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Are international technology gaps growing or shrinking in the age of globalization?

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Abstract

This article examines changing international technology gaps over the recent period of globalization, 1972–2001, using a novel measure of technology. It evaluates each economy's technology level based on the goods it exports, considering each product's average productivity and relative quality level. The analysis reveals a growing disparity between the most- and least-sophisticated economies and a lack of intradistributional mobility. Results are consistent with a view of globalization in which emergent specialization patterns in advanced economies allow them to maintain and even extend their lead over technological latecomers, even as some developing economies are climbing up the ladder.

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1. Introduction

A central proposition in theories of economic geography and macroeconomic growth is that differences in technological sophistication give rise to uneven development (Romer, 1990; Grossman and Helpman, 1991; Krugman, 1991; Storper, 1997; Baldwin et al., 2001). Technology, meaning the rules, ideas and practices that direct the production of goods and services, spurs growth by allowing agents to produce more output using fewer inputs, and also by generating novel products (Solow, 1957; Aghion and Howitt, 1992). And while technologies might eventually be available to everyone, they are generated in specific geographical locations because of concentrations of specific human and physical capital, as well as because proximity continues to play an important role in the production of many innovations (Gertler, 2003; Storper and Venables, 2004; Rodríguez-Pose and Crescenzi, 2008). Evidence points to a complex and variegated geography of technology creation that distinguishes advanced economies from one another, both at a national and a subnational level (Lundvall, 1992; Saxenian, 1996). Perhaps the strongest distinctions, however, should arise when comparing developed to developing countries. Schematically, we hold that advanced economies innovate and push the technological frontier outward, earning monopoly rents in the process, while developing economies imitate, adapt and try to close the technology gaps that separate them from the leaders. But should international technology gaps be expanding or contracting? Can developing economies reasonably hope to join the group of technological leaders, or move, at minimum, in that general direction?

The literature is less clear on these questions, for two main reasons. First, we lack unambiguous theoretical predictions about the shape of technology gaps. Catch-up should be premised on two countervailing systematic forces. Contingent on local technological effort, comparatively unsophisticated economies can make headway in catching up to leaders if links between leader and follower economies are sufficiently rich as to diminish lags between innovation and successful imitation (Fagerberg, 1994; Keller, 2004). On the other hand, investments in technology can be cumulative. An economy whose innovative agents place it near the global frontier might reap gains from virtuous cycles of innovation that allow it to outrun the pace of imitation (Patel and Pavitt, 1994). The late 20th century intensification of economic integration – globalization – plausibly strengthens both these forces, and hence it compounds uncertainty about the contemporary shape of technology gaps. Over the last several decades, the pace and geographical scope of international trade, investment, production fragmentation and information technology have dramatically expanded, ushering in a new era of global interconnection. By linking economies ever more intensively, globalization should therefore provide enhanced opportunities for technological laggards to learn from and catch up to leaders (Keller, 1997; Blömstrom and Kokko, 1998; Girma, 2005). But integration might also be stimulating a new division of labor that establishes separate and unequal realms of competition. In one realm, technological leaders focus on rent-producing, territorially rooted production rich in tacit knowledge, while in the other, followers are locked into contestable, footloose activities subject primarily to cost-minimization (Storper, 1997; Leamer, 2007).

Second, given the acknowledged centrality of technology in explaining uneven economic development, we have surprisingly little data on technology levels. This is primarily because technology cannot be directly observed in the economy. Standard macroeconomic growth empirics, however, provide some suggestive evidence. The absence of income convergence in most robust econometric studies, as well as the weak explanatory power of factor accumulation in growth accounting models, imply that international technology levels remain highly unequal (Klenow and Rodriguez-Clare, 1997; Easterly and Levine, 2001). This is far from conclusive, however, since this work proxies for technology using total factor productivity (TFP), which is simply the residual that persists after accounting for other factors, in addition to being a black box. Other indicators of technological sophistication, including research and development (R&D) expenditures and patent counts, also point to large international technology differences, but each fails to document important categories of technological effort, especially those that we expect to be prevalent among developing economies (Bell and Pavitt, 1993; Jovanovic, 1995; Viotti, 2002). Meanwhile, rich case studies in economic geography and development studies have documented the ways in which technologically advanced regions and nations sustain their advantage, and how select latecomers have caught up (Freeman, 1987; Scott, 1993; Saxenian, 1996). From this literature, however, we cannot determine whether these cases represent intriguing anomalies or if they signify sweeping changes in the dynamics of technology gaps.

This article seeks to document changes in international technology gaps using a novel indicator of macroeconomic technology levels, *TECH*. This measure evaluates the technology level of an economy based on the products it exports. Each good is assigned an ‘implied productivity’ score, which is the weighted average of the incomes of its exporters, following Hausmann et al. (2007). The implied productivity of a good will increase as high-income economies become progressively more specialized in its export. Each economy's instance of exporting a product is then assigned a relative quality level using unit prices, following recent evidence that highlights the importance of intraproduct differentiation in international trade (Hummels et al., 2001; Schott, 2004). Finally, products' relative quality and productivity scores are combined and summed across each economy's export basket to yield their *TECH* score. I construct a measure of annual technology levels for as many as 142 U.S. trading partners between 1972 and 2001. I explore variation in this technology index in order to investigate three main questions.

(1) Have international technology gaps that separate technological leader and follower economies grown or shrunk over the recent period of globalization?
(2) What are the prospects for intradistributional mobility over the period studied: are economies 'stuck' in the relative positions in which they began or do they make pronounced leaps forward and back?
(3) Do countries at different initial levels of sophistication upgrade their technology levels in similar ways?

I report three main results. First, technology's leading edge has expanded faster than the least sophisticated economies have upgraded, consistent with a growing gap between technological leaders and followers. At the same time, the technology index also reveals a secular upward trend in technology that 'lifts all boats,' and some initially unsophisticated exporters have upgraded fairly substantially. Second, relative technology levels of individual countries are generally stable between 1972 and 2001. Most economies do not leap from one broad category of sophistication to another, and countries that began with the highest *TECH* scores are those that most improve their level of technology. Third, markedly different forces drive the performance of leaders and followers. Upgrading among initially advanced economies has been the result of reallocation within goods already exported toward those whose sophistication has grown over time, as well as through changes in relative quality. By contrast, less sophisticated economies have increased their technology levels overwhelmingly as a function of adding more sophisticated commodities to their repertoire that are new (to them). Overall, the results in this article are consistent with a view of globalization in which specialization patterns in advanced economies allow them to maintain and even extend their lead over technological latecomers, even as select developing economies move up the ladder.

This article proceeds as follows. In the next section, I review theory and empirics that examine the geographical unevenness of innovation and technological learning. In Section 3, I specify the approach taken to build my index, describe the data used and evaluate the robustness of my measure. Section 4 presents empirical results. I conclude in Section 5.

2. The geography of technology: the literature

What explains the uneven distribution of production and income across countries? The answer, for many economic geographers, economists and historians is international technology gaps (Lucas, 1988; Romer, 1990; Bairoch, 1991; Fagerberg, 1994;

Grossman and Helpman, 1994; Klenow and Rodriguez-Clare, 1997; Storper, 1997; Baldwin et al., 2001; Easterly and Levine, 2001; Fujita and Thisse, 2002). Agents in economies invest differently in technology, and find their effort differently rewarded, and these facts might explain the existence of technology gaps. Gross R&D expenditures in the USA in 2000, for example, were 500 times greater than in Chile, and they remain 28 times greater when we account for differences in population. Also in 2000, Japan took out 20 times more patents than Canada at the US Patent and Trademark Office.[1] But even if some countries are more innovative than others, does that mean that new ideas are not available for use everywhere after they are created? Should we not share a global pool of technology in today's interconnected world?

Economic geographers theorize that technological change remains a territorial phenomenon because technology has not just technical but social and organizational aspects. Technology involves rules and ideas that can be formalized in blueprints and acquired from textbooks, but also tacit knowledge sustained in shared intellectual contexts, formal and informal institutions and repeated interactions (Lundvall, 1992; Nelson, 2007). 'Being there' matters for many technological developments, inasmuch as these social dimensions are hard to sustain at a distance, even in the internet age (Leamer and Storper, 2001; Gertler, 2003). Geographically removed agents face effective exclusion from adoption and imitation because technologies, at least initially, 'cross hallways and streets more easily than oceans and continents' (Glaeser et al., 1992, 1127). Hence, much tacit and context-dependent knowledge remains spatially 'sticky,' even in a global knowledge economy that has increasingly facilitated the exchange of codified information. This stickiness creates technology gaps, reinforces agglomeration and upholds the uneven distribution of production and income.

Varied empirical scholarship supports this theory. Examinations of specific localized industries find that local context plays an essential role in the dissemination of novel and nonroutine ideas. Context can determine whether a region's agents earn monopoly rents or if they fall behind (Glasmeier, 1988; Scott, 1993; Storper, 1993; Saxenian, 1996; Lissoni, 2001). And case studies of 'innovation systems' indicate that formal and informal institutions support a platform upon which tacit ideas can be spread more easily, leading to industries with distinctly national technological bases (Freeman, 1987; Lundvall, 1992; Nelson, 1993). Econometric analyses reveal that American and European scientists typically cite patents from their home countries, and also from their most geographically proximate colleagues (Jaffe et al., 1993; Jaffe and Trajtenberg, 1999; Greunz, 2003). Moreover, the idea that R&D expenditures and other inputs into innovation generate productivity gains is much more strongly supported by evidence at a national level, rather than for individual firms (Audretsch and Feldman, 2004). We therefore have a wealth of suggestive evidence that new technologies are to a significant extent localized in regional agglomerations, as well as in national economies.

In the long run, however, individual technologies must cross borders, oceans and continents. Many technologies that rely initially on nonroutine, context-dependent tasks become increasingly standardized and codified. Their geographical specificity is exhausted, and they can be transmitted from place to place at little cost. As technology can be increasingly imitated, rents from it are bid down. Far-flung agents can effectively absorb once localized knowledge, and enter markets for goods that employ them, often

1 Author's calculations from Lederman and Saenz (2005).

competing at a lower cost (Norton and Rees, 1979). Schumpeterian competition is thus replaced by price competition (Storper and Walker, 1989).

This theory of technological spread and backwash explains the continuing importance of geographical proximity and suggests that interregional and international technology gaps are persistent features of economic development. But because it is largely focused on individual regions, and on particular technologies' procession from being placebound to footloose, the literature offers less clear predictions on the dynamics of these gaps at an aggregate level. We can, however, discern opposing and systematic forces that should, in addition to local countries' technological efforts, govern the shape of technology gaps.

