The Product Space Conditions the Development of Nations

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ing epibiotic and pelagic communities. These icebergs can be compared to estuaries that supply surrounding coastal regions with nutrients. In that respect, icebergs may be thought of as "Lagrangian estuaries," drifting through the Southern Ocean while enriching the surrounding pelagic zone. Our preliminary studies suggest that free-drifting icebergs and their associated communities could serve as areas of increased production and sequestration of organic carbon to the deep sea, a process unaccounted for in current global carbon budgets (*33*).


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34. We thank all the shipboard scientific personnel on the research vessel *Laurence M. Gould* cruise LMG05-14A for excellent support, including R. Wilson, K. Reisenbichler, R. Sherlock, J. Ellena, M. Vardaro, K. Osborn, D. Chakos, J. Derry, L. Ekern, J. Kinsey, C. Koehler, and K. Noble. Captain R. Verret and his crew made sampling around icebergs a reality even under the most difficult conditions. The Raytheon Polar Services support group of S. Suhr-Sliester, J. Spillane, P. Fitzgibbons, K. Pedigo, J. Dolan, E. Roggenstein, and D. Elsberg provided excellent deck and laboratory support. D. Long (Brigham Young University) provided timely QuikSCAT images of the location of iceberg A-52 during our cruise. RADARSAT images of our study area were forwarded to the ship through Palmer Station. This research was supported by NSF grants ANT-0529815, ANT-0650034, and OCE-0327294, and by the David and Lucile Packard Foundation. We thank P. Penhale (NSF, Polar Programs) for having the foresight and courage to fund this speculative project. W. Moore and C. Hexel contributed to the $^{224}$Ra analysis and data synthesis. C. Stoker of NASA/Ames Research Center loaned us the ROV, and H. Thomas at MBARI trained us in its operation.


**Supporting Online Material**

www.sciencemag.org/cgi/content/full/1142834/DC1
Materials and Methods
Figs. S1 to S3
Table S1
References


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# The Product Space Conditions the Development of Nations


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**Economies grow by upgrading the products they produce and export. The technology, capital, institutions, and skills needed to make newer products are more easily adapted from some products than from others. Here, we study this network of relatedness between products, or "product space," finding that more-sophisticated products are located in a densely connected core whereas less-sophisticated products occupy a less-connected periphery. Empirically, countries move through the product space by developing goods close to those they currently produce. Most countries can reach the core only by traversing empirically infrequent distances, which may help explain why poor countries have trouble developing more competitive exports and fail to converge to the income levels of rich countries.**


Does the type of product that a country exports matter for subsequent economic performance? The fathers of development economics held that it does, suggesting that industrialization creates spillover benefits that fuel subsequent growth (*1–3*). Yet, lacking formal models, mainstream economic theory has been unable to incorporate these ideas. Instead, two approaches have been used to explain a country's pattern of specialization. The first focuses on the relative proportion between productive factors (i.e., physical capital, labor, land, skills or human capital, infrastructure, and institutions) (*4*). Hence, poor countries specialize in goods intensive in unskilled labor and land, whereas richer countries specialize in goods requiring infrastructure, institutions, and human and physical capital. The second approach emphasizes technological differences (*5*) and has to be complemented with a theory of what underlies them. The varieties and quality ladders models (*6*, *7*) assume that there is always a slightly more advanced product, or just a different one, that countries can move to, disregarding product similarities when thinking about structural transformation and growth.

Think of a product as a tree and the set of all products as a forest. A country is composed of a collection of firms, i.e., of monkeys that live on different trees and exploit those products. The process of growth implies moving from a poorer part of the forest, where trees have little fruit, to better parts of the forest. This implies that monkeys would have to jump distances, that is, redeploy (human, physical, and institutional) capital toward goods that are different from those currently under production. Traditional growth theory assumes there is always a tree within reach; hence, the structure of this forest is unimportant. However, if this forest is heterogeneous, with some dense areas and other more-deserted ones, and if monkeys can jump only limited distances, then monkeys may be unable to move through the forest. If this is the case, the structure of this space and a country's orientation within it become of great importance to the development of countries.

