Quality Differentiation, Comparative Advantage, and International Specialization Across Products

Ulrich Schetter

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Ulrich Schetter
Center for International Development at
Harvard University
Cambridge, MA 02138
ulrich.schetter@hks.harvard.edu

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Abstract

We introduce quality differentiation into a Ricardian model of international trade. We show that (1) quality differentiation allows industrialized countries to be active across the full board of products, complex and simple ones, while developing countries systematically specialize in simple products, in line with novel stylized facts. (2) Quality differentiation may thus help to explain why richer countries tend to be more diversified and why, increasingly over time, rich and poor countries tend to export the same products. (3) Quality differentiation implies that the gains from inter-product trade mostly accrue to developing countries. (4) Guided by our theory, we use a censored regression model to estimate the link between a country’s GDP per capita and its export quality. We find a much stronger relationship than when using OLS, in line with our theory.

Keywords: Comparative Advantage, Export Diversification, Nestedness, Product Complexity, Quality Differentiation

JEL: F10, F11, F14

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1 Introduction

Most products can be produced at different quality levels, allowing countries to specialize within products on quality. Indeed, richer countries tend to export higher quality versions of the same product. As an example, while you can buy an analog watch for less than a Euro on the Internet, many Swiss watches are sold at a price of several thousand Euros and Vacheron Constantin even sells its ‘Tour de l’Ile’ at a price of more than one million Euros.\footnote{For the purpose of our discussion here and below, a product’s quality summarizes all product attributes that increase a consumer’s willingness to pay for that product.} This observation is well established in the literature at least since Schott (2004).\footnote{Cf. e.g. Hummels and Klenow (2005), Pham (2008), Khandelwal (2010), Hallak and Schott (2011), Feenstra and Romalis (2014).} However, little do we know about its bearings on comparative advantage – and hence international specialization – across products. In this paper, we build on the seminal contribution of Costinot (2009a) and ask how quality differentiation affects Ricardian comparative advantage across products in a world where countries differ in their levels of economic development and products differ in their complexity.

When analyzing causes and consequences of comparative advantage across products (or industries), theories of international trade typically assume that countries compete within products by producing the exact same (or perfectly symmetric) output. Yet this is not the case with quality differentiation. The choice of quality allows firms – for a given product – to tailor their output to match the skills of workers in their country. Put differently, products that are simple in nature become skill intensive when produced at high quality in industrialized high-skill countries.\footnote{In that sense, quality differentiation may be seen as a form of ‘directed technological change’.} The ‘Tour de l’Ile’, for example, is a mechanical watch with 834 components that requires more than 10,000 hours of development and manufacturing. We argue that this endogenous control over the skill-intensity of production weakens comparative advantage across products.

To the best of our knowledge, this paper is the first to formalize this fundamental observation in a simple Ricardian model of international trade. We show that quality differentiation has profound consequences in this context: (1) It allows industrialized countries to be active across the full board of products, complex and simple ones, while developing countries systematically specialize in simple products, in line with novel stylized facts. (2) Quality differentiation may thus help to explain why richer countries tend to be more diversified and why, increasingly over time, rich and poor countries tend to export the same products. (3) Quality differentiation implies that the gains from international specialization across products mostly accrue to developing countries. (4) Our theory motivates the use of a censored regression model to estimate
the link between a country’s GDP per capita and the quality of its exports. Following this approach, we find a much stronger relationship than when using OLS, in line with our theory.

We start our analysis with reconsidering international specialization across products in Section 2. Under the standard presumption that – on balance – industrialized countries are relatively better at making complex products, we should expect to observe a (noisy) ladder of international specialization, with industrialized countries specializing in complex products and vice versa (Costinot, 2009a). Yet, while international specialization is indeed systematically related to countries’ development and products’ complexity, the data does not point to a ladder of international specialization, but rather to an ‘upper-triangular pattern’. In particular, we document first the well-known fact that richer countries tend to be more diversified, even when controlling for their total GDP. Second, we show that – on balance – complex products are exported by fewer countries. Most importantly, we consider thirdly countries’ five most and least complex significant exports as a function of their GDP per capita. As we show, the average complexity of a country’s five least complex products is not systematically related to its GDP per capita. As opposed to that, a country’s five most complex products are – on balance – the more complex the richer the country. Hence, while rich countries successfully export both simple and complex products, poor countries tend to be systematically excluded from exporting the complex products. This is true in the cross section of countries, but also supported – albeit less strongly – by variations within countries over time.

We show that quality-differentiation within products can help explaining this upper-triangular pattern of international specialization across products. To take this point home, we consider a Ricardian model with many countries, many products (or industries) and free trade following Costinot (2009a), which we outline in Section 3. Countries differ in one reduced form parameter only, which we call a country’s skill level (of its labor), for concreteness, but which can be interpreted as reflecting anything that promotes a country’s economic strength such as institutions or technologies. Products differ in their difficulty of production. The key novelty of our set-up is that this difficulty has two components: the product-intrinsic complexity and the endogenously chosen quality. High skill countries have a comparative advantage in difficult products, because the skill-intensity of production increases with its difficulty. At a formal level, we assume that productivity is strictly log-supermodular in the skill level of labor employed and the difficulty of production, and that this difficulty is increasing in a product’s complexity and its quality. In the absence of quality differentiation, this gives rise to a ladder of specialization of countries on products, i.e. high-skill countries specialize in complex products and vice versa (Costinot, 2009a).

\footnote{An upper-triangular pattern of international specialization was originally observed in Hausmann and Hidalgo (2011) and Bustos et al. (2012). We discuss their findings and how our stylized facts differ at the end of Section 2. There, we also discuss the relation to the stylized facts in Sutton and Trefler (2016).}
This changes, however, if we introduce an endogenous choice of product quality into our model. Then high-skill countries can successfully compete for simple products by producing high quality, and across-product specialization is replaced by within-product specialization. Formally, we assume that quality upgrading is more demanding for more complex products, and show that quality differentiation weakens the strict log-supermodularity of productivity and may even entirely offset it. We show this first by considering the motivating example of an O-ring technology following Kremer (1993), but with an endogenous choice of quality, and then by considering a generalized production technology. We use the generalized production technology to derive conditions for when quality differentiation exactly offsets comparative advantages across products, and provide suggestive evidence in support of these conditions in Section 5.2. The basic intuition is simple: quality differentiation is a form of ‘directed technological change’ that allows firms to tailor their output to better match the skill levels of workers in their country. Quality differentiation therefore assimilates the difficulty of production within countries across products.

Does this rationale imply that there are no comparative advantages across products? Our answer is no. The reason for this is the existence of minimum-quality requirements. These minimum-quality requirements arise from different sources. Every product has product-intrinsic functional minimum-requirements. Referring to the watch example, even the cheapest version of a watch requires a balance wheel (pendulum), a spring, and a suspension of reasonable quality, and these parts need to be assembled in a reasonably accurate manner for the watch to serve its intended purpose. Similarly, banknotes and computer software certainly have to meet minimum requirements in terms of security, air beds and glass in terms of resistance, photo lenses and clinical diagnostics in terms of precision, and autopilots and refrigerated trucks in terms of reliability. Yet (stricter) minimum-quality requirements are also often introduced by law. Many products sold within the European Economic Area, for example, have to bear the CE mark indicating that they conform to European product requirements.5

The crucial observation is that satisfying these minimum-quality requirements is more demanding for complex products than for simple ones. Producing a functional air bed is certainly less of a challenge than producing an autopilot that can safely navigate you through Mexico City’s traffic snarl. Minimum-quality requirements thus impose critical restrictions on the specialization of countries on quality, and they give rise to an upper-triangular structure of comparative advantages across products. While high-skill countries can always compete by producing high quality, minimum requirements prevent low-skill countries from successfully competing for complex products. Products like aircrafts and high-tech machines are just too difficult to produce,

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5Minimum-quality requirements may also implicitly arise from the competitive fringe. In particular, high-quality competition may imply that low-quality providers cannot cover their variable cost of production and are therefore forced to exit (Aizcorbe and Kortum, 2005; Sutton, 2007).
even in a functional minimum-version. In our model, we reflect such requirements by introducing a minimum-quality that is normalized to 1 for all products. Importantly, however, while we introduce such a strong form of minimum-quality requirements for ease of presentation, our insights equally apply to a set-up with a weak form of such requirements, where a lower quality has a stronger negative effect on the value of a product once quality is below a certain threshold.

In the remainder of the paper, we analyze implications of this pattern of comparative advantages. To highlight the novel effects that arise from our framework, we revert to the O-ring technology where quality differentiation exactly offsets comparative advantages across products. In Section 4, we consider equilibrium trade flows. We show that the upper-triangular pattern of comparative advantages translates into an upper-triangular pattern of international specialization across products if there are sufficient skills in the global economy. We derive a recursive condition for sufficient skills in the global economy. This condition is satisfied if for every level of complexity there is greater global supply of workers that are sufficiently skilled to handle this complexity than global demand for labor in all products of at least this level of complexity. Whenever this is the case, some high skilled labor must be employed in simpler products and the unique equilibrium is one where wages just offset absolute advantages of higher skilled workers in the simplest products. Importantly, the upper-triangular pattern of international specialization is not only consistent with our stylized facts from Section 2, but it also provides an intuitive explanation why richer countries tend to be more diversified and why the share of products that are co-exported by rich and poor countries tends to increase over time.\(^6\) As countries develop, they are less affected by functional minimum-requirements, allowing them to be competitive in additional, more complex products.\(^7\)

We discuss further implications in Section 5. We first show that in our Ricardian model gains from inter-industry trade mostly accrue to developing countries. This is reminiscent of the textbook 2-countries, 2-products case where one country is large such that it makes both products in equilibrium and therefore does not gain from international trade. We show, however, that quality differentiation can give rise to a similar result in a Ricardian world with many countries and products following Costinot (2009a) – a world where this is not the case in the absence of quality differentiation. More specifically, we show that with common homothetic preferences across products the gains from trade are inversely related to a country’s skill level.

We finally show that our work has implications for the empirical literature analyzing the link between a country’s economic development and the quality of its exports. If low-skill countries

\(^6\)Cf. Schott (2004) and Pham (2008), for example. China is an important driver of this development (Pham, 2008).

\(^7\)Note that when making this observation, Schott (2004) classifies countries as rich and poor based on a comparison with the cross-section of countries.
cannot successfully compete for complex products because they are bounded by a minimum-quality constraint, then this information could – and should – be exploited in an empirical analysis of the link between a country’s GDP per capita and the quality of its exports. We show that our theoretical set-up rationalizes the use of a censored regression model. Taking this model to the data, we observe a much stronger link between a country’s GDP per capita and the quality of its exports than when using OLS, and this link is not systematically related to product complexity, as to be expected according to our theory.

Relation to the literature

Our work contributes to several strands of literature. It complements a growing literature that studies various aspects related to quality upgrading in international trade. Flam and Helpman (1987), Stokey (1991), Murphy and Shleifer (1997), and Matsuyama (2000), for example, consider non-homothetic preferences for quality in models of North-South trade to study product cycles and the gains from trade, among others. More recently, Baldwin and Harrigan (2011), Kugler and Verhoogen (2012), Johnson (2012), Hallak and Sivadasan (2013), Benedetti Fasil and Borota (2013), and Flach and Unger (2018), for example, integrate quality into trade models with firm-level heterogeneity to derive richer predictions on the exporting behavior of firms and countries. Yet none of these strands in the literature addresses the implications of quality differentiation for comparative advantages and hence international specialization over a heterogeneous set of products, which is the main focus here.

These implications are the topic of only a few papers. Alcalá (2016) presents a model with firm-level heterogeneity to study specialization within and across a heterogeneous set of products. He considers the case of ‘quality-biased efficiency’, i.e. more productive firms optimally choose higher quality. Then, quite intuitively, conditional on wages and trade frictions coun-

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8 Auer et al. (2018) also consider non-homothetic preferences for quality in a North-South trade model to study firms’ pricing decisions and how they are affected by interactions between quality and consumers’ income.

9 It is sometimes argued that whether competition happens within or across products is an arbitrary aspect of how trade data is organized. It is therefore worth noting that in our model there is a clear conceptual difference between these two dimensions: Products represent different consumption needs of households while qualities of a given product represent different means of satisfying the same need.

10 Fajgelbaum et al. (2011), Jainovich and Merella (2012), and Dingel (2017) study horizontal and vertical product differentiation in models with non-homothetic preferences, but they do not analyze how vertical differentiation feeds back into the specialization across products. Jainovich and Merella (2012) show how differences in the scope for quality upgrading of products can lead to income divergence when aggregate productivity increases in a model of North-South trade. Fajgelbaum et al. (2011) prescind from technological differences and study trade driven by home-market effects. Their model provides a demand-sided rationale explaining why richer countries export higher quality. Dingel (2017) augments this model with heterogeneous types of workers and distinguishes specialization driven by home market effects versus factor-endowments. In his model, higher skilled workers are relatively better at producing higher quality, similar to our set-up. In his model, however, as in Fajgelbaum et al. (2011) – the horizontal product differentiation arises from random demand shocks, i.e. this model does not speak to comparative advantages and international specialization over a heterogeneous set of products (or industries), which is our main focus.
tries export higher quality in industries for which they have a revealed comparative advantage. Jaimovich and Merella (2015) analyze quality upgrading in a model with non-homothetic preferences that satisfy the Armington Assumption. They consider random differences in the scope for quality upgrading at the country-product level, which in their set-up implies that the specialization of countries across products intensifies as the world becomes richer and consumers demand higher quality. In both papers, technological differences between products or industries relate only to the scope for quality upgrading.

Both our focus and the main implications are different. We analyze how fundamental country and product characteristics shape comparative advantage in the presence of quality differentiation. We start from Costinot (2009a) and consider a Ricardian trade model where comparative advantage is driven by a complementarity between the skill level of a worker and the difficulty of production. The key novelty of our set-up is that the difficulty of production is increasing in the exogenously given complexity and the endogenously chosen product quality. Quality upgrading is more demanding for more complex products, implying that firms in a given country upgrade quality less for more complex products.\footnote{\textsuperscript{11}Country- and product- specific scopes for quality upgrading have previously been considered in the literature, Khandelwal (2010), Jaimovich and Merella (2012), and Kugler and Verhoogen (2012), for example, also model product-specific scope for quality upgrading. Khandelwal (2010) presents empirical evidence in support of this modeling choice. In Jaimovich and Merella (2015), the ability of a country to upgrade quality of a given product is randomly drawn. As opposed to that, in our model the scope for quality upgrading is systematically related to a country’s skill level and a product’s complexity: Higher skilled countries are better at upgrading quality, and quality upgrading is more demanding for complex products.} In turn, this assimilates the difficulty of production within countries across products and thus attenuates comparative advantages. Importantly, while our main focus is on international trade, similar forces may well be at play in other contexts, and our work may thus add a relevant perspective to the broader literature following Costinot (2009a) that is centered on the assumption of log-supermodularity and then analyzes comparative advantages and patterns of specialization in various contexts, e.g. Costinot and Vogel (2010); Sampson (2014); Costinot and Vogel (2015); Grossman and Helpman (2018); Gaubert (2018); Davis and Dingel (2020).

In the presence of functional minimum-requirements, quality differentiation can explain why industrialized countries successfully compete for both simple and complex products while developing countries tend to systematically specialize in the simpler ones. Our work thus also speaks to the literature analyzing how the (export) diversification of countries changes with their income. The empirical literature on this issue is somewhat inconclusive regarding whether there is a monotonic (De Benedictis et al., 2009; Parteka and Tamberi, 2013) or hump-shaped relationship (Imbs and Wacziarg, 2003; Cadot et al., 2010). In either case, countries’ diversification tends to be increasing over a broad range of income levels. On the theory side, Sutton

\footnote{\textsuperscript{12}Note that we do not take a stand on how consumers value a given quality of one product relative to the same quality of some other product.}
and Trefler (2016) present a model with a hierarchy of countries and products. Countries develop into higher order products by gradually building up the capability to produce high quality. Their model gives rise to an inverse U-shape of specialization across products where the built-up of new capabilities initially allows countries to diversify into new products and where at later stages the associated labor-cost effect drives them out of business in low-order products. Our theory is closer to Hidalgo and Hausmann (2009) and Hausmann and Hidalgo (2011), who provide an alternative rationale for an upper-triangular pattern of international specialization over products that differ in their complexity. They suggest that there exists a large set of non-tradeable capabilities and that products differ in their capability requirements. Countries can then naturally make products in accordance with their capabilities. They do, however, not analyze the implications of their model in the general equilibrium of international trade which will be our focus here. We show how quality differentiation can support an upper-triangular pattern of international specialization even under the plausible assumption that high-skill countries – countries with many capabilities in Hidalgo and Hausmann (2009); Hausmann and Hidalgo (2011) – have a comparative advantage for complex products – products that require many capabilities. We further derive a recursive ‘sufficient skills condition’ that needs to be satisfied for an upper triangular pattern to emerge in equilibrium, be it with or without such comparative advantages.

Our set-up also has interesting implications for empirical strategies to estimate the link between a country’s GDP per capita and the quality of its exports. We detail these implications and the associated literature in Section 5.

2 Motivation and stylized facts

We introduce quality differentiation into a multi-country, multi-product Ricardian model following Costinot (2009a) and demonstrate how it attenuates and potentially even offsets comparative advantages across products. Our theory gives rise to an upper-triangular pattern of international specialization, in contrast to the ladder-pattern that the complementarity between skills and complexity would predict in the absence of quality differentiation (Costinot, 2009a). To motivate our set-up, we therefore present three simple stylized facts that indeed point to an upper-triangular pattern of international specialization. First, richer countries tend to be more diversified. Second, complex products tend to be significantly exported by fewer countries. And third, rich countries tend to successfully export both simple and complex products, while poor countries tend to systematically specialize in the simpler products.

Throughout, we consider international specialization at the extensive product margin, limiting attention to countries’ significant exports. We rank countries by their GDP per capita in pur-
chasing power parities, and products by four different measures of complexity found from the literature: First, a measure of required on-the-job-learning for a worker to become fully productive, taken from Costinot (2009b). Second, a measure of intermediate input diversification, taken from Levchenko (2007). Third, a measure of the non-routine content of jobs in a given industry, based on Acemoglu and Autor (2011). And fourth, a measure of the skill-intensity of production. These four measures are available at different levels of disaggregation, using differing industry-classification standards. We match H0 product codes at the six-digit level to these measures and then summarize the trade data at the level of disaggregation of the respective measure of complexity. Details are provided in Appendix A.

