PSL Quarterly Review

vol. 77 n. 310 (September 2024)

Special issue on structural change, social inclusion, and environmental sustainability

Complex systems: Introductory notes on a dialogue among political economy, evolutionary economics and physics

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Abstract:
Complex systems may be a useful methodological tool to address "challenges for research in development". There is a huge and growing literature on complex systems and economic theory that might be related to early intuitions of classical economists on the workings of capitalist economies. Kondratiev and Slutsky have worked with features of complex systems – how technological revolutions change the system. This may underlie one peculiarity of capitalism – a complex system that changes its level of complexity over time. The inclusion of the periphery broadens its turbulent nature: a complex system that combines regions with self-organization dynamics – the center – and regions with random behavior – the periphery.

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How to cite this article:
Albuquerque E.M. (2024), "Complex systems: Introductory notes on a dialogue among political economy, evolutionary economics and physics", *PSL Quarterly Review*, 77 (310), pp. 247-261.

DOI: https://doi.org/10.13133/2037-3643/18651

JEL codes:
P160, O33, B510

Keywords:
technological revolutions, periphery, complex systems, metamorphoses of capitalism, simulation models

Journal homepage:
http: //www.pslquarterlyreview.info

For any economist, the simple reading of any introductory article on complex systems may show many identities with the operation of modern economies, of modern capitalism.[1] Nussenzveig (1999), for instance, summarizes a complex system as follows: 1) it is a dynamic system, in

* A draft version of this paper was presented at the international workshop "Structural change, social inclusion and environmental sustainability: new perspectives and polices in economic development" – Plenary Conference: "State of the art and challenges for research in development" (Montevideo, 7 September 2023). I would like to thank Carlos Bianchi for his invitation to participate in this international workshop, José Gabriel Porcile for his comments in that session, the participants for questions and observations that contributed to the paper's improvement, and Leonardo Costa Ribeiro for his comments on an earlier draft. Financial support from CNPq is acknowledged (Grant number 307516/2022-9). This paper is one outcome of a long relationship with two physicists: Leonardo Costa Ribeiro (UFMG) and Américo Tristão Bernardes (UFOP). In the first half of 2023, at the Department of Economics, UFMG, Leonardo Costa Ribeiro and I organized a course on Complex Systems and Economic Theory – an opportunity for me to listen and learn even more from him. The ongoing research of Laura Soares and Bruno C. Melo for their dissertations and my academic interactions with them have also been permanent sources of learning for me. The usual disclaimer holds.

[1] This paper is a counterpart to Ribeiro (2022), which is a very clear article that summarizes Ribeiro's trajectory, at least since his Master's degree. It searches for complex systems and reaches a rich interpretation of how the global capitalist system was impacted in 2020 by a virus that caused a global recession and a sequence of events, captured by the different impacts on the rate of profits of countries, firms and sectors. Ribeiro's paper is an exposition of a physicist looking to the economy as a complex system. This paper is the attempt of an economist to look to physics and its lessons on complex systems.

permanent evolution and formed by a huge number of unities; 2) each unity interacts with others, the system is open and interacts with a broader environment; 3) each unit reacts to signs that it receives from others; 4) there is learning, the system is adaptive; 5) there is randomness; 6) there is emergent order, the system self-organizes; 6) the system is hierarchical; 7) there are multiple attractors (pp. 11-12).

From this very basic impression, this paper suggests that complex systems may be a useful tool to address "challenges for research in development" – the topic of this conference.

A specific challenge, within a broader program of research, is how to model the making of global capitalism, including its periphery as part of the whole process. A conjecture that underlies the research in which I have been participating is that the capitalist economy might have very peculiar properties as a complex system, properties that might become even more complicated as the topic of the periphery is included in the agenda.

In physics, the origins of elaboration on complex systems may be identified in the 1950s (Goldenfeld and Kadanoff, 1999, pp. 88-89), and the development of this field may be shown by the 2021 Nobel Prize. As a very recent development, complex systems have been increasingly explored and used in economics. Given a far-from-equilibrium dynamics, a plethora of nonlinear phenomena and fractal properties, it makes sense to establish a dialogue between economics and physics in this subject. And for research in development, this is a potential and fertile dialogue – the discomfort of the field of development with the constraints of equilibrium has very old roots (Meier and Seers, 1984; Meier, 1987).

