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Institute of Economics
Scuola Superiore Sant'Anna

Piazza Martiri della Libertà, 33 - 56127 Pisa, Italy
ph. +39 050 88.33.43
institute.economics@sssup.it

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Evolutionary Growth Theory

Giovanni Dosi[1]
Andrea Roventini[1,2]

[1] Istituto di Economia and L'EMbeDS, Scuola Superiore Sant'Anna, Pisa, Italy
[2] OFCE-Sciences Po, France

2024/02 January 2024
ISSN(ONLINE) 2284-0400

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Giovanni Dosi[1] and Andrea Roventini[†1]

[1]Institute of Economics and L'EMbeDS, Scuola Superiore Sant'Anna (Italy)

February 13, 2024

Abstract

This work presents the evolutionary growth theory, which studies the drivers and patterns of technological change and production together with the (imperfect) mechanisms of coordination among a multitude of firms. This requires to study economies as complex evolving systems, i.e. as ecologies populated by heterogenous agents whose out-of-equilibrium local market interactions lead to the emergence of some collective order at higher level of aggregation, while the system continuously evolves. Accordingly a multi-country multi-industry agent-based model is introduced, where the restless competition of firms in international markets leads to the emergence of growth and persistent income divergence among countries. Moreover, each economy experiences a structural transformation of its productive structure during the development process. Such dynamics results from firm-level virtuous (or vicious) cycles between knowledge accumulation, trade performances, and growth dynamics. The model also accounts for a rich ensemble of empirical regularities at macro, meso and micro levels of aggregation. Finally, the model is employed to assess different strategies that laggard countries can adopt to catch up with leaders. Results show that in absence of government interventions, laggards will continue to fall behind. On the contrary, industrial policies can successfully drive international convergence among countries.

Keywords Endogenous growth, structural change, technology-gaps, industrial policies, evolutionary economics, agent-based models.

JEL classification F41, F43, O4, O3

*This work has been written for the forthcoming *An Introduction to Alternative Theories of Economic Growth*, 2nd Edition, edited by Mark Setterfield. Thanks to Alessandro Caiani and Emanuele Russo and Mark Setterfield. Naturally, all usual disclaimers apply.

[†]Corresponding author: andrea.roventini@santannapisa.it - Institute of Economics, Scuola Superiore Sant'Anna, piazza Martiri della Libertá 33, 56127, Pisa (IT).

1 Introduction

Since the publication of the Wealth of the Nations (Smith, 1776), economics has studied the causes of growth and the emerging disparities across countries. Economists and historians (see Landes, 1969; Cipolla, 1994; Allen, 2001, among many contributions) have come to the conclusion that technological change is the major driver of both phenomena. However, while Neoclassical economic theory has recognised the importance of technology, the progresses to explain its evolution and how it affects economic growth has been slow and insufficient. On the one hand, in Solow (1956) and subsequent contributions, economic growth stems from exogenous technological progress. On the other hand, new growth theories (see e.g. Romer, 1990; Aghion and Howitt, 1992) have successfully endogenised innovation into economic dynamics, but this has been done just as either a learning externality or as the outcome of purposeful expensive efforts by a representative profit-maximising agent. In the latter case, such an endogenisation comes at the major price of reducing innovative activities to an equilibrium outcome of optimal intertemporal allocation of resources, with or without (probabilisable) uncertainty.

At the opposite extreme, evolutionary economics (Nelson and Winter, 1982; Dosi et al., 1988; Metcalfe and Foster, 2010) starts from the Schumpeterian disequilibrium processes of innovation generation and diffusion and market competition to explain different patterns of macroeconomic growth and the ultimate causes of countries' prosperity or misery. Disequilibrium dynamics is considered indeed as a general feature of "restless capitalism" (Metcalfe, 1998; Metcalfe and Ramlogan, 2006) observed at the firm, industry and country levels of aggregation. Evolutionary theory does not only analyse the drivers and patterns of change of the capitalistic engine of innovation and production, but it also studies the (imperfect) mechanisms of coordination among a multitude of self-seeking agents agents often characterised by conflicting interests (Dosi, 2023).

In that respect, evolutionary theory studies economies as *complex evolving systems* (Kirman, 2010, 2016; Rosser, 2011; Dosi and Roventini, 2019), i.e. as ecologies populated by heterogenous agents whose out-of-equilibrium local market interactions lead to the emergence of some collective order at higher level of aggregation, while the system continuously changes. In such a framework, *more is different* (Anderson, 1972): there is not any isomorphism[1] between the micro, meso and macro levels and aggregation can lead to the emergence of new phenomena (e.g. structural change and self-sustained growth), new statistical regularities (e.g. twin peaked cross-country growth rate distribution) and totally new structures (i.e. markets, industries, institutions). In a complex world, *deep uncertainty* (Knight, 1921; Keynes, 1936) is so pervasive that agents cannot build the "right" model of the economy, and, even less so, share it among them as well as with the modeler (Kirman, 2014). Rather, agents must rely on *heuristics* (Simon, 1955, 1959; Cyert and March, 1992), which turns out to be robust tools for inference and actions (Gigerenzer and Brighton, 2009; Dosi et al., 2020a). At the same time boundedly-rational agents can learn and discover new behavioural patterns and new technologies, thus incessantly introducing *novelty* (and uncertainty) into the economic system. Finally, agents *locally interact* in markets which

[1]Relatedly, the (often misunderstood) notion of Adam Smith's invisible hand should be considered as a proposition about the lack of isomorphisms between the greediness of individual butchers and bakers and they relatively orderly delivery of meat and bread across markets (Dosi and Roventini, 2019).

work as both mechanisms of information exchange and coordination and selection devices. Such interactions are responsible for the apparent self-organisation of markets without leading to efficient outcomes or optimal equilibria, as well as to repentine crises triggered by the crossing of some tipping point.

The study of complex evolving systems requires the use of *agent-based models* (ABM; Tesfatsion, 2006; LeBaron and Tesfatsion, 2008; Fagiolo and Roventini, 2017; Dosi and Roventini, 2019), which have been pioneered by evolutionary economics since its foundations (Nelson and Winter, 1982).[2] ABMs build the economy from the bottom-up (Tesfatsion, 2002) and straightforwardly embeds heterogeneity, bounded rationality, direct interactions among agents, endogenous out-of-equilibrium dynamics. In that, agent-based models provide *realistic microfoundations*, i.e. rooted in the actual empirical micro-economic evidence (Simon, 1977; Kirman, 2016). Note that evolutionary microfoundations are anthitetical to Neoclassical ones. The latter lead to models with a solitary representative hyper-rational agent[3] who shares the "true" model of the economy with the modeller. Neoclassical microfoundations thus shrinks the macroeconomic level to the microeconomic one. At the opposite, evolutionary theorists reject the silly and outrageous idea that one can model the dynamics of a beehive studying that of a "representative bee" (Dosi and Roventini, 2019) and consider that aggregation leads to emergence. Evolutionary microfoundations are thus needed to understand how the interaction of heterogenous entities yields emergent properties at the meso and macro levels.

Evolutionary agent-based growth models have blossomed in the last decades. Due to space constraints, this works does not provide a survey,[4] but it presents evolutionary growth theories by way of the multi-country multi-industry model developed in Dosi et al. (2019b, 2020b). The model studies a world economy populated by an ensemble of firms belonging to different countries and industries and competing in international markets. Firms strive to innovate and imitate their competitors in order to increase their productivity, their competitiveness and, ultimately, their market shares. Thus, the model features a fully micro-founded Schumpeterian engine of endogenous technical change. At the same time, well in tune with a Keynes-Kaldor perspective, changes in domestic and international demand conditions affect both economic fluctuations, international trade and growth trajectories.[5]

Simulation results show that the evolutionary model is able to account for the emergence of growth, while countries' growth trajectories diverge over time. Such a dynamics is driven by the evolving *absolute* technological advantages/disadvantages which shape national specialisation

[2]Evolutionary economics does not resort exclusively on agent-based models, but it relies also on appreciative theories and more aggregate models as the one presented in Metcalfe and Foster (2010). This work focuses only on evolutionary agent-based models.

[3]See Kirman (1992) for a devastating critique to the fiction of the representative agent.

[4]Naturally, the first evolutionary growth model appeared in Nelson and Winter (1982). Since then, the number of works has been blossoming. A first set of models explore the emergence of growth in a single-country framework, see Silverberg and Lehnert (1994), Silverberg and Verspagen (1994), Fagiolo and Dosi (2003), Dosi et al. (2010), and Caiani et al. (2019b) among a vast literature. Other contributions study endogenous growth from a multi-country perspective, see e.g. Dosi et al. (1994a), Silverberg and Verspagen (1995), Llerena and Lorentz (2004), and Caiani et al. (2019a). Finally, a series of works focuses on structural change and economic growth, see Saviotti and Pyka (2004, 2008), Ciarli et al. (2010, 2017), Lorentz et al. (2016) and Dosi et al. (2022).

[5]The model thus meets Solow's (2005) plea for accounting the complex feedbacks between demand and supply at medium- and long-run frequencies in a multi-country framework.

and trade patterns among countries (Dosi et al., 1990). The formation of absolute advantages across countries stems from Kaldorian cumulative feedbacks at the firm level between innovation and demand dynamics which amplify at the country level (Kaldor et al., 1967; Myrdal, 1957). Indeed, the innovative and imitative activities of firms (or lack thereof) determine their competitiveness and market shares in world markets, boosting (or not) their sales and their resources for search and learning. As a result of these mechanisms, a group of leading nations emerges together with a larger club of laggards accumulating *technological gaps* (Cimoli, 1988; Dosi et al., 1990; Freeman and Soete, 1997; Reinert, 2009; Cimoli and Porcile, 2013; Lavopa and Szirmai, 2018) in most of their industries. The structure of such gaps and leads, rooted in firm-specific learning trajectories, is also responsible for the process of structural transformation that each country experiences along its growth path. The story described so far emerges together with a rich list of stylised facts matched by the model at the micro, meso, and macro levels.