We use data on GDP per capita and population from World Bank (2017) and trade data from Centre d’Etudes Prospectives et d’Informations Internationales (CEPII) (2013), which reports bilateral trade data for more than 200 countries at the HS6 classification level for the period from 1995 to 2011. From this dataset, we exclude countries with less than 1m inhabitants in 1995. We then sum a country’s exports across all destinations. To get a scale-independent criterion for connecting countries to products, we consider a country to be a significant exporter of a product if (a) its exports to GDP are at least 50% of the world’s exports to GDP of the same product. To reduce noise in the data, we further require (b) that a country’s global annual exports of a product amount to at least USD 1m. In our cross-country specifications, we use data for 1995, which is within the range of years of the data underlying our proxies for product complexity. We present various robustness checks in Online Appendix D.

**Stylized fact 1: Diversification of countries**

We begin by reconsidering the diversification of countries: the number of products exported. Table 1 reveals that, on balance, countries with a higher GDP per capita tend to be more diversified, controlling for their population size. This is true at the 6, 4, and 2 digit level of HS product classification.

Note that this is not a pure ‘gravity effect’ operating via total GDP: For each specification considered in Table 1, the coefficient on \( \ln(GDP/cap) \) is greater than the one on \( \ln(Population) \), and this difference is significant, i.e. richer countries are more diversified even when controlling for total GDP.\(^{14}\)

\(^{13}\)The relationship between income per capita and (export) diversification is analyzed in several papers – see literature review for a discussion. This literature is somewhat inconclusive regarding whether there is a monotonic (De Benedictis et al., 2009; Parteka and Tamberi, 2013) or hump-shaped relationship (Imbs and Wacziarg, 2003; Cadot et al., 2010). Our main focus here is somewhat different: We document that rich countries tend to be active across simple and complex products while poorer countries tend to systematically specialize in the simpler products (see stylized fact 3 below).

\(^{14}\)This observation is in line with the work by Hummels and Klenow (2005) who show that the extensive margin of a country’s exports is more important for richer as opposed to larger economies.
Table 1: Diversification of countries

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>1.25</td>
<td>1.01</td>
<td>0.62</td>
</tr>
<tr>
<td>(0.08)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ln(Population)</td>
<td>0.59</td>
<td>0.40</td>
<td>0.16</td>
</tr>
<tr>
<td>(0.08)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p(\beta_1 = \beta_2)$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.69</td>
<td>0.61</td>
<td>0.44</td>
</tr>
<tr>
<td>N</td>
<td>135</td>
<td>135</td>
<td>135</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the diversification of countries at the 6-, 4-, and 2-digit HS level on ln(GDP/cap), ln(Population), and a constant term. A country’s diversification is defined as the number of products that it significantly exports. P-values in the third to last row refer to a Wald test of equality of the coefficients of ln(GDP/cap) and ln(Population). Standard errors are displayed in parentheses. * $p < .10$, ** $p < .05$, *** $p < .01$.

Stylized fact 2: Ubiquity of products

The second stylized fact refers to the ubiquity of products: the number of countries exporting a given product. Figure 1 plots the ubiquity of a product against its complexity for each of the four proxies. It reveals that, on average, more complex products are exported by fewer countries.

Stylized fact 3: Richest and poorest exporters by product / most and least complex exports by country

While the previous two simple facts are consistent with an upper triangular structure of international specialization, they do not necessarily contradict a ladder. In particular, we may think that the lower ubiquity of complex products is due to a ‘size effect’. Complex products are exported by richer countries. As, ceteris paribus, richer countries are also larger in economic terms it may seem natural that the products they specialize in, i.e. the complex products, are exported by fewer countries. We therefore consider the richest and poorest exporters of a product next.

In Figure 2, we locate products in a graph with complexity on the horizontal and ln(GDP/cap) on the vertical axis. For each product, a red dot (blue cross) indicates the average ln(GDP/cap) of the five richest (poorest) exporters of that product. Interestingly, while the average ln(GDP/cap) of the five richest exporters of a product is virtually constant across the full board of products, ranging from the simplest to the most complex, the average ln(GDP/cap) of the poorest countries exporting a product is increasing with its complexity. This suggests that while rich countries successfully compete for both the complex and the simple products, poorer countries tend to be competitive for the simpler products only.
Figure 1: Ubiquity of products

(a) Required learning  (b) Intermediate diversification

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Ubiquity is defined as the number of countries that are significant exporters of a product. Each dot represents a different product according to the level of disaggregation of the respective measure of complexity.

A potential caveat with Figure 2 is that the top line may be driven by a few large and rich countries that – due to their size – export many products. We therefore consider the flip side of Figure 2 next. Figure 3 locates each country in a graph with $\ln(GDP/cap)$ on the horizontal and complexity on the vertical axis. For each country, the red dot (blue cross) now indicates the average complexity of the five most (least) complex products exported. This figure confirms that rich countries indeed export both simple and complex products while poorer countries tend to systematically specialize in a subset of these products, the simpler ones.

Interestingly, this pattern of international specialization not only emerges in the cross-section. Countries, as they develop, also tend to start exporting more complex products while still being active in simpler products. In Table 2 (Table 3), we consider the within-country variation of the average complexity of the 5 least (most) complex products over time. To exclude countries
that are already active across the full range of products at the beginning of our sample period, we limit attention to countries with below-median GDP per capita in 1995. This analysis supports the view that, along the growth path, countries do indeed divert into more complex products with little impact on their activities in the simpler ones. In particular, in our main specification using country fixed effects only the coefficient on ln(GDP/cap) is positive and significant at the 1% level when considering a country’s 5 most complex products (Table 3) and close to zero and – with the exception of the intermediate input diversification – no longer

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Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different products according to the level of disaggregation of the respective measure of product complexity. For each product, the blue cross (red dot) indicates the average log GDP per capita of the 5 poorest (richest) significant exporters of that product.
Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different countries. For each country, the blue cross (red dot) indicates the average complexity of the 5 least (most) complex products that it significantly exports. Only countries with significant exports in at least 10 product categories have been considered.

significant at any conventional level when considering a country’s 5 least complex products (Table 2).\textsuperscript{16}

Our cross-sectional plots are related to stylized facts previously shown in the literature. Schott

\textsuperscript{16}When including year fixed effects, the estimated coefficients on \( \ln(GDP/cap) \) are – with the exception of the non-routine content of tasks – no longer significant in Table 3 as well. Recall, however, that the complexity scores of different products are not time varying. That is, the complexity of a country’s 5 most or least complex products can change only if its product mix changes. This is precisely what we are interested in, and in particular in the complexity up- and downgrading of a country along its growth path, irrespective of the growth of other countries (see also the discussion in Section 4.3). This is captured by the regressions using country fixed effects only. As opposed to that, when including country and year fixed effects, we have a ‘diff-in-diff’ estimator. That is, the coefficient on \( \ln(GDP/cap) \) in Table 3 is positive if countries that grow faster than the average country in our sample upgrade more the complexity of their 5 most complex products.
Table 2: Average complexity of 5 least complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Interm. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>-0.02</td>
<td>-0.01</td>
<td>-0.00</td>
<td>-0.00</td>
</tr>
<tr>
<td>(0.01)</td>
<td>(0.02)</td>
<td>(0.02)</td>
<td>(0.01)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>Year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Country FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>N</td>
<td>1,075</td>
<td>1,148</td>
<td>1,148</td>
<td>1,112</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 least complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.

Table 3: Average complexity of 5 most complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Interm. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>0.07***</td>
<td>0.10***</td>
<td>0.06***</td>
<td>0.06***</td>
</tr>
<tr>
<td>(0.02)</td>
<td>(0.04)</td>
<td>(0.04)</td>
<td>(0.01)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>Year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Country FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.06</td>
<td>0.14</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>N</td>
<td>1,075</td>
<td>1,148</td>
<td>1,148</td>
<td>1,112</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 most complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.

(2004) and Sutton and Trefler (2016) demonstrate that products are often co-exported by rich and poor countries. Sutton and Trefler (2016, Fig. 4-6) further show an upper-triangular pattern in a ‘country-country’ graph with the poorest exporter on the horizontal and the richest exporter on the vertical axis. Our ‘product-country’ graph is different in important ways: First, we show that all products tend to be successfully exported by at least some rich countries. In terms of the figures shown in Sutton and Trefler (2016), this suggests that all dots should be aligned around a horizontal line at the top of the figure, which is indeed true for the majority of dots.\footnote{Note that there is an important difference between our approach to treating a product as a significant export and the approach followed in Sutton and Trefler (2016). We normalize exports by country size \textit{and} by industry size. As opposed to that Sutton and Trefler (2016) normalize by country size (total exports) only. As rich countries tend to have large total exports, this may imply for products with a small global market that a rich country is not a significant exporter of that product according to the Sutton and Trefler (2016) threshold} Second, we show that poor countries tend to be excluded from exporting
some products,\textsuperscript{18} and, most importantly for our purpose, that this is systematically related to countries’ GDP per capita and products’ complexity. The fact that we arrange countries and products according to these proxies is also a key distinguishing feature between our graphs and the graphs in Hausmann and Hidalgo (2011) and Bustos et al. (2012), who show a ‘nested’ pattern of international specialization, but when ordering countries by their ‘diversification’ and products by their ‘ubiquity’, which makes it more difficult to interpret this pattern.\textsuperscript{19} Moreover, we document that a similar pattern also emerges within countries over time.

In summary, our stylized facts are seemingly at odds with our understanding of fundamental determinants of comparative advantage. We rank countries by a proxy for their skill level – their GDP per capita – and products by different proxies for their complexity. We find that international specialization is systematically related to these fundamental characteristics. The data, however, does not point to a ladder of specialization as we might have expected based on Costinot (2009a), but rather to an upper-triangular pattern, both when considering the cross-section of countries and when considering variations within countries over time. As we will show next, this upper-triangular pattern is, however, consistent with a complementarity between a country’s skill level and a product’s complexity once we allow for an endogenous choice of quality.

## 3 Model

To analyze the implications of quality differentiation for comparative advantages and, hence, international specialization across products, we now consider a framework where the only sources of heterogeneity are countries’ skill levels (of their workforce) and products’ complexities, and where comparative advantage is rooted in a complementarity between skills and the difficulty of production. We will assume that every product has a functional minimum-quality version that can be improved upon by raising quality. Higher quality versions of a product are more valuable to consumers, but they serve the same need. Increasing quality renders production more difficult, but there are no other costs involved in producing higher quality.\textsuperscript{20}

\textsuperscript{18}This is in line with the fact that in the Sutton and Trefler (2016) graph the dots at the top are spread out from left to right.

\textsuperscript{19}Moreover, the focus on the most and least complex significant exports of countries – as opposed to a ‘nested’ pattern – helps to robustly isolate the pattern of international specialization that is most relevant for the purpose of our paper – see Footnote 38 for a discussion.

\textsuperscript{20}Note that in the set-up considered here, all countries but the highest skilled will produce quality that is lower than what is technically feasible. Prototypes for such lower quality versions will be freely available in a world with growth through quality upgrading and in the absence of patents or secrecy for varieties not at the technological frontier, for example.
We first present a special case of our theoretical set-up that admits a closed-form solution and allows introducing the main mechanisms of interest in a transparent way, before considering a generalized production technology in Section 3.3.

3.1 Economic environment

We consider a world with many countries that is populated by a continuum of measure 1 of households. Countries differ in one parameter $r$ only. $r$ may reflect any factor promoting a country’s ‘economic strength’, such as technology, institutions, or human capital. For concreteness, we refer to $r$ as the skill level of a country (of its workforce) and will henceforth identify countries with their skill level. Across the world these skills are distributed according to some distribution function $F_{r}(r)$ with support $\mathcal{R} \subseteq (0, 1)$, implying that $\mathcal{R}$ denotes the set of countries.\footnote{We are assuming that workers’ skills are homogeneous within and heterogeneous across countries. This is for expositional purposes only. In principle, households can be heterogeneous within countries and the skill levels of households can overlap across countries.} We will use $\underline{r}$ and $\overline{r}$ to denote the smallest and largest element in this set, respectively. Households derive utility from consumption of products (or industries) $i \in \mathcal{I}$. Utility depends on the quantity and the quality consumed, as detailed below. Households inelastically supply $L$ units of their labor which is perfectly mobile across products but perfectly immobile across countries. There is perfect competition in all markets, and all goods are freely traded across countries. We use $p_{i,q}$ to denote the world price for quality $q > 0$ of product $i$.

3.1.1 Preferences

Our ultimate interest is in analyzing the implications of quality differentiation within products for comparative advantages and, hence, specialization across products. This, of course, requires comparing different quality versions of the same product. We consider the case of all products being final consumption goods and are therefore interested in consumers’ taste for quality.

Our main focus is on the supply side of the economy. We will therefore assume that all households consume the same quality(ies) of each product, irrespective of their income.\footnote{In combination with comparative advantages over different qualities of the same product, non-homothetic preferences for quality promote co-exporting of products in a way similar to trade costs, as they allow countries to co-export the same product by serving different ‘markets’ when defined as a group of customers. We focus on the supply side and therefore tie our hands here.} In particular, we will normalize quality in terms of consumption value and assume that households have ‘box-size-quality’ preferences (Baldwin and Harrigan, 2011), i.e. they are indifferent between consuming a box of size 2 and quality 1 of a product or a box of size 1 and quality 2. To close the model, we will further assume that they have CES preferences over products which is a standard assumption in the literature and admits neat predictions with regards to
uniqueness of the equilibrium and the gains from trade. Note, however, that this assumption is not essential for our main insight with regards to the implications of quality differentiation for international specialization across products. We will discuss this further in Section 4.2. In summary, we assume

\[ U \left( \left\{ c_{i,q} \right\}_{(i,q) \in \mathcal{I} \times \mathcal{Q}_i} \right) = C \quad (1) \]

\[ C := \int_{\mathcal{I}} \left( \int_{\mathcal{Q}_i} \mathbb{1} [q \geq 1] q c_{i,q} \, dq \right) \frac{v-1}{\nu} \, di \quad , \quad (2) \]

where \( c_{i,q} \) denotes the amount of the variety with quality \( q \) of product \( i \) consumed and \( \mathcal{Q}_i \) denotes the set of qualities of product \( i \) available.\(^{23}\) \( \mathbb{1} [\cdot] \) is the indicator function that takes on value of 1 if the statement in brackets is true and 0 otherwise, i.e. \( \mathbb{1} [q \geq 1] \) captures the functional minimum-requirement that every product needs to satisfy for it to be able to serve its intended purpose as discussed in the introduction. We normalize the minimum quality to be 1 for all products, i.e. we think of a complex product as one that is difficult to produce at minimum quality as will become apparent in the next section.\(^{24}\) Note that we introduce this strong form of minimum-quality requirements for expositonal purposes only. All we need for subsequent analyses is all quality drops below the minimum level, a lower quality can less easily be compensated for by higher quantity such that the value of \( c_{i,q} \) units of quality \( q \) of product \( i \) is less than \( q c_{i,q} \) once \( q < 1 \).

Box-size-quality preferences imply that households consume qualities with the lowest quality-adjusted price \( \rho_i := \frac{\nu_{i,q}}{q_i} \) only, and that they are indifferent between consuming any of these. Let \( \bar{c}_i := \int_{\mathcal{Q}_i} q c_{i,q} \, dq \) denote total effective consumption of product \( i \) by the representative household. Following standard steps, we then get

\[ \bar{c}_i = CP^v [\rho_i]^{-v} \quad (3) \]

\[ PC = L \int_{\mathcal{I}} \int_{\mathcal{Q}_i} w_r \, dF_{r}(r) \quad (4) \]

\[ \text{with} \quad P := \left( \int_{\mathcal{I}} [\rho_i]^{1-v} \, di \right)^{-v} , \quad (5) \]

where \( w_r \) is the wage rate in country \( r \), and \( P \) is the CES price index.

### 3.1.2 Production – the case of an O-ring technology

In this section, we outline assumptions pertaining to production which will be the main focus of our work. Throughout we will assume that production is constant returns to scale using

\(^{23}\)The equilibrium approach also works for finite or discrete countable sets of countries, industries, and / or qualities. In this case the respective integrals are replaced by their corresponding sums throughout the paper.

\(^{24}\)The specification in (2) implies that the consumption-value of a variety with functional minimum-quality is the same for all products. This is for notational clarity only, and introducing product-specific taste parameters would not impact any of our main insights.
labor as the only input. It will be instructive to consider a special case first and to postpone a more general discussion to Section 3.3.

Production technology

Production is based on an O-ring technology in the spirit of Kremer (1993), but with an endogenous choice of quality. In particular, let \( f(r, i, q) \) denote the constant productivity of a worker in country \( r \) when working on quality \( q > 0 \) of product \( i \). This productivity is given by

\[
f(r, i, q) = [r]^{iq^\lambda},
\]

where, recall, \( r \in (0, 1) \). The O-ring technology has the following interpretation: Producing product \( i \) requires successful accomplishment of a continuum of measure \( i \) of simultaneous tasks, i.e. we use \( i \) to identify both a product and its complexity – the number of tasks in production. If the firm hires a worker with skill level \( r \) to work on a set of tasks with measure \( \Delta \), then the worker will successfully accomplish these tasks with probability \( [r]^{\Delta q^\lambda} \). This probability is the same, irrespective of the tasks the worker is working on, i.e. there are no gains from specialization of labor on a specific set of tasks. The intensity of tasks depends on output quality: This intensity is 1 when producing the minimum-quality version of a product. Higher output quality requires higher quality of every task, in line with the concept of Total Quality Management from the management literature. In turn, this renders the successful accomplishment of each task more demanding, i.e. it increases its intensity. \( \lambda > 0 \) is a parameter determining how difficult it is to raise quality. Let \( L_i(r) \) denote the labor input for product \( i \) in country \( r \) and suppose that firms produce quality \( q \). Production technology (6) then implies that total output is given by

\[
x_{i,q} = [r]^{iq^\lambda} L_i(r).
\]

\(^{25}\)Kremer (1993) discusses differences in the number of tasks which he attributes to both complexity and quality. We disentangle the two and analyze their interactions in determining equilibrium specialization in international trade.

\(^{26}\)Antràs and Chor (2013) also consider quality upgrading in a production process with a continuum of tasks. In their model, these tasks are sequential and they study vertical integration of firms. As in our model, all tasks are essential. However, in the model presented by Antràs and Chor (2013), higher quality in one task can partly compensate for lower quality in other tasks.

\(^{27}\)Throughout this paper, we follow the convention and apply the law of large numbers to a continuum of random variables.

\(^{28}\)The specification of the production technology in Equation (6) implies that all workers working in a team have the same skill level, i.e. we rule out the possibility that the firm hires different skill levels of labor to work on different tasks involved in production. With the assumptions made on the cross-country distribution of skills, this is trivially not possible. Note, however, that the supermodularity of \( f(\cdot) \) in the skill levels of workers working on different tasks implies that it is never optimal for a firm to form heterogeneous teams (see Kremer, 1993), i.e. ruling out this possibility does not impair the applicability of our subsequent analyses to alternative cross-country distributions of skills.
Note that the productivity of a worker is a function of $r$ and the quality-weighted measure of tasks, $\sigma := iq^\lambda$, only. To emphasize that $i$ and $q$ enter productivity only via their effect on $\sigma$ we will henceforth use $f(r,\sigma(i,q))$ to denote this productivity, and we will refer to $\sigma(\cdot)$ as the overall difficulty of production. The O-ring production technology implies that there is a complementarity between the skill level of a worker, $r$, and the difficulty of production, $\sigma$. Intuitively, higher skilled workers are better at performing tasks. Then, naturally, they have a comparative advantage in products that are more intensive in these tasks. Formally, $f(\cdot)$ is log-supermodular in $r$ and $\sigma$, analogous to assumptions often made in the literature.