In theory, many possible factors may cause relatedness between products, that is, closeness between trees; such as the intensity of labor, land, and capital (*8*), the level of technological sophistication (*9*, *10*), the inputs or outputs involved in a product's value chain (e.g., cotton, yarn, cloth, and garments) (*11*), or requisite insti-


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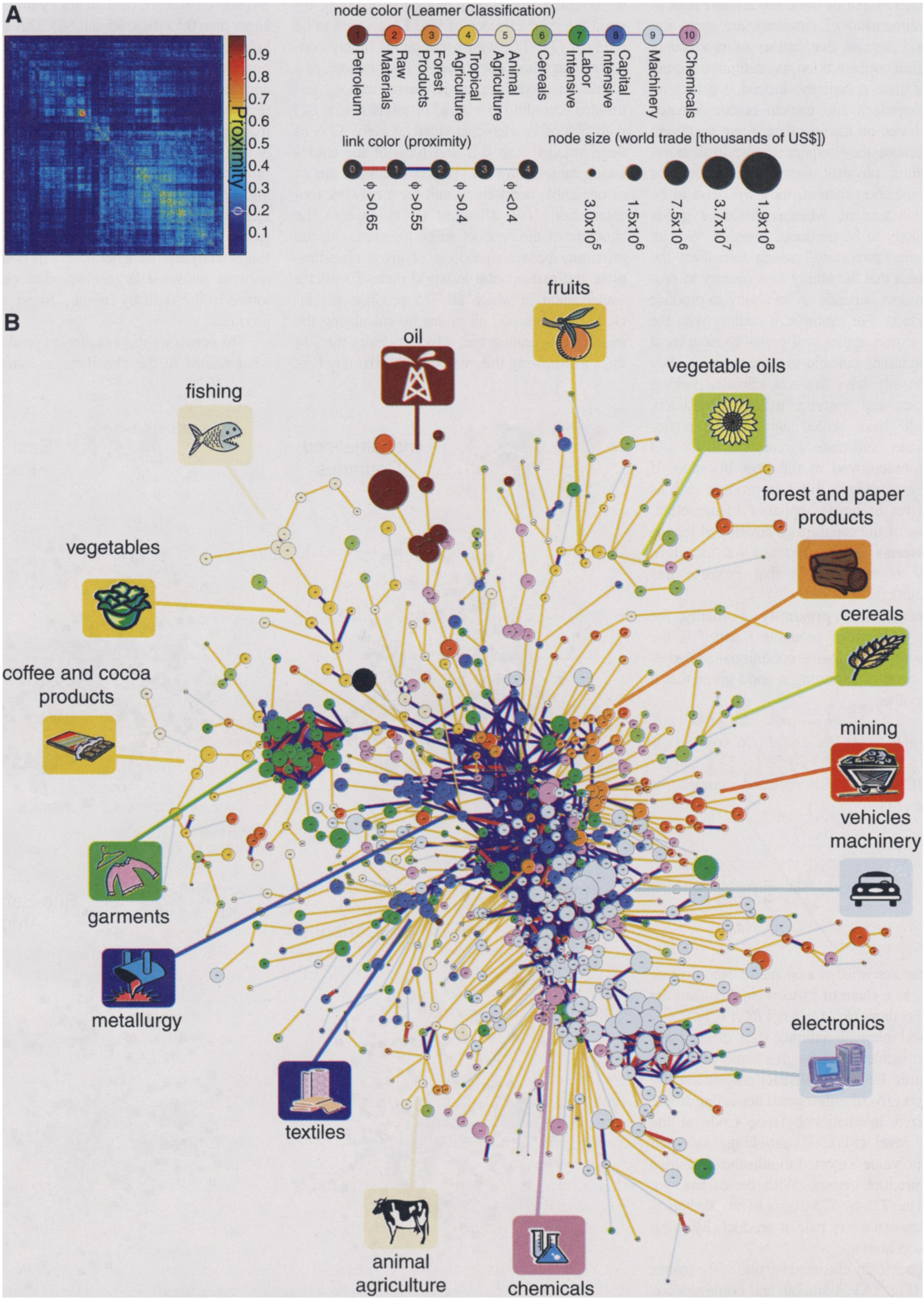


