these last three patterns among manufacturing exporters in the United States, Chile, China, Colombia, and Indonesia in recent decades.

We see several possible directions for future research. One would be to generalize the sources of growth to include not only creative destruction but also new varieties and innovation by incumbent firms on their own products. Hsieh, Klenow, and Shimizu (2022) is a recent multicountry trade and growth model in this vein. As long as there are idea spillovers across countries, we conjecture that such models will continue to feature dynamic gains from trade and openness.

Another direction for future work would be to explicitly incorporate frictions to reallocating workers in response to global creative destruction. These might mitigate the dynamic gains from idea flows. A further route would be to study events such as China joining the World Trade Organization and see how this affected the extent of job reallocation and innovation. Another avenue would be to obtain more direct evidence on knowledge spillovers (e.g., the frequency of imitation of rich country producers

by developing country producers or of learning from domestic producers vs. foreign sellers in the local market).

We again stress that knowledge spillovers, either embodied in trade or foreign direct investment or disembodied, may be necessary to generate realistic trade elasticities and export dynamics at the firm and industry levels. Whether trade policy or other policies have dynamic growth benefits, however, hinges on whether the spillovers are largely embodied or disembodied.

A final direction for future research would be to model the probabilities of innovation. We held these fixed for simplicity. Endogenizing innovation rates would allow one to study optimal innovation policy in our setting. Because of domestic knowledge spillovers, national governments may find it optimal to subsidize domestic R&D. But they might not internalize knowledge spillovers to foreign producers who build on domestic innovations. The world might need a “global technical change accord” to internalize these positive global externalities, just as we need global climate change agreements to internalize negative global pollution externalities.

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