The key observation is that in our case $\sigma$ is not exogenous, but it depends on the product-intrinsic (exogenously given) complexity $i$ and the endogenously chosen quality $q$: More complex products are more difficult to produce as are higher quality versions of the same product. This will have profound consequences for comparative advantages in our economy. We will discuss these in Section 3.2 and will study the optimal choice of quality first.

**Optimal quality**

Recall that consumers care about quality-adjusted consumption only. Firms will therefore compete over providing this quality-adjusted output to consumers. They will choose quality to maximize their productivity in quality-adjusted terms, which we denote by $g(r,i,q)$

$$g(r, i, q) := qf(r, \sigma(i, q)),$$

subject to the functional minimum-requirement $q \geq 1$. This decision problem involves a simple trade-off: When raising $q$, firms weigh the gain from a more valuable product to consumers against the loss of a lower output due to the increased difficulty of production. Ignoring the functional minimum-requirement for now, the associated first order condition is

$$1 = -\lambda iq^\lambda \ln(r),$$

with solution

$$\tilde{q}_i(r) = \left[-\frac{1}{\lambda i \ln(r)}\right]^\frac{1}{\lambda}.$$  \hspace{1cm} \text{(8)}

Intuitively, an interior solution for quality is such that the quality-elasticity of $f(\cdot)$, $\frac{\partial \ln(f(r,\sigma(i,q)))}{\partial q} q = \lambda iq^\lambda \ln(r)$, is equal to $-1$, i.e. the increase in value of each output unit is exactly offset by the decrease in productivity. We will henceforth refer to $\tilde{q}_i(r)$ as preferred quality for reasons that will become apparent in a second. In line with what we observe from the data, this preferred quality will be higher for higher skilled countries, reflecting the fact that they have a comparative advantage for the more difficult high-quality versions of any given product. And for any

---

\(^{29}\)Cf. Costinot (2009a) and Costinot and Vogel (2015) for a review of this literature.
given country $r \in R$, preferred quality will be decreasing in the complexity of the product. This is because quality upgrading requires higher quality of every task involved in production, i.e. quality upgrading is more demanding for more complex products.

The optimal choice of quality for product $i$ in country $r$, $q_i(r)$, is either given by the unique solution to (7) or, in case this preferred quality does not meet the functional minimum-requirements, firms can do no better than producing the minimum-quality version instead ³⁰

$$q_i(r) = \max \left\{ 1, \left[ -\frac{1}{\lambda i \ln(r)} \right]^\frac{1}{\lambda} \right\}.$$  

(9)

Note that (9) implies that for every country there will be some threshold complexity level $\tilde{i}(r)$ such that it will be able to produce products at preferred quality up to this complexity level. The threshold is determined by the optimality of the minimum-quality

$$\tilde{q}_{\tilde{i}(r)}(r) = 1,$$

which implies

$$\tilde{i}(r) = -\frac{1}{\lambda \ln(r)}.$$  

(10)

Analogously, we can define a threshold skill level that is needed to produce a given product at preferred quality. In particular, countries $r \in R : \tilde{i}(r) \geq i$ can produce product $i$ at preferred quality. Clearly, these are all countries with skill level above a threshold level $\tilde{r}(i)$ which is the inverse of $\tilde{i}(r)$

$$\tilde{r}(i) = e^{-\frac{1}{\lambda i}}.$$  

(11)

For any product $i \geq \tilde{i}(r)$, firms in country $r$ will be bound by the minimum-quality requirement which in turn will be associated with an efficiency loss in production. As high-skill countries specialize in producing high quality, the threshold level will naturally be higher for these countries. This observation will be an important factor for comparative advantages and hence specialization across products which we consider next.

### 3.2 Comparative advantages

We now analyze comparative advantages in the framework as outlined above. With box-size-quality preferences, comparative advantages are determined by productivities in quality-adjusted terms, $g(\cdot)$. Now, with constant quality $\bar{q}$, the log-supermodularity of $f(\cdot)$ and the

³⁰ Note that

$$\frac{\partial}{\partial q} \left[ f(q^\lambda) \right] = q^\lambda \left[ 1 + \lambda iq^\lambda \ln(r) \right] \begin{cases} < 0 & \text{if } q > \bar{q}_i(r) \\ > 0 & \text{if } q < \bar{q}_i(r) \end{cases}$$

and, hence, the productivity in quality-adjusted terms is strictly decreasing as we move away from $\bar{q}_i(r)$ in either direction. It follows that, indeed, $q_i(r)$ is uniquely optimal.
fact that $\sigma(\cdot)$ is increasing in $i$ immediately imply that

$$
\frac{g(r^h, i^h, \bar{q})}{g(r^l, i^h, \bar{q})} = \left[ \frac{r^h}{r^l} \right]^{i^h \bar{q}^\lambda} > \left[ \frac{r^h}{r^l} \right]^{i^l \bar{q}^\lambda} = \frac{g(r^h, i^l, \bar{q})}{g(r^l, i^l, \bar{q})}, \quad \forall i^h > i^l, r^h > r^l, \quad (12)
$$

i.e. high-skill countries have a comparative advantage for the complex products. It is well known that in equilibrium this will give rise to a ladder of specialization (Costinot, 2009a; Costinot and Vogel, 2015).

This, however, need not be the case if we allow for quality differentiation. In such case what matters for comparative advantages are relative productivities, taking into account the respective optimal choice of quality, i.e. they are shaped by $\frac{\partial^2 \ln(g(r, i, q_i(r)))}{\partial r \partial i}$ as opposed to $\frac{\partial^2 \ln(g(r,i,q_i(r)))}{\partial r^h \partial q^h}$. Quality differentiation allows firms for a given product to endogenously tailor the characteristics of their output to better match the skill level of their workforce. The implications for comparative advantages across products may be seen most clearly when considering the case of no functional minimum-requirements first. In that case we have

$$
g(r, i, q_i(r)) = g(r, i, \bar{q}_i(r)) = \left[ -\frac{1}{e^{\lambda i \ln(r)}} \right]^{\frac{1}{i}} \quad (13)
$$

and, hence,

$$
\frac{g(r^h, i, \bar{q}_i(r^h))}{g(r^l, i, \bar{q}_i(r^l))} = \left[ \frac{\ln(r^h)}{\ln(r^l)} \right]^{\frac{1}{i}}, \quad \forall i, r^h, r^l, \quad (14)
$$

i.e. relative productivities are the same, irrespective of the complexity of the product. This is deeply rooted in the fact that quality differentiation provides firms with endogenous control over the difficulty of production. To get some further economic intuition for why quality differentiation exactly offsets comparative advantages, note that countries ideally always operate at the same overall difficulty of production, irrespective of the complexity of the product

$$
\sigma(i, \bar{q}_i(r)) = -\frac{1}{\lambda \ln(r)}. 
$$

This is exactly what eliminates comparative advantages across products. We will discuss this further in Section 3.3, where we consider a generic production technology and show that under plausible restrictions quality differentiation attenuates comparative advantages. It will exactly offset comparative advantages if with an endogenous choice of quality the overall difficulty of production is the same across products. It turns out that this is the case if and only if $\sigma(\cdot)$ is a function of the quality-weighted complexity $i\bar{q}^{\lambda}$ only, in line with the O-ring theory. We will provide suggestive evidence in support of these implications in Section 5.2.

---

31Here and below, the partial derivative $\partial$ of $g(\cdot)$ with respect to $r$ or $i$ refers to the derivative holding constant the choice of quality, $q$, while the derivative $d$ refers to the total derivative taking into account also the implied change of $q_i(r)$. 

20
Quality differentiation is, however, constrained by the functional minimum-requirements. Firms in country \( r \in \mathcal{R} \) can produce products at preferred quality only up to the threshold complexity level \( \tilde{i}(r) \). As a consequence, quality differentiation promotes a ‘nestedness’ pattern of comparative advantages across products. This is illustrated in Figure 4 which draws countries’ threshold complexity level \( \tilde{i}(r) \) in a diagram with skills \( r \) on the vertical and complexity \( i \) on the horizontal axis, and locates three countries in this diagram – a high-skill, a medium-skill, and a low-skill country, \( r^{h}, r^{m}, r^{l} : r^{h} > r^{m} > r^{l} \). As \( \tilde{i}(r) \) is increasing in countries’ skills, ‘simple’ products \( i \leq \tilde{i}(r^{l}) \) that can be produced at preferred quality in country \( r^{l} \) can also be produced at preferred quality in the medium- and high-skill countries, i.e. quality differentiation offsets comparative advantages for these products. All more complex products, however, cannot be produced at preferred quality in the low-skill country which therefore suffers from an efficiency loss. In turn, this implies that it has a comparative dis-advantage for these products when compared to the simple products and the higher skilled countries which can either still operate at preferred quality or suffer from a smaller efficiency loss. The same argument implies that comparative advantages between the medium- and the high-skill country are offset by quality differentiation for the broader range of products up to \( \tilde{i}(r^{m}) \), while for all more complex products country \( r^{h} \) has a comparative advantage. In general, the shaded area to the left of \( \tilde{i}(r) \) highlights for every country the products that it can produce at preferred quality. For any
pair of countries \( r^h > r^l \) and products \( i^h > i^l \) in this area (i.e. such that \( i^h \leq \tilde{i}(r^l) \)) there is no comparative advantage, while the high-skill country has a comparative advantage for the complex product whenever \( i^h > \tilde{i}(r^l) \). We summarize these insights in the following proposition and relegate the proof to Appendix B.1.

**Proposition 1**

*For any pair of countries \( r^h > r^l \) and products \( i^h > i^l \):

(i) There is no comparative advantage iff \( i^h \leq \tilde{i}(r^l) \).

(ii) Country \( r^h \) has a comparative advantage for product \( i^h \) otherwise.*

Proposition 1 carries our main message. The remainder of the paper will be dedicated to studying implications of this pattern of comparative advantages. Before considering these, however, we will consider a generalized production technology. This will help clarifying key assumptions embedded in our O-ring theory and robustness of our main insight to alternative functional forms.

### 3.3 Generalized production technology

The O-ring technology implies that the constant productivity of a worker is a function of his skill level \( r \) and the overall difficulty of production \( \sigma, f(r, \sigma(i, q)) \). Productivity is lower for higher \( \sigma \) and there is a complementarity between skills and difficulty of production, i.e. high-skill workers have a comparative advantage for difficult products. Formally, the O-ring theory implies that \( f(\cdot) \) is log-supermodular in \( r \) and \( \sigma \), analogous to assumptions often made in the literature.\(^{32}\) The key novelty is that we argue that \( \sigma(\cdot) \) is not exogenously given but depends on both the product-intrinsic complexity and the endogenously chosen quality. Complex products are more difficult to produce as are higher quality versions of the same product. Specifically, we argue that higher output quality requires higher quality of every task which in turn makes every task in production more demanding. This implies further that quality upgrading is more demanding for more complex products in the sense that productivity in physical units is the more elastic with respect to quality the more complex the product.\(^{33}\) In summary, the O-ring technology has the following properties:

\(^{32}\)Cf. Footnote 29.

\(^{33}\)This can happen either because \( \ln(f(\cdot)) \) is concave in \( \sigma \), implying that the proportional effect of a further increase in the difficulty of production is the more negative the more difficult the production process. Or because a given increase in quality has a stronger effect on the overall difficulty of production the more complex the product, as in the case of the O-ring technology. To see this note that Assumption 1(v) below can be rewritten as

\[
\frac{\partial}{\partial i} \left( \frac{\partial \ln(f(\cdot))}{\partial q} q \right) = \frac{\partial}{\partial \sigma} \left( \frac{\partial \ln(f(\cdot))}{\partial \sigma} \frac{\partial \sigma}{\partial q} q \right) < 0.
\]
Assumption

(i) $\frac{\partial f(\cdot)}{\partial \sigma} < 0$  (ii) $\frac{\partial^2 \ln(f(\cdot))}{\partial r \partial \sigma} > 0$  (iii) $\frac{\partial \sigma(\cdot)}{\partial i} > 0$  (iv) $\frac{\partial \sigma(\cdot)}{\partial q} > 0$  (v) $\frac{\partial}{\partial \sigma} \left[ \frac{\partial \ln(f(\cdot))}{\partial q} \cdot q \right] < 0$

It turns out that for every production technology with these properties quality differentiation attenuates comparative advantages across products. In particular, with constant quality $\bar{q}$, the log-supermodularity of $f(\cdot)$ (Assumption 1(ii)) and the fact that $\sigma(\cdot)$ is increasing in $i$ (Assumption 1(iii)) immediately imply that high-skill countries have a comparative advantage for the complex products:

$$\frac{\partial^2 \ln(g(r, i, \bar{q}(r)))}{\partial r \partial i} = \frac{\partial^2 \ln(f(r, \sigma(i, \bar{q}(r))))}{\partial r \partial \sigma} \frac{\partial \sigma(i, \bar{q}(r))}{\partial i} > 0 . \tag{15}$$

With quality differentiation, however, we need to take into account the respective optimal choices of quality. To see how this impacts comparative advantages, it is instructive to again consider the case of no functional-minimum requirements first. Totally differentiating $\ln(g(\cdot))$ and applying the Envelope Theorem then yields

$$\frac{d^2 \ln(g(r, i, \bar{q}(r)))}{drdi} = \frac{\partial^2 \ln(f(r, \sigma(i, \bar{q}(r))))}{\partial r \partial \sigma} \frac{\partial \sigma(i, \bar{q}(r))}{\partial i} + \frac{\partial^2 \ln(f(r, \sigma(i, \bar{q}(r))))}{\partial r \partial \sigma} \frac{\partial \sigma(i, \bar{q}(r))}{\partial q} \frac{d\bar{q}(r)}{di} . \tag{16}$$

The first summand is the right-hand side of Equation (15) and just captures comparative advantages across products at constant quality. The second summand captures the effect of quality differentiation. Whether or not this attenuates comparative advantages across products depends on the sign of $\frac{d\bar{q}(r)}{di}$ since $\frac{\partial^2 \ln(f(r, \sigma(i, \bar{q}(r))))}{\partial r \partial \sigma} \frac{\partial \sigma(i, \bar{q}(r))}{\partial q} > 0$ by Assumption 1(ii) and 1(iv). In our case $\frac{d\bar{q}(r)}{di} < 0$, reflecting the fact that quality differentiation is more demanding for more complex products (Assumption 1(v)).

Intuitively, comparative advantages are driven by a complementarity between skills and difficulty of production. A product is more difficult to produce if it is more complex (first summand in (16)), and if it is of higher quality (second summand in (16)). If quality differentiation is inversely related to complexity, it therefore assimilates the difficulty of production within countries across products. This is precisely what attenuates comparative advantages across products.

The O-ring technology further implies that the difficulty of production is a function of the quality-weighted measure of tasks, $iq^\lambda$, only. It turns out that this latter condition is both

$$\frac{\partial \ln(f(r, \sigma(i, q)))}{\partial q} \cdot q = -1 . \tag{17}$$

Assuming, for simplicity, that this decision problem is well behaved such that in the absence of functional minimum-requirements Equation (17) is necessary and sufficient for the optimal choice of quality, this equation implicitly defines preferred quality $\bar{q}(r)$ as a function of $i$ and $r$. Assumption 1(v) then immediately implies that – for a given $r$ – the optimal quality is smaller for more complex products.
necessary and sufficient for quality differentiation to exactly offset comparative advantages across products. To get an intuition for why this is the case, recall that the optimal choice of quality is such that the elasticity of productivity \( f(\cdot) \) with respect to quality \( q \) is equal to \(-1\)

\[
\frac{\partial \ln(f(r, \sigma(i, q)))}{\partial q} q = -1 .
\] (18)

With \( \sigma(i, q) = \sigma(iq^\lambda) \) this can be rewritten as

\[
\frac{\partial \ln(f(r, \sigma(iq^\lambda))))}{\partial \sigma}(iq^\lambda)iq^\lambda = -\frac{1}{\lambda} ,
\]

i.e. for any given country, preferred quality is such that \( iq^\lambda \) and, hence, the overall difficulty of production \( \sigma(iq^\lambda) \) is the same for all products. This is exactly what offsets comparative advantages across products. We summarize these insights in the following proposition.

**Proposition 2**

(i) \( \frac{d^2 \ln(g(r,i,q(r)))}{drdi} < \frac{d^2 \ln(g(r,i,q(r)))}{drdq} \)

(ii) \( \frac{d^2 \ln(g(r,i,q(r)))}{drdq} = 0 \) if and only if \( \sigma(i, q) = \sigma(iq) \) for an arbitrary twice continuously differentiable function \( \sigma(\cdot) \) satisfying Assumption 1.

The proof of Proposition 2(ii) is given in Appendix B.2. Proposition 2(ii) implies that, indeed, quality differentiation exactly offsets comparative advantages across products if and only if difficulty of production, \( \sigma(\cdot) \), is determined by quality-weighted complexity, \( iq \), only, as discussed above. In the case of the O-ring technology, we actually use \( iq^\lambda \). We introduce \( \lambda \) to emphasize that the difficulty of production need not have the same elasticity with respect to \( i \) and \( q \) while maintaining the interpretation of \( i \) as the number of tasks in the O-ring process. Note that complexity matters only for its impact on production. Hence, with a slight abuse of notation, we can redefine complexity as \( i := i^\lambda \) and \( \sigma(\cdot) := \sigma((\cdot)^{1/\lambda}) \), to get \( \sigma(i, q) = \sigma(iq^\lambda) \). See also Appendix B.2.

4 Equilibrium

In this section, we derive the equilibrium in our economy. In doing so, we will revert to the O-ring technology as this will allow distilling the novel implications of our theory. We will briefly discuss robustness of the implied pattern of international specialization at the end of this section.

The competitive equilibrium will be such that consumers maximize utility, firms maximize profits, and the markets for all products and all types of labor clear. This equilibrium will, of
course, be shaped by non-trivial interactions between demand and supply-side forces. It turns out, however, that summarizing these interactions in one simple and intuitive condition will go a long way towards characterizing the equilibrium, in particular with respect to international specialization across products, which is our main focus.

To derive this condition, we consider labor market clearing first.

### 4.1 Equilibrium wage

With inelastic labor supply, labor markets clear if firms are willing to fully employ all types of labor at the prevailing equilibrium wage rate. To analyze when this will be the case, it is instructive to again consider a world with no functional minimum-requirements first, and to then analyze how such requirements affect equilibrium wages.