Technology gaps can be diminished through contact between leader and follower economies. Greater integration between economies promotes a social congruence that aids absorption (Abramovitz, 1986; Fagerberg, 1994). Integration also provides opportunities for 'demonstration effects' that allow less-advanced economies to gain awareness of new technologies, and perhaps sufficient familiarity to attempt imitation (Barry et al., 2004; Keller, 2004). On this basis, we should expect that the pace of diffusion has significantly increased in the current period of globalization. New communication technologies introduced over the last decades of the 20th century make it easier to share ideas, and they permit the formation of new kinds of social links across space. Intensified flows of trade and investment could also help to spread technology. Under certain (and possibly quite limited) conditions, local agents become more productive when foreign multinationals enter their markets (Blömstrom and Kokko, 1998; Borensztein et al., 1998; Xu, 2000), as well as when economies engage in trade (Rivera-Batiz and Romer, 1991; Coe and Helpman, 1995). The increasing dispersal of production into geographically disparate stages might also spur innovation in developing economies, since production and innovation have historically been complements (Leamer, 2007). Therefore, integration in general should promote greater technological convergence, and the current phase of globalization provides some distinctive opportunities for its achievement.

Technology gaps might increase, however, if investments in technological change are sufficiently cumulative and localized. Evolutionary accounts of technology emphasize its path-dependent nature (Nelson and Winter, 1982; Verspagen, 1993; Arthur, 1994). Given the uneven geography of innovation, advanced regions might enjoy virtuous cycles in which one economically valuable and localized innovation leads to another. Globalization also exerts an influence on this force for divergence. Increasing integration and technological change together plausibly induce a sharpening of the geographical division of labor into two distinct and unequal realms of competition. In one, advanced economies can increasingly focus on nonroutine tasks rich in tacit knowledge, and for which they enjoy price-setting power. In the other, developing economies focus on mature, standardized production and compete based on cost-minimization (Autor et al., 2003; Grossman and Rossi-Hansberg, 2006; Leamer, 2007). This new division of labor might actually be occurring, though product differentiation and fragmentation, within individual products themselves. Research has shown that rich and poor countries are increasingly producing and trading the same kinds of goods, but varieties produced by developed economies earn systematically higher unit values than those of their poor-country competitors (Schott, 2001, 2004). Most importantly for the shape of technology gaps, the rewards from specialization in non-routine, high-sophistication activities may be such that advanced economies outrun the pace of imitation in developing countries. The deepening global division of labor may provide initial leaders with self-perpetuating technological advantages that reinforce existing gaps.

Empirical measurement should shed light on which of these countervailing forces dominates. But we lack satisfying empirics on technology gaps, primarily because technology is latent in the economy, and therefore it cannot be directly measured. Researchers have taken three main approaches to evaluating technological differences, each revealing particular dimensions of technology while obscuring others. First, scholars measure the inputs and outputs into innovation. Second, they make use of TFP. Third, they take a bottom-up approach, gauging the sophistication of individual products or industries and aggregating across products to the economy-wide level.

Inputs into innovation include expenditures on R&D or dedicated human capital. Outputs include counts of patents and new product introductions, as well as bibliometrics. As indicators of innovation, each has strengths and weaknesses that have been widely discussed (Pavitt, 1984; Griliches, 1990; Godin, 2005). But innovation and technology should not be conflated. By some estimates, R&D accounts for at most 0.5% of U.S. productivity growth (Comin, 2004), while firms in advanced economies spend 20–30 times more on adoption than invention (Jovanovic, 1995). Indicators like R&D expenditures, thereby, reveal something about ongoing formal research processes, but they say less about technological effort more generally. And they are likely to be still less useful as metrics in developing countries, where there is less innovation and scant formal R&D. Figure 1 plots gross R&D expenditures against 60 countries' per capita Gross Domestic Product (GDP) in 1995.[2] The scatterplot demonstrates that many developing and developed countries have low levels of gross expenditures, especially as compared with levels of R&D in Germany and Japan. Gross R&D expenditures remain only moderately correlated with per capita income after removing evident outliers such as Japan, Germany, France and Great Britain.[3] While broadly indicating that investments in technology vary from country to country, R&D expenditures do not provide a nuanced representation of technology gaps across a wide range of economies.[4]

Many economists favor the use of TFP as an indicator of technological sophistication, because it flows from neoclassical growth theory, and because its measurement is relatively straightforward. A number of scholars have shown that factor accumulation does not explain the observed lack of convergence in income levels and growth rates, which means that TFP must be the cause (Klenow and Rodriguez-Clare, 1997; Easterly and Levine, 2001). Studies that seek to measure TFP levels more explicitly confirm the existence of international TFP differences, but this work tends to be either cross-sectional (Hall and Jones, 1999; Harrigan, 1999) or it compares only a small handful of industrialized countries (Jorgenson, 1988; Van Ark et al., 1993; Gersbach, 1998). Nonetheless these findings point to persistent international technology dfferences, since

2 R&D data come from Lederman and Saenz (2005), who in turn get their data from the United Nations Educational, Scientific and Cultural Organization (UNESCO) Statistical Yearbook. I present data from the year 1995 because it maximizes country coverage.

3 The correlation coefficient after removing the outliers is 0.49 ($p = 0.0001$). It is 0.36 ($p = 0.0049$) when unusually high-expenditure economies remain in the sample.

4 Scatterplots using U.S.P.T.O. patent counts are even less helpful in this regard, since many developing countries do not take out any patents in many years.

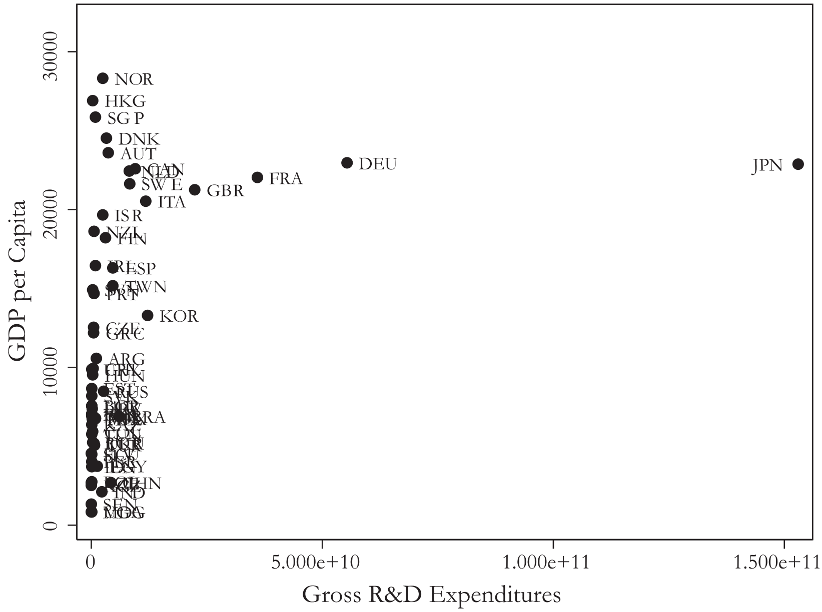

Figure 1. Gross R&D expenditure and per capita GDP in 1995, $n = 60$.

technology plays a large, if not entirely well-defined role in TFP. But these definitional problems are not minor because scholars do not agree on how to distinguish technology from other components of TFP (Prescott, 1997). Perhaps more importantly, attempts by 'growth accountants' to divide output growth into contributions from capital accumulation and technical efficiency ignore the fundamental interdependence between these variables (Maddison, 1987; Barro and Sala-i-Martin, 2004). Rather than being the sum of distinct factors like capital and labor accumulation and technical efficiency, changes in each one can spur changes in the others. The application of a new technology, for example, may require new rounds of investment in capital and labor (Nelson and Winter, 1973). Moreover, technological change may be biased toward the use of either capital or labor, not factor neutral as most growth accounting exercises assume. In this case, a new, factor-biased technology's intensive use will appear as significant accumulation of the given factor, rather than arising from a shift in technology (Abramovitz and David, 1973).

Other scholars favor bottom-up approaches that start by classifying individual products or industries according to their embodied technological sophistication. Product-level analyses provide granularity, since a 'high-technology' industry can contain a wide mix of low- and high-technology products. The computer components industry, for example, contains both experimental nanotechnology as well as the comparatively routine manufacture of computer keyboards. The central challenge with this approach is deciding on an effective and efficient manner by which to assign technology levels to products. Economists commonly use R&D intensity to rank goods. But R&D figures are typically available for only sectors or industries, not products. A recent paper by Hausmann, Rodrik and Hwang (2007) addresses this problem by combining widely available trade and income data to classify individual products on the basis of the average income level of their exporters.[5] At its most basic level, they assume that a good must be sophisticated if rich countries are highly specialized in its production. Variation in per capita income might capture both differences in productive efficiency and in the extent of Schumpeterian rents from innovation. Their measure of export 'quality' is, therefore, a promising technology indicator, and it can be practically implemented at a very fine-grained level.

Where Hausmann et al. (2007) describe interproduct variation as a source of differences in sophistication, other scholars measure intraproduct specialization, which also has some promising applications for the bottom-up measurement of technology gaps. Schott (2004) and Hummels and Klenow (2005) use unit price differences to indicate that exporters are increasingly specialized not simply in one good or another, but vertically differentiated within products themselves on the basis of quality and other factors. For example, both Italy and China produce and export *HS #6204.29.40.40*: 'women's and girl's silk trousers, containing 70% silk by weight'. We cannot directly observe that Chinese and Italian trouser varieties are produced at different levels of quality. But we can observe from US import data that the Italian trousers sell in the USA for almost six times the price of their Chinese competitors. This supports our intuition that the Italian pants are likely to be made with greater craftsmanship, to be more closely keyed to rapidly changing fashions and to benefit from sophisticated branding. If, as scholars have shown, intraproduct differentiation is a significant and growing aspect of international trade, we would like a measure that describes both inter- and intraproduct technology differences. Xu (2007) represents the first known attempt to do so, and he shows how the addition of unit price differences into the original measure proposed by Hausmann et al. (2007) challenges Rodrik's (2006) finding that Chinese exports to the U.S. are highly sophisticated relative to China's level of per capita income.

Overall, while theories of the geography of innovation and diffusion provide a integrative theory that explains the conditions under which technologies are localized and when they become less placebound, they do not provide clear expectations with regard to the shape of international technology gaps. The literature does offer two systematic forces, one pushing toward technological convergence and the other pushing away from it. Increasing global integration should strengthen both of these forces, such that the coming shape of technology gaps remains very much an open question. Moreover, existing empirics are largely not up to the task of examining the shape of technology gaps for a large sample of economies at a wide range of development levels, although some recent bottom-up approaches offer some promise.

3. Empirical framework

3.1 Construction of *TECH*

My technology index builds on two bottom-up approaches described above. Specifically, I combine the product-specific productivity measure proposed by Hausmann et al. (2007) with an indicator of unit price variation adapted from

5 Lall, Weiss and Zhang (2006) follow a similar course, but the authors use a somewhat different method, with data that is much more highly aggregated.