**Fig. 1.** The product space. (**A**) Hierarchically clustered proximity (ϕ) matrix representing the 775 SITC-4 product classes exported in the 1998–2000 period. (**B**) Network representation of the product space. Links are color coded with their proximity value. The sizes of the nodes are proportional to world trade, and their colors are chosen according to the classification introduced by Leamer.

tutions (*12*, *13*). All of these are a priori notions of what dimension of similarity are most important and assume that factors of production, technological sophistication, or institutional quality exhibit little specificity. Instead, we take an agnostic approach and use an outcomes-based measure, based on the idea that, if two goods are related because they require similar institutions, infrastructure, physical factors, technology, or some combination thereof, they will tend to be produced in tandem, whereas dissimilar goods are less likely to be produced together. We call this measure "proximity," which formalizes the intuitive idea that the ability of a country to produce a product depends on its ability to produce other products. For example, a country with the ability to export apples will probably have most of the conditions suitable to export pears. They would certainly have the soil, climate, packing technologies, and frigorific trucks. In addition, they would have skilled agronomists, phytosanitary laws, and trade agreements that could be easily redeployed to the pear business. If instead we consider a different product such as copper wires or home appliance manufacture, all or most of the capabilities developed for the apple business render useless. We introduce proximity as the concept that captures this intuitive notion.

**The concept of proximity.** Formally, the proximity $\phi$ between products $i$ and $j$ is the minimum of the pairwise conditional probabilities of a country exporting a good given that it exports another.

$$\phi_{i,j} = \min\{P(RCAx_i|RCAx_j), P(RCAx_j|RCAx_i)\}$$

Where RCA stands for revealed comparative advantage (*14*)

$$RCA_{c,i} = \frac{x(c,i)}{\sum_i x(c,i)} \bigg/ \frac{\sum_c x(c,i)}{\sum_{c,i} x(c,i)}$$

which measures whether a country $c$ exports more of good $i$, as a share of its total exports, than the "average" country ($RCA > 1$ not $RCA < 1$).

We used international trade data, cleaned and made compatible (*15*) through a National Bureau of Economic Research (NBER) project lead by R. Feenstra (*16*), disaggregated according to the Standardized International Trade Code at the four-digit level (SITC-4), providing for each country the value exported to all other countries for 775 product classes. With these data, we calculated the 775-by-775 matrix of revealed proximities between every pair of products by using the equation above.

A hierarchically clustered version of the matrix is shown (Fig. 1A). A smooth and homogeneous product space would imply uniform values (homogenous coloring), whereas a product-ladder model (*7*) would suggest a matrix with high values (or bright coloring) only along the diagonal. Instead the product space of Fig. 1A appears to be modular (*17*, *18*), with some goods highly connected and others disconnected. Furthermore, as a whole the product space is sparse, with $\phi_{ij}$ distributed according to a broad distribution (fig. S2) with 5% of its elements equal to zero, 32% of them smaller than 0.1, and 65% of the entries taking values below 0.2. These substantial number of negligible connections call for a network representation (*19*), allowing us to explore the structure of the product space together with the proximity between products of given classifications and participation in world trade. To offer a visualization in which all 775 products are included, we reached all nodes by calculating the maximum spanning tree, which includes the 774 links maximizing the tree's added proximity (fig. S4) and superposed on it all links with a proximity larger than 0.55 (figs. S5 and S6). This set of 1525 links is used to visualize the structure of the full proximity matrix, which is far from homogenous and appears to have a core-periphery structure (Fig. 1B). The core is formed by metal products, machinery, and chemicals, whereas the periphery is formed by the rest of the product classes. The products in the top of the periphery belong to fishing, tropical, and cereal agriculture. To the left there is a strong peripheral cluster formed by garments and another one belonging to textiles, followed by animal agriculture. The bottom of the network shows a large electronics cluster, followed to the right by mining, forest, and paper products.