With no functional minimum-requirements, all countries always produce at preferred quality, implying that there is no comparative advantage. It immediately follows that the unique equilibrium wage scheme consistent with labor market clearing for all types of labor just compensates for the differences in quality-adjusted productivity, which are constant across products (see (14)). Choosing the wage rate in country $r$ to be the numéraire, the wage in country $r$ is therefore

$$w_r = \left[ \frac{\ln(r)}{\ln(r)} \right]^{\frac{1}{\lambda}} \forall r \in \mathcal{R}. \quad (19)$$

Note that this is an equilibrium with complete indifference regarding the allocation of production to countries.

How will this equilibrium wage scheme be affected by the functional minimum-requirements? The answer is: not at all if there are sufficient skills in the economy. This follows from a simple recursive argument. Suppose wages are given by (19). Then the cost per unit of effective output of product $i$ are

$$\frac{w_r}{g(r, i, q_i(r))} = \begin{cases} \left[ -e^{\lambda i \ln(r)} \right]^{\frac{1}{\lambda}}, & \forall r \in \mathcal{R} : \tilde{i}(r) \geq i \\ \left[ \frac{\ln(r)}{\ln(r)} \right]^{\frac{1}{\lambda}} \frac{1}{r^i} > \left[ -e^{\lambda i \ln(r)} \right]^{\frac{1}{\lambda}}, & \text{otherwise} \end{cases},$$

i.e. countries $r \in \mathcal{R} : \tilde{i}(r) \geq i$ that can produce product $i$ at preferred quality will be competitive for this product.\(^{36}\) Clearly, these are all countries with skill level above the threshold level $\tilde{r}(i)$ as defined in (11).

\(^{36}\)The inequality in the lower case follows from

$$\left[ \frac{\ln(r)}{\ln(r)} \right]^{\frac{1}{\lambda}} \frac{1}{r^i} = \frac{1}{\left[ -e^{\lambda i \ln(r)} \right]^{\frac{1}{\lambda}}} \frac{1}{r^i}.$$
Now, because all countries with skill level \( r \geq \bar{r}(i) \) are competitive for product \( i \), the following two conditions are sufficient for labor market clearing in all countries: First, for every product \( i \in \mathcal{I} \) it must be possible to locate total production in countries with skill level \( r \geq \bar{r}(i) \), i.e. there must be no excess demand for skills. Second, the overall labor market must clear.

Let us turn to the former condition first. Production at preferred quality eliminates comparative advantages but of course absolute advantages still prevail. The total take-up of physical units of labor in production of product \( i \) will therefore depend on the location of production. It will therefore be convenient to introduce the following notion of effective labor in country \( r \)

\[
\tilde{L}(r) := Lf_r(r) \left[ \frac{\ln(r)}{\ln(\bar{r})} \right]^{\frac{1}{r}},
\]

where \( Lf_r(r) \) is aggregate supply of labor in country \( r \). \( \tilde{L}(r) \) normalizes labor in country \( r \) in terms of labor in the lowest skilled country, given that both are operating at preferred quality. The demand for effective labor will therefore be the same, irrespective of the location of production among countries \( r \geq \bar{r}(i) \). We will henceforth denote total demand for effective labor in product \( i \) by \( \tilde{L}^d_i \).

Now, consider the most complex product \( \tilde{i} := \max \mathcal{I} \). Only the highest skilled countries \( r \in \mathcal{R}_{\tilde{i}} := \{ r \in \mathcal{R} : \tilde{i}(r) \geq \tilde{i} \} \) are competitive for this product. If there is more labor available in these countries than demanded for production of product \( \tilde{i} \) then some of their labor will spill over to simpler products.

Consider the second most complex product \( \tilde{i}-1 \) next. All countries \( r \in \mathcal{R}_{\tilde{i}} \) will be competitive for this product plus some additional countries \( r \in \mathcal{R} : \tilde{i}(r) < \tilde{i} \). If, on top of the above condition, there is more labor available in countries \( r \in \mathcal{R}_{\tilde{i}-1} := \{ r \in \mathcal{R} : \tilde{i}(r) \geq \tilde{i}-1 \} \) than total demand for labor in production of products \( \tilde{i} \) and \( \tilde{i}-1 \) then some of their labor will spill over to simpler products.

Repeted iteration of the same argument eventually results in the following Sufficient Skills Condition:

**Definition 1 (Sufficient Skills)**

*We say that there are sufficient skills in the economy if given wage scheme (19) the following condition is satisfied:*

\[
L \int_{r \in \mathcal{R} : r \geq \bar{r}(i)} \left[ \frac{\ln(r)}{\ln(\bar{r})} \right]^{\frac{1}{r}} dF_r(r) \geq \int_{i \in \mathcal{I}, i \geq \tilde{i}} \tilde{L}^d_i \, di, \quad \forall \tilde{i} \in \mathcal{I}.
\]

(\(SSC\))

in combination with the fact that

\[
\frac{1}{[-e\lambda l \ln(r)]^{\frac{1}{r}}} > r^i
\]

because \( q_i(r) \) would uniquely maximize the productivity in quality-adjusted terms if it was feasible.
While Condition (SSC) may seem technical, it simply rules out that given wage scheme (19) there is excess demand for skills. We will derive a variant of Condition (SSC) based on structural parameters of the model in Section 4.2, and get back to discussing this condition in Section 4.3. For now, we note that it guarantees that labor markets are in equilibrium if it holds with equality for the simplest product. We summarize our insights in the following proposition:

**Proposition 3**

(i) If and only if Condition (SSC) is satisfied, there is a unique equilibrium with \( w_r := \left( \frac{\ln(r)}{\ln(R)} \right)^{\frac{1}{\lambda}} \) \( \forall r \in \mathcal{R} \).

(ii) Otherwise, the equilibrium wage scheme satisfies

\[
\frac{w_{r,h}}{w_{r,l}} \geq \left[ \frac{\ln(r^h)}{\ln(r^l)} \right]^{\frac{1}{\lambda}} \forall r^l, r^h \in \mathcal{R} : r^h \geq r^l,
\]

with the inequality being strict for some \( r^l, r^h \in \mathcal{R} \).

Sufficiency in Proposition 3(i) follows from the above. Necessity follows immediately from the fact that without sufficient skills \( w_r = \left( \frac{\ln(r)}{\ln(R)} \right)^{\frac{1}{\lambda}} \) would yield excess demand for some high-skilled labor. We show uniqueness in Appendix B.3. Proposition 3(ii) follows from the fact that \( \frac{w_{r,h}}{w_{r,l}} < \left( \frac{\ln(r^h)}{\ln(r^l)} \right)^{\frac{1}{\lambda}} \) for some \( r^h > r^l \) would contradict labor market clearing in country \( r^l \). Intuitively, a lack of skills in the economy will bid-up wages for workers in high-skill countries.

Proposition 3 is the key result characterizing specialization across products in our economy: With wages given by (19), countries are competitive for all products up to their threshold complexity level \( \tilde{t}(r) \). In other words, the equilibrium will be one where high-skill countries are competitive for the full range of products, the complex ones but also the simpler ones, while lower skilled countries systematically specialize in the simple products. Quality differentiation can thus explain the stylized facts shown in Section 2. This pattern is in contrast to the ladder of specialization that we would observe in our model in the absence of quality differentiation. In essence, by introducing an endogenous choice of product quality, across-product specialization is replaced by within-product specialization in the spirit of Schott (2004). Within-product specialization is truncated by the functional minimum-requirements. In equilibrium this implies that high-skill countries can successfully compete for even the simplest products by specializing on high quality, but not vice versa. Low-skill countries cannot successfully compete for complex products because these products are just too difficult, even in their minimum-quality version.\(^{37}\)

\(^{37}\)To highlight the main mechanisms of interest, we analyze quality differentiation in a Ricardian model with free trade following Costinot (2009a) and consider the case where quality differentiation exactly offsets comparative advantages across products. Yet the mechanisms considered here matter more generally for international specialization across products. We briefly illustrate this in Online Appendix C, where we embed our structure of fundamental productivities into a multi-product Eaton and Kortum (2002) model and follow Costinot et al. (2012) to show that trade patterns inherit the structure of fundamental productivities.
Corollary 1

In an equilibrium with sufficient skills, each country \( r \in \mathcal{R} \) is competitive for all products \( i \in \mathcal{I} : i \leq \tilde{i}(r) \).

Importantly, while we introduce a strong form of minimum-quality requirements for expository purposes, the exact same pattern of international specialization across products would arise with a weak version of such requirements as discussed in Section 3.1.1.

4.2 A sufficient skills condition based on structural parameters

The Sufficient Skills Condition is based on the exogenous distribution of supply of effective labor across countries and the endogenous distribution of demand for effective labor across products. Whether or not this condition is satisfied depends on preferences, technologies, and the distributions of complexities across products and skills across countries. In the end, it boils down to an assumption on these structural parameters of the model. This assumption can be derived by solving for the entire equilibrium. We show this in Appendix B.4 and summarize the main insight in the following proposition.

Proposition 4

If and only if

\[
\int_{r \in \mathcal{R} : r \geq \tilde{i}(i)} [-\ln(r)]^{-\frac{1}{\lambda}} dF_r(r) \geq 1 - \left( \frac{i}{N} \right)^{\frac{1+\lambda-u}{\lambda}}, \quad \forall i \in [0, N]
\]  

Condition (SSC) is satisfied in equilibrium and the unique equilibrium wage is

\[
w_r = \left[ \frac{\ln(r)}{\ln(i)} \right]^\frac{1}{\lambda} \quad \forall r \in \mathcal{R}.
\]

To derive Condition (21), we have assumed that \( \mathcal{I} = [0, N] \), for simplicity. This condition is further based on the assumption of CES preferences across products, the choice of which is motivated by their tractability, their importance in the literature, and because they allow for particularly neat predictions with respect to uniqueness and the gains from trade, as we will see in Section 5.1. Note, however, that our main insights with regards to the implications of quality differentiation for comparative advantages and international specialization across products do not hinge on this assumption: As long as Condition (SSC) is satisfied, there will be an equilibrium where wages just offset productivity differences for the case of production at preferred quality, and each country \( r \) is competitive for all products up to its threshold complexity level \( \tilde{i}(r) \).
4.3 Discussion

In summary, in this section we have shown how quality differentiation allows high-skill countries to successfully export both complex and simple products while developing countries systematically specialize in the simpler products, in line with our stylized facts of Section 2. This pattern of specialization arises in an equilibrium with sufficient skills.\footnote{More precisely, in an equilibrium with sufficient skills there is a perfectly ‘nested’ structure of countries’ competitiveness, that is, less developed countries are competitive for a subset of the products for which more developed countries are competitive. This, however, does not necessarily imply that countries’ (significant) exports are also nested. This may be seen most easily when considering the limiting case where Condition (SSC) holds with equality everywhere. In such case, we are back with a ladder of specialization, but, importantly, wages increase less steeply with countries’ skill levels when compared to a model without quality differentiation. More generally, the fact that less developed countries are not competitive for the complex products implies that industrialized countries are – on balance – net exporters of these products and, hence, (assuming homothetic preferences across products and balanced trade) net importers of the simpler products. Nevertheless, as long as Condition (SSC) is slack, high skill countries will be exporting some of the simpler products. This is why we focus on countries’ most and least complex significant exports rather than a ‘nestedness’ pattern in Section 2.} It is important to note the recursive nature of Condition (SSC). This condition rules out that at some level of complexity $i$ the total demand for effective labor in products $i \geq i$ is larger than the total supply of effective labor in countries that can produce $i$ at preferred quality, i.e. countries $r \geq r(i)$. Hence, the condition does not require the highest-skilled countries to be large, but is in fact a condition on the entire distribution of skills in the economy relative to the distribution of product complexities. It is precisely this sufficient supply of skills in the world as a whole that implies that labor in the high skill countries is not fully absorbed by production in the complex products. In turn, this pushes them into being competitive for even the simplest products.

Zeros in international trade can also arise from e.g. trade costs or the absence of necessary inputs for production, and there are potentially other ways of rationalizing our stylized facts. It is, however, important to keep in mind that these zeros are systematically related to a countries GDP per capita and a product’s complexity (see stylized fact 3), implying that e.g. trade costs would need to be systematically related to these characteristics as well in order to be able to explain the pattern we observe from the data. Moreover, in line with our stylized facts, we are considering a world where countries and products can be ranked by some underlying characteristics, i.e. by countries’ skill levels and products’ complexities. In such a world, we would typically presume that – on balance – high-skill countries should have a comparative advantage in complex products and vice versa. If so, there need to be some offsetting force that prevents a ladder of specialization. So, for example, in a world with heterogeneous non-tradeable inputs for production, countries can potentially produce all products for which they have the required inputs, implying that countries with many different inputs available can produce most or all products while countries with few inputs can produce a subset of these products only (Hausmann and Hidalgo, 2011). Yet for this pattern to also emerge in equilibrium, we would
need to assume that there is no underlying deep pattern of comparative advantages in the 
spirit of Costinot (2009a); Costinot and Vogel (2015). In particular, we may think that strong 
countries – countries with many different inputs available in this example – have a comparative 
advantage in complex products – products that require many different inputs. Then, we will 
observe a ladder of specialization in such a model as well. Our work shows that this is no 
longer true if we allow for quality differentiation and a condition analogous to the sufficient 
skills condition is satisfied. In fact, a condition analogous to (SSC) is needed for an upper-
triangular pattern of international specialization to emerge in the Hausmann and Hidalgo (2011) 
model even in the case with no comparative advantages.\footnote{In the absence of sufficient skills, countries with most or all inputs available would specialize in making products that require many different inputs.}

Importantly, our theory is not only consistent with the cross-section pattern documented in 
Figures 2 and 3, but also with the fact that countries, as they develop, start exporting more 
complex products while continuing to export the simpler products (see Tables 2 and 3). As 
developing countries upgrade their skill level, they gain the ability to produce additional, more 
complex products at preferred quality. This offsets their comparative dis-advantage for these 
products and, hence, allows them to start exporting these products. The key point is that in an 
equilibrium with sufficient skills this does not compromise their competitiveness for the simpler 
products. This is true, irrespective of the growth in the rest-of-the-world. As a consequence, 
our theory can also help explaining two related empirical findings in the literature. First, 
the finding that along the growth path, countries tend to diversify (Imbs and Wacziarg, 2003; 
De Benedictis et al., 2009; Cadot et al., 2010; Parteka and Tamberi, 2013).\footnote{The related empirical literature is somewhat inconclusive regarding whether or not there is some re-concentration at high levels of income. See literature review.} And second, it helps explaining why increasingly over time rich and poor countries export the same products (Schott, 2004).

The equilibrium pattern of international specialization has interesting further implications. We 
consider these implications next.

## 5  Further implications

In this section, we discuss further implications of our theoretical framework. We begin with 
considering the gains from trade. We then show that our model gives rise to a censored 
regression model for estimating the link between a country’s GDP per capita and its export 
quality and use this regression model to confront implications of our theory with the data.
5.1 Gains from trade

In an equilibrium with sufficient skills, the highest skilled countries, those with skill level \( r \geq \tilde{r}(7) \), are competitive for all products. In turn, this immediately implies that these countries have zero gains from international trade in our model: Relative free trade prices are just equal to relative cost of production in these countries.

The flip side of this observation are strong gains from trade for developing countries. Under autarky, these countries would suffer from being confronted with the functional minimum-requirements for the complex products. Free trade allows them to overcome this inefficiency in its entirety: They can import all products at a (relative) price that would prevail under autarky if it was not for these requirements. Intuitively, the large supply of high-skill workers pushes them into working on simpler products that can also be produced at preferred quality by lower skilled workers. In turn, this pushes down relative wages to the ratio of productivities with production at preferred quality. As this ratio of productivities is constant across products, this exactly allows developing countries to overcome inefficiencies associated with functional minimum-requirements under autarky. Any remaining differences in real income when compared to industrialized countries are due to a pure baseline effect of their higher productivity.

These inefficiencies in production are the more severe the lower skilled a country. With common homothetic preferences across products the gains from trade are therefore monotonically decreasing in a country’s skill level.\(^{41}\)

**Proposition 5**

*In an equilibrium with sufficient skills, the gains from trade are monotonically decreasing in a country’s skill level and there are no gains from trade among countries with skill levels \( r \geq \tilde{r}(7) \).*

The proof of Proposition 5 is given in Appendix B.5.

This pattern of gains from trade is in contrast to the pattern that we would observe in our Ricardian model in the absence of quality differentiation. It is reminiscent of two classic ideas on this issue. First, in our textbook Ricardian trade model with two countries and two products, as one country gets increasingly large, it will eventually start producing both products and therefore have zero gains from trade. The mechanism uncovered here is similar in spirit. Note, however, that it applies in a world with many countries and products and, in particular, what

\(^{41}\)As we argued in Section 4.2, our main insight regarding international specialization across products in an equilibrium with sufficient skills readily extends to alternative set-ups with non-homothetic preferences and / or heterogeneous tastes across countries. Non-homothetic preferences across products as in e.g. Föllmi and Zweimüller (2006) can, however, give rise to additional cross-country differences in the gains from trade. Yet the ‘supply-side’ sources of heterogeneous gains from trade considered here remain intact, and it is generally still true that countries at the top have zero gains from trade while lower skilled countries have positive gains from trade.
matters here is not a country’s own size, but the overall availability of skills in the entire world economy.

Second, it has long been argued that international trade delivers particularly large gains to developing countries as it provides them with access to high-tech products or medication, for example, that under autarky they would not at all have access to. While we do not postulate that low-skill countries are not at all capable of producing the complex products, we argue that it would involve potentially large efficiency losses due to the functional minimum-requirements.\textsuperscript{42,43}

5.2 Empirical analysis of quality differentiation in international trade

Our theoretical model is centered on the observation that richer countries export higher quality. This observation is well established in the empirical literature and has been documented measuring quality by unit values (Schott, 2004), based on a demand-side rationale (Khandelwal, 2010; Hallak and Schott, 2011), or based on a rationale that embodies both demand and supply-side effects (Feenstra and Romalis, 2014). When evaluating the link between a country’s GDP per capita and the quality of its exports these papers ignore zeros in international trade. To the extent to which zeros are random and not systematically related to quality this should not be a major concern. Our work, however, suggests that this may not be the case: If low-skill, low-income countries ideally produce low quality, they are more likely to be affected by the functional minimum-requirement of a product. The associated inefficiency in production may prevent them from being competitive in equilibrium, i.e. the prevalence of zeros is systematically related to preferred quality.\textsuperscript{44} This rationale naturally lends itself to a censored regression model to estimate the link between a country’s GDP per capita and the quality of its exports.

In what follows, we implement this empirical strategy and discuss how our findings are consistent with our theoretical model. We begin with a more thorough motivation based on our theoretical set-up.

\textsuperscript{42}This point is also related to the work by Ossa (2015) who shows in the context of quantitative trade models that a small trade elasticity in few industries can translate into large gains from trade.