This paper presents the approach that our research group is currently working on.[2] It is organized in five sections. The first section presents a short literature review, to give an idea of the size of the community of researches in economics that are currently exploring issues related to complex systems (or complexity) – and the mosaic of different approaches that connect complex systems and economic theory. The second section summarizes previous intuitions of classical political economy that anticipate elements of complex systems, reviews the emergence of complex systems in physics – and how evolutionary economics has learned and interacted with this new approach – and suggests one possible (and additional) form of dialogue between economics and physics around complex systems. The third section, based on this initial development, explores how an interpretation of economic long-term dynamic inspired by Kondratiev may, through a dialogue with Slutsky and Mandelbrot, be an avenue for research. The fourth section, based on preliminary results from the research agenda of our group, shows how, at the capitalist center, its dynamic uncovers a very peculiar complex system, as Goldenfeld and Kadanoff (1999) have suggested. The fifth section looks to the periphery of the capitalist system and investigates new specificities of complex systems in economics – preliminary steps for the inclusion of the periphery in our modelling effort. The conclusion resumes the reflection on the "challenges for research in development".

[2] The research group that has been working with topics related to complex systems includes Leonardo Costa Ribeiro, Américo Tristão Bernardes, Pedro Mendes Loureiro, Leonardo Gomes de Deus, Jorge Nogueira de Paiva Britto, Márcia Siqueira Rapini and Leandro Alves Silva. Important participants are graduate students supervised by those researchers, especially Bruno Carrara Melo, Laura Soares, and Lídia Magyar.

1. Literature review: complex systems and economic theory

The literature on complex systems, or complexity, and economic theory is huge and growing.[3] There are many forms to summarize the diverse strands of this literature. There are excellent papers dealing with complex systems as a chapter of the history of economic thought (Fontana, 2010). The interaction between physics and economics is two-way, as shown in a site organized by *Nature Physics Review* (2021): "from economics to physics". This series presents papers from Arthur (2021) and Hidalgo (2021) that show the diversity of approaches in this growing field.

Melo (2024) presents a very broad review, showing how different approaches in economics are building connections with complex systems. For example, Foley (2003) articulates classical political economy, from Smith to Marx, with complex systems; Cardoso and Lima (2008) articulate Keynes and complex systems, and evolutionary economics has many links to complex systems; and Elsner (2017) presents review on complexity.

For this paper, there is a special interest in the Santa Fé Institute, given its original objective to organize a dialogue between economics and physics (Anderson et al, 1988). Therefore, chapters prepared by Arrow (1988) and by Anderson (1988) are important references for the problems identified in economic theory then, and for the potential of complex systems to offer alternatives to equilibrium as an organizing concept for economics. The history of the Santa Fé Institute, as presented by Fontana (2010), has different phases related to different ways to deal with equilibrium and its constraints on economic theorizing.

The relationship between evolutionary economists and complex systems is an important chapter of this history. From the evolutionary economics side, there is Dosi (1997, p. 1531) suggesting building blocks of evolutionary economics and highlighting the need to understand aggregate phenomena as "emergent properties" – an explicit incorporation of concepts of complex systems in the theoretical foundations of evolutionary economics. From the side of the Santa Fé Institute, there is Arrow, who mentions Nelson and Winter (Arrow, 1988, p. 280) and "European students of the economics of innovation" (Arrow, 1988, p. 281); there is a reference from Anderson (1997, p. 566) to Dosi and Winter, who "have suggested evolutionary models of the economy", and there is a reference in Fontana (2010, p. 180) to a research group on technological innovation created at the institute in the 1988-1996 period, a group with Dosi, Malerba and Orsenigo.