Schott (2004) and Xu (2007). I make three main contributions. First, I modify the measure in Hausmann et al. (2007) to account for changes in the sophistication of products themselves over time. Second, I refine Xu's (2007) relative price index to describe product quality, ensuring sufficient signal remains after eliminating noise in the unit price data. Third, I build my index using a significantly longer time series than those used in related work, which permits me to investigate long-run dynamics in the distribution. This longer period is appropriate since technological advancement is a long-run phenomenon.

TECH is a function of three product-level components:

(1) the average level of productivity, or 'revealed productivity' of the goods an economy exports, p
(2) the quality of those exports relative to those of direct competitors, q
(3) The relative importance that each good plays in an economy's overall exports, measured by each product's value share, x

Let nations, indexed by n, produce goods g at time t. Hence,

$$TECH_{nt} = [p_g, q_{ng}, x_{ng}] \tag{3.1}$$

To build an identity for the revealed productivity associated with an individual good, I calculate the average income of its exporters. Specifically, following Hausmann et al. (2007), p (or as they call it, $PRODY$) is a weighted average of exporters per capita GDP, where the weight is each exporter's revealed comparative advantage in the good being evaluated. Unlike Hausmann et al. (2007), who construct a time invariant indicator, my measure of implied productivity varies by product and year (but, like them, not by country). Hence,

$$p_g = \sum_n \left(\frac{x_{ng}}{\sum_n x_{ng}} \right) Y_n \tag{3.2}$$

where Y_n indicates a nations real per capita GDP. The numerator of the weight, x_{ng}, is the value of good g as a share of the total value of exports for country n. Its denominator $\sum_n x_{ng}$ aggregates the value shares of all the exporters of good g. The procedure of weighting incomes by revealed comparative advantage is grounded in Ricardian trade theory that predicts the specialization patterns of an economy as a function of the goods its agents produce most productively. Simply, we should expect rich countries to be highly specialized in sophisticated products, while poor economies specialize in unsophisticated goods. Revealed comparative advantage, since it is a relative measure, is also useful since it levels the playing field across countries of varying size.

Next, I construct an index of relative unit prices, q, for each good that describes each exporter's position on a product quality ladder. Unit price differences signal variation in product quality. Following Xu (2007), I compare an economy's unit price of a particular good to the unit prices of other countries' varieties of that same good, weighting the importance of prices on the basis of market share. This method rewards exporters with higher than average unit prices with a q score >1, while a score <1 denotes lower unit prices and thus substandard quality. If $s = (X_{ng})/(\sum_g X_{ng})$ is an economy's market share for good g (where X is the real value of its exports), and

$u = (value_{ng})/(quantity_{ng})$ is its exported unit price, the relative price q of its variety is given as:

$$q_{ng} = \frac{u_{ng}}{\sum_n (s_{ng} \cdot u_{ng})} \tag{3.3}$$

Traded unit prices are an imperfect measure of product quality, for a few reasons. First, unit prices can differ for nontechnological reasons, for example, as a result of factor cost differences, terms of trade effects and exogenous variations in exchange rates. While Hallak and Schott (2008), Khandelwal (2009) and Baldwin and Ito (2008) have recently sought to decompose unit prices to distinguish a few of these elements, 'raw' unit price differences are presently the only practical way to capture quality differences across time and a wide range of goods. Second, what looks like substantive quality upgrading over time could actually be the result of entry of new, low-price competition. For example, exports of Italian trousers could appear to be upgrading even if their unit price remains constant, if new Chinese varieties appear at a lower price. While we cannot directly observe the relationship between unit prices and underlying technology, the entry of a low-price competitor into the market should, all things equal, disturb the pricing strategy of higher priced exporters in a competitive market. I assume that maintenance of higher pricing indicates some form of defensive differentiation, and therefore justifies being classified as a form of 'upgrading.'

Last, I assemble *TECH* scores from quality and productivity values. The product of q and p creates a country- and good-specific value that reflects both the average productivity of the good across all exporters and the particular exporter's quality ladder position for this good. The multiplication of these terms and x weights each product's score according to the relative intensity with which it is exported. In Equation 3.4, the product of q, p, and x, summed across all goods in an economy's export basket produces a country-specific *TECH* score in a given year.

$$TECH_{nt} = \sum_g p_g \cdot q_{ng} \cdot x_{ng} \tag{3.4}$$

Overall, *TECH* estimates the level of technological advancement associated with an economy's specialization pattern.

3.2 Data description

I build an annual technology indicator for between 115 and 142 countries over the period 1972–2001, using data from two main sources. Income data, in the form of Chain-series per capita GDP, come from Penn World Table, version 6.2 (Heston et al., 2006). I use data on U.S. imports between 1972 and 2001 for product-level trade information. The U.S. Census Bureau records import information, which Feenstra, Romalis and Schott subsequently clean and compile, as documented in Feenstra et al. (2002). The database contains complete records of merchandise imports into the US from 1972 to 2001. Each record describes the import into the US of a single type of manufactured or natural resource product from a particular economy in a given year. Imports of services are excluded. From 1972 to 1988, products are identified using a seven-digit number based on the Tariff Schedule for The United States, Annotated (TSUSA). From 1989 to 2001, goods are identified using 10-digit codes based on the

Harmonized System (HS). As well as dollar-denominated customs values for each instance of importing, the Census Bureau tracks quantity, unit type, country of origin and other information. For intertemporal comparability as well as concordance with GDP figures, I adjust nominal US dollar customs values to base-year 2000 US dollars, using Consumer Price Index data from the US Bureau of Labor Statistics (Bureau of Labor Statistics, 2007).

To arrive at each good's unit price, q in Equation (3.3), I divide the customs value of a particular good by the quantity of units imported.[6] This step demands the fine-grained detail provided by 7- and 10-digit product codes, since I derive my quality index by comparing the prices of goods that are presumed to competitors, as defined by their shared code. For example, the fine granularity ensures that countries exporting *HS #7210.90.60.00* are each selling precisely the same kind of electrical-coated flat rolled steel, subject to the same competitive pressures. Applying this kind of procedure using aggregate sector- or industry-level classifications would create an uninterpretable relative price index, since sectoral or industry classes are broad enough that their constituent goods need not share a close resemblance.

Even with 7- and 10-digit detail, however, the initial distribution of relative price differences remains surprisingly wide. Inaccuracies in record keeping may explain outliers in the distribution of unit prices. An exploratory study by the General Accounting Office (GAO) finds a considerable number of errors in US import prices, and concludes that implausible values could result from data entry errors, overly broad product classifications and other problems (General Accounting Office, 1995). I take several steps to minimize these errors, since they cannot be corrected. First, because 90% of the values of the quality index are between the plausible bounds of 0.1 and 8.2, I adjust only outliers that exert undue influence on country-level *TECH* scores.[7] I set unit prices of country/product pairs whose quality scores are below the 1st and above the 99th percentile to the average unit price among all other exporters of the product. The distorting effect of outliers is then eliminated, since the exporter's q value for the product is set to 1. This method is relatively nondestructive, preserving the general effect of unit prices while avoiding severe assumptions.[8] I also set all q values for natural resource goods to 1.[9] Variability in international prices for natural resource imports should largely reflect comparative cost differences that are unrelated to technology.

6 Exporters may have multiple instances of exports of a product in a particular year. Of the 5,213,708 total records, 9% (463,761) are multiple country/product/year observations. Fortunately, multiples are in consistent unit types (for example: pounds or dozens) at the TSUSA or HS level. Hence, I collapse these instances into one observation per country/product/year, where the final unit price is a value-share weighted sum.

7 The highest and lowest varieties of a good thereby differ by a maximum factor of 82. But, the true range for any given product is likely to be smaller than a comparison of the highest to the lowest q scores. This is because a given pair of low and high scores need not correspond to the same good.

8 A very small number of unusually high, and temporally inconsistent *TECH* scores remain after this adjustment, which are uniformly the result of a single good in a highly undiversified country. I adjust the offending product's unit price to the average of its remaining exporters if either of the following two conditions are met: Condition (1): the country has either never exported this good in other years; Condition (2): the country has exported the product in other years, but it has done so within a comparatively moderate range of q scores. If neither of these conditions are met, I consider the price 'true,' and I leave it unadjusted. This process eliminates these few remaining outliers.

9 I define natural resources as goods with Standard International Trade Classification (SITC) revision 2 codes 0–4, and 9, not including 95.

I expect a good's level of technological sophistication to change over three decades, as products are rendered more or less complex. To describe these dynamics, I recalculate a good's revealed sophistication score, *p*, each year, using annual data on export shares and income.[10] Hence, the *p* value for a product that becomes progressively the focus of poorer countries will diminish, while one in which richer countries come to specialize will increase its revealed productivity. However, a product's score can also fluctuate from year to year in ways that can reflect composition effects rather than technological shifts. For example, a product's implied sophistication will bounce from high to low if it has only a few exporters that vary from one year to the next. To minimize these nontechnological effects, I smooth *p* scores using a 5-year moving average.[11]

Unlike Hausmann et al. (2007), I also maximize the number of countries in each year instead of using a balanced panel.[12] I do so for two reasons. First, US import data differ from the United Nations Commodity Trade Statistics Database (COMTRADE) used by Hausmann et al. (2007) in that they do not depend on voluntary reporting from exporters. In the data used in this study, the increasing number of countries thereby reflects actual growth in the diversity of sources of US imports, not a decline in nonreporting. Second, technology values do not appreciably differ when built from the unbalanced panel. For these reasons, I describe the sophistication of exports from 115 countries for much of the period, expanding to 142 during the 1990s.

3.3 Robustness

How does my indicator conform to our general expectations regarding the international distribution of technology? Table 1 displays the 10 most- and least-advanced countries in 1972 and 2001 according to their *TECH* scores. Leaders in 1972 are all high-income Western European economies. The least sophisticated economies include low-income South Asian and African nations. This pattern repeats in 2001, with Ireland being added to the top five. Those at the bottom are all in Africa, except Tajikistan and Kiribati. As expected, the table suggests that rich countries generally have high *TECH* scores, while poor countries do not. In fact, *TECH* and per capita GDP have an average annual correlation coefficient of 0.84. As Hausmann et al. (2007) note, however, a given economy's level of per capita GDP does not lead mechanically to their *TECH* score, despite the implication of GDP in *TECH* by construction. Independence between the two variables is, in theory, more distinct in my index, given the additional consideration of quality differentiation. In practice, however, the effect of unit prices strengthens the correlation between GDP and *TECH*, since we know from research by Schott (2004) that rich countries export goods with systematically high relative unit prices.

How does my index compare with other indicators of technology? Table 2 shows the degree of association between *TECH* and the share of students enrolled in tertiary study of social and physical sciences (Higher Education), the mean U.S.P.T.O.-filed patents

10 By contrast, Hausmann et al. (2007) create a singular, static *PRODY* score for each good as a 3-year average of the years 1999–2001, and apply this score backwards for each year between 1992 and 2003.

11 After experimenting with different smoothing methods, I arrived at the following approach: $x(t) = p = (1/5)^*[x(t-1) + 1^*x(t) + x(t+1) + x(t+2) + x(t+3)]$. This method struck the best balance between capturing trends in implied productivity, while eliminating implausible variation.