The network shows clusters of products somewhat related to the classification introduced by

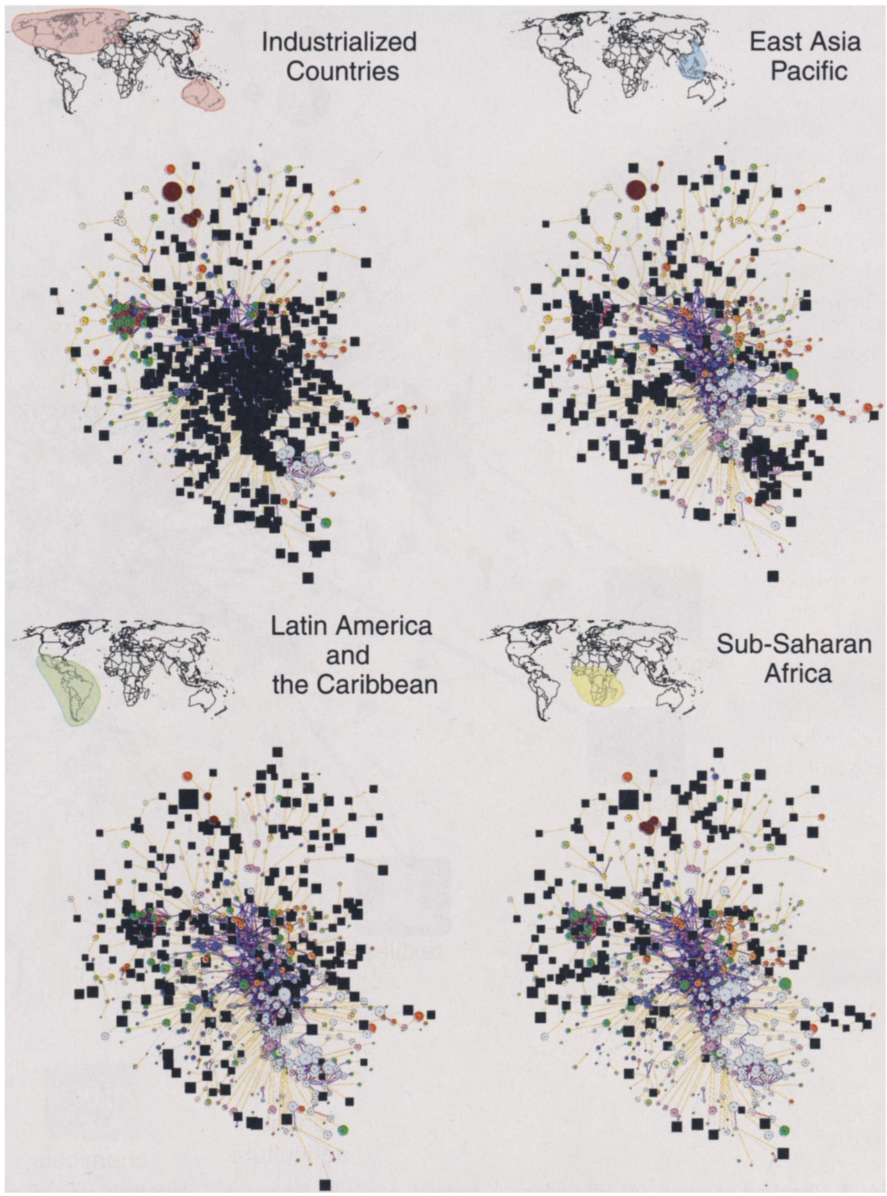


**Fig. 2.** Localization of the productive structure for different regions of the world. The products for which the region has an $RCA > 1$ are denoted by black squares.

Leamer (*8*), which is based on relative factor intensities (table S1 and fig. S8), that is, the relative amount of capital, labor, land, or skills required to produce each product. Although the classification performed by Leamer was done with a different methodology, the agreement between it and the structure of the product space is striking. Yet it also introduces a more detailed split of some product classes. For example, machinery is naturally split into two clusters, one consisting of vehicles and heavy machinery and another one belonging to electronics. The machinery cluster is interwoven with some capital-intensive metal products but is not tightly connected to similarly classified products such as textiles.

The map obtained can be used to analyze the evolution of a country's productive structure. For this purpose we held the product space fixed and studied the dynamics of production within it, although changes in the product space represent an interesting avenue for future research (*20*).