The evolutionary model is finally employed to asses which policies allow laggard countries to catch up with leaders. Simulation results show that market-friendly policies never allow laggard countries to reach the technological frontier; on the contrary, they reinforce the polarisation among different clubs of economies. Conversely, industrial policies (Cimoli et al., 2009) targeting the development of firms' capabilities and R&D investments as well as trade restrictions for infant industry protection do foster international convergence of the laggards. The relatively minor static costs (e.g., rising domestic prices) introduced by industrial policies are more than compensated by the strong dynamic gains stemming from learning and the absorption of foreign technologies. Protectionism alone is not sufficient to support catching up and countries get stuck in a sort of middle-income trap. Finally, in a global trade war, where high-income economies impose retaliatory tariffs, both laggards and leaders are worse off and world productivity growth slows down.

The rest of the work is organised as follows. Section 2 introduces some stylised facts at different levels of aggregation which ought to be reproduced by any growth model. The foundations of evolutionary agent-based models are discussed in Section 3. The baseline evolutionary multi-country model is presented in Section 4. Simulation results are shown in Section 5. Finally, Section 6 concludes discussing the possible fruitful complementarities between evolutionary and other alternative growth theories.

2 What is the to be explained? Multi-scale evidence on innovation and growth patterns

To repeat, self-sustained economic growth ought to be explained as a multi-scale phenomenon. Indeed, the apparent orderly exponential growth experienced by the GDP of many countries emerges from turbulent dynamics occurring at lower levels of aggregation wherein firms engage in a Schumpeterian competition, innovating to survive the market selection. At the same time, new industries emerge and expand, while others decline in a perpetual process of structural change. Such autocatalytic processes occurring at the micro and meso levels are at the root of the evolutionary process of growth captured by macro statistics (Metcalfe and Foster, 2010). For these reasons, one must start reviewing the empirical evidence on economic growth in a multi-country perspective at macro, meso and micro levels of aggregation (see Dosi et al., 1994b, Durlauf et al., 2005, and Jones, 2016, for surveys). The stylized facts (SF) presented in this section should be considered the test-bed for evaluating the explanatory power of competing growth theories and models.[6]

2.1 Macroeconomic growth and fluctuations

Many historical accounts have documented an exceptional rise in living standards over the past two centuries (Landes, 1969; Bordo et al., 2007; Maddison, 2010). Nevertheless, such a take-off has taken place in a relatively small set of Western nations while, only in the post-WWII period, their club was joined by Japan and later by few East Asian economies. Such catching up episodes have been rather rare as have been phenomena of forging ahead or falling behind (Abramovitz, 1986). More generally, the era of self-sustained economic growth is undoubtedly associated to "the great divergence" (Allen, 2001): starting from similar pre-industrial conditions (Bairoch, 1981), countries are nowadays extremely differentiated in terms of several indicators including productivity levels and wealth per capita.

Not surprisingly, the empirical growth literature has largely rejected the convergence hypothesis on the grounds of different econometric techniques. Indeed, there is no empirical support for the so-called σ*-convergence* (i.e. decreasing income dispersion among countries - Sala-i Martin, 1996), and β*-convergence* (i.e. countries with initially low per capita income grow faster) occurs only in subsamples of economies characterized by similar initial conditions and common characteristics (Durlauf and Johnson, 1995) and in some specific historical periods. Considering the dynamics of the whole cross-sectional distribution of country incomes, a series of works has shown instead a strong shift over time towards bimodality and polarization (Quah, 1996; Bianchi et al., 1997; Henderson et al., 2008; Castaldi and Dosi, 2009), and low mobility across income "clubs" (Quah, 1993, 1997). Relative rankings among countries tend to be sticky and only few economies successfully completed the transition from low-income to high-income clubs (and few from high-income to lower ones, e.g. Argentina).

Contrary to what implied by any equilibrium model, steady growth trajectories are hardly found in real data. Across-period correlation in growth rates of individual countries are rather weak suggesting that development paths are relatively unstable (Easterly et al., 1993; Pritchett et al., 2000) with alternating phases of acceleration and deceleration (Rodrik, 1999; Hausmann et al., 2005; Lamperti and Mattei, 2016).

Concerning the statistical properties of growth rates distributions, Castaldi and Dosi (2009) find evidence of fat tails in the empirical density obtained by pooling together growth rates from different countries and years. Symmetrically, data display a negative relation between income levels and growth rates variability (Canning et al., 1998; Castaldi and Dosi, 2009). Loosely speaking, laggard countries tend to experience more severe aggregate fluctuations.

[6] This section largely draws on Dosi et al. (2019b).

Let us sum up the first set of stylized facts (SF) concerning international growth patterns:

SF 1 Over last two centuries per capita incomes have grown exponentially in all countries affected by the process of industrialization.

SF 2 There have been (not too frequent) historical episodes of catching up, forging ahead and falling behind.

SF 3 Aggregate income dispersion has increased over time with no σ-convergence.

SF 4 β-convergence does not appear unless under some form of *ex-ante* selection bias.

SF 5 The cross-sectional income distribution reveals a tendency towards bimodality and polarization.

SF 6 There is a general lack of mobility across income clubs; relative rankings are rather sticky.

SF 7 Growth rates are weakly correlated across periods; growth trajectories are relatively unstable.

SF 8 The distribution of international growth rates displays a Laplacian shape with fat tails.

SF 9 The volatility of growth rates is negatively associated to income levels.

Next, we consider the behaviour of economies at the medium and short-run frequencies. First, there is clear evidence that mild recessions coexist with deep crises (Stiglitz, 2011, 2015). This is consistent with the evidence on fat-tailed distributed GDP growth-rate distributions provided by Fagiolo et al. (2008). At the short-run frequencies, since the seminal work of Burns et al. (1946), there are robust stylized facts concerning co-movements and relative volatility between output, consumption and investment (see e.g. Stock and Watson, 1999; Napoletano et al., 2006). Total investment expenditure is more volatile than GDP which, in turn, fluctuates less than consumption. Investment and consumption co-move with GDP and are coincident and procyclical variables. We can then add other stylized facts to the list:

SF 10 Output grows exponentially displaying large endogenous fluctuations.

SF 11 Mild recessions coexist with deep downturns.

SF 13 Investment is more volatile than output while consumption is less volatile.

SF 14 Investment and consumption are both procyclical and coincident variables.

2.2 Industrial dynamics

The process of development involves a structural transformation of the economy (Kuznets, 1966). Structural change continuously shapes growth trajectories as production migrates from traditional agricultural activities to manufacturing and, possibly, nowadays, to information-intensive sectors (Lavopa and Szirmai, 2018). Using cross-country data for manufacturing sub-sectors Dosi et al. (1990) finds that advanced nations tend to develop absolute advantages in most industrial activities, respectively of more finely defined "comparative advantages". Conversely, there appear to be country-specificities in productivity gaps/leads which do not vary significantly when lowering the scale of observation to individual industries. This seems to suggest the presence of broad patterns led by externalities and country-wide virtuous (vicious) feedback linking finer, sub-sectoral processes of learning and "self-discovery" (Hausmann and Rodrik, 2003; Cimoli et al., 2009). However, also at the sectoral level growth proceeds with fits and starts: Castaldi and Sapio (2008) analyzing the distributional properties of industry growth rates find evidence supporting fat-tailed densities in line with what observed at the country level.

The empirical regularities at the meso level can be summarized as follows:

SF 15 Endogenous structural change accompanies the whole development and growth trajectories.

SF 16 Leading countries tend to accumulate absolute technological advantages in most industries

SF 17 The distribution of industry growth rates are fat-tailed..

2.3 Firm-level empirical regularities

Firms are major *loci* where innovation and technical change occurs. As a consequence, they are one of the primary engines of the dynamics observed at the industry and country level. For this reason, one should take into account also the microeconomic stylized facts concerning firm dynamics (see Dosi, 2007, for a survey on the topic).

All available data suggest strong and persistent heterogeneity among firms. Firms differ profoundly in their capabilities and organizational forms, they master different technologies and follow idiosyncratic learning trajectories (Nelson and Winter, 1982; Dosi et al., 2001). This maps in firm productivity data which always reveal a large dispersion persisting over time (Bartelsman and Doms, 2000; Syverson, 2011). In turn, heterogeneous efficiency levels translate into different profitabilities and performances. Together, the firm size distribution robustly shows a departure from the (log) Gaussian benchmark, while micro growth rates distributions are well approximated by fat-tailed Laplace density (Bottazzi and Secchi, 2003, 2006). In turn, the presence of fat tails can be directly related to some underlying lumpiness in the growth process of firms as well as to the correlation structure stemming from the very process of competition (more in Dosi, 2007; Dosi et al., 2016b). Note that growth-rate distributions observed at the firm, industry, and country level suggest that such lumpy process survives aggregation and possibly point at a universal scaling conjecture (Fagiolo et al., 2008).

The heterogenous growth trajectories of countries affect their trade patterns and firm performances in international markets. First, exporting businesses are only a little fraction of the total firm population (Bernard and Jensen, 1999; Bernard et al., 2012). Then a natural question arises: do exporters display any specific characteristics? Empirical evidence robustly shows that exporting firms are generally larger, more productive, have higher capital-intensity, employ more skilled workers and pay higher wages than non-exporting competitors (Bernard and Jensen, 1999; Bernard et al., 2012).

The foregoing firm-level empirical regularities conclude our list of multi-scale stylized facts:

SF 17 There are large and persistent productivity differentials across firms within the same sector and country, at all the levels of aggregation, and even more so across countries.

SF 18 The distribution of firm size departs from log-normality and is right skewed.

SF 19 The distribution of firm growth rates exhibit fat tails.

SF 20 Only a relatively small subset of firms are exporters.

SF 22 Exporters are larger and more productive than non-exporters.

3 Evolutionary agent-based models

To repeat, the tall ambition of the evolutionary research program is to jointly account for the emergence of economic growth and fluctuations together with the multi-scale stylised facts listed above. This is done by developing agent-based models (ABM, Tesfatsion, 2006; LeBaron and Tesfatsion, 2008; Fagiolo and Roventini, 2017; Dosi and Roventini, 2019), which provides the computational study of economies thought as complex evolving systems (cf. Section 1). ABMs builds an economy from the *bottom up* where the out-of-equilibrium interactions of heterogenous agents (firms, workers, banks, etc.) yield some collective order, even if the structure of the system continuously change.