\textsuperscript{43}Countries at the top no longer have zero gains from trade once we embed our structure of country-product level productivities into richer environments. A careful account of the welfare implications of quality differentiation in the context of gravity models is beyond the scope of the current paper and it is left for future research. Yet the fact that quality differentiation fundamentally changes the gains from trade in the context of a Ricardian trade model following Costinot (2009a) is of interest in and of itself, and the basic mechanisms underlying Proposition 5 also matter in richer environments.

\textsuperscript{44}Note that this is also true with a weak version of a minimum-quality requirement where a lower quality has a stronger effect on the value of a product to consumers once it drops below a certain threshold.
5.2.1 A Censored Regression Model to estimate the link between a country’s GDP per capita and the quality of its exports

In an equilibrium with sufficient skills, countries’ wages and therefore GDP per capita, $y$, are proportionate to their productivities in quality-adjusted terms with production at preferred quality

$$y(r) = a_i \bar{q}_i(r) f(r, \sigma(i, \bar{q}_i(r)))$$

where $a_i$ is an industry-shifter that is the same for all countries. A higher skill level $r$ allows for a higher GDP per capita via two channels: (preferred) quality $\bar{q}_i(r)$ and productivity in physical output units $f(r, \sigma(i, \bar{q}_i(r)))$. As long as both channels contribute constant shares to growth in GDP per capita, the above equation implies a log-linear relationship between a country’s GDP per capita and the (preferred) quality of its exports

$$\ln(\bar{q}_i(r)) = \alpha_i + \beta_i \ln(y(r)) \ .$$

Specifically, (8) and (19) imply, after some straightforward modifications, that

$$\ln(\bar{q}_i(r)) = - \frac{1}{\lambda} \left[ \ln(\lambda) + \ln(i) + \ln(-\ln(r)) \right] + \ln(y(r)) \ ,$$

i.e. our model predicts a unit elasticity between a country’s GDP per capita and its preferred quality. We will get back to this point in Section 5.2.4 below and note for now that this need not be true in general. We therefore proceed with the more general Equation (22).

A log-linear relationship between a country’s GDP per capita and its export quality has previously been considered in the literature. According to our theoretical model, however, it applies to *preferred* quality. The econometrician will be able to observe this preferred quality only if it meets the functional minimum-requirements of the product. In other words, our work suggests that our sample of observed qualities is censored from below. Now, suppose that each country exports all products that it is competitive for,\textsuperscript{45} and let $\tilde{q}_{i,t}^k$ denote the latent preferred quality of product $i$ in country $k$ with skill level $r_i^k$ at time $t$. Our theoretical set-up then lends itself to the following censored regression model for product $i$

$$\ln(\tilde{q}_{i,t}^k) \begin{cases} \begin{align*} \ln(\bar{q}_{i,t}^k) & \sim d_i^t \alpha_i + \beta_i \ln(y_t^k) + u_{i,t}^k, & \text{if } \tilde{q}_{i,t}^k \geq 1 \\ \text{NaN} & \text{otherwise} \end{align*} \end{cases}$$

where $y_t^k$ is GDP per capita of country $k$ at time $t$, $d_i^t$ is a $1 \times T$ vector of product-time dummies capturing (time-varying) product characteristics, $\alpha_i$ is a $T \times 1$ vector of coefficients on these

\textsuperscript{45}This assumption is broadly in line with the data. In 2010, for example, countries such as Austria, Australia, Belgium, Canada, France, Germany, Japan, Switzerland, and the US had strictly positive exports in more than 97% of the products at the HS4 classification level.
dummies, $u_{i,t}^k$ is a productivity-neutral preferred quality shock, and where we have assumed that the distribution of $\ln (\tilde{p}_{i,t}^k)$ given $d_i^t$ and $y_i^k$ is homoscedastic normal.

To take the censored regression model to the data, we use unit values, $p_{i,t}^k$, as a proxy for quality (in line with our theoretical model), and estimate the censoring threshold by the minimum of observed unit values$^{47}$

$$
\ln (\tilde{p}_{i,t}^k) = d_i^t \alpha_i + \beta_i \ln(y_i^k) + u_{i,t}^k, \quad u_{i,t}^k \sim N(0, \sigma_i^2) \quad (25a)
$$

$$
\ln (p_{i,t}^k) = \begin{cases} 
\ln (\tilde{p}_{i,t}^k) & \text{if } \tilde{p}_{i,t}^k \geq \min_{k \in \{1,2,\ldots,N_k\}} p_{i,t}^k \\
\text{NaN} & \text{otherwise}
\end{cases} \quad (25b)
$$

The latent variable model, Equation (25a), is, in essence, regression model (2) in Schott (2004) and regression model (17) in Khandelwal (2010). Both papers estimate their models using OLS. The reasoning developed here suggests that using OLS on the subsample with $\tilde{p}_{i,t}^k \geq \min_{k \in \{1,2,\ldots,N_k\}} p_{i,t}^k$ is inconsistent, and that we should use maximum likelihood instead (Wooldridge, 2002, p. 524). Precisely, we may expect OLS to underestimate the true link between a country’s GDP per capita and the quality of its exports.

### 5.2.2 Data

Export data is taken from Centre d’Etudes Prospectives et d’Informations Internationales (CEPII) (2013), which reconciles importer and exporter declarations, and provides bilateral data on export values and export quantities for more than 200 countries at the HS6 classification level for the period from 1995 to 2011. From this dataset, we exclude countries with less than 1m inhabitants in 1995. We then sum a country’s exports across all destinations and summarize data at the HS4 classification level.

Unit values are computed as the ratio of export values over export quantities. The resulting data is trimmed by excluding observations with extreme unit values. In our base-case scenario observations are dropped whenever

$$
p_{i,t}^k \geq 10 \times \text{median}_k(p_{i,t}^k) \quad \text{and} \quad p_{i,t}^k \geq 5 \times \text{median}_t(p_{i,t}^k)
$$

or

$$
p_{i,t}^k \leq \frac{1}{10} \times \text{median}_k(p_{i,t}^k) \quad \text{and} \quad p_{i,t}^k \leq \frac{1}{5} \times \text{median}_t(p_{i,t}^k),
$$

$^{47}$Khandelwal (2010) proposes an alternative measure for product quality that takes into account demand conditional on prices. We use unit values because first, they are consistent with our theory. And second, our theory suggests that the exact pattern of international trade is a matter of indifference, i.e. if we use trade flows conditional on prices to refine our measure of quality we erroneously interpret idiosyncratic sources of specialization as differences in quality.

$^{47}$This does not affect consistency and asymptotic efficiency of the maximum-likelihood estimator (Carson and Sun, 2007).
i.e. observations are classified as outliers whenever they deviate strongly from the median observation across countries in the same year and from the median observation over time for the same country.

Data on GDP per capita is in purchasing power parities and taken from World Bank (2017).

5.2.3 Estimation results

We begin with estimating Equation (25a) by OLS, using the subsample of data for which we observe an exporter’s unit value. We run the estimation separately for each of the 1241 HS4 product categories included in our data. Standard errors are clustered by country. The estimation results are summarized in column (1) of Table 4.

These results are in line with what has previously been observed by Schott (2004). Roughly 50% of the coefficients on ln(GDP/cap) are positive and significant at the 5% level. Moreover, the average of the β’s indicates that a 10% increase in GDP per capita is associated with an 1.3% increase in unit values.

We next estimate the censored regression model (25) by maximum likelihood, using the full sample available. Again, we run the estimation separately for each of the 1241 HS4 product categories included in our data, and cluster standard errors by country. The estimation results are summarized in column (2) of Table 4.

These results reveal a much stronger link between a country’s GDP per capita and the unit values of its exports. The coefficient on ln(GDP/cap) is significantly positive even at the 1% level in more than 98% of the 1241 HS4 product categories. We obtain a negative coefficient in only 3 out of 1241 regressions, none of which is significant at any conventional level.48 Furthermore, the estimated relationship is much stronger: The maximum-likelihood estimates suggest that on average across all product categories, a 10% higher GDP per capita is associated with a 9.6% higher unit value of the same product. Interestingly, this suggests that a higher skill level is mostly reflected in higher output quality as opposed to higher productivity in physical output units.

Columns (3) to (8) of Table 4 present several robustness checks for our main findings. In columns (3) and (4), we control for a country’s real market potential taken from Centre d’Etudes Prospectives et d’Informations Internationales (CEPII) (2017) and the log of its share of natural resource rents in GDP taken from World Bank (2017).49 In columns (5) and (6) we apply the

---

48 The three HS4 product categories with negative coefficients are: 8504 – Transformers; 6309 – Worn Textiles; 4403 – Wood.

49 The measure of market potential used is the log of the real market potential according to Head and Mayer (2004).
following more liberal selection criterion for outliers

\[ p_{i,t}^k \geq 100 \times \text{median}_k(p_{i,t}^k) \quad \text{and} \quad p_{i,t}^k \geq 50 \times \text{median}_t(p_{i,t}^k) \]

or

\[ p_{i,t}^k \leq \frac{1}{100} \times \text{median}_k(p_{i,t}^k) \quad \text{and} \quad p_{i,t}^k \leq \frac{1}{50} \times \text{median}_t(p_{i,t}^k) \].

And in columns (7) and (8) we exclude products that are traded on organized exchanges according to the Rauch (1999) classification.\(^{50}\) These robustness checks confirm our conclusions from above.

### 5.2.4 Discussion

Our estimation results in Table 4 point to an elasticity of export quality with respect to a country’s GDP per capita of around 1. This coefficient is substantially larger than previous estimates in the literature. The key difference is that our maximum-likelihood estimator refers to the latent preferred quality as opposed to observed quality. That is, in our estimation we explicitly account for the fact that countries are not exporting products that are too complex for their skill level such that they would ideally produce quality lower than the functional minimum-version of that product, in line with our theory. By contrast, when estimating Equation (25a) by

\(^{50}\)The Rauch classification data has been downloaded from http://econweb.ucsd.edu/~jrauch/rauch_classification.html on 6 November 2015. H0 product codes at the four-digit level were matched to SITC rev. 2 industry codes using the concordance table from WITS, as downloaded from http://wits.worldbank.org/product_concordance.html on 6 November 2015.
OLS using the subsample of data with observed export prices we are ignoring this fact and our estimate is a linear approximation to $E \left[ \ln \left( p_{i,t}^k \right) \left( d_{i,t}^k, y_{i,t}^k, p_{i,t}^k \geq \rho_{i,t} \right) \right]$. Importantly, conditional on exporting the error term in Equation (25a) has expected value that is inversely related to $\beta_i \ln(y_i^k)$, implying that the OLS estimate of $\beta_i$ suffers from an omitted variable bias.

While these empirical findings do not provide a formal test of our theory, it is interesting to note that they are consistent with our theoretical predictions in important ways: First, consistent with the predicted omitted variable bias of the OLS regression, we find that in our base case specification the difference between the maximum-likelihood and the OLS estimate of the coefficient on $\ln(GDP/cap)$ is positive for each of the 1241 HS4 product categories considered.\(^{51}\)

Second, our theory actually predicts a unit elasticity of preferred quality with respect to GDP per capita (see Equation (23)). While this need not be the case with generalized production technologies,\(^{52}\) it is still worth noting that a unit elasticity is consistent with the O-ring technology.

Finally, our theory predicts that quality differentiation is constant across products and, in particular, is not systematically related to product complexity (see Equation (23)). This is rooted in the fact that for any given country preferred quality is such that the overall difficulty of production is the same, irrespective of the product’s complexity. In turn this implies that $\tilde{q}_i(r)$ is inversely proportionate to $i^{-\lambda}$ and, hence, $\tilde{q}_i(r)$ is constant across products for any pair of countries $r, r' \in R$. As we discussed in Section 3.3, this is at the very heart of why quality differentiation exactly offsets comparative advantages across products. We therefore use our estimates of quality differentiation to check whether it is systematically related to product complexity.

In particular, we re-run our base-case censored regression model summarizing trade data at the different product categories for each of our four proxies for product complexity. In Figure 5, we plot the estimated coefficients on $\ln(GDP/cap)$ against product complexity to observe that,

\(^{51}\)As previously discussed, the OLS estimate using the subsample of data with observed export prices is a linear approximation to $E \left[ \ln \left( p_{i,t}^k \right) \left( d_{i,t}^k, y_{i,t}^k, p_{i,t}^k \geq \rho_{i,t} \right) \right]$ and, hence, technically a direct comparison of the maximum-likelihood and the OLS estimates is not meaningful. Yet if we ignored the censoring of our data we would typically interpret the OLS estimates as indicating the link between a country’s GDP per capita and the unit values of its exports.

\(^{52}\)Augmenting the O-ring technology by a country-specific productivity shifter

$$f(r, \sigma(i, q)) = [-\ln(r)]^\gamma \sigma^\delta$$

implies, after some straightforward derivations, that

$$[\tilde{q}_i(r)]^{1-\delta} = a_i w_r.$$
Figure 5: Quality differentiation and product complexity
(a) Required learning (b) Intermediate diversification
(c) Non-routine intensity (d) Skill intensity

Notes: This figure shows the ML estimates of $\beta_{\ln(GDP/cap)}$. In each plot (a)–(d) complexity refers to the measure as indicated in the title. Each dot represents a different product according to the level of disaggregation of the respective measure of product complexity.

Indeed, these are not systematically related, in line with our theory.$^{53,54}$

6 Conclusion

This paper studies the implications of quality differentiation for comparative advantages and, hence, international specialization across products. The key novelty is that we allow firms to endogenously choose the quality of their product in an otherwise standard Ricardian framework. Such quality differentiation is subject to functional minimum-requirements. We show

$^{53}$The slight upward trend when using the non-routine intensity or the skill intensity as a proxy for complexity is driven by the positive outlier ‘aerospace products and parts’ (IPUMS industry classification code 359).

$^{54}$The estimated coefficients in Figure 5 are smaller on average than in our main specifications as reported in Table 4. This is because we use much more aggregated data in Figure 5.
that it therefore gives rise to an upper-triangular pattern of international specialization where industrialized countries successfully export both complex and simple products while developing countries specialize in the simpler ones. Quality differentiation may therefore help explaining why richer countries tend to be more diversified, why increasingly over time rich and poor countries export the same products, and it is in line with novel stylized facts on the international specialization across products.

To distill the main mechanisms of interest, we analyze how quality differentiation impacts fundamental sources of comparative advantage in the tradition of Costinot (2009a). Such sources of comparative advantage are also present in other contexts, and our insights may well be relevant for the broader literature that builds on Costinot (2009a) and analyzes patterns of specialization across countries, cities, or workers, for example. Future work may set out to embed our theory in gravity-models to investigate implications for trade and the gains from trade in such models. The mechanisms we identify also matter for related fields in the literature, and it would be interesting to analyze their implications for trade policies, for the growth prospects of developing countries, for matters of ‘economic complexity’, and for income inequality, for example. Our theoretical framework is tractable enough to lend itself to such analyses in future.
Appendix

A  Details on proxies for product complexity

In this appendix, we provide some additional information on the proxies for product complexity used in the main body of our paper, and describe how we match them to HS product categories at the six-digit level.

Costinot (2009b) – required on-the-job-learning

Costinot (2009b) uses data on the average number of months that it will take for an educated and experienced worker to become fully productive at his job to proxy for product complexity. Data are taken from the PSID surveys of 1985 and 1993. Excluding industries with less than 25 observations, he gets complexity measures for 40 SIC72 manufacturing industries at differing levels of disaggregation. SIC72 codes are first matched to SIC87 codes using the concordance table provided by the NBER. Whenever a SIC72 industry is assigned to several SIC87 industries in this concordance table, the SIC87 industry with the largest share of shipment is chosen. H0 product codes at the six-digit level are then matched to SIC87 industry codes using the concordance table from WITS.

Levchenko (2007) – intermediate input diversification

We use the inverse of the Herfindahl index of intermediate input concentration as a second proxy for product complexity. The index is taken from Levchenko (2007) who computed it based on the US Input-Output table for 1992, yielding measures for 389 SIC87 industries at the 4-digit level. H0 product codes at the six-digit level are matched to SIC87 industry codes using again the concordance table from WITS.

Acemoglu and Autor (2011) – non-routine intensity

Based on O*Net data, Acemoglu and Autor (2011) summarize various characteristics of occupations. Based on their measures, we compute the non-routine intensity of an occupation as follows

\[ NR = nr_{cog\_anal} + nr_{cog\_pers} - r_{cog} - r_{man}, \]

where the right-hand-side variables measure the importance of the following task types

---

55 The data has been downloaded from http://www.nber.org/nberces/nberces5811 on 17 February 2016.
56 The data has been downloaded from http://wits.worldbank.org/product_concordance.html on 17 November 2015.
• ‘nr_cog_anal’: ‘Non-routine cognitive: Analytical’

• ‘nr_cog_pers’: ‘Non-routine cognitive: Interpersonal’

• ‘r_cog’: ‘Routine cognitive’

• ‘r_man’: ‘Routine manual’.

Occupations are mapped to industries based on occupation shares as computed from the IPUMS Census 2000 survey data.\textsuperscript{57,58} IPUMS industry categories are mapped to NAICS industry codes using the crosswalk provided by IPUMS.\textsuperscript{59} H0 product codes at the six-digit level are then mapped to NAICS industry codes using the concordance table provided by Pierce and Schott (2009). Whenever six-digit HS product categories are mapped into several NAICS industries, the NAICS industry with the highest share of US exports in 1995 is chosen.\textsuperscript{60} This procedure results in complexity measures for 83 IPUMS industries, out of which the 74 manufacturing industries are included in our sample.

**Skill intensity**

The skill intensity of an industry is measured by the average years of schooling of workers within that industry as computed from the IPUMS Census 2000 survey data. These measures are then mapped to HS product categories using the procedure as described for our non-routine measure.

All proxies are standardized to lie in the interval $[0, 1]$. Table 5 shows the three most and least complex industries for each of the four product rankings. All in all these rankings suggest that the four proxies applied here do indeed measure different facets of product complexity.

\textsuperscript{57} Only workers of age 16 to 64 not living in group quarters are included in the sample.

\textsuperscript{58} The data has been downloaded from https://usa.ipums.org/usa-action/variables/group on 19 February 2016.

\textsuperscript{59} The crosswalk has been downloaded from https://usa.ipums.org/usa/volii/occ_ind.shtml on 19 February 2016.