12 All exporting countries are included except member nations of the Organization of the Petroleum Exporting Countries (OPEC). Because of their unusually high GDP as a result of petroleum exports, the OPEC countries apply undue leverage on the *TECH* distribution.

Table 1. Most and least sophisticated economies, 1972 and 2001

Most advanced		Least advanced	
Country	*TECH*	Country	*TECH*
1972 ($n = 115$)			
Switzerland	21,191	Nepal	995
Sweden	17,868	Sudan	1181
Austria	17,604	Bangladesh	1302
Germany	14,996	Mongolia	1458
Denmark	13,685	Malawi	1468
Iceland	13,678	Benin	1499
France	13,388	Mozambique	1621
Canada	13,231	Chad	1706
Israel	12,904	Sri Lanka	1742
Belgium-Lux.	12,726	Togo	1782
2001 ($n = 141$)			
Denmark	36,590	Liberia	605
Austria	34,297	Sudan	951
Switzerland	30,645	Tajikistan	1460
Ireland	29,862	Chad	1636
Finland	29.246	Malawi	1752
Sweden	27,949	Burundi	1765
Malta	27,243	Ethiopia	1806
Iceland	26,324	Uganda	1864
Czech Republic	25.063	Benin	1982
Germany	24,108	Kiribati	1147

Table 2. Correlation between *TECH* and other technological measures

Measures	1990	2000
Higher education	0.72	0.64
Infrastructure	0.73	0.74
Patent	0.70	0.58
TFP (1988)	0.68	—

All coefficients significant at $p < 0.001$.

per million inhabitants (Patents), the unweighted average of population-weighted measures of internet, landline, cellular and electricity penetration (Infrastructure) and TFP.[13] My technology index displays a strong correlation with each indicator in 1990 and 2000. However, there remain important differences that pertain to their use as measures of international technology gaps. Nonlinearity in the relationship between

13 Education, patent and infrastructure measures are taken from Archibugi and Coco (2004). The 1988 TFP measure is taken from Hall and Jones (1999). In both cases, the primary advantage of these data sources is their country coverage.

TECH and the education and infrastructure indices points to the limitations of these latter measures as indicators of sophistication (or for that matter, economic growth): a highly educated populace, and similarly appropriate infrastructure are necessary but insufficient criteria for development (Criscuolo and Narula, 2008).[14] Meanwhile, the relationship between *TECH* and patents is strongly subject to the sample of analyzed countries. When I split my sample of 135 countries at the 1990 mean per capita income of $7692, the correlation for those below the mean drops to only 0.24, as compared with 0.61 for those countries above the mean. As with indicators of R&D expenditures described in relation to GDP in Section 2, patents appear to more accurately gauge sophistication among countries closer to the technological frontier.[15] The last row in the table indicates a fairly strong relationship between TFP and *TECH* in 1988, the only year for which TFP values for a large and diverse group of countries are available.

Overall, *TECH* is reasonably strongly correlated with common proxies for technology levels, but it is not mechanically so. It is impossible to distinguish which of these proxies for technology is most valid on the basis of correlations. But it appears, as expected, that *TECH* better gauges sophistication among less-developed economies, as compared with the human capital, patenting and infrastructure indicators employed here. The comparison with TFP is less clear, although the theoretical problems described earlier pose a challenge to its interpretation as a measure of technology.

The validity of my technology index as an broad, macroeconomic indicator relies on the presumption that exports reveal an economy's overall technological structure. Traded goods are widely held to be a reasonable indicator of the leading edge of domestic technological capabilities, since exports signal an economy's ability to competitively produce for the world market, while untraded or trade-protected goods may persist despite being of poor quality. Still, several limitations of existing trade data might bias the results. First, the rise of trade in intermediates within a geographically fragmented production process has occurred largely during the period studied here, growing to as much as 30% of world trade by 1995 (Hummels et al., 2001). Since we lack information on the full genealogy of a product's subcomponents, an import will be assigned a productivity values presuming that final producers have created it from start to finish. While this may not be accurate in many cases, the detailed product level data used to build *TECH* mitigate the severity of this issue by more carefully identifying components trade rather than conflating them with a final product type, which might occur at higher aggregation. Second, trade data in general, and records of US imports specifically, exclude trade in services that are of growing importance in a number of economies. While this may bias estimates, I expect that countries exporting advanced services are also specialized in the production of comparatively sophisticated commodities.

Assuming that trade is a valid basis from which to gauge technology levels, *TECH* also depends on the idea that US imports are a reasonable proxy for world trade flows. At least two main forces support the relationship between US exports and world trade patterns: the openness of the US economy and the attractiveness of its large market (Schott, 2008). At the same time, the analogy is likely to be imperfect, since bilateral

14 The same general relationship is found in scatterplots between per capita GDP and human capital, and, although to a lesser extent, infrastructure.

15 The diminished correlation between *TECH* and patents in 2000 largely reflects the increased sample of countries, which includes a larger number of developing economies.

trade volumes decline with distance (McCallum, 1995; Wei, 1996; Anderson and van Wincoop, 2004). For robustness, I build an additional version of the *TECH* index using trade data from the World Trade Flows (WTF) data set.[16] The two indices have a strong and positive relationship, with a correlation coefficient of 0.86, which lend support for the idea that exports to the USA are a reasonable proxy for world trade patterns.[17]

4. Results

In this section, I make use of annual *TECH* scores from 1972 to 2001 in order to explore the shape of technology gaps in the age of globalization. I determine if technology gaps have grown or shrunk, whether economies significantly leapfrog from lower to higher relative positions, and if countries with similar technological starting points in 1972 upgrade their technology levels in consistent ways.

4.1 Have technology gaps grown or shrunk among US trading partners?

My first research question asks whether international technology gaps have expanded or contracted between 1972 and 2001. At the beginning of the period studied, technology's geography is strikingly uneven. Of the 115 countries for which I measure technology levels in 1972, 41 are above the mean level. These 41 nations contribute 64% of the sum of *TECH* among all US trading partners in that year, yet they number 36% of the analyzed countries, and only 23% of their total population.[18] In fact, technology in 1972 appears even more concentrated in the hands of the few. The 10 most sophisticated economies have a 23% share of the sum of *TECH* across all countries, while representing only 6% of the population.

This gap between advanced and unsophisticated exporters is a persistent phenomenon. Table 3 describes the distribution of *TECH* in 1972, 1980, 1990 and 2001. Mean sophistication has steadily increased from 1972 to 2001, consistent with generalized technological progress. Median scores consistently below the mean are consistent with a scenario in which most economies start and remain less sophisticated than the world average. The standard deviation has increased, but since the mean of the distribution is nonstationary over time, this statistic is not very informative. The fourth and fifth rows of the table display averages of the top and bottom five economies' *TECH* scores. While the sophistication levels of the leading countries nearly double from 1972 to 2001, scores of the least advanced economies remain roughly stagnant. Ratios of the five highest to five lowest *TECH* scores show that the most sophisticated economies are 13 times as advanced as those at the bottom in 1972, but they become 25 times as advanced by the end of the period. The gap between these least and most

16 World Trade Flows records bilateral trade flows between over 100 countries from 1962 to 2000 at the SITC, revision 2, four-digit level (for full documentation, see Feenstra et al. (2005)). Lacking disaggregate data, I construct country-level scores without quality adjustments. Such a quality adjustment is impossible in any case, since World Trade Flows contains price and quantity data for only selected records and starting only in 1984.

17 I plot this relationship at various cross-sections in the data appendix.

18 In 1972, the total population of analyzed countries is 80% of the total world population as estimated by the US Census Bureau (3.87 billion). As countries are added to the sample over time, the total population of countries described in this analysis begins to approach the estimated world population, rising as high as 88% of the 6.15 billion people in 2001.

Table 3. Descriptive statistics for *TECH*, 1972–2001

	1972	1980	1990	2001
Mean	5784	7140	8706	10,773
Median	4514	5664	6266	8163
Standard deviation	4178	4939	6514	7729
Most sophisticated[a]	17,069	20,661	26,627	32,128
Least sophisticated[a]	1281	1555	1674	1281
Ratio of highest to lowest[a]	13	13	16	25
Coefficient of variation	72	69	75	72
Gini coefficient	0.38	0.36	0.39	0.39

[a]Average of top and bottom five observations.

advanced economies therefore grows by a factor of 1.88 over the 30-year period. Interestingly, most of this change occurs in the 1990s.[19] Together, this evidence suggests that technological differences as measured by *TECH* are substantial, and they have grown.

This suggestion of divergence between advanced and unsophisticated economies accords with evidence from the distribution of per capita incomes. However, the expansion of income gaps is larger, almost doubling as the richest countries are 33 times as rich as the poorest in 1972 and become 64 times as rich by 2001. Thus, the dynamics of the distribution of global sophistication broadly parallel, but are more constrained than that of income.[20]

The final rows in Table 3 apply common metrics of statistical dispersion to my technology index: the coefficient of variation and the Gini coefficient. The coefficient of variation is a normalized measure of the deviation of the average country from the mean of the distribution. *TECH*'s coefficient of variation will equal zero if all economies share the same level of technological sophistication, while a value approaching 100% indicates greater spread among country technology levels. The Gini coefficient ranges between zero and one, and it is typically used to measure income inequality. A Gini value of zero would mean that countries share equally in the total *TECH* available in the world, while a score of one indicates perfect technological inequality. Table 3 shows that *TECH* scores maintain a consistent and high coefficient of variation, ranging between 69 and 75%. The Gini coefficient for my technology measure is similarly invariant. These 'dimensionless' indices suggest that the scale of gaps between advanced and less sophisticated economies remain in 2001 as they began in 1972. The results in Table 3 therefore point to an expansion in the range of the

19 The year 2001 is not an outlier: the increase in the gap between the tails of the distribution starts in 1991, and progresses through the decade. The average annual ratio between 1991 and 2001 is 21. The explanation appears to be an absolute decline in the sophistication of US exports for several African and Asian economies, combined with superior upgrading among the worlds technological leaders. Moreover, the gap is not simply an artifact of a few under- or overperforming economies. The gap grows by a factor of 1.75 when we compare top and bottom 10 economies between 1972 and 2001, and by a factor of 1.4 for the top and bottom 20.

20 This may be partly by construction since p scores are weighted averages of income levels. However, the independent impact from relative prices q ensures that this difference is not mechanical.