The pattern of specialization for four regions in the product space is shown in Fig. 2 (*21*). Products exported by a region with $RCA > 1$ are shown with black squares. Industrialized countries occupy the core, composed of machinery, metal products, and chemicals. They also participate in more peripheral products such as textiles, forest products, and animal agriculture. East Asian countries have developed RCA in the garments, electronics, and textile clusters, whereas Latin America and the Caribbean are further out in the periphery in mining, agriculture, and the garments sector. Lastly, sub-Saharan Africa exports few product types, all of which are in the far periphery of the product space. These results indicate that each region has a distinguishable pattern of specialization clearly visible in the product space. Links to the maps for the 132 countries included in the study can be found in the Supporting Online Material (SOM) text.

Next, we show how the structure of the product space affects a country's pattern of specialization. Figure 3A shows how comparative advantages evolved in Malaysia and Colombia between 1980 and 2000 in the electronics and the garments sectors, respectively. Both countries follow a diffusion process in which comparative advantage move preferentially toward products close to existing goods: garments in Colombia and electronics in Malaysia.

**Testing diffusion.** Beyond this graphical illustration, is it true that countries develop comparative advantage preferentially in nearby goods? We used two different approaches to this question. First, we measured the average proximity of a new potential product *j* to a country's current productive structure, which we call "density" and define as

$$\omega_j^k = \frac{\sum_i x_i \phi_{ij}}{\sum_i \phi_{ij}}$$

where $\omega^k_j$ is the density around good *j* given the export basket of the *k*th country and $x_i = 1$ if $RCA_{ki} > 1$ and 0 otherwise. A high density value means that the *k*th country has many developed products surrounding the *j*th product. To study the evolution of comparative advantage, we considered "transition products" as those with an $RCA_{c,i} < 0.5$ in 1990 and an $RCA_{c,i} > 1$ in 1995. As a control, we considered "undeveloped products" those that in 1990 and 1995 had an $RCA_{c,i} < 0.5$ and disregarded those cases not fitting any of these two criteria. Figure 3B shows how density is distributed around transition products (yellow) and compares it to densities around undeveloped products (red). Clearly, these distributions are very distinct, with a higher density around transition products than among undeveloped ones [analysis of variance (ANOVA) $P < 10^{-30}$].

At the single product level, we considered the ratio between the average density of all countries in which the *j*th product was a transition product and the average density of all countries in which the *j*th product was not developed. Formally, we define the "discovery factor" $H_j$ as

$$H_j = \frac{\sum_{k=1}^{T} \omega^k{}_j / T}{\sum_{k=T+1}^{N} \omega^k{}_j / (N-T)}$$

where *T* is the number of countries in which the *j*th good was a transition product and *N* is the total number of countries. Figure 3C shows the frequency distribution of this ratio. For 79% of products, this ratio is greater than 1, indicating that $\omega_j^k$ is greater in countries that transitioned into the $j^{th}$ good than in those that did not, often substantially.

An alternative way of illustrating that countries develop *RCA* in goods close to those they