\textsuperscript{60} The export data are from Schott (2008). Export data and concordances have been downloaded from http://faculty.som.yale.edu/peterschott/sub_international.htm on 19 February 2016.
Table 5: Three most and least complex products by measure

<table>
<thead>
<tr>
<th>Measure</th>
<th>Code</th>
<th>Most complex Description</th>
<th>Code</th>
<th>Least complex Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required learning</td>
<td>383-5a</td>
<td>Optical &amp; health services supplies</td>
<td>225a</td>
<td>Knitting mills</td>
</tr>
<tr>
<td></td>
<td>372a</td>
<td>Aircraft &amp; parts</td>
<td>239a</td>
<td>Misc. fabricated textile products</td>
</tr>
<tr>
<td></td>
<td>283a</td>
<td>Drugs &amp; medicines</td>
<td>231-8b</td>
<td>Apparel &amp; accessories</td>
</tr>
<tr>
<td>Interm. diversific.</td>
<td>3728b</td>
<td>Aircraft parts &amp; auxiliary equipment</td>
<td>2011b</td>
<td>Meat packing plants</td>
</tr>
<tr>
<td></td>
<td>3296b</td>
<td>Mineral wool</td>
<td>2075b</td>
<td>Soybean oil mills</td>
</tr>
<tr>
<td></td>
<td>3842b</td>
<td>Orthopedic, prosthetic, and surgical appliances</td>
<td>2015b</td>
<td>Poultry slaughtering and processing</td>
</tr>
<tr>
<td>Non-routine intensity</td>
<td>336c</td>
<td>Computer and peripheral equipment</td>
<td>168c</td>
<td>Cut and sew apparel</td>
</tr>
<tr>
<td></td>
<td>359f</td>
<td>Aerospace products &amp; parts</td>
<td>147c</td>
<td>Fiber, yarn, and thread mills</td>
</tr>
<tr>
<td></td>
<td>219f</td>
<td>Pharmac. &amp; medicines</td>
<td>238c</td>
<td>Tires</td>
</tr>
<tr>
<td>Skill intensity</td>
<td>219c</td>
<td>Pharmac. &amp; medicines</td>
<td>169c</td>
<td>Apparel accessories and other apparel</td>
</tr>
<tr>
<td></td>
<td>359c</td>
<td>Aerospace products &amp; parts</td>
<td>118c</td>
<td>Animal slaughtering and processing</td>
</tr>
<tr>
<td></td>
<td>336c</td>
<td>Computer and peripheral equipment</td>
<td>168c</td>
<td>Cut and sew apparel</td>
</tr>
</tbody>
</table>

a SIC72 industry classification code  
b SIC87 industry classification code  
c IPUMS industry classification code

B Proofs

B.1 Proof of Proposition 1

Recall that $\tilde{i}(r^h) > \tilde{i}(r^l)$. Part (i) then immediately follows from noting that for $i^h \leq \tilde{i}(r^l)$ both countries produce both products at preferred quality in combination with Equation (14).

Part (ii): If $i^l \geq \tilde{i}(r^h)$, both countries produce functional minimum-quality $q = 1$ of both products, and the result follows from Equation (12). Finally, if $i^h > \tilde{i}(r^l)$ and $i^l < \tilde{i}(r^h)$ there is a range of products $\hat{I} \subseteq [i^l, i^h]$ such that $\tilde{i}(r^h) \geq i > \tilde{i}(r^l) \forall i \in \hat{I}$. Country $r^h$ can produce these products at preferred quality while country $r^l$ cannot. Equations (6) and (13) therefore imply

$$
\frac{g(r^h, i, q_i(r^h))}{g(r^l, i, q_i(r^l))} = (r^l)^{-i} \left[-e\lambda i \ln(r^h)\right]^{-\frac{1}{\lambda}} , \quad \forall i \in \hat{I} .
$$

The desired result then follows from

$$
\frac{d}{di} \left[ \frac{g(r^h, i, q_i(r^h))}{g(r^l, i, q_i(r^l))} \right] = (r^l)^{-i} \left[-e\lambda i \ln(r^h)\right]^{-\frac{1}{\lambda}} \left[ -\frac{1}{\lambda i} - \ln(r^l) \right] > 0 ,
$$

42
where the inequality follows from the fact that country $r^i$ is constrained by the functional minimum-requirement, which implies

\[-\frac{1}{\lambda} - \ln(r^i) > 0\]

in combination with the results above for the cases of $i^h \leq \tilde{i}(r^i)$ and $i^l \geq \tilde{i}(r^h)$, respectively.

\[\square\]

**B.2 Proof of Proposition 2**

Part (i) follows from the discussions in the main text.

To show part (ii), note first that by (16) and Assumption 1(ii) we have

\[
\frac{d^2 \ln(g(r, i, \tilde{q}_i(r)))}{dr di} = 0 \Leftrightarrow \frac{\partial \sigma(i, \tilde{q}_i(r))}{\partial i} + \frac{\partial \sigma(i, \tilde{q}_i(r))}{\partial q} \frac{d\tilde{q}_i(r)}{di} = 0 .
\]

(B.1)

Hence, \(\frac{d^2 \ln(g(r, i, \tilde{q}_i(r)))}{dr di} = 0\) if and only if the interior solution for quality is such that the overall difficulty of production is independent of complexity, i.e.

\[\sigma(i, \tilde{q}_i(r)) = \sigma^*(r) .\]

We now proceed showing necessity and sufficiency in turn.

\[\sigma(i, q) = \sigma(\gamma(i)q) \Rightarrow \frac{d^2 \ln(g(r, i, \tilde{q}_i(r)))}{dr di} = 0 \quad \text{Using the functional form for } \sigma(\cdot) \text{ in the first order condition for quality (17) and applying the chain rule, we get}
\]

\[\frac{1}{q} + \frac{\partial \ln(f(r, \sigma(\gamma(i)q)))}{\partial \sigma} \sigma'(\gamma(i)q)\gamma(i) = 0 ,\]

which implies

\[- \frac{\partial \ln(f(r, \sigma(\gamma(i)q)))}{\partial \sigma} \sigma'(\gamma(i)q)\gamma(i)q = 1 .\]

Note that $q$ enters the above equation only via $z := \gamma(i)q$. Moreover, by assumption there exists a unique solution to this first order condition. This solution $\tilde{q}_i(r)$ must therefore be such that $\gamma(i)\tilde{q}_i(r)$ and hence $\sigma(i, \tilde{q}_i(r))$ is constant across complexity levels, and the result then follows from the above.

\[\frac{d^2 \ln(g(r, i, \tilde{q}_i(r)))}{dr di} = 0 \Rightarrow \sigma(i, q) = \sigma(\gamma(i)q) \quad \text{Applying the chain rule to the optimality condition for quality we get}
\]

\[\frac{1}{q} + \frac{\partial \ln(f(r, \sigma(i, q)))}{\partial \sigma} \frac{\partial \sigma(i, q)}{\partial q} = 0 .\]

From the above, \(\frac{d^2 \ln(g(r, i, \tilde{q}_i(r)))}{dr di} = 0\) implies that $\sigma(i, \tilde{q}_i(r)) = \sigma^*(r)$ and, hence

\[\tilde{q}_i(r) = -\frac{1}{\mu(r) \frac{\partial \sigma(i, \tilde{q}_i(r))}{\partial q}} , \quad \text{(B.2)}\]
where $\mu(r) := \frac{\partial \ln(f(r, \sigma^*(r)))}{\partial \sigma}$. Differentiating with respect to $i$ yields

$$
\frac{d\tilde{q}_i(r)}{di} = \frac{1}{\mu(r)} \frac{\partial^2 \sigma(i, \tilde{q}_i(r)) + \partial^2 \sigma(i, \tilde{q}_i(r)) \cdot d\tilde{q}_i(r)}{\partial q \partial \tilde{q}} \cdot \left( \frac{\partial \sigma(i, \tilde{q}_i(r))}{\partial \tilde{q}} \right)^2, 
$$

which we rearrange to get

$$
\frac{d\tilde{q}_i(r)}{di} = \mu(r) \left( \frac{\partial \sigma(i, \tilde{q}_i(r))}{\partial \tilde{q}} \right)^2 - \frac{\partial^2 \sigma(i, \tilde{q}_i(r))}{\partial \sigma \partial \tilde{q}}. 
$$

(B.3) describes how the optimal $q$ varies with complexity if $\frac{d^2 \ln(g(r, i, \tilde{q}_i(r)))}{dr di} = 0$ (and hence $\sigma(\cdot)$ is such that $\sigma(i, \tilde{q}_i(r)) = \sigma^*(r)$). This, we know, will be the case if and only if

$$
\frac{d\tilde{q}_i(r)}{di} = -\frac{\partial \sigma(i, \tilde{q}_i(r))}{\partial \sigma \partial \tilde{q}}. 
$$

Combining the last two equations and rearranging terms we get

$$
\frac{\partial^2 \sigma(i, \tilde{q}_i(r))}{\partial \sigma \partial \tilde{q} \partial i} = -\mu(r) \frac{\partial \sigma(i, \tilde{q}_i(r))}{\partial \tilde{q}} + \frac{\partial^2 \sigma(i, \tilde{q}_i(r))}{\partial \sigma \partial \tilde{q}} = \frac{1}{\tilde{q}_i(r)} + \frac{\partial^2 \sigma(i, \tilde{q}_i(r))}{\partial \sigma \partial \tilde{q}}, 
$$

where the last equality follows from using (B.2). Now, let $\frac{d^2 \ln(g(r, i, \tilde{q}_i(r)))}{dr di} = 0$ for all $r, i$ in some connected subregion $\Omega_1 \subseteq \mathbb{R}_+^2$. Then, by the continuity of $\tilde{q}_i(r)$ (B.4) must be satisfied for all $q, i$ in some connected subregion $\Omega_2 \subseteq \mathbb{R}_+^2$. Integrating yields

$$
\tilde{\gamma}(i) + \ln \left( \frac{\partial \sigma(i, q)}{\partial i} \right) = \ln(q) + \ln \left( \frac{\partial \sigma(i, q)}{\partial q} \right) 
\iff
\exp(\tilde{\gamma}(i)) \frac{\partial \sigma(i, q)}{\partial i} = q \frac{\partial \sigma(i, q)}{\partial q} \quad (B.5)
$$

for an arbitrary function $\tilde{\gamma}(\cdot)$. Note that (B.5) along with $\sigma(\cdot)$ twice continuously differentiable imply that $\tilde{\gamma}(\cdot)$ is continuously differentiable. (B.5) is a homogeneous linear partial differential equation. Its general solution can be obtained by solving the characteristic equation (John, 1982, pp. 9–14)

$$
\frac{di}{dq} = -\frac{\exp(\tilde{\gamma}(i))}{q},
$$

with solution

$$
\ln(q) + \tilde{k} = -\int \exp(-\tilde{\gamma}(i)) \, di 
\iff
q \gamma(i) = k,
$$

44
where \( \gamma(i) := \exp \left( \int \exp (-\tilde{\gamma}(i)) \, di \right) \) and \( k \) is a constant. \( \sigma(\cdot) \) is constant along the characteristic curves \( q \gamma(i) = k \). The general solution to (B.5) is therefore

\[
\sigma(i, q) = \sigma(\gamma(i)q)
\]

(B.6)

for an arbitrary twice continuously differentiable function \( \sigma(\cdot) \). Finally, to get at the expression in Proposition 2, note that complexity matters only for its impact on production. Hence, with a slight abuse of notation but without further loss of generality, we can redefine complexity as \( i := \gamma(i) \) and Equation (B.6) simplifies to \( \sigma(i, q) = \sigma(iq) \).

\[\square\]

### B.3 Proof of Proposition 3

Most parts of Proposition 3 have been shown in Section 4.1. It remains to be shown that an equilibrium according to Proposition 3(i) is unique. We proceed by ruling out all other possibilities. For the purpose of this proof, it will be convenient to use \( \tilde{g}(r) := \left[ \frac{\ln(r)}{\ln(r^h)} \right]^\frac{1}{h} \) to denote the productivity of labor with skill level \( r \) relative to the lowest skilled labor given that both can operate at preferred quality. Moreover, to simplify the exposition, we will consider the case where both \( \mathcal{R} \) and \( \mathcal{I} \) are discrete sets.\(^{61}\)

Note first that a wage scheme where for any pair of countries \( r^h \geq r^l \) it holds that \( \frac{w^{r^h}}{w^{r^l}} < \left[ \frac{\ln(r^l)}{\ln(r^h)} \right]^\frac{1}{h} = \frac{\tilde{g}(r^h)}{\tilde{g}(r^l)} \) can never be an equilibrium as in such case country \( r^h \) would provide all products at lower cost when compared to country \( r^l \). Such a wage scheme would therefore violate labor market clearing in country \( r^l \). Hence, a candidate equilibrium wage scheme \( \hat{w}_r \) satisfies

\[
\frac{\hat{w}_{r^h}}{\hat{w}_{r^l}} \geq \left[ \frac{\ln(r^l)}{\ln(r^h)} \right]^\frac{1}{h} = \frac{\tilde{g}(r^h)}{\tilde{g}(r^l)} \forall r^l, r^h \in \mathcal{R} : \ r^h \geq r^l ,
\]

with the inequality being strict for some \( r^l, r^h \in \mathcal{R} \). We proceed by showing that such an alternative wage scheme contradicts labor market clearing in the high-skill countries \( \mathcal{R}^h := \left\{ r \in \mathcal{R} : \frac{\hat{w}_r}{\hat{w}_r} = \frac{\tilde{g}(r)}{\tilde{g}(r)} \right\} \) where \( \tau := \max \mathcal{R} \) denotes the highest skilled country.

Clearly, production in countries \( r \in \mathcal{R}^h \) will be at preferred quality for otherwise production would be strictly cheaper in the highest skilled country \( \tau \). Let \( \mathcal{I}^h \) denote the set of industries for which country \( \tau \) is competitive under wage scheme \( \hat{w}_r \). All countries \( r \in \mathcal{R}^h \) are competitive for a subset of these industries. Moreover, \( \mathcal{I}^h \) is a subset of industries \( \left\{ i \in \mathcal{I} : i > \tilde{i}(\tau) \right\} \) where \( \tilde{\tau} := \max \mathcal{R} \setminus \mathcal{R}^h \). In turn, this implies that all production in industries \( \mathcal{I}^h \) is located in countries

\(^{61}\)At the expense of additional notational complexity, this assumption can be dispensed with.
\( \mathcal{R}^h \) under the equilibrium wage scheme \( w_r^* = \bar{g}(r) \) \( \forall r \in \mathcal{R} \) as well. It therefore suffices to show that total demand for effective labor in these industries is lower under wage scheme \( \hat{w}_r \).

Choosing again \( w_\pi \) to be the numéraire and starting from the equilibrium wage scheme \( w_r^* \), the alternative wage scheme \( \hat{w}_r \) can be reached by the following iterative procedure:

1. Let \( r_1 := \min \{ r \in \mathcal{R} : \hat{w}_r > \bar{g}(r) \} \). Increase wages in countries \( r \geq r_1 \) by the factor \( \frac{\hat{w}_r}{\bar{g}(r)} \).

2. Let \( r_j := \min \left\{ r \in \mathcal{R} : \hat{w}_r > \bar{g}(r) \frac{\hat{w}_{r_{j-1}}}{\bar{g}(r_{j-1})} \right\} \) \( j = 2, 3, \ldots \). Increase wages in countries \( r \geq r_j \) by the factor \( \frac{\hat{w}_{r_j}}{\bar{g}(r_j)} \frac{\bar{g}(r_{j-1})}{\hat{w}_{r_{j-1}}} \).

3. Continue until the wage in country \( \pi \) is equal to \( \hat{w}_\pi \).

After step \( j = 1, 2, \ldots \), country \( \pi \) will be competitive for industries \( \mathcal{I}_j \subset \{ i \in \mathcal{I} : i > \tilde{i}(\hat{r}_j) \} \) where \( \hat{r}_j := \max \{ r \in \mathcal{R} : r < r_j \} \). Clearly, all countries \( r \geq r_j \) will be competitive for a subset of industries \( \mathcal{I}_j \) and all production in these countries will be at preferred quality. From the perspective of the representative consumer, step \( j \) of the above procedure then involves a Slutsky compensated proportionate increase in the prices of all products \( i \in \mathcal{I}_j \). By additive separability of preferences, this will not affect relative demand for any pair of products in the set \( \mathcal{I}_j \). It follows that total demand for products \( i \in \mathcal{T}^h \subset \mathcal{I}_j \), and therefore total demand for effective labor in these products, will decline in step \( j \). To show this, two cases need to be distinguished.

(i) \( \mathcal{I}_j = \{ i \in \mathcal{I} : i > \tilde{i}(\hat{r}_j) \} \). Then demand for these products declines by the composite commodity theorem (cf. e.g. Woods, 1979) and the fact that with \( \nu > 0 \) the own substitution effect is negative.\(^{62}\)

(ii) \( \mathcal{I}_j = \{ i \in \mathcal{I} : i \geq i' \} \subset \{ i \in \mathcal{I} : i > \tilde{i}(\hat{r}_j) \} \) for some cutoff \( i' > \tilde{i}(\hat{r}_j) \). Then, in addition to a compensated proportionate increase in the prices of all products \( i \in \mathcal{I}_j \), step \( j \) involves a non-compensated but smaller increase in the prices of all products \( \{ i \in \mathcal{I} : \tilde{i}(\hat{r}_j) < i < i' \} \) and we can apply a similar sequential reasoning. Specifically, we can split the price changes into a sequence of proportionate price increases for all products \( i \geq k_j \) and where \( k_j \) is the \( j^{th} \)—smallest element of the set \( \{ i \in \mathcal{I} : \tilde{i}(\hat{r}_j) < i \leq i' \} \). In each of these steps total demand for products \( i \in \mathcal{T}^h \) declines by the above and the fact that all products are normal goods.

It follows that aggregate demand for effective labor in countries \( \mathcal{R}^h \) is strictly smaller under the alternative wage scheme \( \hat{w}_r \) than under the equilibrium wage scheme \( w_r^* = \bar{g}(r) \), a contradiction to labor market clearing in these countries.