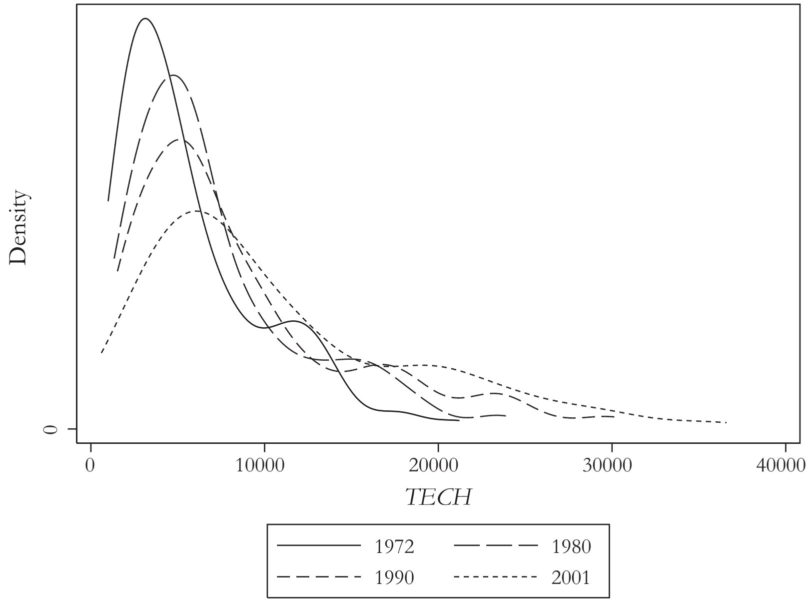

Figure 2. Absolute densities of *TECH* values, $n = 115$ (141 in 2001).

distribution of *TECH*, while countries' technology scores have remained at the same average distance from the mean, across the 30 years studied.

To clarify the morphology of *TECH*, I provide a Gaussian kernel-smoothed density plot showing results by decade in Figure 2.[21] This image can help to reconcile constant inequality levels with the growing gap between the most and least sophisticated economies. The horizontal axis of Figure 2 gauges absolute *TECH* scores, while the vertical axis describes the number of economies at a given technology level. I highlight three main results. First, the dominant peak in the distribution is found at *TECH*'s low end. By contrast, only a small number of economies appear highly sophisticated. This general imbalance holds throughout the 30-year period. Second, the positive skew evident in the distribution in 1972 has steadily increased up to 2001. This indicates that there has been significant and consistent outward expansion of the technological frontier. Third, while the club of less advanced countries remains numerically dominant, its shape has been transformed. Specifically, it has shifted from a dense peak with a steep drop-off on either side, to a wider, lower mode at a greater level of technological sophistication. The decreased height suggests that membership in the club of unsophisticated economies has steadily shrunk. The increase in the peak's breadth signifies growing heterogeneity. As well as laggard countries toward the left, this mode contains middle-sophistication economies by the end of the 1990s. By 2001, Taiwan, Hong Kong, Philippines, Malaysia as well as a number of postcommunist transition economies have upgraded their technological sophistication, and they approach the sophistication level of some OECD economies.

21 To ensure that I have not chosen anomalous years, I also generate kernel-smoothed densities using 3-year averages of *TECH* (1972–1974; 1979–1981; 1989–1991; 1999–2001). I do not report these here since the results are almost indistinguishable.

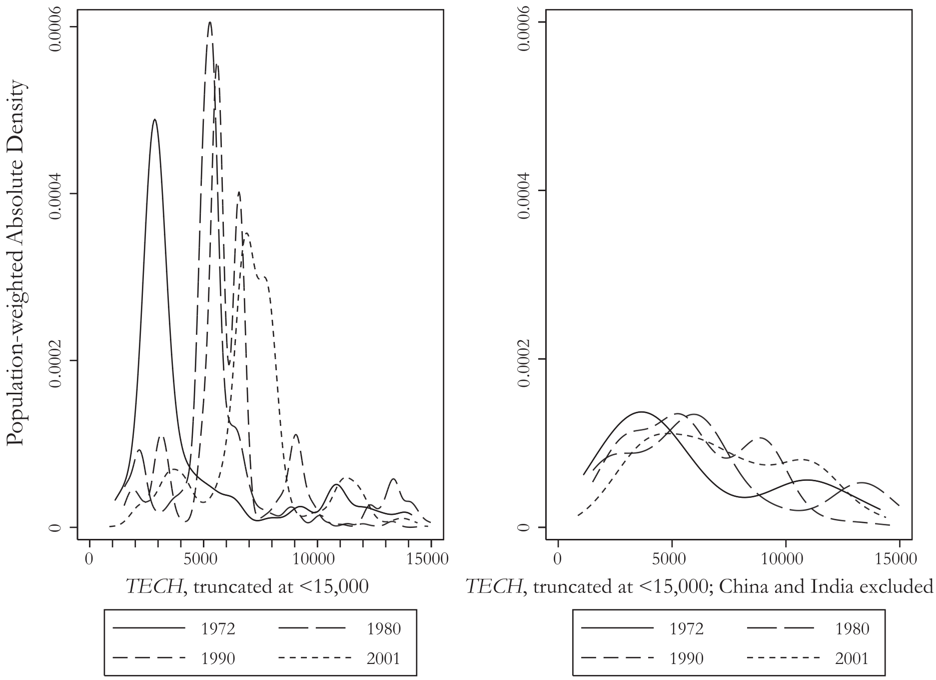

Figure 3. Population-weighted absolute densities of *TECH*, truncated sample.

This picture cannot be reduced to a story of simple technological convergence or divergence. The real gap between the most and least sophisticated economies has increased over the period, mostly as a result of expansion in technological sophistication levels at the top end. This fits the evidence shown in the middle rows of Table 1. At the same time, however, most economies with low initial *TECH* scores have upgraded the sophistication of their exports, and the changing shape of the dominant peak provides evidence that a group of moderately sophisticated countries has emerged. So, Figure 2 confirms the suggestions found in Table 3: stagnation at the very bottom, upgrading in the lower middle and significant expansion of technology levels among technological leaders.

The statistics presented thus far treat each economy as an undifferentiated point. Figure 3 shows absolute kernel density estimates that weight each economy according to its population size. I truncate results along the horizontal axis at *TECH* $\leq$15,000 to aid interpretation of the lower end, since above a threshold of 15,000 the plot generally conforms to the unweighted diagram shown in Figure 2. Figure 3 therefore focuses on the unsophisticated economies, where the bulk of the world's population resides. The left panel of the figure displays results from all economies below the cutoff. It shows that economies housing a large share of the world's population have increased their sophistication between 1972 and 2001. Moreover, the shape of the distribution changes from a single dominant mode to a bimodal, 'twin peaks' form between 1980 and 1990. In 1972, the single peak is dominated by China, India, Brazil and Indonesia, who together consist of over 50% of the population of all economies for which I have data. By 1980, Brazil accelerates out of this group, and can subsequently be discerned in smaller peaks around 6500 (1980), 9100 (1990) and 11,000 (2001). However, the other economies remain. In 1990, the emergence of a strong bimodal shape is explained by India's comparatively more rapid technological upgrading. It dominates the mode centered on 7000, while China and Indonesia remain near their scores in 1980. While each country has increased their *TECH* score, the same pattern repeats in 2001.

The right panel of Figure 3 displays the same kernel density estimates but omits results from China and India. To facilitate comparison, both panels use the same scale. This figure demonstrates to what extent the changes seen on the left are explained by the development of China and India. Lacking those giant economies, there is evidence of a modest reduction in the most unsophisticated mode and a similarly small increase in a second, somewhat less advanced club. The key finding here is that technological upgrading in the context of China and India's massive populations push forward the peak of relatively unsophisticated economies over time; however, their technological advance remains quite modest in comparison with expansion at the higher end of the distribution.

Figure 3 depends on the strong assumption that technology is evenly distributed within country populations. This assumption is suspect, especially in countries like China and India that display strong geographic patterns of income inequality. Xu (2007) investigates China's technological inequality further, noting that Chinese exporting regions — some of which have populations that exceed that of many countries — have per capita incomes that are 1.3–4.5 times higher than the national average in 2004. Nonetheless, the figure provides some sense of the effect of China and India's rise on the distribution of technology in terms of global population, even while it is overstated by distributional assumptions.

4.2 Is the hierarchy of technology stable over time?

The preceding analysis could characterize a distribution in which countries hold their relative positions over time or one in which they switch places. My second research question asks: do initially technologically unsophisticated economies remain unsophisticated in 2001? Are those countries that are technological leaders at the beginning of the period still leaders at the end? More generally, do we see intradistributional stability or churning over time?

To begin exploring these questions, I model an economy's expected technology level on the basis of its starting point and time in years. Country results are likely to be serially correlated across time, therefore I cannot satisfy the independence assumptions required for ordinary least squares (OLS). Instead, I estimate the following two-stage random effects growth model, including a first-order autoregressive structure, or AR(1), to account for intertemporal correlation within country units:

$$\begin{aligned} TECH_{nt} &= \beta_{0n} + \beta_{1n} Year + \epsilon_{nt} \\ \beta_{0n} &= \mu_0 + \tau_{00} \qquad \mu_0 \sim N(0, \sigma^2_{\mu 0}) \\ \beta_{1n} &= \mu_1 + \tau_{10} \qquad \mu_1 \sim N(0, \sigma^2_{\mu 1}) \\ & \qquad\qquad\qquad\quad Cov\ (\beta_{0n}, \beta_{1n} = \tau_{01}) \end{aligned} \tag{4.1}$$

where

β_{0n} is the intercept of country n in the initial year it begins exporting;
β_{1n} is the unique, country-specific slope;

Table 4. Random effects estimate: *TECH* growth model, 1972–2001 (standard errors in parentheses)

Variable	Coefficient
Intercept (μ_0)	6086.81
	(319.30)
Year (μ_1)	190.71
	(15.68)
τ_{00}	13,243,343
τ_{10}	27,163
τ_{01}	473,785
AR(1)	0.426

μ_0 is the average starting *TECH* score for the population of countries;
τ_{00} is the population variance among countries' initial technology levels;
μ_1 is the average rate of technology growth for the population;
τ_{10} is the population variance among country growth rates;
τ_{01} is the population covariance between growth rates and intercepts.

Table 4 presents the model's output. I find a positive, statistically significant ($p = 0.000$) relationship between time in years and *TECH*. With each additional year, the model predicts an associated increase in *TECH* of 191 (expected 30-year growth is estimated at 5730). The variance component of the estimates provides details about the stability of the hierarchy of technology. Specifically, the large conditional variance for the intercept, τ_{00}, suggests that countries begin at substantially different technology levels, which we know from the results presented in Section 4.1 above. The large conditional variance for the slope, τ_{10}, suggests that countries increase their technology levels at significantly different rates. The large covariance between growth rates and intercepts reveals that those countries with high initial *TECH* scores have the steepest slopes. The AR(1) autoregressive correlation >0.4 signals that country technology values are moderately strongly correlated across adjacent years.

The results in Table 4 provide initial evidence that country technology levels and growth rates vary markedly from one country to the next, and that levels within countries are relatively predictable in adjacent years. Most importantly, we learn that initially sophisticated economies have the highest subsequent rates of technological upgrading. All this confirms the existence of divergence in technology levels, while pointing to considerable temporal stability in relative technological positions.