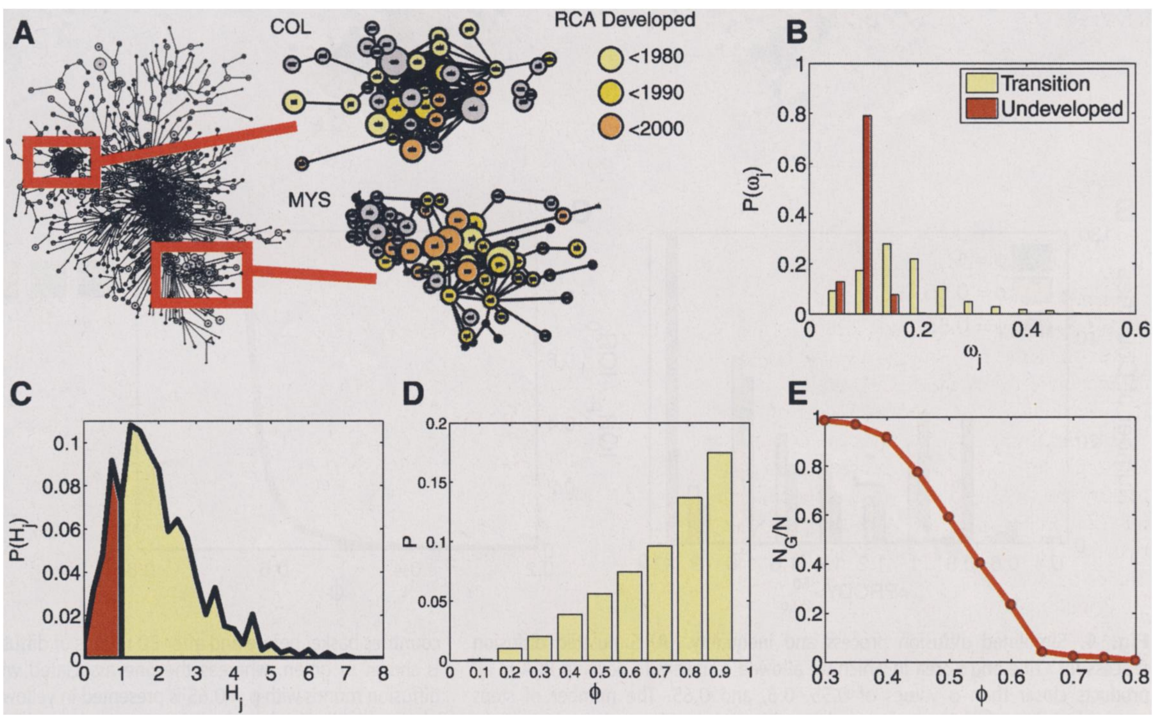


**Fig. 3.** Empirical evolution of countries. **(A)** Examples of RCA spreading for Colombia (COL) and Malaysia (MYS). The color code shows when this countries first developed $RCA > 1$ for products in the garments sector in Colombia and in the electronics cluster for Malaysia. **(B)** Distribution of density (ω) for transition products and undeveloped products **(C)** Distribution for the relative increase in density for products undergoing a transition with respect to the same products when they remain undeveloped. **(D)** Probability of developing RCA given that the closest connected product is at proximity ϕ. **(E)** Relative size of the largest connected component $N_G$ with respect to the total number of products in the system *N* as a function of link ϕ.

already had is to calculate the conditional probability of transitioning into a product given that the nearest product with $RCA > 1$ is at a given $\phi$. There is a monotonic relationship (Fig. 3D) between the proximity of the nearest developed good and the probability of transitioning into it. Although the probability of moving into a good at $\phi = 0.1$ in the course of 5 years is almost nil, the probability is about 15% if the closest good is at $\phi = 0.8$ (*22*).

Because production shifts to nearby products, we asked whether the product space is sufficiently connected that given enough time, all countries can reach most of it, particularly the richest parts. Lack of connectedness may explain the difficulties faced by countries trying to converge to the income levels of rich countries: they may not be able to undergo structural transformation because proximities are just too low. A simple approach is to calculate the relative size of the largest connected component as a function of $\phi$. At $\phi \geq$