Agent-based models are grounded on sound *microfoundations*, i.e. based on realistic assumptions concerning agent behaviours and interactions, where *realistic* here means rooted in the actual empirical micro-economic evidence (Simon, 1977; Kirman, 2016). In that, evolutionary microfoundations represent a radical step forward vis-á-vis neoclassical ones, which recklessly assume that the theorist and the representative agent knows as God the "true" model of the economy, irrespectively of the information they have. This implies a weird isomorphism between the knowledge embodied in the observer and that embodied in the object of observation. Moreover, human-agents are not endowed with "Olympic rationality", but behave according to rules, routines and heuristics (Gigerenzer, 2007; Gigerenzer and Brighton, 2009, see) which adaptively change over time via learning.

After the crucial tenet concerning *behaviors,* let us consider *interactions.* The evolutionary agent-based methodology is prone to build whatever macro edifice, whenever possible, upon actual micro interactions. They concerns what happens *within organizations* — a subject beyond the scope of this work—, and *across organizations and individuals*, that is the *blurred set of markets*. Even if this is far from any comprehensive understanding of "how market works", it does not castrate the quest for market interactions invoking the existence of some fixed point as neoclassical models do. More evidence on the specific institutional architecture of market interactions and their outcomes is certainly needed (a good starting point is Dosi and Kirman, 2023). Short of that, much more concise (and more blackboxed) representations come from network theory (e.g., Albert and Barabasi, 2002) and social interactions (e.g., Brock and Durlauf, 2001) which move away from non-trivial interaction patterns. That together with evidence on persistent heterogeneity and turbulence characterizing markets and economies focus the investigation on out-of-equilibrium dynamics endogenously fueled by the interactions among heterogenous agents.

All those building blocks are more than sufficient to yield the properties of *complex environments*. But what about *evolution*? Basically, that means the *emergence of novelty*. That is new technologies, new products, new organizational forms, new industries, etc. emerging at some point along the arrow of time, which were not those from the start. All this — which is essential to understand different growth patterns — may well be captured by *endogenous* dynamics on the "fundamentals" of the economies (more in Dosi and Winter, 2002 and Dosi and Virgillito, 2017).

These are the evolutionary pillars concerning behaviours, interactions and evolution on which the agent-based model presenteded in the next Section is grounded.

4 The baseline evolutionary growth model

The multi-country multi-industry model in Dosi et al. (2019b, 2020b) features N economies (indexed by i) composed of M consumption-good industries (indexed by h) and a capital-good sector.[7] Each consumption-good sector is populated by S firms (indexed by j). Technologies of production are heterogeneous across firms and endogenously evolve via Schumpeterian (stochastic) processes of innovation and imitation. For simplicity, we assume that search and innovation occur only in the consumption-good sector and take the form of labour productivity increases, i.e. technical progress is Harrod neutral. Finally, countries are endowed with an infinite supply of labor, which is a simplifying hypothesis that nevertheless is broadly in line with what observed in less developed nations.

4.1 Timeline of the events

In each each time step t events proceed as follows:

1. Firms in the consumption-good industries perform R&D in order to discover new techniques and to imitate competitors closer to the technology frontier. Successful firms are able to improve their labor productivity.

2. Production, investment and employment decisions take place. Given their expected demand, consumption-good firms set their desired production, hire workers accordingly and, if necessary, expand their productive capacity.

3. The capital-good sector in each country receives orders from firms in the consumption-good industries, hire workers, and start production.

4. Monetary wages and exchange rates are set at the national level.

[7] This Section draws on Dosi et al. (2019b, 2020b).

5. International imperfectly competitive consumption-good markets opens. Workers spend their income on both domestic and imported goods. Firms' market shares evolve according to their price competitiveness.
6. Entry and exit occur. Firms with quasi-zero market share exit the market and are replaced by new ones.
7. Machines ordered at the beginning of the period are delivered and become part of the capital stock for the following one.

At the end of each time step, the aggregate variables (e.g. GDP, investments, consumption, exports, imports, etc.) are computed by summing the corresponding microeconomic variables.

4.2 Innovation, imitation and production

The consumption-good sector in each country is composed by M industries and S firms per industry. Firms invest in R&D (RD) a fixed proportion of their past sales (SS):[8]

$$RD^i_{j,h}(t) = \rho SS^i_{j,h}(t-1), \tag{1}$$

with $\rho \in (0, 1]$. Total R&D expenditures are then split between innovative (IN) and imitative (IM) efforts:

$$IN^i_{j,h}(t) = \lambda RD^i_{j,h}(t) \tag{2}$$

$$IM^i_{j,h}(t) = (1-\lambda) RD^i_{j,h}(t), \tag{3}$$

with $0 \leq \lambda \leq 1$.

Innovation and imitation are modelled as a two-step stochastic process. In the first step, a draw from a Bernulli distribution (θ) determines whether firms succeed in their search activities. Probabilities of success (θin,θim) are an increasing function of R&D expenditures and of firms' search capabilities ($\xi_{1,2}$>0):[9]

$$\theta in^i_{j,h}(t) = \min\left\{\theta_{max}; 1 - e^{-\xi_1 IN^i_{j,h}(t)}\right\} \tag{4}$$

$$\theta im^i_{j,h}(t) = \min\left\{\theta_{max}; 1 - e^{-\xi_2 IM^i_{j,h}(t)}\right\} \tag{5}$$

Firms succeeding in innovation discover a new production technique associated with a labour productivity coefficient Ain:

$$Ain^i_{j,h}(t) = A^i_{j,h}(t-1)(1 + x^i_{j,h}(t)) \qquad \text{where:} \quad x \sim Beta(\alpha_1, \beta_1) \tag{6}$$

[8]As common in other evolutionary models (Chiaromonte and Dosi, 1993; Dosi et al., 1994a, 2010), R&D strategies are assumed to be entirely routinized and time-invariant. Notice that the assumption of fixed R&D expenditure coefficients is quite in tune with firms actual behaviours (Nelson and Winter, 1982; Dosi, 1988; Dosi and Egidi, 1991).

[9]There is an upper bound $\theta_{max} < 1$ to account for the fact that there is always a minimum degree of uncertainty involved in search activities.

The multiplicative increase (x) is drawn from a Beta distribution with parameters (α_1,β_1) and support $[\underline{x}_1, \bar{x_1}]$, with $\underline{x}_1 \in [-1, 0]$ and $\bar{x_1} \in [0, 1]$. The shape and support of the Beta distribution captures technological opportunities. Given the high degree of uncertainty characterizing the innovation process, the newly discovered techniques may well be less productive than the ones currently mastered by firms. Technological opportunities and firms' search capabilities are shaped by the characteristics of the *technological regimes* (Dosi, 1988; Dosi and Nelson, 2010).

Firms able to successfully imitate their competitors will copy randomly a technique (Aim) from the latter. The probability to imitate a specific technology is inversely proportional to the technological distance and it depends on firms' *absorptive capacity* (Cohen and Levinthal, 1990; Griffith et al., 2003). More specifically, in line with the extended version of the model in Dosi et al. (2020b), the probability for a successfully imitating firm j in country i to copy a specific competitor l in country k is related to the inverse of the (Euclidean) technological distance (d), re-scaled by the absortive capacity variable ϕ:[10]

$$d_{j,l}(t) = \frac{1}{1 + \phi^i_{j,h}(t)[\hat{A}^k_{l,h}(t-1) - \hat{A}^i_{j,h}(t-1)]} \tag{7}$$

The evolution of $\phi^i_{j,h}$ is firm-specific and depends on past cumulated R&D expenditures ($RDcum$):

$$\phi^i_{j,h}(t) = \phi_0 \exp[-\phi_1 RDcum^i_{j,h}(t-1)], \quad \text{where: } \phi_0 = \begin{cases} 1 & \text{if } i = k \\ \epsilon & \text{if } i \neq k \end{cases} \tag{8}$$

with $\phi_1 > 0$ and $\epsilon \geq 1$. The parameter ϕ_1 reflects the skills and competencies of the firm, while ϵ accounts for structural barriers to foreign imitation (e.g. restrictive IPR legislation). Hence, as firms accumulate experience in *R&D*, the variable ϕ will fall, making more likely the access to technologically distant techniques. As a result of this process, firms will receive from competitors a productivity coefficient ($\hat{A}$), which represents a potential requiring further learning and adaptation in order to be fully exploited. The speed of learning at which the new coefficient will be internalised by the firm is, again, a function of its absorptive capacity (ω):

$$A[im]^i_{j,h}(t) = (1 - \omega^i_{j,h}(t))A[im]^i_{j,h}(t-1) + \omega^i_{j,h}(t)\hat{A}^i_{j,h}(t), \tag{9}$$

where $A[im]$ is the actual productivity coefficient available from the imitation process. The absortive capacity variable (ω) evolves according to firm-specific cumulative R&D:

$$\omega^i_{j,h}(t) = \omega_0 - \omega_0 \exp[-\omega_1 RDcum^i_{j,h}(t-1)], \tag{10}$$

with $\omega_0 \in (0, 1]$ and $\omega_1 > 0$.

Finally, once both the innovation and imitation processes are completed, each firm selects

[10] To get probabilities defined in $[0, 1]$ we normalize by the sum over l of $d_{j,l}$. This mechanism is grounded on strong empirical basis. Indeed, the literature on technology-gaps supports the idea that strong absortive capacities can help in overcoming the constraints to imitation posed by technological distance and by other institutional barriers to technology adoption (see e.g. Abramovitz, 1986; Dosi et al., 1990; Fagerberg et al., 2005).

the most efficient production technique among those that it can master, i.e. the one entailing the higher labor productivity:

$$A^i_{j,h}(t) = \max\left\{A^i_{j,h}(t-1); Ain^i_{j,h}(t); Aim^i_{j,h}(t)\right\} \tag{11}$$

Given the nominal wage level (W) fixed at the country level (see Equation 26 below), firms set price (p) as a mark-up (m) on the unit cost of production:

$$p^i_{j,h}(t) = (1 + m^i_{j,h}(t))\frac{W^i_{j,h}(t)}{A^i_{j,h}(t)} \tag{12}$$

The mark-up ratio evolves according the dynamics of past market shares (f):

$$m^i_{j,h}(t) = m^i_{j,h}(t-1)(1 + \upsilon\frac{f^i_{j,h}(t-1) - f^i_{j,h}(t-2)}{f^i_{j,h}(t-2)}), \tag{13}$$

with $\upsilon > 0$.