To investigate further, I plot countries' initial technology levels against their levels at the end of the period in Figure 4.[22] I display two interpretive aids on this plot: a linear fit line, as well as a 45° line. Data point above the dashed 45° line have increased their sophistication in real terms. Almost all countries remain above 45°, which confirms the secular upward trend in levels of technology between 1972 and 2001 found in the random effects model. Only a handful of economies have suffered an absolute decline in their technological capabilities, and these include war-ravaged Liberia. The solid linear

22 To ensure that 1972 and 2001 are not idiosyncratic years, I graph a 3-year average of 1972–1974, against average scores from 1999 to 2001.

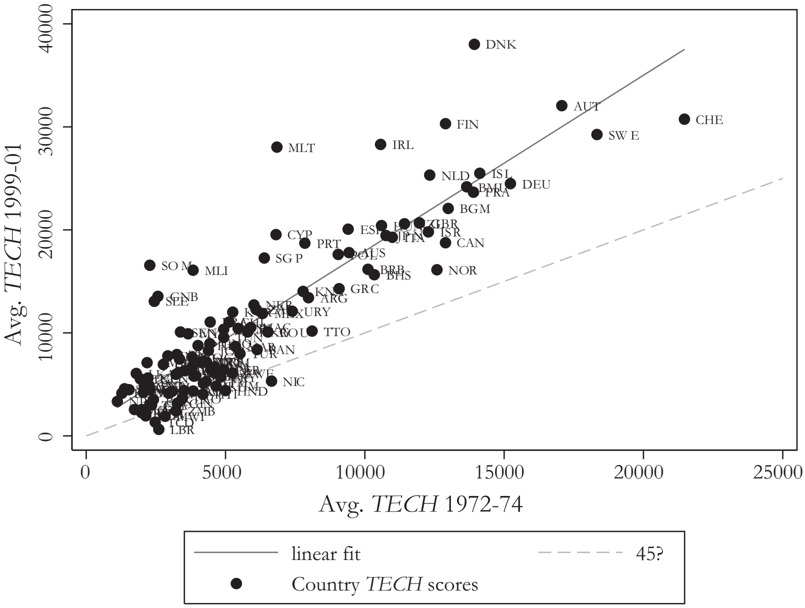

Figure 4. *TECH*, average of 1972–1974 versus average of 1999–2001.

fit line predicts a relationship between starting and ending *TECH* scores using OLS. It is thus a visual indicator of correlation. Economies directly on the linear fit line are those whose starting *TECH* score perfectly predict their level of technology in 2001. Countries below the solid line have dropped down the ladder of technological sophistication relative to their peers, while those above have leapfrogged.

Figure 4 corroborates the general story of positional stability drawn from the growth model. Starting and ending *TECH* scores are highly correlated, with a coefficient of 0.89. The strength of this relationship is clearest among countries with low and moderate initial levels of technology. These economies remain in roughly the same low and moderate positions where they began. Above an initial *TECH* score of 7000, the results are mixed. While technology in each of these nations has been significantly upgraded in absolute terms, they have larger deviations from the linear estimate. Denmark, Ireland and Finland and a few others have upgraded their export sophistication at a rate notably higher than the entire distribution's linear trend. By contrast, Switzerland, Bermuda and Germany have grown more slowly than the trend. However, even if these countries have underperformed relative to the average annual growth trend, they remain members of the club of advanced economies in 2001.

A few economies that had lower *TECH* levels in 1972 appear to have leapt forward by century's end. India and China are not among them. India and China remain very close to the regression line, around 5000 in 1972 and 10,000 in 2001. Their technological upgrading has kept pace with, but not particularly exceeded, the distribution as a whole. By contrast, Mali and Somalia have increased their *TECH* scores at a substantially faster rate than the norm, such that they rival Canada's sophistication level by 2001. This implausible result is sensitive to the number of years used to create starting and ending averages for Figure 4. More importantly, it is an artifact of these

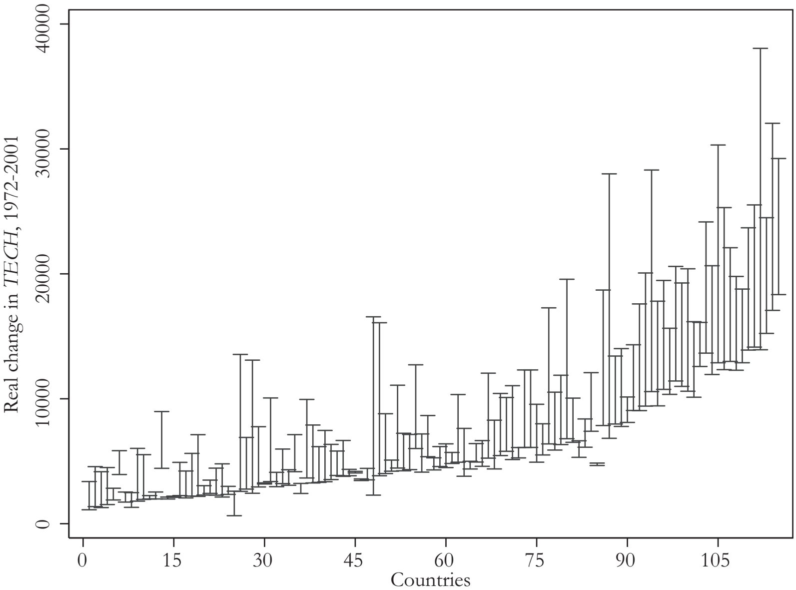

Figure 5. Real change in *TECH*, balanced panel.

countries' highly undiversified exports. A single product's implied productivity or relative quality position can distort an economy's overall *TECH* score if it occupies a large share of the country's export basket. Mali, Somalia and a few other countries only export a handful of products to the USA in each year. Results from these exporters must be interpreted with caution.

Among nations with moderate initial *TECH* scores, Singapore, Malta, Cyprus and Ireland have outperformed their peers. Malta's score appears to be largely due to its small economy's emergent specialization in electronic integrated circuits. These goods are imported to the USA at a price premium, and they account for almost half of the imports from Malta at century's end. Malta's score, like Mali's, is therefore an artifact of its lack of diversification. That is not to say that Malta's shift toward these goods does not represent an actual instance of technological upgrading, but that the country's size and the uniformity of its exports limits the usefulness of *TECH* as a measure of its level of technology.

The growth in the *TECH* scores of Ireland and Singapore, however, reflect more authentic and multifaceted shifts toward greater sophistication. Throughout the 30-year period, 75% of Singapore's US exports are focused on various kinds of machinery and transport equipment. Its focus shifts, however, from cathode ray tubes, photocells, radio broadcast receivers, diodes and transistors in 1972 to hard disk drives and other computer components by 2001. The latter compose part of a large and varied export basket, consisting of almost 2400 distinct goods.

While Singapore may be an instance of a successful leap from one 'category' of sophistication to another, Figure 4 suggests that it is among a small set of exceptions to the rule. The general trend has been to reinforce the position of initial technological leaders, while broadly maintaining the hierarchy of the distribution. Figure 5 highlights this result, by plotting starting and ending *TECH* scores for all countries for which

I have complete 30-year results. Each country represents a vertical line, with its lower bound being its starting point and its upper bound presenting its ending *TECH* score in 2001. A few economies with lower technology levels have made large gains, and some initially highly sophisticated economies have upgraded only modestly. But overall, the strongest gains are on the right side of the figure, visually confirming the strong relationship between initial *TECH* levels and subsequent technological upgrading shown in the growth model. Between 1972 and 2001, the largest real gains have been made by Denmark, followed by Malta, Ireland, Finland and Austria.

4.3 Do initially sophisticated and unsophisticated economies upgrade differently?

Although the anecdotes above provide some sense of the determinants of upgrading in Singapore, Malta and other countries, it remains hard to pin down the nature of a change in an economy's *TECH* score. This is primarily because each shift may be a function of as many as 15,000 different products exported, each subject to changes in relative quality, implied productivity and export share. Nonetheless, we want some meaningful way to account for changes in technology gaps over time. With such a method, we can determine whether high-performing economies have upgraded their sophistication in ways that unify them or if their upgrading experiences are idiosyncratic. Among late-industrializing economies, we can discern the reasons behind Singapore's comparative success, and contrast them to the less impressive upgrading of others. Furthermore, we can document the factors that have driven the expansion of China and India.

To address this third research question, I adapt a method proposed by Foster et al. (1998) to decompose year-on-year changes in *TECH* into contributions from several distinct components. Let the change in *TECH* in a given country n between years $t\text{-}1$ and t be given by:[23]

$$\begin{aligned}\Delta TECH_{nt} = {} & \sum_{g\in C} x_{t-1}p_t\Delta q_t + \sum_{g\in C} x_{t-1}q_{t-1}\Delta p_t + \sum_{g\in C}(p_{t-1}q_{t-1} - TECH_{t-1})\Delta x_t \\ & + \sum_{g\in C} p_t\Delta q_t\Delta x_t + \sum_{g\in C} q_{t-1}\Delta p_t\Delta x_t + \sum_{g\in E} x_t(p_tq_t - TECH_{t-1}) \\ & - \sum_{g\in L} x_{t-1}(p_{t-1}q_{t-1} - TECH_{t-1})\end{aligned} \tag{4.2}$$

The first two terms are 'within-effects,' in that they measure technological upgrading due to changes in sophistication within individual exported goods. The first term captures the contribution made to a country's technology level due to changes in relative quality as measured by unit prices, q, holding all else constant, for products an economy continues to export in adjacent paired years ($g \in C$). The second term similarly measures adjacent-year changes in *TECH* that are due to changes in revealed

23 Foster et al. (1998) review literature that seeks to measure productivity differences among plants in the same industry. Hence, the authors decompose a given industry's productivity level into contributions as individual plants become more or less productive and contributions as plants occupy varying market shares. In the case of *TECH*, we need a second-order decomposition: not only between changes in export shares and product characteristics but also between implied productivity and quality, within individual product values. See Appendix B for derivation of Equation (4.2).

productivity, *p*. The third term is a 'between-product' component that quantifies the effect on *TECH* of shifting specialization patterns from one consistently exported good to another. The fourth and fifth terms measure covariance, permitting the separation of between and within (*q* and *p*) effects. The fourth term describes the effect of covariance in quality and export share, holding revealed productivity constant. The fifth term measures the impact from changes in both revealed productivity and export share, holding quality constant. Sixth, the 'product entry' component measures the impact on *TECH* as an economy adds new goods that it did not export in an earlier year, holding all else equal. Seventh, the 'product exit' component explains the effect on *TECH* as an economy stops exporting goods that it exported in an earlier year, again *ceteris paribus*.

The between-product, exit and entry terms include deviations of individual country/product sophistication *pq* from the overall country *TECH* score. For the between-product term, this means a shift in export share will contribute positively only when the good toward which the economy is being refocused has an above-average level of revealed productivity. Similarly, a product's entry or exit drives a change in *TECH* only insofar as the goods added or subtracted diverge from the country's initial level of technological sophistication.