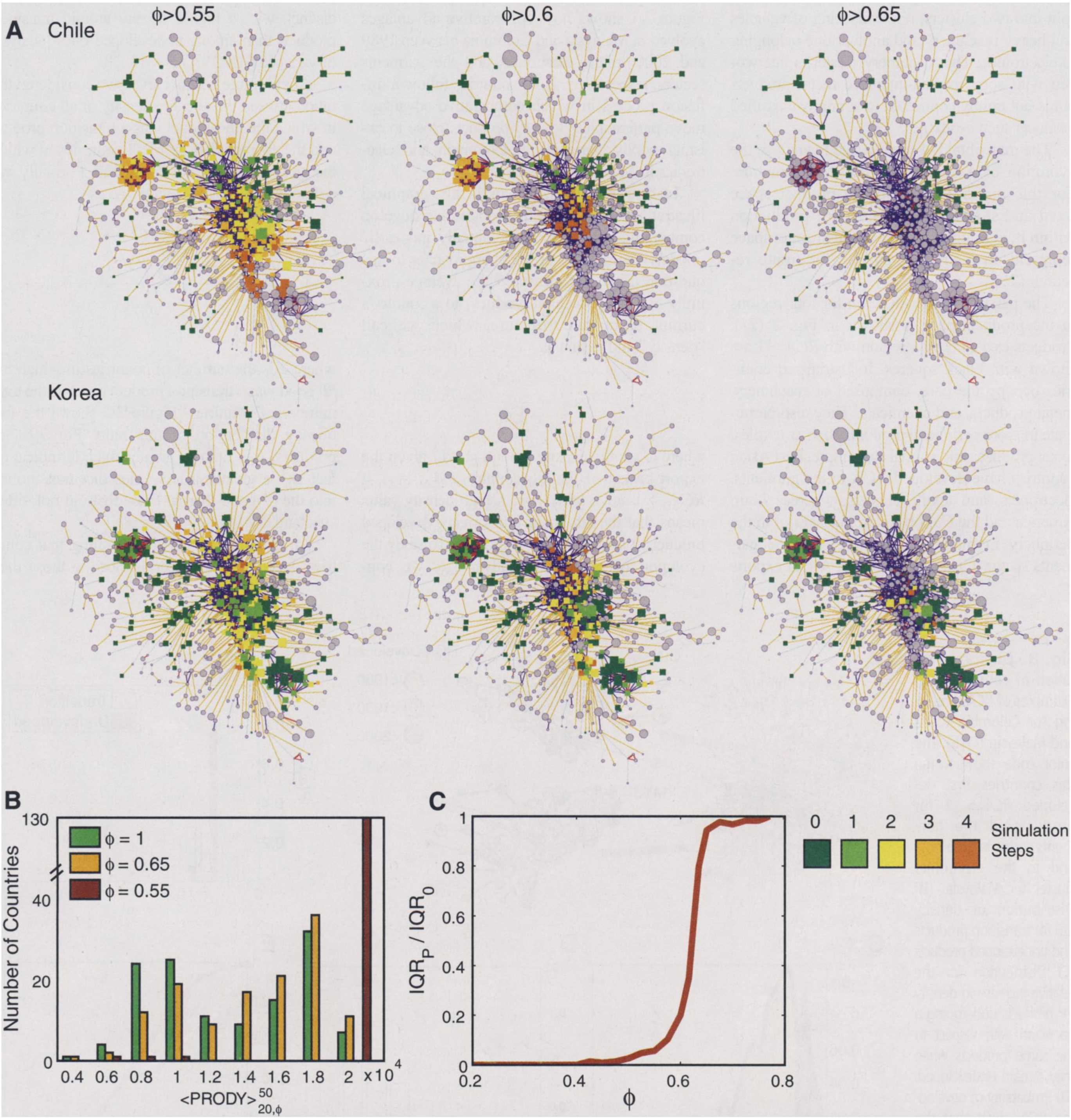


**Fig. 4.** Simulated diffusion process and inequality. **(A)** Simulated diffusion process for Chile and Korea in which we allowed countries to develop RCA in all products closer than $\phi$ values of 0.55, 0.6, and 0.65. The number of steps required to develop RCA can be read from the color code on the bottom right corner. **(B)** Distribution for the average PRODY of the best 50 products in a countries basket before and after 20 rounds of diffusion. The original distribution is shown in green, whereas the one associated with the distribution after 20 diffusion rounds with $\phi = 0.65$ is presented in yellow and $\phi = 0.55$ in red. **(C)** IQR of the distribution of the best 50 products after diffusing with a given $\phi$ normalized by the IQR of the best 50 products in absence of diffusion.

0.6, the largest connected component has a negligible size compared with the total number of products (Fig. 3E), whereas for $\phi \leq 0.3$ the product space is almost fully connected, meaning that there is always a path between two different products.

We studied the impact of the product space structure by simulating how the position of countries evolve when allowed to repeatedly move to products with proximities greater than a certain $\phi_o$. If countries diffuse to nearby products and these are sufficiently connected to others, then after several iterations, 20 in our exercise, countries would be able to reach richer parts of the product space. On the other hand, if the product space is disconnected, countries will not be able to find paths to the richer part of the product space, independently of how many steps they are allowed to make.

The results of our simulation for Chile and Korea are presented in Fig. 4A. At a relatively low proximity ($\phi_o = 0.55$), both countries are able to diffuse through to the core of the product space; however, Korea is able to do so much faster, thanks to its positioning in core products. For higher proximities, the question becomes whether a country can spread at all. At $\phi_o = 0.6$, Chile is able to spread slowly throughout the space, whereas Korea is still able to populate the core after four rounds. At $\phi_o = 0.65$, Chile is not able to diffuse, lacking any close-enough products, whereas Korea develops RCA slowly to a few products close to the machinery and electronics cluster.