\( \square \)

\(^{62}\)With Leontief preferences and Condition (SSC) holding with equality for some \( \hat{i} > \min \mathcal{I} \), there would be indeterminacy in the wages for labor in countries \( r^h \geq \hat{r}(\hat{i}) \) relative to wages for labor in countries \( r^l < \hat{r}(\hat{i}) \).
B.4 Proof of Proposition 4

In this appendix, we fully characterize the equilibrium in our economy for the case of sufficient skills and show that it implies Proposition 4. In doing so, it will be convenient to assume \( \mathcal{I} = [0, N] \), but this will not be essential in any way. We further assume that the elasticity of substitution between products satisfies \( 0 < \nu < 1 + \lambda \), which guarantees that all products will be consumed in equilibrium.\(^6\) Moreover, it will be convenient to use \( \mathcal{R}_i \) to denote the set of countries with positive output of product \( i \), and \( \tilde{L} \) to denote the aggregate supply of effective labor in the economy

\[
\tilde{L} := L \int_{r \in \mathcal{R}} \left[ \frac{h(r)}{\ln(r)} \right]^\frac{1}{x} dF_r(r).
\]

With this notation at hands, we can fully characterize the equilibrium with sufficient skills as follows:

**Proposition 6**

*If and only if*

\[
\frac{\int_{r \in \mathcal{R}} \left[ -\ln(r) \right]^{-\frac{1}{x}} \left[ -\ln(r) \right]^{-\frac{1}{x}} dF_r(r)}{\int_{r \in \mathcal{R}} \left[ -\ln(r) \right]^{-\frac{1}{x}} dF_r(r)} \geq 1 - \left( \frac{\nu}{N} \right)^{\frac{1+\lambda-\nu}{\lambda}}, \quad \forall i \in [0, N],
\]

*there is an equilibrium with*

(i) \( w_i = \left[ \frac{h(r)}{\ln(r)} \right]^\frac{1}{x} \quad \forall r \in \mathcal{R} \)

(ii) \( \mathcal{R}_i \subseteq \{ r \in \mathcal{R} : r \geq \tilde{r}(i) \} \quad \forall i \in [0, N] \)

(iii) \( q_i(r) = \left[ \frac{1}{\ln(r)} \right]^\frac{1}{x} \quad \forall (i, r) \in [0, N] \times \mathcal{R}_i \)

(iv) \( \rho_i = [-e\lambda \ln(r)]^\frac{1}{x} \quad \forall i \in [0, N] \)

(v) \( \chi_i = \tilde{L} \left[ -\nu \lambda \ln(r) \right]^{-\frac{1}{x}} \left[ \frac{1+\lambda-\nu}{1-\nu+\lambda} \right] N^{-\frac{1+\lambda-\nu}{\lambda}} [i]^{-\frac{1}{x}} \quad \forall i \in [0, N] \)

(vi) \( \tilde{L}_i = \tilde{L} \left[ \frac{1+\lambda-\nu}{1-\nu+\lambda} \right] N^{-\frac{1+\lambda-\nu}{\lambda}} [i]^{-\frac{1}{x}} \quad \forall i \in [0, N] \)

(vii) \( P = [-e\lambda \ln(r)]^\frac{1}{x} \left[ \frac{1+\lambda-\nu}{1-\nu+\lambda} \right] N^{-\frac{1+\lambda-\nu}{\lambda}} \)

(viii) \( C = \tilde{L} \left[ -\nu \lambda \ln(r) \right]^{-\frac{1}{x}} \left[ \frac{1+\lambda-\nu}{1-\nu+\lambda} \right] N^{-\frac{1+\lambda-\nu}{\lambda}} \).

\(^6\) \( \nu < 1 + \lambda \) ensures that households’ love-for-variety is sufficiently large. In the words of Bernard et al. (2003, p. 1276), it ensures that: ‘goods are sufficiently heterogeneous in consumption relative to their heterogeneity in production so that buyers do not concentrate their purchases on a few low-price goods.’ In our case, the need for this restriction arises from our choice of the functional form for \( f(r, i, q) \), which implies that with production at preferred quality productivity of a worker in terms of effective output will be decreasing in a product’s complexity, and the fact that we consider a range of complexities \( i \in [0, N] \). At the expense of additional notational complexity, this restriction can easily be dispensed with by introducing e.g. a strictly positive lower bound on complexity, \( \xi > 0 \), or product-specific taste parameters.
The equilibrium is unique up to the allocation of total effective output of product $i$, $\chi_i$, to countries, $R_i$, and hence the choice of qualities, and output and labor input levels for these qualities.

Proof:

To show the desired result, we solve for all equilibrium values in Proposition 6, assuming that there are sufficient skills. We then use the derived demand for effective labor in the Sufficient Skills Condition to show that there is an equilibrium with sufficient skills if and only if Condition (21) in Proposition 4 is satisfied.

From Proposition 3(i) and Corollary 1 we know that with sufficient skills the unique equilibrium wage scheme is

$$w_r = \left[ \frac{\ln(r)}{\ln(\tau)} \right]^\frac{1}{\lambda},$$

and country $r$ is competitive for all products $i \leq \tilde{i}(r)$. Along with (13), this implies for $\rho_i$

$$\rho_i = [-e^\lambda \ln(r)]^\frac{1}{\lambda}. \quad (B.8)$$

Substituting (B.8) in (5) and solving the integral yields the equilibrium price index $P$

$$P = [-e^\lambda \ln(r)]^\frac{1}{\lambda} \left[ \frac{\lambda}{1 - \upsilon + \lambda} \right] \tilde{L}_d \tau^\frac{1 - \upsilon}{\lambda} N \frac{1 - \upsilon + \lambda}{\lambda}. \quad (B.9)$$

Note that here we used the restriction $\upsilon < 1 + \lambda$. Using (B.8) in the demand for product $i$ (3), we obtain

$$\chi_i = CP^\upsilon [-e^\lambda \ln(r)]^\frac{1 - \upsilon}{\lambda}, \quad (B.10)$$

where we use $\chi_i$ to denote total quality-adjusted output of product $i$. Combining this result with Equation (13) and our definition of effective labor yields

$$\tilde{L}_i^d = CP^\upsilon [-e^\lambda \ln(r)]^\frac{1 - \upsilon}{\lambda}. \quad (B.11)$$

Now Condition (SSC) guarantees that there is no excess demand for skills in our economy. In addition, labor-market clearing requires that total demand for effective labor equals total supply

$$\tilde{L} = \int_{i=1}^{\tilde{i}(r)} \tilde{L}_i^d \, di$$

$$= CP^\upsilon [-e^\lambda \ln(r)]^\frac{1 - \upsilon}{\lambda} \frac{\lambda}{1 + \lambda - \upsilon} N \frac{1 + \lambda - \upsilon}{\lambda},$$

where the second equality follows from using (B.11) and solving the integral, and where $\tilde{L}$ denotes the aggregate supply of effective labor in the economy

$$\tilde{L} := L \int_{r \in R} \left[ \frac{\ln(r)}{\ln(\tau)} \right]^\frac{1}{\lambda} dF_r(r). \quad (B.12)$$
Solving for $C$ and using Equation (B.9) yields

$$C = \tilde{L} \left[ -e\lambda \ln(r) \right]^{-\frac{1}{\lambda}} \left[ \frac{\lambda}{1 + \lambda - v} \right]^{\frac{1}{\lambda}} N^{\frac{1 + \lambda - v}{\lambda}}. \quad (B.13)$$

Using Equations (B.9) and (B.13) in Equation (B.10) we obtain

$$\chi_i = \tilde{L} \left[ -e\lambda \ln(r) \right]^{-\frac{1}{\lambda}} \frac{1 + \lambda - v}{\lambda} N^{-\frac{1 + \lambda - v}{\lambda}} [i]^{-\frac{v}{\lambda}}. \quad (B.11)$$

Using Equations (B.9) and (B.13) in Equation (B.11) yields

$$\tilde{L}_i^d = \frac{1 + \lambda - v}{\lambda} N^{-\frac{1 + \lambda - v}{\lambda}} [i]^{\frac{1}{\lambda}}. \quad (B.14)$$

Using (B.14) in Condition (SSC) we get

$$L \int_{r \in \mathbb{R}, r \geq \tilde{r}(i)} \left[ \frac{\ln(r)}{\ln(r)} \right]^\frac{1}{\lambda} dF_r(r) \geq \int_{i}^{N} \left[ \frac{1 + \lambda - v}{\lambda} N^{-\frac{1 + \lambda - v}{\lambda}} [i]^{\frac{1}{\lambda}} \right] di, \quad \forall i \in [0, N].$$

Finally, solving the integral on the right-hand side, using the definition of $\tilde{L}$ given in Equation (B.12), and rearranging terms, yields

$$\frac{\int_{r \in \mathbb{R}, r \geq \tilde{r}(i)} [-\ln(r)]^{-\frac{1}{\lambda}} dF_r(r)}{\int_{r \in \mathbb{R}} [-\ln(r)]^{-\frac{1}{\lambda}} dF_r(r)} \geq 1 - \left( i \frac{\lambda + \lambda - v}{N} \right), \quad \forall i \in [0, N],$$

which is Condition (21).

\[ \square \]

### B.5 Proof of Proposition 5

The fact that countries with skill levels $r \geq \tilde{r}(i)$ have zero gains from trade follows from the discussion in the main text. To show that the gains from trade are monotonously decreasing in a country’s skill level, we consider the equivalent variation of moving from autarky to free trade and show that it is relatively larger for lower skilled countries.

Let $\rho$ denote the vector of quality-adjusted prices for all products. With homothetic preferences, the expenditure function can be written as

$$e(\rho, u) = \phi^{-1}(u) \frac{1}{a(\rho)},$$

where $\phi(\cdot)$ is strictly increasing and $\phi(ya(\rho))$ is the (indirect) utility that a household can achieve with price vector $\rho$ and income $y$. $a(\rho)$ is strictly decreasing in all of its arguments.
Consider two countries $r^h > r^l$ such that $\tilde{i}(r^l) < \tilde{i}$, i.e. the most complex product cannot be produced at preferred quality in country $r^l$. The equivalent variation of moving from autarky to free trade for consumers in country $r^l$ is

$$EV_{r^l} = e(\rho^a_{r^l}, \phi(w_{r^l}, a(\rho^{ft}_{r^l}))) - e(\rho^{ft}_{r^l}, \phi(w_{r^l}, a(\rho^{ft}_{r^l})))$$

$$= \left[ \frac{a(\rho^{ft}_{r^l})}{a(\rho^{a}_{r^l})} - 1 \right] w_{r^l},$$

where superscripts $a$ and $ft$ denote autarky and free-trade values, respectively, and where we have normalized the wage under autarky in country $r^l$ to be equal to its free trade wage. The second equality then follows from using the expression for the expenditure function and from $\phi(\cdot)$ being injective. Dividing both sides of the above expression by $w_{r^l}$ and adding and subtracting $e(\rho^a_{r^h}, \phi(a(\rho^{ft}_{r^l})))$ to the right hand side yields

$$\frac{EV_{r^l}}{w_{r^l}} = \left[ \frac{e(\rho^{ft}_{r^l})}{e(\rho^{a}_{r^l})} - \frac{a(\rho^{ft}_{r^l})}{a(\rho^{a}_{r^l})} \right] + \left[ \frac{a(\rho^{ft}_{r^l})}{a(\rho^{a}_{r^l})} - 1 \right]$$

Now, normalize the wage under autarky in country $r^h$ to be equal to its free trade wage, $w^a_{r^h} = w^{ft}_{r^h} = w_{r^h}$. The second summand is then just $\frac{1}{w_{r^h}} EV_{r^h}$. The first summand is strictly positive because $\rho^a_{r^l} > \rho^a_{r^h}$ and therefore $a(\rho^a_{r^l}) < a(\rho^a_{r^h})$ by Corollary 1, Proposition 1, and the fact that $\tilde{i}(r)$ is increasing. It follows that

$$\frac{EV_{r^l}}{w_{r^l}} > \frac{EV_{r^h}}{w_{r^h}}.$$

$\square$
References


Online Appendix for ‘Quality Differentiation, Comparative Advantage, and International Specialization Across Products’

This online appendix provides additional robustness checks for the findings in ‘Quality Differentiation, Comparative Advantage, and International Specialization Across Products’. In particular, in Online Appendix C we illustrate the importance of quality differentiation for international specialization across products in a setting with trade costs and the generalized production technology of Section 3.3. In Online Appendix D we show robustness of our stylized facts of Section 2 to alternative specifications.

C Further results on specialization across products with quality differentiation

The discussions in Section 3.3 show that quality differentiation will exactly offset comparative advantages only under certain conditions. Whenever these conditions are not met, some comparative advantage will prevail even when operating at preferred quality, and we are back with a ladder of international specialization. Similarly, trade costs will break the indifference in our main equilibrium of interest, and, again, we are back with a ladder of international specialization.64

This lack of robustness of the main equilibrium of interest arises from the parsimonious structure of our model. In turn, this parsimony allows to embed the basic structure in richer environments. A natural question is then to ask whether the predicted pattern of international specialization is merely an artifact of considering a knife-edge case, or whether the underlying mechanisms are relevant more generally. To address this concern, we briefly discuss a ‘polar case’ when compared to our main set-up: A multi-product (industry) variant of the Eaton and Kortum (2002) (EK) model as in Costinot et al. (2012), but where fundamental productivities follow our baseline model. While in the basic version of our model a country will never export a product for which it is bounded by the functional minimum-requirement, in the multi-product

64 In particular, we can show that the set of products for which a country is competitive is weakly increasing in the strong set order, and that the lowest skilled country is excluded from exporting the most complex products, while the highest skilled country is excluded from exporting products that can be produced at preferred quality in the lowest skilled country.
EK model all countries will always be exporting some varieties of every product. In that sense we say it forms a polar case.

In particular, suppose that there are many varieties \( \omega \in \Omega_i \) of every product \( i \), and that the fundamental quality-adjusted productivity \( g(r, i, q_i(r)) \) is subject to an idiosyncratic shock \( \varphi_i^r(\omega) \) such that in country \( r \) the quality-adjusted productivity for variety \( \omega \) of product \( i \) is given by

\[
z_i^r(\omega) = \varphi_i^r(\omega)g(r, i, q_i(r))
\]

Following EK, let \( \varphi_i^r(\omega) \) be the realization of a random variable drawn independently and identically across countries and products from the following Fréchet distribution

\[
F(\varphi) = e^{-\varphi^{-\theta}},
\]

where \( \theta > 1 \).\(^{65}\) Moreover, suppose that trade is subject to an iceberg cost such that \( d_{rr}^i \geq 1 \) units of a variety of product \( i \) need to be shipped from country \( r \) for one unit to arrive in destination country \( \tilde{r} \). Then following standard steps and applying the ‘diff-in-diff’ approach in Costinot et al. (2012), we get for the relative exports of any pair of countries \( r' > r \) and products \( i' > i \) to destination country \( \tilde{r} \)

\[
\frac{\pi_{i'r'}^{r'}}{\pi_{ir}^r} = \left[ \frac{g(r',i',q_{i'}(r')) d_{i'r'}^{i'}}{g(r,i,q_i(r)) d_{ir}^i} \right]^\theta.
\]

Hence, trade patterns inherit the structure of fundamental productivities as long as interactions between trade costs, skill levels, and complexity do not systematically affect these, i.e. as long as trade costs are multiplicatively separable (Costinot et al., 2012, Corollary 1)

\[
d_{rr}^i = d_{\tilde{r}i}^i d_{\tilde{r}\tilde{r}}^i.
\]

It follows that with the O-ring technology the ratio of exports of country \( r^h \) to exports of country \( r^l < r^h \) is constant for any destination country \( \tilde{r} \) and all products up to \( \tilde{i}(r^l) \), and increasing thereafter in complexity. More generally, this ratio is increasing more steeply in the range of products that cannot be produced at preferred quality in the lower skilled country.

### D Alternative specifications for stylized facts

In this appendix, we present several robustness checks for the tables and figures presented in Section 2. Throughout, a product’s ubiquity is defined as the number of countries that are

\(^{65}\)Note that our set-up with differences in \( r \) is equivalent to the random draw of \( z_i^r(\omega) \) from a Fréchet distribution with parameters \( T_{ir}^r := g(r, i, q_i(r))^{\theta} \) and \( \theta \).
significant exporters of that product, while a country’s diversification is defined as the number of products it is a significant exporter of. Criteria used to identify a country as a significant exporter of a given product are described at the onset of each subsection.

**Year 2000**

In this part of the appendix, we present cross-section results using data for the year 2000. We consider a country to be a significant exporter of a product if (a) its exports to GDP are at least 50% of the world’s exports to GDP of the same product and (b) the country’s global exports of that product amount to at least USD 1m.

### Table 6: Diversification of countries

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**Notes:** This table reports estimation results obtained from regressing the diversification of countries at the 6-, 4-, and 2-digit HS level on ln(GDP/cap), ln(Population), and a constant term. A country’s diversification is defined as the number of products that it significantly exports. P-values in the third to last row refer to a Wald test of equality of the coefficients of ln(GDP/cap) and ln(Population). Standard errors are displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Figure 6: Ubiquity of products

(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Ubiquity is defined as the number of countries that are significant exporters of a product. Each dot represents a different product according to the level of disaggregation of the respective measure of complexity.
Figure 7: 5 richest and poorest exporters by product

(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different products according to the level of disaggregation of the respective measure of product complexity. For each product, the blue cross (red dot) indicates the average log GDP per capita of the 5 poorest (richest) significant exporters of that product. Only products with at least 10 significant exporters have been considered.
Figure 8: 5 most and least complex products by country
(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different countries. For each country, the blue cross (red dot) indicates the average complexity of the 5 least (most) complex products that it significantly exports. Only countries with significant exports in at least 10 product categories have been considered.
Year 2005

In this part of the appendix, we present cross-section results using data for the year 2005. We consider a country to be a significant exporter of a product if (a) its exports to GDP are at least 50% of the world’s exports to GDP of the same product and (b) the country’s global exports of that product amount to at least USD 1m.

Table 7: Diversification of countries

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Notes: This table reports estimation results obtained from regressing the diversification of countries at the 6-, 4-, and 2-digit HS level on ln(GDP/cap), ln(Population), and a constant term. A country’s diversification is defined as the number of products that it significantly exports. P-values in the third to last row refer to a Wald test of equality of the coefficients of ln(GDP/cap) and ln(Population). Standard errors are displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Figure 9: Ubiquity of products
(a) Required learning  (b) Intermediate diversification
(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Ubiquity is defined as the number of countries that are significant exporters of a product. Each dot represents a different product according to the level of disaggregation of the respective measure of complexity.
Figure 10: 5 richest and poorest exporters by product

(a) Required learning

(b) Intermediate diversification

(c) Non-routine intensity

(d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different products according to the level of disaggregation of the respective measure of product complexity. For each product, the blue cross (red dot) indicates the average log GDP per capita of the 5 poorest (richest) significant exporters of that product. Only products with at least 10 significant exporters have been considered.
Figure 11: 5 most and least complex products by country
(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different countries. For each country, the blue cross (red dot) indicates the average complexity of the 5 least (most) complex products that it significantly exports. Only countries with significant exports in at least 10 product categories have been considered.
Cut-off exporter: Export per GDP ≥ world exports per world GDP

In this part of the appendix, we consider a country to be a significant exporter of a product if (a) its exports to GDP are larger than or equal to the world’s exports to GDP of the same product and (b) the country’s global exports of that product amount to at least USD 1m. Cross-section results refer to year 1995.