I first decompose annual changes in each country's level of technology between 1972 and 2001.[24] To get a clearer sense of the differences that separate technological upgrading performance across countries, the results from this decomposition, shown in Table 5, are grouped according to countries' starting *TECH* score in 1972. Countries in the most advanced group have initial technology levels that are more than twice the mean. The upper-middle group consists of countries with initial *TECH* scores greater than or equal to the mean and less than twice the mean. Economies in the lower-middle group have *TECH* scores below the mean and above half the mean. Those in the least advanced group have starting *TECH* scores below half the 1972 mean. These cutoffs were chosen since they broadly conform to components of the initial kernel density curve, in particular separating the high-performing economies as a distinct group, and distinguishing between laggards and latecomers, as shown in Figure 6.[25] To ensure that these groups vary meaningfully from each other, I perform a one-way analysis of variance using countries' 28-year average change in *TECH*. The test reveals that the groups have significantly different mean changes in *TECH*, with an associated p-value= 0.000. As seen in the first row of Table 5, these group differences have a notable pattern: average growth in *TECH* is positively related to initial level of technological sophistication. The remaining rows present percentage contributions for each component of the decomposition.[26]

Table 5 shows several striking results. Intraproduct quality upgrading contributes significantly to the growth of technology levels among high- and upper-middle *TECH* groups, while it plays little role among initially less sophisticated economies. As expected, advanced economy exporters appear to have differentiated themselves from

24 This range does not include the span between 1988 and 1989, since US imports switch from the TSUSA to the HS classification system between these two years.

25 Results using groups formed from initial-*TECH* quartiles did not importantly differ but were less preferable for substantive reasons.

26 I show results from a balanced panel to ensure that country-group contributions add up to 100%, though the use of an unbalanced panel does not materially change the results across all but a few terms for the Low–Middle group.

Table 5. Composition of growth in *TECH* 1972–2001, by country group[a]

	Initial *TECH* group			
	High	Hi-Mid	Low-Mid	Low
$\overline{\Delta TECH}$ 1972–2001	364.98	244.04	106.03	107.13
Components				
Quality	32%	42%	8%	10%
Implied productivity	37%	31%	33%	29%
Between-product	102%	111%	44%	−4%
Covariance *qx*	−85%	−110%	−40%	−3%
Covariance *px*	7%	−5%	−13%	−24%
Net entry	7%	30%	68%	92%
Entry	53%	122%	313%	357%
Exit	−46%	−92%	−245%	−265%

[a]High: $n=15$; Hi-Mid: $n=25$; Low-Mid: $n=39$; Low: $n=31$.

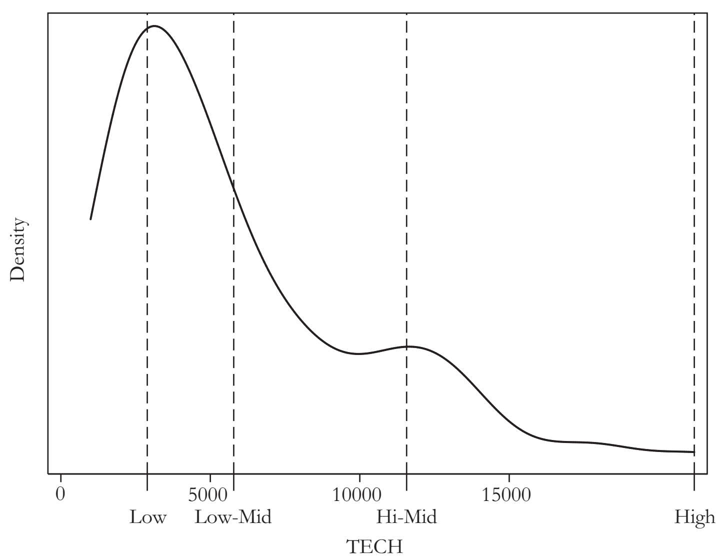

Figure 6. 1972 Kernel density plot with cutoffs by initial-*TECH* group.

developing economy competitors by refining the relative quality of their output, with significant results in terms of the growth of their overall technological sophistication. Increases in implied productivity contribute around 30% of the growth in *TECH* for all country groups. More and less sophisticated economies have each notably upgraded their sophistication levels by producing goods whose *p* scores increased between 1972 and 2001. Growing per capita incomes across the board goes some way toward an explanation. But changes in revealed comparative advantage are likely to be additional factors, since relative specialization patterns are involved in the construction of *p*.

The between-product component accounts for very large positive contributions among the two higher sophistication groups, which is then more than halved for the lower-middle group, and rendered small and negative for the group of initially low-*TECH* countries. Within consistently exported products, sophisticated economies have therefore increased their *TECH* scores the most by progressively specializing in high-quality goods or in goods that are associated with greater implied productivity, as compared with the initial country averages. Countries at lower initial technology levels have undergone notably less of this kind of reallocation within the goods they already produce. However, the entry and exit terms in the final rows of Table 4 shed more light on this issue of structural change. Over 90% of the growth in *TECH* among the least sophisticated group is the result of their emergence in markets for goods that are more advanced than the average sophistication of the products the countries already produced, as well as from their phasing out of exports of less sophisticated products. Overall, net entry (entry less exit) has a pronounced, negative relationship to initial *TECH* position. Initially advanced economies did not derive a great deal of their technological upgrading from the addition of new goods and dropping existing ones, while this source provided a large share of the upgrading in technology-scarce countries.

The first cross-term (Covariance qx) is large and negative among high and upper-middle country groups. A negative covariance can arise because exporters are exporting relatively less of a product that has undergone quality upgrading or because export shares are rising among goods whose unit prices have fallen. Close examination of product-level data for high- and upper-middle *TECH* groups reveals no clear pattern. Among products with a significant contribution to a given country's large negative cross-term, some show a rise in quality along with a decrease in export share, while others show the reverse. Moreover, advanced economies in general appear to have a small number of products with very large negative contributions to the overall covariance between q and x. In some cases, this seems to be driving the overall result, but again idiosyncratically, in terms of a dominant pattern of movement for each term. Without consistent indications, it remains difficult to tell a clear story about the cause of the large negative covariance term between quality and export share. It may, however, dampen the strength of upgrading sources described above.

The second cross-term (Covariance px) is positive and small among more advanced groups, though it accounts for an almost 25% reduction in the growth in *TECH* for the group of low sophistication countries. Unsophisticated economies had their upgrading to some extent tempered by their progressive de-specialization in goods with rising p scores, but this needs to be understood in a context in which new, more sophisticated goods were being added. This latter effect significantly overwhelms the negative covariance between p and x.

By-decade decompositions reveal notable short-run variation within the overall patterns observed above. Most notably, developing economies appear to be making inroads in advanced economies' quality upgrading advantage in the most recent decade. While full-period regularities offer a reasonable sketch of general patterns, there remains significant variation in the components of technological upgrading over time. This is a plausible result given the breadth of countries and products.

Next I consider results for a handful of particular economies. Figure 7 shows the composition of growth in *TECH* for Singapore and Taiwan. Both are East Asian 'Tigers' that experienced rapid income growth over the period studied. Singapore is among the fastest-upgrading economies, with an average annual growth in *TECH* of

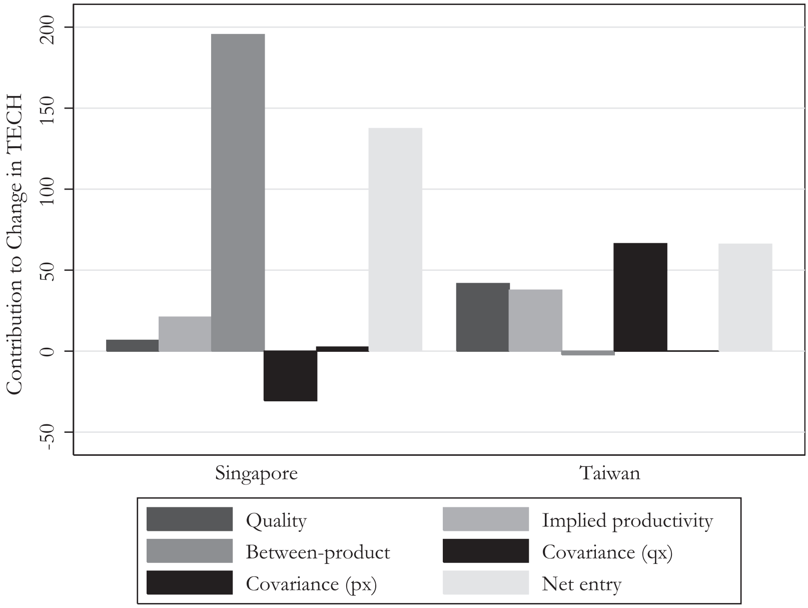

Figure 7. Composition of growth in *TECH* (1972–2001), Singapore and Taiwan.

332.3, while Taiwan's annual average upgrading registers 209.5, just above the world average of 201.3. Figure 7 reveals notable differences in each economy's upgrading pattern. For Singapore, between-product and net entry components dominate. Singapore has upgraded its level of technology by reorienting its exports towards goods that it produces at a higher quality level, or which have greater implied productivity. It has also undergone notable structural change toward new goods that enhance the overall sophistication of its export basket. Taiwan meanwhile has upgraded for a number of reasons, none of which dominate. Quality upgrading, increases in implied productivity, and the adoption of new, more sophisticated goods have each contributed in approximately comparable magnitudes to the overall change in *TECH*. As well, the positive covariance (*px*) term signifies that Taiwan has substantially upgraded by more intensively exporting goods whose implied productivity has grown.

Singapore and Taiwan's upgrading are thus driven by different factors, which point to the fact that, while broad patterns may tie together countries' performances, economic development remains somewhat idiosyncratic and uneven, as suggested by Rodrik (2000) at an international level, by Baumol et al. (1989) across sectors of a particular economy, and by authors studying the entry and exit of firms within a given industry, such as Caves (1998).

Next I turn to India and China, whose decompositions yield interesting results, shown in Figure 8. Both economies' average annual technological upgrading has not measured up to the global standard. China increased its *TECH* at an annual rate that measured only 75% of the average economy's technological growth, while India's annual rate of upgrading was a somewhat better 81%. China experienced quality downgrading among consistently exported goods, with a great deal of its growth coming as a function of net entry. The decomposition reinforces recent evidence that

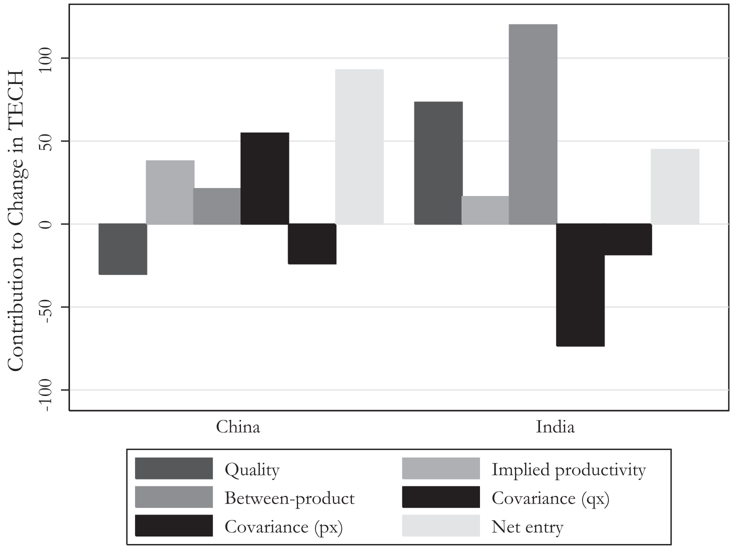

Figure 8. Composition of growth in *TECH* (1972–2001), China and India.