To generalize this analysis for the whole world, we needed a measure to summarize the position of a country in the product space. We adopted a measure based on Hausmann, Hwang, and Rodrik (*23*), which involves a two-stage process. First, for every product we assigned a value, which is the weighted gross domestic product (GDP) per capita of countries with comparative advantage in that good, called PRODY (*23*). We then averaged the PRODYs of the top $N$ products that a country has access to after $M$ iterations at $\phi_o$ and denoted it by $< PRODY >^{N}_{M\phi_o}$. Figure 4B shows the distribution of $< PRODY >^{N}_{M\phi_o}$ for $N = 50$, $M = 20$, and $\phi_o = 1$ (green), $\phi_o = 0.65$ (yellow), and $\phi = 0.55$ (red). The distribution for $\phi_o = 1$ allows us to characterize the current distribution of countries in the product space, which shows a bimodal distribution, a signature of a world divided into rich and poor countries with few countries occupying the center of the distribution. When we allow countries to diffuse up to $\phi_o = 0.65$, this distribution does not change significantly: it shifts slightly to the right because of the acquisition of a limited number of sophisticated products by some countries. This diffusion process, however, stops after a few rounds, and the world maintains a degree of inequality similar to its current state. Contrarily, when we consider $\phi_o = 0.55$, most countries are able to diffuse and reach the most sophisticated basket in the long run. Only a few countries are left behind, which unsurprisingly make up the poorest end of the income distribution.

To quantify the level of convergence we calculated the interquartile range (IQR) for the $< PRODY >^{50}_{20\phi}$ distribution and normalized this quantity by dividing it with the IQR for the original distribution. Figure 4C shows that the convergence of the system goes through an abrupt transition and that convergence is possible if countries are able to diffuse to products located at a proximity $\phi > 0.65$.

The bimodal distribution of international income levels and a lack of convergence of the poor toward the rich has been explained by using geographic (*24*) and institutional (*12*, *13*) arguments. Here, we introduced another factor to this discussion: the difficulties involved in moving through the product space. The detailed structure of the product space is shown here and, together with the location of the countries and the characteristics of the diffusion process undergone by them, strongly suggests that not all countries face the same opportunities when it comes to development. Poorer countries tend to be located in the periphery, where moving toward new products is harder to achieve. More interestingly, among countries with a similar level of development and seemingly similar levels of production and export sophistication, there is significant variation in the option set implied by their current productive structure, with some on a path to continued structural transformation and growth and others stuck in a dead end.

These findings have important consequences for economic policy, because the incentives to promote structural transformation in the presence of proximate opportunities are quite different from those required when a country hits a dead end. It is quite difficult for production to shift to products far away in the space, and therefore policies to promote large jumps are more challenging. Yet it is precisely these long jumps that generate subsequent structural transformation, convergence, and growth.

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19. Good introductions to networks are (*26*, *27*).
20. The network shown here represents the structure of the product space as determined from the 1998–2000 periods. Holding the product space as fixed is a good first approximation, because the dynamics of the network is much slower than the one of countries. The Pearson correlation coefficient (PCC) between the proximity of all links present in this network and the ones obtained from the same network in 1990 and 1985 are 0.69 and 0.66, respectively (SOM text). This indicates that, although the network changes over time, after 15 years the strength of past links still predicts the strength of the current links to a considerable extent.
21. An alternative approach in which the network of trade relationships was studied was undertaken by (*28*–*30*).
22. We repeated the same exercise with the rank of proximity instead of proximity itself in order to assess whether what matters is absolute or relative proximity. We found that absolute distance appears to be what matters most. Although transition probability increases linearly with proximity, they decay with rank as a power law. Moreover, the rank effect is stronger for products in sparser parts of the product space, where transitions are also less frequent. Thus, densely connected products can develop RCA through more paths than sparsely connected ones, indicating the importance of absolute proximity.
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**Supporting Online Material**

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References

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