Consumption-good firms produce their output using both labour and capital. While labor productivity grows over time as result of technical change, the capital-output ratio (B) remains constant (in line with Kaldor, 1957 and Dosi et al., 1990). Firms set desired production (Qd) according to adaptive demand expectations (D):[11]

$$Qd^i_{j,h}(t) = f(D^i_{j,h}(t-1), D^i_{j,h}(t-2), ..., D^i_{j,h}(t-k)). \tag{14}$$

Desired production is constrained by productive capacity. Thus, actual production (Q) is computed as:

$$Q^i_{j,h}(t) = \min\left\{Qd^i_{j,h}(t), \frac{K^i_{j,h}(t)}{B}\right\}, \tag{15}$$

where K is the stock of capital.

Capacity constrained firms invest to expand their capital stock. More specifically, expansion investments (Ie) occur whenever the desired capital stock (Kd) exceeds the actual one.

$$Ie^i_{j,h}(t) = Kd^i_{j,h}(t) - K^i_{j,h}(t), \tag{16}$$

with $Kd^i_{j,h}(t) = BQd^i_{j,h}(t)$. Firms invest also to cover (constant) capital depreciation (δ). Hence, replacement investments (Ir) are simply:

$$Ir^i_{j,h}(t) = \delta K^i_{j,h}(t), \tag{17}$$

with $\delta \in (0, 1)$. The law of motion of capital stocks is then equal to:

$$K^i_{j,h}(t+1) = K^i_{j,h}(t) + Ie^i_{j,h}(t). \tag{18}$$

[11] We assume myopic expectations, i.e. $Qd^i_{j,h}(t) = D^i_{j,h}(t-1)$. In line with Dosi et al. (2006, 2020a), the results of the model are robust when more complex expectation rules are employed.

In each country, domestic firms acquire their machines from an aggregate (i.e. unmodeled "single firm") capital-good sector. Total production (Q_k) equals the sum of the orders from domestic firms (I^i), i.e $Q_k^i(t) = I^i(t)$. The labor productivity in capital-good sectors is assumed to track the average country level $A^i(t)$. Finally, prices track the unit cost of production.

4.3 Market dynamics and selection

Market selection regulates the distribution of international demand for different consumption goods across firms. In each country, total consumption corresponds to the wage bill. For simplicity, we assume that workers spend an equal proportion $d_h = 1/M$ of their income in each consumption-good industry.[12]

Each firm is competing in N national markets all characterized by imperfect information. As goods are homogeneous within each industry, firms' competitiveness depends on the price they charge. Naturally, in foreign markets, firms' prices are affected by exchange rate and trade costs (Anderson and Van Wincoop, 2004). More specifically, given a firm j, operating in industry h and based in country i, its competitiveness in country k is given by:

$$E_{j,h}^{i,k}(t) = \frac{1}{p_{j,h}^i(t)e^{i,k}(t)(1+\tau)}, \tag{19}$$

where $e^{i,k}$ stands for the nominal exchange rate between countries i and k, and the parameter τ captures additional costs for competing in foreign markets (equal to zero if $i = k$ and strictly positive if $i \neq k$). The average competitiveness ($\bar{E}$) for industry h in country k is computed summing up firm competitiveness over countries weighted by their market shares:

$$\bar{E}_h^k(t) = \sum_{i=1}^{N}\sum_{j=1}^{S} E_{j,h}^{i,k}(t) f_{j,h}^{i,k}(t-1). \tag{20}$$

Finally, market selection affects firms' market shares (f) by means of a quasi-replicator dynamics:[13]

$$f_{j,h}^{i,k}(t) = f_{j,h}^{i,k}(t-1)(1 + \chi\frac{E_{j,h}^{i,k}(t) - \bar{E}_h^k(t)}{\bar{E}_h^k(t)}), \tag{21}$$

with $\chi > 0$. In a nutshell, the market shares of more competitive firms in each market will expand, while those of the less efficient ones (charging higher prices) will shrink. The parameter χ accounts for the strength of competition in the market. The market share in the global market

[12] Such assumption implies that sectoral income elasticities of demand are constant and equal to 1.This is obviously a simplification: within the evolutionary tradition, the role of structural change driven by changes in patterns of consumption is extensively analyzed in Verspagen (1992), Montobbio (2002), Ciarli et al. (2010) and Lorentz (2015).

[13] The quasi-replicator dynamics differs from the canonical one since it allows for negative market shares. The standard replicator dynamics instead evolves on the unit simplex. Conversely, the "quasi-replicator" also determines firms death: through the entry and exit process, firms with near zero or negative market shares are replaced by a new entities. For a deeper discussion of the replicator dynamics model see Silverberg et al. (1988), Dosi et al. (1995) and Dosi et al. (2016b).

of firm j competing in industry h is:

$$f^i_{j,h}(t) = \sum_{k=1}^{N} f^{i,k}_{j,h}/N. \tag{22}$$

Given the wage (W) and aggregate national employment (L), the domestic demand ($Dint$) of each firm corresponds to:

$$Dint^i_{j,h}(t) = W^i(t)L^i(t)d_h f^{i,k}_{j,h}(t), \qquad \text{with:} \quad i = k \tag{23}$$

Symmetrically the demand for exports ($Dexp$) is:

$$Dexp^i_{j,h}(t) = \sum_{k \neq i}^{N} W^k(t)L^k(t)e^{k,i}(t)d_h f^{i,k}_{j,h}(t) \tag{24}$$

Finally, total individual demand is given by:

$$D^i_{j,h}(t) = Dint^i_{j,h}(t) + Dexp^i_{j,h}(t) \tag{25}$$

International competition is also characterized by Schumpeterian exit and entry dynamics. At each time step, firms with quasi-zero market shares exit the market and are replaced by entrants. The number of firms is thus constant in each industry.[14] The technology of entrants evolve according to the domestic average productivity in the industry.[15] In tune with empirical evidence, we also assume that entrants are on average smaller than incumbents (Caves, 1998; Bartelsman et al., 2005), and their initial stock of capital is equal to the minimum level in the industry.

4.4 The macroeconomic framework

In each country, the supply of labour is infinitely elastic to variations in demand (in line with Lewis, 1954 and Cornwall, 1977). Hence, total employment is determined in the goods markets by the total labour demand of consumption- and capital-good firms and by the distribution of labour productivities. Monetary wages are determined by institutional factors as in Dosi et al. (2010):

$$W^i(t) = W^i(t-1)[1 + \psi g^i_{prod}(t-1)], \tag{26}$$

where g_{prod} is the lagged productivity growth and $\psi \geqslant 0$.

Exchange rates (e) evolve according to past current account conditions with a stochastic

[14]Empirical evidence supports indeed the idea that entrants are (roughly) proportional to the number of incumbents (Geroski, 1995).

[15]More precisely, firms' initial techniques are obtained applying to the domestic average productivity in the industry a multiplicative shock drawn from a Beta (α_2, β_2) with support $[\underline{x}_2, \bar{x_2}]$ (where: $\underline{x}_2 \in [-1, 0]$ and $\bar{x_2} \in [0, 1]$). Such assumption is consistent with recent theoretical and empirical appraisals pointing out the cumulativeness and the specificity of national learning patterns (Fagerberg, 1994; Cimoli and Dosi, 1995; Fagerberg and Verspagen, 2002; Cimoli et al., 2009).

noise:

$$e^i(t) = e^i(t-1)(1+\gamma\frac{TB^i(t-1)}{\bar{Y}(t-1)} + u_i(t)) \qquad u_t \sim \mathcal{N},(0,\, \sigma_e), \tag{27}$$

where TB stands for trade balance, $\bar{Y}$ is world GDP, u is a white noise, and the parameter γ regulates the sensitivity of the adjustment defining the exchange rate regime.[16] The formulation is in tune also with those used in models of balance-of-payment constrained growth (see e.g. McCombie and Thirlwall, 1994; Thirlwall, 1979).

At the end of each time step, national aggregates are determined simply summing up the corresponding micro variables. Thus, national consumption (C), total exports (EXP) and imports (IMP) are computed as:

$$C^i(t) = W^i(t)L^i(t); \tag{28}$$

$$EXP^i(t) = \sum_{h=1}^{M}\sum_{j=1}^{S} Dexp^i_{j,h}(t); \tag{29}$$

$$IMP^i(t) = C^i(t) - \sum_{h=1}^{M}\sum_{j=1}^{S} Dint^i_{j,h}(t). \tag{30}$$

Of course, the trade balance is $TB^i(t) = EXP^i(t) - IMP^i(t)$. The GDP ($Y$) of country i is then equal to:

$$Y^i(t) = C^i(t) + I^i(t) + EXP^i(t) - IMP^i(t) \tag{31}$$

Needless to say, trade balances of all countries cancel out at the global level:

$$\sum_{i=1}^{N} TB^i(t)e^i(t) = 0.$$

5 Accounting for growth, structural change and multi-scale empirical regularities

How does the model fare in reproducing the empirical regularities presented in Section 2?[17] The model imposes identical initial conditions and structural parameters (cf. Table A.1 in Appendix A) across countries, industries and firms. This strategy of introducing "mirror image" countries allows to transparently observe the emergence of heterogeneity across firms and industries, and study its effect on international growth patterns isolating the key underlying mechanisms. Indeed, simulation results will show that, in presence of emerging absolute technological advantages/disadvantages, divergence can occur without the need for exogenous differences in countries' structural characteristics (e.g. factor endowments, human capital, geography, etc.).

The results generated by the model are analysed by means of Monte Carlo numerical simulations. (50 runs). For a detailed explanation of the empirical validation of agent-based models,

[16] The exchange rate between two countries i and j can be computed as: $e^{i,k} = \frac{e^i}{e^k}$.