China produces low-quality versions of many goods also produced in advanced economies (Xu, 2007; Schott, 2008). It also echoes Amiti and Freund's (2008) finding that Chinese exports to the USA have suffered an annual price drop of 1.5% between 1997 and 2005, while their competitors' prices have dropped by an annual rate of only 0.4%. My results indicate that this tendency has roots that predate 1997. The large contribution of net entry to growth in *TECH* also accords with Amiti and Freund's (2008) analysis of HS eight-digit customs data from China Customs Beijing., which suggest that Chinese specialization patterns have dramatically shifted from agriculture and apparel to machinery and electronics. Nonetheless, as those authors note, the processing of intermediates accounts for around 50% of Chinese export in the 1990s. The overall growth in the sophistication of Chinese exports represented by *TECH*, albeit weak by global standards, may remain overstated. Overall, these results indicate that, while the value of Chinese exports have grown by triple-digit percentages over the past several decades, the expansion in China's technological upgrading has not kept pace. In India, quality and reallocation effects dominate, with some contribution from net entry as well. India's score is likely understated as a result of the absence of service trade data in the construction of *TECH*. However, it still suggests that while India is reallocating its specialization among manufactured goods toward higher sophistication products, it does not appear to be doing so at a rate that threatens the position of today's technological leaders.

5. Conclusion

Countries enjoy economic growth when their agents produce innovations and when they learn from technologies produced elsewhere. Scholars have long envisioned a technology race between advanced economies that innovate and developing economies that imitate and adopt. The dynamics of this race give shape to the income differences we observe in the global economy. Yet, despite the centrality of this technological leader-and-follower dynamic in theories of economic growth, we lack evidence about the state of technology gaps. This paper has sought to model these forces in the contemporary period of globalization, using *TECH*, a novel measure of technology. *TECH* describes countries' technology levels as a function of the products they export, considering (i) the average per capita income associated with exports of a product, (ii) the quality level of an exporter's product, relative to direct competitors, and (iii) the share that each good occupies in an economy's exports. While some similar features have been used selectively or combined in earlier analyses by Hausmann et al. (2007), Rodrik (2006), Lall et al. (2006), Schott (2008) and Xu (2007), none have put them together to shed light on long-run changes in international technology gaps.

Major findings can be summarized as follows:

(1) A large technology gap separates the most and least sophisticated economies, and it has grown between 1972 and 2001. Overall, changes in the distribution are characterized by stagnation at the bottom, moderate technological upgrading in the middle and rapid expansion of technology levels at the top. Still, the distribution of technology as a whole retains its general shape over the 30-year period, with the largest concentration of economies at the bottom and a very small number of economies near the technological frontier.

(2) Positional stability is the norm in the changing distribution of technology. Less sophisticated economies made small leaps forward and back, but generally they remain in 2001 in the same category of sophistication in which they began in 1972. Technologically advanced countries remain in their 'club', but they have achieved the most accelerated upgrading over the 30 year study period. Initial leaders have gained the most among all studied economies.

(3) Advanced economies have increased their lead primarily by increasing their relative quality position in goods they continue to export, as well as by intensively specializing in more sophisticated products. By contrast, developing countries have increased their technology level by adding new, more sophisticated goods that they did not export in earlier periods. Hence, advanced economies have taken a 'refinement' strategy, while developing countries are expanding the range of goods they can produce at a globally competitive level toward goods that demand more sophistication. At the same time, considerable heterogeneity remains within country groups and across industries in individual countries, a reminder of the multitude of idiosyncratic forces that shape each economy's pathway to economic development.

As expected, changes in the shape of technology gaps between 1972 and 2001 are complex, hinting at both dissemination effects and technological gains from specialization among leaders. The existence of dissemination effects are supported by the secular upward trend in *TECH* between 1972 and 2001. Moreover, a handful of countries have upgraded surprisingly fast, Singapore and Ireland among them. On balance, however, this hopeful picture of dispersion is outweighed by the pace of technological change at the frontier. The hypothesis put forward here has been that advanced economies are reaping the benefits of increasing returns from their greater specialization in knowledge-intensive production. Given the existing data, this point remains speculative. It would benefit from more direct analysis in the future.

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Appendix A

A. US imports and world trade

As discussed in the body of the article, my analysis assumes that US Imports are reasonable stand-in for world trade as whole. Figure 9 compares nonquality adjusted *TECH* results (*TECH* with $q = 1$ for all products) for US imports and the World Trade Flows rendering of world trade.

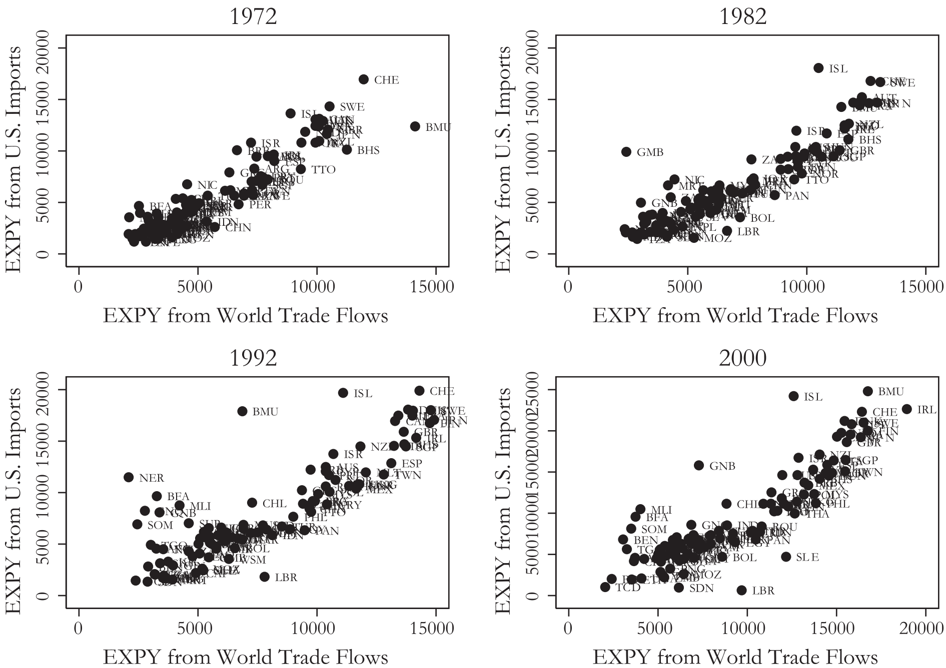

Figure 9. Scatterplots of US import and WTF-derived *TECH* scores, selected years.

Appendix B

B. Derivation of decomposition equation

B.1 Consecutively-exported products (g ϵ C)

$$\Delta TECH_{nt} = \underbrace{\sum q_t p_t x_t}_{\text{TECH}_\text{t}} - \underbrace{\sum q_{t-1} p_{t-1} x_{t-1}}_{\text{TECH}_{\text{t}-1}} \tag{B-1a}$$

$$= \sum q_t p_t x_t - \sum q_{t-1} p_t x_t + \sum q_{t-1} p_t x_t - \sum q_{t-1} p_{t-1} x_{t-1} \tag{B-1b}$$

$$= \sum p_t x_t \Delta q_t + \sum q_{t-1} p_t x_t - \sum q_{t-1} p_{t-1} x_{t-1} \tag{B-1c}$$

$$= \sum p_t x_t \Delta q_t - \sum p_t x_{t-1} \Delta q_t + \sum p_t x_{t-1} \Delta q_t + \sum q_{t-1} p_t x_t - \sum q_{t-1} p_{t-1} x_{t-1} \tag{B-1d}$$

$$= \underbrace{\sum p_t x_{t-1} \Delta q_t}_{\text{Term1}} + \underbrace{\sum p_t \Delta x_t \Delta q_t}_{\text{Term4}} + \sum q_{t-1} p_t x_t - \sum q_{t-1} p_{t-1} x_{t-1} \tag{B-1e}$$

$$= \sum p_t x_{t-1} \Delta q_t + \sum p_t \Delta x_t \Delta q_t + \sum q_{t-1} p_t x_t - \sum q_{t-1} p_{t-1} x_t + \sum q_{t-1} p_{t-1} x_t - \sum q_{t-1} p_{t-1} x_{t-1} \tag{B-1f}$$

$$
\begin{aligned}
&= \sum p_t x_{t-1}\Delta q_t + \sum p_t \Delta x_t \Delta q_t + \sum q_{t-1}\Delta p_t x_t \\
&\quad + \sum q_{t-1}p_{t-1}x_t - \sum q_{t-1}p_{t-1}x_{t-1} && \text{(B-1g)} \\
&= \sum p_t x_{t-1}\Delta q_t + \sum p_t \Delta x_t \Delta q_t \\
&\quad + \underbrace{\sum q_{t-1}\Delta p_t x_t - \sum q_{t-1}\Delta p_t x_{t-1}}_{\text{Term5}} + \underbrace{\sum q_{t-1}\Delta p_t x_{t-1}}_{\text{Term2}} \\
&\quad + \sum q_{t-1}p_{t-1}x_t - \sum q_{t-1}p_{t-1}x_{t-1} && \text{(B-1h)} \\
&= \sum p_t x_{t-1}\Delta q_t + \sum p_t \Delta x_t \Delta q_t + \sum q_{t-1}\Delta p_t \Delta x_t \\
&\quad \times \sum q_{t-1}x_t \Delta p_t + \underbrace{\sum (q_{t-1}p_{t-1}x_t - q_{t-1}p_t x_{t-1})}_{\text{Term3}} && \text{(B-1i)} \\
&= \sum x_{t-1}p_t \Delta q_t + \sum x_{t-1}q_{t-1}\Delta p_t + \sum (p_{t-1}q_{t-1} - TECH_{t-1})\Delta x_t \\
&\quad + \sum p_t \Delta q_t \Delta x_t + \sum q_{t-1}\Delta p_t \Delta x_t && \text{(B-1j)}
\end{aligned}
$$

B.2 Product entry and exit ($g \in E$, $g \in L$)

Entry and exit terms consist of deviations from the initial country-level index $TECH_{t-1}$. The product entry term considers the impact of a new product in terms of its relation to the $TECH$ value that predates it. Exit terms compare the sophistication level of the good being discontinued to the $TECH$ value from which it contributed.