Table 8: Diversification of countries

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</tr>
</thead>
<tbody>
<tr>
<td>HS6</td>
<td>ln(GDP/cap)</td>
<td>1.18***</td>
<td>0.92***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.09)</td>
<td>(0.08)</td>
</tr>
<tr>
<td>HS4</td>
<td>ln(GDP/cap)</td>
<td>0.52***</td>
<td>0.32***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.08)</td>
<td>(0.07)</td>
</tr>
<tr>
<td>HS2</td>
<td>ln(GDP/cap)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p(β1 = β2)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>R²</td>
<td>0.64</td>
<td>0.54</td>
<td>0.35</td>
</tr>
<tr>
<td>N</td>
<td>135</td>
<td>134</td>
<td>133</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the diversification of countries at the 6-, 4-, and 2-digit HS level on ln(GDP/cap), ln(Population), and a constant term. A country’s diversification is defined as the number of products that it significantly exports. P-values in the third to last row refer to a Wald test of equality of the coefficients of ln(GDP/cap) and ln(Population). Standard errors are displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Figure 12: Ubiquity of products
(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Ubiquity is defined as the number of countries that are significant exporters of a product. Each dot represents a different product according to the level of disaggregation of the respective measure of complexity.
Figure 13: 5 richest and poorest exporters by product
(a) Required learning   (b) Intermediate diversification

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different products according to the level of disaggregation of the respective measure of product complexity. For each product, the blue cross (red dot) indicates the average log GDP per capita of the 5 poorest (richest) significant exporters of that product. Only products with at least 10 significant exporters have been considered.
Figure 14: 5 most and least complex products by country
(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different countries. For each country, the blue cross (red dot) indicates the average complexity of the 5 least (most) complex products that it significantly exports. Only countries with significant exports in at least 10 product categories have been considered.
### Table 9: Average complexity of 5 least complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>-0.01</td>
<td>-0.02</td>
<td>-0.02*</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.03)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>country FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>N</td>
<td>995</td>
<td>1,136</td>
<td>1,059</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 least complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.

### Table 10: Average complexity of 5 most complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>0.04**</td>
<td>0.03</td>
<td>0.07***</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.04)</td>
<td>(0.02)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>country FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.03</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>N</td>
<td>995</td>
<td>1,136</td>
<td>1,059</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 most complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Cut-off exporter: Export per GDP $\geq 0.25 \times$ world exports per world GDP

In this part of the appendix, we consider a country to be a significant exporter of a product if (a) its exports to GDP are at least 25% of the world’s exports to GDP of the same product and (b) the country’s global exports of that product amount to at least USD 1m. Cross-section results refer to year 1995. Cross-section results refer to year 1995.

Table 11: Diversification of countries

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>1.29**</td>
<td>1.05**</td>
<td>0.62***</td>
</tr>
<tr>
<td></td>
<td>(0.08)</td>
<td>(0.07)</td>
<td>(0.06)</td>
</tr>
<tr>
<td>ln(Population)</td>
<td>0.65***</td>
<td>0.45***</td>
<td>0.20***</td>
</tr>
<tr>
<td></td>
<td>(0.08)</td>
<td>(0.07)</td>
<td>(0.06)</td>
</tr>
<tr>
<td>$p(\beta_1 = \beta_2)$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.72</td>
<td>0.65</td>
<td>0.46</td>
</tr>
<tr>
<td>$N$</td>
<td>135</td>
<td>135</td>
<td>135</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the diversification of countries at the 6-, 4-, and 2-digit HS level on ln($\text{GDP/cap}$), ln($\text{Population}$), and a constant term. A country’s diversification is defined as the number of products that it significantly exports. P-values in the third to last row refer to a Wald test of equality of the coefficients of ln($\text{GDP/cap}$) and ln($\text{Population}$). Standard errors are displayed in parentheses. * $p < .10$, ** $p < .05$, *** $p < .01$. 
Figure 15: Ubiquity of products
(a) Required learning  (b) Intermediate diversification
(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Ubiquity is defined as the number of countries that are significant exporters of a product. Each dot represents a different product according to the level of disaggregation of the respective measure of complexity.
Figure 16: 5 richest and poorest exporters by product
(a) Required learning  (b) Intermediate diversification
(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different products according to the level of disaggregation of the respective measure of product complexity. For each product, the blue cross (red dot) indicates the average log GDP per capita of the 5 poorest (richest) significant exporters of that product. Only products with at least 10 significant exporters have been considered.
Figure 17: 5 most and least complex products by country

(a) Required learning

(b) Intermediate diversification

(c) Non-routine intensity

(d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different countries. For each country, the blue cross (red dot) indicates the average complexity of the 5 least (most) complex products that it significantly exports. Only countries with significant exports in at least 10 product categories have been considered.
Table 12: Average complexity of 5 least complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>-0.02**</td>
<td>-0.03</td>
<td>-0.02**</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td>(0.02)</td>
<td>(0.01)</td>
<td>(0.02)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>N</td>
<td>1,114</td>
<td>1,114</td>
<td>1,151</td>
<td>1,151</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 least complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.

Table 13: Average complexity of 5 most complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>0.07***</td>
<td>0.03</td>
<td>0.11***</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.03)</td>
<td>(0.02)</td>
<td>(0.04)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.05</td>
<td>0.07</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>N</td>
<td>1,114</td>
<td>1,114</td>
<td>1,151</td>
<td>1,151</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 most complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Cut-off exporter: $RCA \geq 0.5$

In this part of the appendix we consider a country to be a significant exporter of a product if (a) it has a revealed comparative advantage for that product of at least 0.5 where revealed comparative advantage refers to the measure as proposed by Balassa (1965) and (b) the country’s global exports of that product amount to at least USD 1m. Cross-section results refer to year 1995.

Table 14: Diversification of countries

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ln(GDP/cap)$</td>
<td>1.22***</td>
<td>0.97***</td>
<td>0.51***</td>
</tr>
<tr>
<td></td>
<td>(0.07)</td>
<td>(0.06)</td>
<td>(0.04)</td>
</tr>
<tr>
<td>$\ln(\text{Population})$</td>
<td>0.66***</td>
<td>0.49***</td>
<td>0.25***</td>
</tr>
<tr>
<td></td>
<td>(0.07)</td>
<td>(0.06)</td>
<td>(0.04)</td>
</tr>
<tr>
<td>$p(\beta_1 = \beta_2)$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.74</td>
<td>0.71</td>
<td>0.60</td>
</tr>
<tr>
<td>$N$</td>
<td>135</td>
<td>135</td>
<td>135</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the diversification of countries at the 6-, 4-, and 2-digit HS level on $\ln(GDP/cap)$, $\ln(\text{Population})$, and a constant term. A country’s diversification is defined as the number of products that it significantly exports. P-values in the third to last row refer to a Wald test of equality of the coefficients of $\ln(GDP/cap)$ and $\ln(\text{Population})$. Standard errors are displayed in parentheses. * $p < .10$, ** $p < .05$, *** $p < .01$. 
Figure 18: Ubiquity of products

(a) Required learning

(b) Intermediate diversification

(c) Non-routine intensity

(d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Ubiquity is defined as the number of countries that are significant exporters of a product. Each dot represents a different product according to the level of disaggregation of the respective measure of complexity.
Figure 19: 5 richest and poorest exporters by product
(a) Required learning 
(b) Intermediate diversification
(c) Non-routine intensity
(d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different products according to the level of disaggregation of the respective measure of product complexity. For each product, the blue cross (red dot) indicates the average log GDP per capita of the 5 poorest (richest) significant exporters of that product. Only products with at least 10 significant exporters have been considered.
Figure 20: 5 most and least complex products by country

(a) Required learning

(b) Intermediate diversification

(c) Non-routine intensity

(d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different countries. For each country, the blue cross (red dot) indicates the average complexity of the 5 least (most) complex products that it significantly exports. Only countries with significant exports in at least 10 product categories have been considered.
Table 15: Average complexity of 5 least complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>-0.04***</td>
<td>-0.04***</td>
<td>-0.02**</td>
<td>-0.01*</td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td>(0.01)</td>
<td>(0.02)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>country FE</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R^2 ('within')</td>
<td>0.04</td>
<td>0.06</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>N</td>
<td>1,149</td>
<td>1,154</td>
<td>1,151</td>
<td>1,151</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 least complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.

Table 16: Average complexity of 5 most complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>0.08***</td>
<td>0.12***</td>
<td>0.04**</td>
<td>0.04***</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.02)</td>
<td>(0.01)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>country FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R^2 ('within')</td>
<td>0.07</td>
<td>0.13</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>N</td>
<td>1,149</td>
<td>1,154</td>
<td>1,151</td>
<td>1,151</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 most complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Cut-off exporter: RCA ≥ 0.25

In this part of the appendix we consider a country to be a significant exporter of a product if (a) it has a revealed comparative advantage for that product of at least 0.25 where revealed comparative advantage refers to the measure as proposed by Balassa (1965) and (b) the country’s global exports of that product amount to at least USD 1m. Cross-section results refer to year 1995.

Table 17: Diversification of countries

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>1.28***</td>
<td>1.04***</td>
<td>0.56***</td>
</tr>
<tr>
<td></td>
<td>(0.08)</td>
<td>(0.06)</td>
<td>(0.04)</td>
</tr>
<tr>
<td>ln(Population)</td>
<td>0.69***</td>
<td>0.52***</td>
<td>0.27***</td>
</tr>
<tr>
<td></td>
<td>(0.07)</td>
<td>(0.06)</td>
<td>(0.04)</td>
</tr>
<tr>
<td>p(β1 = β2)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>R²</td>
<td>0.75</td>
<td>0.72</td>
<td>0.63</td>
</tr>
<tr>
<td>N</td>
<td>135</td>
<td>135</td>
<td>135</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the diversification of countries at the 6-, 4-, and 2-digit HS level on ln(GDP/cap), ln(Population), and a constant term. A country’s diversification is defined as the number of products that it significantly exports. P-values in the third to last row refer to a Wald test of equality of the coefficients of ln(GDP/cap) and ln(Population). Standard errors are displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Figure 21: Ubiquity of products
(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Ubiquity is defined as the number of countries that are significant exporters of a product. Each dot represents a different product according to the level of disaggregation of the respective measure of complexity.
Figure 22: 5 richest and poorest exporters by product

(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity   (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different products according to the level of disaggregation of the respective measure of product complexity. For each product, the blue cross (red dot) indicates the average log GDP per capita of the 5 poorest (richest) significant exporters of that product. Only products with at least 10 significant exporters have been considered.
Figure 23: 5 most and least complex products by country
(a) Required learning
(b) Intermediate diversification
(c) Non-routine intensity
(d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different countries. For each country, the blue cross (red dot) indicates the average complexity of the 5 least (most) complex products that it significantly exports. Only countries with significant exports in at least 10 product categories have been considered.
### Table 18: Average complexity of 5 least complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Interm. div.</th>
<th>Non-routine</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>-0.05***</td>
<td>-0.02</td>
<td>-0.04***</td>
<td>-0.02***</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td>(0.02)</td>
<td>(0.01)</td>
<td>(0.02)</td>
<td>(0.01)</td>
</tr>
</tbody>
</table>

| year FE    | No            | Yes          | No          | Yes         | No     | Yes |

| country FE | Yes           | Yes          | Yes         | Yes         | Yes    | Yes |

| R²(‘within’) | 0.06 0.08 | 0.07 0.08 | 0.02 0.04 | 0.02 0.03 |

| N           | 1,149 1,149 | 1,154 1,154 | 1,151 1,151 | 1,151 1,151 |

**Notes:** This table reports estimation results obtained from regressing the average complexity of a country’s 5 least complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.

### Table 19: Average complexity of 5 most complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Interm. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>0.09***</td>
<td>0.03</td>
<td>0.15***</td>
<td>0.05***</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.03)</td>
<td>(0.02)</td>
<td>(0.02)</td>
</tr>
</tbody>
</table>

| year FE    | No            | Yes          | No          | Yes         | No     | Yes |

| country FE | Yes           | Yes          | Yes         | Yes         | Yes    | Yes |

| R²(‘within’) | 0.07 0.10 | 0.19 0.25 | 0.05 0.07 | 0.04 0.06 |

| N           | 1,149 1,149 | 1,154 1,154 | 1,151 1,151 | 1,151 1,151 |

**Notes:** This table reports estimation results obtained from regressing the average complexity of a country’s 5 most complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Rauch differentiated goods only

In this part of the appendix, we exclude exchange traded products according to the Rauch (1999) classification.\(^66\) We consider a country to be a significant exporter of a product if (a) its exports to GDP are at least 50% of the world’s exports to GDP of the same product and (b) the country’s global exports of that product amount to at least USD 1m. Cross-section results refer to year 1995.

<table>
<thead>
<tr>
<th>Table 20: Diversification of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>ln(GDP/cap)</td>
</tr>
<tr>
<td>(0.09)</td>
</tr>
<tr>
<td>ln(Population)</td>
</tr>
<tr>
<td>(0.08)</td>
</tr>
<tr>
<td>p(β₁ = β₂)</td>
</tr>
<tr>
<td>R²</td>
</tr>
<tr>
<td>N</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the diversification of countries at the 6-, 4-, and 2-digit HS level on ln(GDP/cap), ln(Population), and a constant term. A country’s diversification is defined as the number of products that it significantly exports. P-values in the third to last row refer to a Wald test of equality of the coefficients of ln(GDP/cap) and ln(Population). Standard errors are displayed in parentheses. * p < .10, ** p < .05, *** p < .01.

---

\(^66\)The Rauch classification data has been downloaded from http://econweb.ucsd.edu/~jrauch/rauch_classification.html on 6 November 2015. H0 product codes at the four-digit level were matched to SITC rev. 2 industry codes using the concordance table from WITS, as downloaded from http://wits.worldbank.org/product_concordance.html on 6 November 2015.
Figure 24: Ubiquity of products

(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Ubiquity is defined as the number of countries that are significant exporters of a product. Each dot represents a different product according to the level of disaggregation of the respective measure of complexity.
Figure 25: 5 richest and poorest exporters by product
(a) Required learning
(b) Intermediate diversification
(c) Non-routine intensity
(d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different products according to the level of disaggregation of the respective measure of product complexity. For each product, the blue cross (red dot) indicates the average log GDP per capita of the 5 poorest (richest) significant exporters of that product. Only products with at least 10 significant exporters have been considered.
Figure 26: 5 most and least complex products by country

(a) Required learning  (b) Intermediate diversification

(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different countries. For each country, the blue cross (red dot) indicates the average complexity of the 5 least (most) complex products that it significantly exports. Only countries with significant exports in at least 10 product categories have been considered.
### Table 21: Average complexity of 5 least complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>ln(GDP/cap)</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>(0.02)</td>
<td>(0.04)</td>
<td>(0.01)</td>
<td>(0.02)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>country FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>N</td>
<td>1,047</td>
<td>1,047</td>
<td>1,127</td>
<td>1,127</td>
</tr>
</tbody>
</table>

**Notes:** This table reports estimation results obtained from regressing the average complexity of a country’s 5 least complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.

### Table 22: Average complexity of 5 most complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>ln(GDP/cap)</td>
<td>0.09***</td>
<td>0.06</td>
<td>0.10***</td>
<td>0.00</td>
</tr>
<tr>
<td>(0.02)</td>
<td>(0.05)</td>
<td>(0.02)</td>
<td>(0.05)</td>
<td>(0.02)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>country FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.07</td>
<td>0.08</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td>N</td>
<td>1,047</td>
<td>1,047</td>
<td>1,127</td>
<td>1,127</td>
</tr>
</tbody>
</table>

**Notes:** This table reports estimation results obtained from regressing the average complexity of a country’s 5 most complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Exclude countries with share in GDP of natural resource rent ≥ 0.25

In this part of the appendix, we exclude countries if their average share in GDP of natural resource rents exceeds 25% over the years 1995 to 2011. We consider a country to be a significant exporter of a product if (a) its exports to GDP are at least 50% of the world’s exports to GDP of the same product and (b) the country’s global exports of that product amount to at least USD 1m. Cross-section results refer to year 1995.

Table 23: Diversification of countries

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>1.38***</td>
<td>1.13***</td>
<td>0.73***</td>
</tr>
<tr>
<td></td>
<td>(0.07)</td>
<td>(0.07)</td>
<td>(0.05)</td>
</tr>
<tr>
<td>ln(Population)</td>
<td>0.59***</td>
<td>0.38***</td>
<td>0.14***</td>
</tr>
<tr>
<td></td>
<td>(0.07)</td>
<td>(0.06)</td>
<td>(0.05)</td>
</tr>
<tr>
<td>p(β₁ = β₂)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>R²</td>
<td>0.80</td>
<td>0.76</td>
<td>0.64</td>
</tr>
<tr>
<td>N</td>
<td>114</td>
<td>114</td>
<td>114</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the diversification of countries at the 6-, 4-, and 2-digit HS level on ln(GDP/cap), ln(Population), and a constant term. A country’s diversification is defined as the number of products that it significantly exports. P-values in the third to last row refer to a Wald test of equality of the coefficients of ln(GDP/cap) and ln(Population). Standard errors are displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
Figure 27: Ubiquity of products
(a) Required learning  (b) Intermediate diversification
(c) Non-routine intensity  (d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Ubiquity is defined as the number of countries that are significant exporters of a product. Each dot represents a different product according to the level of disaggregation of the respective measure of complexity.
Figure 28: 5 richest and poorest exporters by product
(a) Required learning  (b) Intermediate diversification

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different products according to the level of disaggregation of the respective measure of product complexity. For each product, the blue cross (red dot) indicates the average log GDP per capita of the 5 poorest (richest) significant exporters of that product. Only products with at least 10 significant exporters have been considered.
Figure 29: 5 most and least complex products by country

(a) Required learning

(b) Intermediate diversification

(c) Non-routine intensity

(d) Skill intensity

Notes: In each plot (a)–(d) complexity refers to the measure as indicated in the title. Crosses and dots represent different countries. For each country, the blue cross (red dot) indicates the average complexity of the 5 least (most) complex products that it significantly exports. Only countries with significant exports in at least 10 product categories have been considered.
Table 24: Average complexity of 5 least complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>-0.03**</td>
<td>-0.03***</td>
<td>-0.02*</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td>(0.01)</td>
<td>(0.01)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>country FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.01</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>N</td>
<td>915</td>
<td>915</td>
<td>968</td>
<td>948</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 least complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.

Table 25: Average complexity of 5 most complex products

<table>
<thead>
<tr>
<th></th>
<th>Req. learning</th>
<th>Intern. div.</th>
<th>Non-routine</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(GDP/cap)</td>
<td>0.08***</td>
<td>0.10***</td>
<td>0.06***</td>
<td>0.06***</td>
</tr>
<tr>
<td></td>
<td>(0.02)</td>
<td>(0.05)</td>
<td>(0.01)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>year FE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>country FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>R²('within')</td>
<td>0.07</td>
<td>0.08</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>N</td>
<td>915</td>
<td>915</td>
<td>968</td>
<td>948</td>
</tr>
</tbody>
</table>

Notes: This table reports estimation results obtained from regressing the average complexity of a country’s 5 most complex products on ln(GDP/cap) for each of the four different measures of product complexity. Countries with above-median GDP per capita in 1995 have been excluded from our sample. Standard errors are clustered by country and displayed in parentheses. * p < .10, ** p < .05, *** p < .01.
References