[17] This Section partially draws on Dosi et al. (2019b, 2020b). In particular, only a subset of the results are presented here. We refer to the two articles for a deeper presentation of the simulation results.

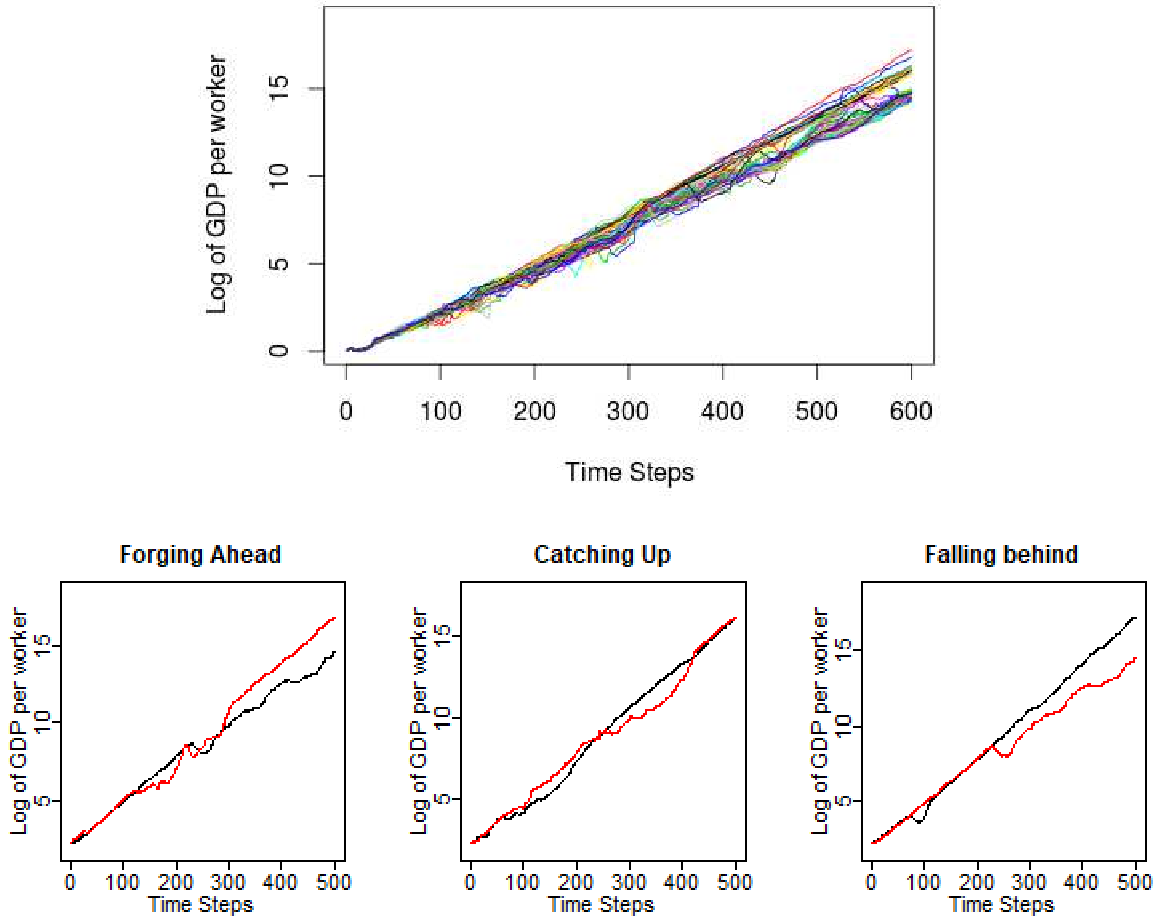

Figure 1: Emerging divergent growth patterns; *top*: GDP per worker dynamics; *bottom*: an illustration of catching up, forging ahead and falling behind. Source: Dosi et al. (2019b).

see Fagiolo and Roventini (2017) and Fagiolo et al. (2019).

5.1 Endogenous growth and divergent patterns

Let us start by considering the dynamics of GDP per worker of the sixty countries composing our world economy (cf. Figure 1).[18] First, the model endogenously generates secular exponential growth in incomes per worker (**SF 1**) and divergent patterns across countries. Figure 1 (bottom panel) displays some archetypal examples of emergent episodes of forging-ahead, catching-up and falling-behind (**SF 2**).

Simulated GDP series do not reveal any tendency to σ-*convergence* (**SF 3**) or β-convergence (**SF 4**).This suggests that, as the technological distance among countries increases, imitation and catching-up become more difficult. The foregoing results are also corroborated by the different convergence tests proposed by Bernard and Durlauf (1991).

However, as the moments of the income distribution do not fully account for its time dynamics (Quah, 1996), we show in Figure 2 the evolution of the whole empirical density of international

[18] Income and productivity variables are always expressed at constant prices and exchange rates.

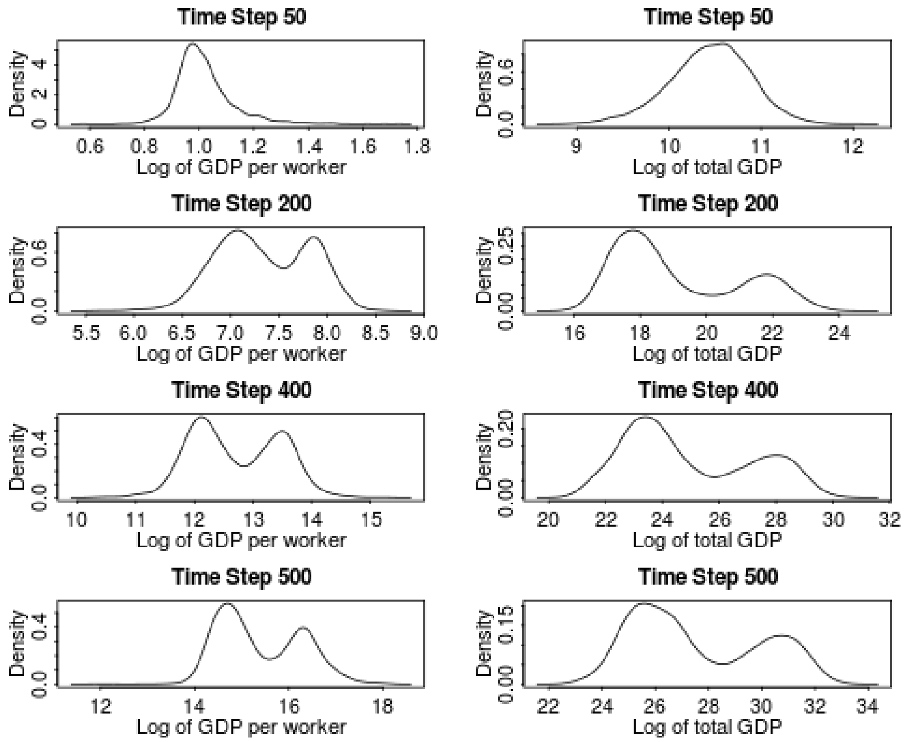

Figure 2: Evolution of the cross-sectional distribution (Monte Carlo pooling); *left*: GDP per worker; *right*: total GDP. Source: Dosi et al. (2019b).

incomes, which clearly moves from an unimodal shape towards a bimodal one at the end of the simulation (**SF 5**).[19] In turn, the model endogenously generates two convergence clubs for poor and advanced countries, with the latter being relatively smaller than the former. Such results are corroborated by bimodality tests commonly employed in the growth literature (Bianchi et al., 1997; Henderson et al., 2008).

Relatedly, the estimation of transition probability matrix for five different classes of country income (cf. Table 1) reveals a general lack of mobility within the distribution.[20] Indeed, the high probability values along the main diagonal suggest that relative country rankings are sticky (**SF 6**). Moreover, the associated ergodic distribution shows that the probability mass tend to (asymptotically) concentrate on the tails, pointing, once again, at an on-going process of polarization.

Let us now consider the scaling behavior of output growth rates. Consistently with Castaldi and Dosi (2009), we find that the volatility of g (in logs) scales negatively with income levels (**SF 9**), suggesting that poor countries are subject to more severe aggregate fluctuations than advanced ones. The positive relationship found between growth rates and income levels instead points at the existence of dynamic increasing returns in production (Castaldi and Dosi, 2009).

Countries do not appear to follow a steady growth trajectory. In line with the empirical evi-

[19] Income (and productivity) data are normalized taking logs and subtracting the cross-country average to remove common trends: $y_{i,t} = \log Y_{i,t} - \log \bar{Y}_t$. Where Y is the original variable and $\bar{Y}$ is an average across countries. As a result, the corresponding growth rate densities are centered on zero. The same normalization is performed for industry- and firm-level data, when studying distributional properties.

[20] Probabilities are computed as $\hat{p}_{i,j} = \frac{n_{i,j}}{n_i}$ where n_i is the number of observations in state i and $n_{i,j}$ is the number of observed transition from i to j. This corresponds to the maximum likelihood estimators of true probabilities (Norris, 1998).

N. obs.	1	2	3	4	5
5751.28	0.9325	0.0663	0.0011	0.0001	0
(213.2393)	(0.0033)	(0.0032)	(0.0001)	(0.0000)	
6601.52	0.0682	0.8528	0.0777	0.0013	0
(160.1320)	(0.0013)	(0.0022)	(0.0018)	(0.0001)	
4979.2	0.0008	0.1222	0.7763	0.0988	0.0019
(132.6577)	(0.0001)	(0.0019)	(0.0020)	(0.0016)	(0.0001)
4161.98	0	0.0022	0.1252	0.7689	0.1037
(124.6708)		(0.0002)	(0.0024)	(0.0029)	(0.0017)
8326.02	0	0.0001	0.0014	0.0458	0.9528
(83.2227)		(0.0000)	(0.0001)	(0.0015)	(0.0014)
Ergodic	0.2495	0.2281	0.1468	0.1166	0.2591
	(0.0099)	(0.0057)	(0.0044)	(0.0041)	(0.0028)

Notes: Variables are normalized dividing by the world sum. Income classes are defined as: (1): $y < 0.5$; (2): $0.5 < y < 0.75$; (3): $0.75 < y < 1$; (4): $1 < y < 1.25$; (5): $y > 1.25$.

Table 1: 3-step transition probability matrix and implied ergodic distribution; *variable*: GDP per worker. Monte-Carlo standard errors are in brackets.

dence, the average across-periods correlation of country growth rates are rather weak, suggesting that growth experiences are relatively unstable (**SF 7**).

We then investigate the statistical properties of output growth rates distributions. More specifically, we fit the exponential-power family of densities over the simulated distribution of cross-country growth rates (Bottazzi and Secchi, 2003). In tune with the empirical evidence (**SF 8**), the estimated b parameter is close to unity (cf. Table 2), i.e. a Laplacian shape with tails much fatter than the Gaussian benchmark provides a good fit of the simulated distribution. Similar results are also found when one considers the time-series distribution of output growth rates for a given country. This in turn implies that the growth process of country is characterized by endogenous fluctuations and (rarer) deep crises (**SFs 10-11**, cf. Fagiolo et al., 2008).

Finally, we consider the business-cycle properties of macroeconomic time series. In line with the empirical evidence (Stock and Watson, 1999), the detrended series of aggregate investment is more volatile than GDP, while the latter fluctuate less than aggregate consumption (**SF 12**). Moreover, cross-correlations among macro variables at the business cycle frequencies suggest that consumption, investment, employment and productivity are procyclical as they track GDP fluctuations (**SF 13**).

5.2 Emergent structural change and firm heterogeneity

The foregoing macroeconomic patterns emerge from a rich dynamics at the industry level shaped by the innovative activities of firms and by processes of market selection.

First, the evolution of industry output shares for four randomly selected countries (cf. Figure 3, top panel) reveals that the model is able to generate endogenous structural change (**SF 14**). Note that at the beginning of the simulation, economies are equal also in terms of specialization. However, the relative weights of industries evolve over time according to countries relative

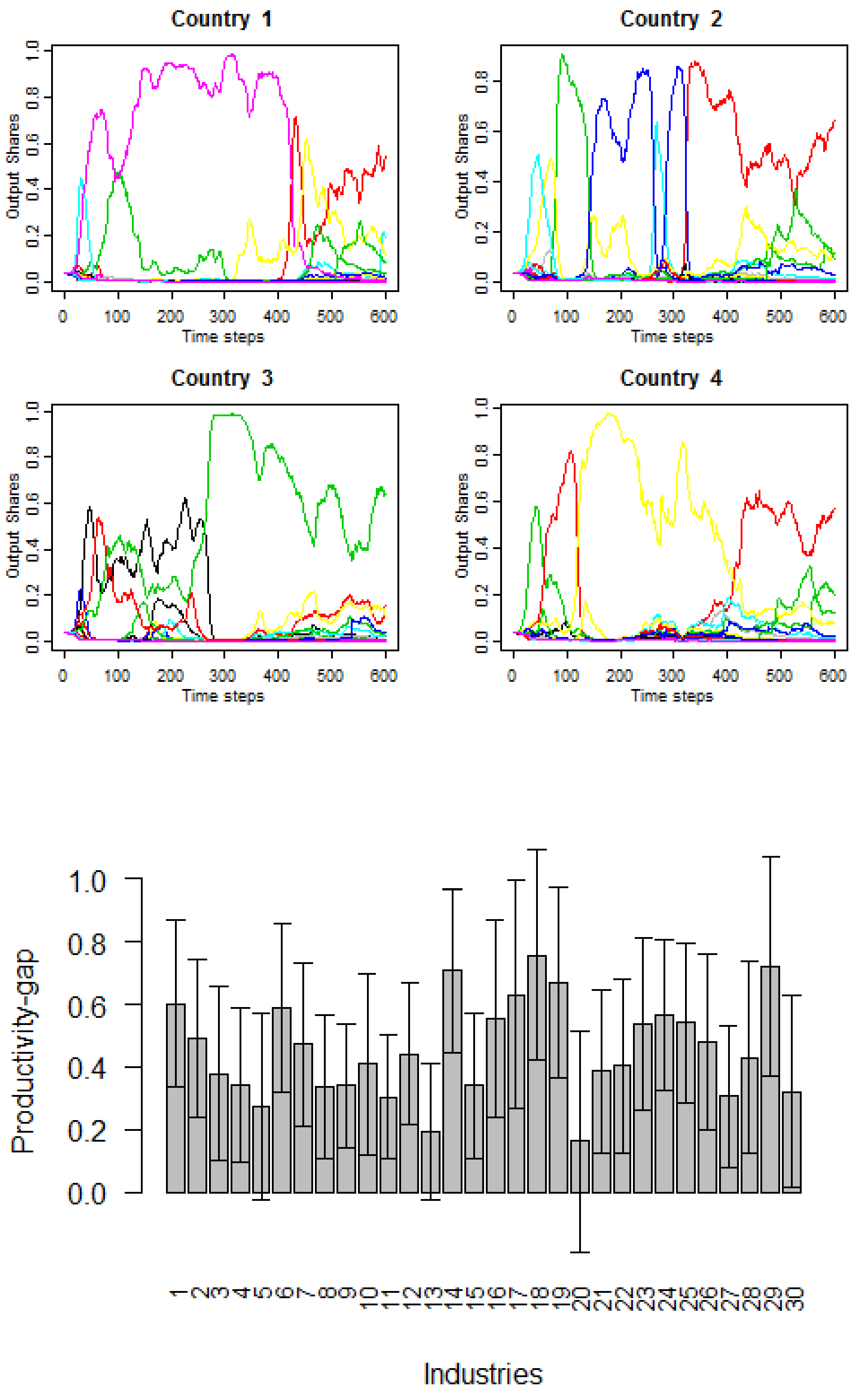

Figure 3: Structural change and productivty gaps; *top:* Industry output shares evolution (4 randomly selected countries); *bottom:*productivity-gaps by industry between leaders and laggards (Monte Carlo 5% confidence intervals are given by black bands.; leaders and laggards are selected as respectively the top and the bottom 10% countries in terms of average income ranking during the last 100 steps). Source: Dosi et al. (2019b).

	b	a	m
GDP per worker	1.0171	0.0248	−0.0028
	(0.0056)	(0.0002)	(0.0001)
Output	0.9776	0.0476	−0.0015
	(0.0061)	(0.0005)	(0.0001)
GDP per worker (time series)	1.1423	0.0252	0.0234
	(0.0378)	(0.0007)	(0.0004)
Output (time series)	1.1102	0.0513	0.0276
	(0.0307)	(0.0011)	(0.0007)
Industry output	0.5791	0.0135	−0.0073
	(0.0026)	(0.0002)	(0.0002)
Firms output (country pooling)	1.1435	0.0926	−0.0105
	(0.0151)	(0.0013)	(0.0005)
Firms output (single industry)	1.1495	0.0926	−0.0105
	(0.0153)	(0.0012)	(0.0005)

Table 2: Exponential power parameters estimation at different levels of aggregation. Monte-Carlo standard errors are in brackets.

competitiveness in specific industries which in turn rest in the competitiveness of their firms. Interestingly, in some economies, sectors appear to emerge and decline rapidly while others seem to experience more stable dynamics. This, of course, implies that the patterns of structural change also differ across countries (McMillan et al., 2014). Moreover, along the simulation, the emerging group of leader nations tend to accumulate absolute advantages in most industries (**SF 15**). To highlight this point, we report in Figure 3 (bottom panel) the productivity gap (at the end of the simulation) disaggregated by industry between the subset of countries in the top income decile vis-á-vis those in the bottom one. The gap appears to be significant in almost all sectors. In line with empirical findings (Dosi et al., 1990), fast-growing economies are those that over time manage to develop technological leads in most activities.

The heterogeneity across sectors is also revealed by the distribution of within-country growth rates for industry output. Once again, there is a strong departure from normality with emerging fat tails (cf. Subbotin estimates in Table 2): different industries experience large growth episodes and sharp contractions (**SF 16**).

In line with other evolutionary models, the stylized facts of industrial dynamics result from the interactions of heterogeneous innovating firms. Consistently with microeconomic evidence (**SF 17**), there is a persistent heterogeneity in productivity across firms. The productivity differentials map into different market shares dynamics and, eventually, very different firm sizes. The distribution of firm size is indeed right-skewed (**SF 18**), suggesting the co-existence of few successful large entities with many small businesses. Firms growth rate distributions exhibit a fat-tailed "tent" shape (**SF 19**), alike those found at the industry and country levels (cf. Table 2). The lumpy growth processes at the micro level do not appear to be washed away by aggregation, suggesting a possible "universal" mechanism of growth for firms, industries and countries.

Finally, the model also replicates some pieces of empirical evidence on firm-dynamics and international trade. In Table 3, we report some Monte Carlo statistics on exporters shares

		Exporters premia		
	Exp. Share (%)	Productivity	Employment	Tot. sales
Country level	6.5975	1.0834	1.1890	1.1698
	(0.0775)	(0.0015)	(0.0061)	(0.0039)
Industry level		1.0262	1.4135	1.1621
		(0.0003)	(0.0127)	(0.0039)

Notes: A firm is considered exporter at t if $f_{i,t} > f_{min} * 1.05$ in at least one country. Where: $f_{min} = \frac{1}{(N*S*10)}$ Export premia are computed as: $\log(X_{EXP})/\log(X_{NEXP})$. Where: X_{EXP} and X_{NEXP} are averages respectively for exporters and non-exporters.

Table 3: Exporters shares and premia. Monte-Carlo standard errors are in brackets.

and premia. Market selection mechanisms allow only a small fraction of total domestic firms (around 6.5%) to penetrate in foreign markets (**SF 20**). As observed in real data, there are premia associated to the export status (**SF 21**) as exporters are more productive, they are bigger in terms of size and, as the second row in Table 3 shows, such features persist also within single industries.

5.3 The Schumpeterian and Kaldorian drivers of growth and divergence

We have just showed that the evolutionary multi-country model can account for endogenous growth together with a rich ensemble of empirical regularities at different levels of aggregation. On the supply side, an endogenous engine of technical change is grounded on firm-specific innovative and imitative activities. On the demand side, Keynesian/Kaldorian mechanisms endogenously determine aggregate demand and its distribution across countries via technological gaps/leads and foreign trade multipliers. Note that the results are generated relying on neither explanatory variables such as "human capital" or the "quality of institutions", nor on different factor endowments, supply and demand conditions across countries and industries. This is not to downplay such factors, but to remark that Keynesian and Schumpeterian drivers, often neglected in the economic debate, can provide compelling results in explaining the ubiquitous divergent dynamics.[21]

The asymmetric accumulation and propagation of (endogenous) idiosyncratic productivity and demand shocks at the firm level yields indeed the emerging macro divergence. At the micro level, a virtuous cycle in our model is driven by idiosyncratic productivity increases via innovation or imitation which, if not compensated by increases in wages or by an appreciation of the exchange rate (both system-level variables in our model), raise firms's price competitiveness in both national and foreign markets, boosting sales, exports, and output. In turns, higher sales entail higher search expenditures which, increase the probability of achieving new productivity increases, etc.

[21]For instance, a long tradition of heterodox scholars has pointed out that technological asymmetries across countries account for the largest part of trade specializations as compared to other drivers commonly found in the literature (Posner, 1961; Vernon, 1966; Cimoli, 1988; Dosi et al., 1990; Storper, 1992).

The foregoing sequence of cumulative feedback propagates to the macroeconomic level both on the supply and on the demand side. First, the emergent Zipf-type distribution of firm size implies that shocks to the largest firms would not dissipate by aggregation, even if firms were characterized by independent stochastic processes, i.e. the granular hypothesis supported by Gabaix (2011).[22] However, in the model, as well as in reality, the competition process entails a powerful correlation mechanism in the dynamics of micro demands and market shares (more in Dosi et al., 2016b). Differential competitiveness among firms amplify its effect via the replicator dynamics yielding differential growth and survival rates among firms. An important result of our modelling exercise is that such replication process carries over to whole countries, as they are correlated via international trade and imitation. However, there is a fundamental difference between firms and countries. The former can die while the latter cannot, but as they are always alive they will grow along correlated (or anti-correlated) paths. That is why we observe in our model, characterized by dynamic increasing returns and interdependencies, a tendency towards bimodality and polarization with countries that become, relatively speaking, poorer, and others that become richer (indeed vindicating the patterns discussed Reinert, 2007).

In general, interdependencies tend to generate co-movements between units at the micro level which will not be averaged out when increasing the scale of observation. In the model, national productivity interdependences are enhanced by the process of firm entry as entrants' initial productivity is linked to the average ones in the country. On the demand side, exports translates into demand impulses for the domestic economy, whereby an external demand shock amplifies itself via more output, more employment, higher wages, yet more demand etc.,that is, the foreign trade multiplier. Therefore, external demand shocks bear a fundamental role in reinforcing technological success across domestic industries. As a result of these transmission mechanisms, self-reinforcing divergence in productivity and income levels will also be found in aggregate data. Moreover, in line with a Kaldorian perspective, high relative productivity growth will be associated also with positive export performances and trade surpluses. Evolutionary microfoundations can indeed robustly yield Kaldorian cycles of cumulative causation (see also Dosi et al., 1994a and Llerena and Lorentz, 2004).

5.4 Policies for catching-up

The simulation results show the emergence of a polarized world of leading and laggard countries. In this section we study what laggard countries can do to catch up with the developed economies assessing the impact of different policies as in Dosi et al. (2020b).

We set the scene by initialise the model with the twin-peaked country GDP distribution resulting from the last step of the simulations analysed in the previous Sections.[23] Note that laggard countries exhibit a strong productivity gap in almost all the industries. (cf. Figure 3).

[22]Indeed, in Dosi et al. (2018a) we show that such granularity applies much more to demand impulses than to the relation between micro productivity shocks and aggregate GDP dynamics.

[23]More precisely, following the procedure proposed by Bianchi et al. (1997), we split countries by setting a cut-off point at the local minimum of the estimated kernel cross-country growth density (cf. the lowest panel in Figure 2). Consequently, all the countries with income levels above this threshold are classified as leaders and vice-versa. For more details, see Dosi et al. (2020b).

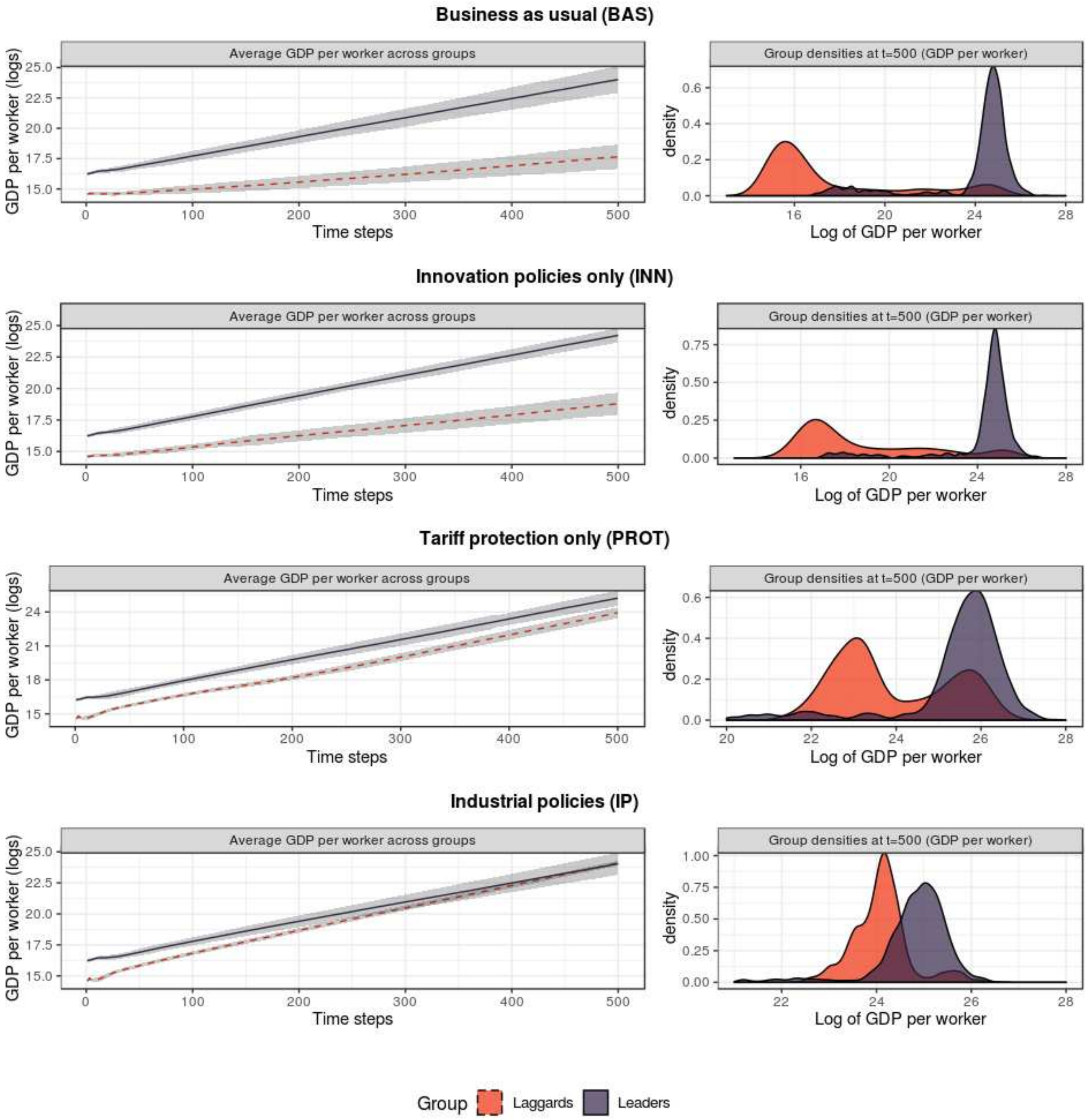

Figure 4: Main policy experiments: evolution of average GDP per worker across groups (left panels); kernel densities of GDP per worker at t=500 (right panels). Source: Dosi et al. (2020b).

In the benchmark business-as-usual (BAS) scenario, wherein laggards are characterized by relatively lower capabilities and R&D investments than leaders and they do not implement any form of industrial policy (cf. the parametrization in Table A.2), the initial polarization is reinforced as shown by the increasing distance of the two modes of the income distribution (cf. Figure 4). This is the trajectory experienced by many developing countries adhering to the free-market policy doctrine of the "Washington consensus".[24]

What can laggard do to break such a divergent pattern? Three archetypal policy regimes are introduced, namely industrial policies (IP), innovation policies without tariff protection (INN) and tariff protection only (PROT). Each policy is characterized by permanent changes in the structural parameters spelled out in Table A.2. The IP regime is intended to mimic the experience of successful East Asian countries or, earlier, Germany and Japan. In such scenario, the gap in country-wide capabilities and R&D investment with respect to leading nations has been closed as a result of policy efforts aimed at fostering the accumulation of knowledge, while a general tariff is introduced to allow native firms to learn and build their own capabilities. For simplicity, we assume that both capabilities and R&D investment shares have been risen exactly to the level of leader countries. In the INN setting, laggards only implement innovation policies and are assumed to have the same capabilities of leaders. In the PROT setup, laggards only impose tariffs without stimulating parallel enhancements in technological capabilities and R&D expenditures.

Results for the IP, INN and PROT scenarios are compared to BAS, as shown in Figure 4. The implementation of industrial policies (IP) results in a process of convergence of backward economies and in a reversal of polarizing forces. In that, our model is able to reproduce a growth dynamics similar to the one followed by East Asian tigers from the 70s and, later on, by China.

The INN scenario shows that even if countries have identical economy-wide capability parameters, the cumulative mechanisms in the model make large incumbents in leader nations keep their competitive advantage over small entrants located elsewhere. In turn, this suggests that infant industry protection is a necessary condition for catching up.

When laggards focus only on protectionist policies (PROT), the process of convergence is also much weaker and at the end of the simulation there is still a positive and significant income gap across the two groups of countries. This is reminiscent of the trajectory followed by some Latin American countries in the post-war period where import-substitution policies were implemented with a strong inward-looking orientation and without substantial efforts in upgrading their innovation systems. As shown by our model, such an exclusive focus on trade restrictions pushes laggard countries into a middle-income trap and to a general failure to reach the income status of developed economies. In Dosi et al. (2020b), we also consider a "trade war" regime where leaders introduce a retaliatory tariff of the same amount of that adopted by laggards. Results suggests that in such a scenario, both leaders and laggards are worse off in terms of GDP per-worker growth, as the lower levels of world demand associated to the adoption of trade

[24] At the opposite, in a Solow-type of world in which knowledge is a pure public good (Solow, 1956; Arrow, 1962) and it can be freely adopted by laggards, unconditional convergence across countries occur. More details in Dosi et al. (2020b).

tariffs by leaders, translates in lower R&D expenditures and in a general slowdown of productivity growth. Our results highlight the widespread negative effects of generalized protectionist policies and suggest that leading countries would be better off if they do not respond to the trade tariffs introduced by laggards. This is coherent with the historical experience and suggests a negative impact on the world economy of recent protectionist trends (cf. the U.K. and the U.S.).

Finally, we study whether different degrees of exchange rate flexibility (cf. γ in Equation 27) may interact, if at all, with industrial policies (IP scenario). The results in Dosi et al. (2020b) show that more flexible exchange rates exert only negligible positive effects on the final productivity gap across groups. At the same time, faster exchange rates adjustments do not appear to reduce final income dispersion. These results suggest that overall the dynamics of exchange rates plays a very limited role in the catching up process.

6 Conclusions

This work presented the evolutionary growth theory (Nelson and Winter, 1982; Metcalfe and Foster, 2010) which can successfully account for endogenous growth, emergent polarisation across countries, restless structural change across industries, as well as a rich ensemble of empirical regularities observed at macro, meso, and micro levels of aggregation.

The remarkable explanatory capability of evolutionary growth theory is grounded on the acknowledgement that *the economy is as a complex evolving system* (more on that in Kirman, 2010, 2016; Rosser, 2011; Dosi and Roventini, 2019; Dosi, 2023), i.e. an ecology populated by heterogenous firms, workers, etc. whose far-from-equilibrium market interactions lead to some emerging order at the industry and country levels, while the structure of the system continuously changes. This implies that higher levels of aggregations can lead to the emergence of new phenomena (e.g. self-sustained growth), new statistical regularities (e.g. twin-peaked cross-country growth distributions) and new structures (i.e. markets, industries). As *more is different* (Anderson, 1972), it is then misleading to shrink the macroeconomic level to the microeconomic one as typically done in Neoclassical theory. At the same time, by focusing only on the macro level, one looses many significant details on how growth and structural change are generated by processes occurring at lower levels of aggregation. For this reason, evolutionary growth theories are grounded on *generative microfoundations*, which grow the economy from the bottom-up (Tesfatsion, 2002) by developing agent-based models (Tesfatsion, 2006; LeBaron and Tesfatsion, 2008; Fagiolo and Roventini, 2017).

Accordingly, the evolutionary agent-based model (Dosi et al., 2019b, 2020b) presented in this work well captures the emergence of complex growth patterns exhibiting a strong tendency towards clubs formation among countries. Moreover, each country experiences an endogenous transformation of its productive structure during the development process. Both aspects are emergent outcomes of the co-evolution of *Schumpeterian* microfoundations and aggregate demand propagation mechanisms in tune with *Kaldorian* development theory. Indeed, at the microeconomic level, the innovative performances of firms lead to knowledge accumulation, increasing production and exports, which in turn trigger structural transformation and changed patterns of specialisation. Overall, such dynamics leads to the emergence of virtuous and vicious development trajectories also at the level of whole countries. The robustness of the model is corroborated by the fact that it accounts for a long list of stylised facts at different levels of aggregation.

Evolutionary agent-based models can also be employed to provide robust policy recommendations. Simulation results show that industrial policies (Cimoli et al., 2009) are a fundamental instrument for low- and middle-income countries to spur economic growth and catch up with leading economies, well in tune with the technology-gap literature (see e.g. Fagerberg and Verspagen, 2002; Cimoli and Porcile, 2013; McMillan et al., 2014; Lavopa and Szirmai, 2018). At the opposite, the free-market "Washington consensus" scenario exhibits a relentless divergent growth process with increasing productivity gaps for laggards. Such results stem from the inability of firms in developing economies to absorb the technological knowledge generated abroad, stifled by the lack of protection for local infant industries. Industrial policies — akin to those implemented by East Asian economies and China — foster the development of domestic technological capabilities. Trade tariffs alone are not sufficient and laggards remain locked in a middle-income trap, as historically happened to many South American countries. Again in line with the historical evidence, an uneven playing field with asymmetric abilities for developing countries to nurture their local industries appears to be a win-win scenario for the world economy as a whole, as indeed happened in the long phase of "conditional convergence" prior to WWI.

Due to space constraints, this work has not sufficiently explored the multifaceted connections between business cycles, crises and economic growth resulting from the co-evolution of Schumpeterian drivers and patterns of technological change and growth, and Keynesian mechanisms of coordination among a multitude of self-seeking economic agents within and between markets.[25] This is relevant as a growing body of empirical literature (Cerra et al., 2023) has shown that hysteresis is a ubiquitous phenomena and recessions can leave long-lasting scarrings to the economy. The evolutionary Schumpeter meeting Keynes model (Dosi et al., 2010, 2016a, 2017) allows to tackle this issue by coupling endogenous innovation and technological-diffusion processes with emerging business cycles and crises due to coordination failures arising from firm's investment decisions. The model shows that Keynesian fiscal policies are a necessary condition for growth even during period of fast technological change (Dosi et al., 2010), and their are mostly needed when income inequality is high (Dosi et al., 2013, 2015). Keynesian and Schumpeterian policies also interact with the institutions of the labour market: hysteresis is more likely to emerge in flexible labour market regimes (Dosi et al., 2018b) and when fiscal austerity policies are in place (Dosi et al., 2019a).

Given the remarkable results achieved by evolutionary economics, how does it relate to the other alternative theories of growth presented in the book? There are certainly fruitful complementarities (see the discussion in Dosi and Roventini, 2017, 2019) starting from the

[25] Another frontier research line involves the study of the coupled climate and economics dynamics. Indeed, unmitigated climate change leads to catastrophic impacts able to stop the very process of economic growth as shown in the evolutionary integrated-assessment models in Lamperti et al. (2018, 2020).

rejection of the foundations of Neoclassical growth theory, that is utility and profit maximisation, olympic rationality, market clearing, equilibrium, as well as the representative agent fiction. Moreover, these theoretical paradigms are genuinely rooted in the works of Classical economists — Smith, Marx, Ricardo, Keynes, Schumpeter — and they share an interdisciplinary vision of the process of economic growth, learning from the others disciplines such as economic history and political science, instead of hegemonically reducing the phenomenon to models whose fancy math is often inversely proportional to their original content. On the policy side, starting from different angles, alternative growth theories come to similar policy conclusions, which attribute to the Government and to industrial policies a fundamental role in fostering growth and the technological convergence of laggard countries.

The most relevant difference between evolutionary economics and the other alternative growth theories concerns *microfoundations*, which often are discarded by the latter to reject the methodological individualism. This is certainly desirable for the pathetic microfoundations of Neoclassical models, which squeeze the richness of the macro to the optimal behaviour of a fictional representative agent. But such an "anthropomorphisation" does not occur in evolutionary agent-based models, wherein microfoundations are necessary to study how the interactions of a multitude of heterogenous agents can lead to the emergence of economic growth, structural change, and other macro phenomena. In fact, there is no isomorphism between the micro and the macro in evolutionary growth theories, but rather the models can be macrofounded (Kirman, 2016; Dosi and Roventini, 2019): the micro behaviours of firms can be constrained by system-level state variables such as GDP or the balance of payment. The *macrofoundation of the micro* is indeed a promising venue of common research between evolutionary economics and the other alternative theories of growth.

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Appendix A Parameter values

Description	Symbol	Value
Number of countries	N	60
Number of industries	M	30
Number of firms (each industry)	S	20
Sectoral demand shares	d_h	1/30
Capital-output ratio	B	3
Mark-up adjustment parameter	υ	0.04
R&D investment propensity	ρ	0.04
R&D allocation parameter	λ	0.5
Firms search capabilities	$\xi_{1,2}$	0.08
First stage probabilities upper bound	θ_{max}	0.75
Beta distribution parameter	(α_1, β_1)	(1,5)
Beta distribution support	$[\underline{x}_1, \bar{x_1}]$	[-0.05,0.25]
Beta distribution parameter (ent.)	(α_2, β_2)	(1,5)
Beta distribution support (ent.)	$[\underline{x}_2, \bar{x_2}]$	[-0.03,0.15]
Foreign imitation penalty	ϵ	5
Foreign competition penalty	τ	0.05
Replicator dynamics parameter	χ	1
Wage sensitivity parameter	ψ	1
Exchange rates flexibility	γ	0.1
Exchange rates shocks std. dev.	σ_e	0.002
Depreciation rate	δ	0.02
Monte-Carlo replications		50

Table A.1: Benchmark parametrization

Description	**Parameter**	**Leaders**	**Laggards**			
			Business as usual (BAS)	Only innovation policies (INN)	Only industry protection (PROT)	Industrial policies (IP)
R&D investment share	ρ	0.04	0.01	0.04	0.01	0.04
Search capabilities (innovation)	ξ_1	0.08	0.02	0.08	0.02	0.08
Search capabilities (imitation)	ξ_2	0.08	0.02	0.08	0.02	0.08
Absorptive capacity (tech. distance)	ϕ_1	0.08	0.02	0.08	0.02	0.08
Absorptive capacity (speed of learning)	ω_1	0.2	0.05	0.2	0.05	0.2
Tariff rate	$tariff$	0	0	0	100	100

Table A.2: Policy scenarios: parameter values