Brian Arthur has a specific role, as he is an intersection between those two approaches since the late 1980s. He participated in two pioneering publications, as a contributor (Arthur, 1988a) to the book from the Santa Fé Institute, *The economy as an evolving complex system* (Anderson et al., 1988), and as a contributor (Arthur, 1988b) to the first book to organize the evolutionary approach, *Technical change and economic theory* (Dosi et al., 1988).

2. Intuitions from classical economists and the emergence of complex systems

The very synthetic literature review presented in the previous sections is enough to show how classical economy had intuitions on the complex nature of economies and those intuitions opened possibilities for dialogues explored by Foley, Cardoso and Lima, Dosi and the others. Louçã (2010,

[3] A search of the WebOfScience shows 1,065,903 results for "economics" (WC=economics), with 7,936 results if we focus the search on "complex systems" or "complexity" (TS="complex system*" OR TS=complexity). The search for "economics and complex systems" shows 776 results. One paper in this list is from participants in this conference: Robert and Yoguel (2016).

p. 105) explores those intuitions from Schumpeter and Keynes, and notes that "both were discussing complexity and yet they had not the tools to understand complexity". As indicated in the introduction of this paper and as presented in this section (see below), the development of these tools, in physics initially, is a post-1950s achievement.

These intuitions can be read in other interpretations. For example, Arthur (2021, p. 136) accepts this interpretation from Louçã (2010) and mentions "forerunners" and says his approach "owes much to earlier work by Thorsten Veblen, Herbert Simon and Friedrich Hayek".

The plurality of forerunners in the history of economic thought is not casual. Since economies, and more specifically capitalist economies, are complex systems, every researcher who was trying to understand their dynamics was seeing elements of them. Therefore, intuitions on complex systems are very common.

Adam Smith (1776) is certainly a thinker who reached diverse perceptions of elements of complex systems. One is an elaboration on positive feedbacks his classical formulation of the relationship between the market, the division of labor and wealth. As the division of labor developed, productivity and production increased, with an impact on markets that grew, a growth that made room for a further increase in the division of labor: the positive feedback between market size and division of labor. Another perception might be the fractal nature of the division of labor, as it began from one person doing the work that would be later divided among three others, and this division would be followed by further subdivision, a process that reproduces itself again and again.

Karl Marx (1867) also has elaborations that contains elements of complex systems. Examples may be his elaboration on how money transforms in capital, a process that reproduces itself again and again, in a fractal-like form. His elaboration on the role of super-profits and their relationship with new forms of production may be read as a simple rule that organizes the whole system, making the system undergo a mechanism of permanent change.

These comments on classical economy only suggest that the list of forerunners in the history of economic thought may be extended very broadly – a very interesting topic for further research.

The emergence of "tools to understand complexity" is a process that occurs after the 1950s. Nussenzveig's summary (1999) is supported by an agenda of research in physics that has its initial elaboration in the 1950s; this may be deduced from a short history of physical ideas presented in a special issue of *Science* dedicated to this topic. Goldenfeld and Kadanoff (1999), on "the development of complexity in physics" cite papers from 1952, written by Turing, from 1967 written by Katchalsly and Curan, and from 1972 written by Anderson. The influence and the importance of this field may be grasped by the Nobel Prize in Physics 2021, which was awarded "for groundbreaking contributions to our understanding of complex physical systems" (Nobel Prize Committee, 2021).

In a very simple definition, Goldenfeld and Kadanoff (1999, p. 87) write: "complexity means that we have structure with variations". Certainly, economies also fit this definition. However, the authors warn of differences in complexity, as "each complex system is different". Furthermore, they highlight the specificities "with complexity in biological or economic situations".

These comments provoke an important research question: how to investigate the peculiarities of complexity in economies? This question leads us to another economist who had intuitions on economies as complex systems: Kondratiev.

3. Kondratiev, Slutsky and Mandelbrot: superposition of cycles as evidence of a complex system?

Louçã (1999, p. 173) identifies the "resilience of the research program on long waves". He adds that, "more recently, in the entirely new framework of complexity theory, some others suggested that the long wave could be thought of as the representation of specific modes of entrainment of oscillations, emerging from the complex nature of economic processes" (p. 173). One author uncovered by Louçã is Mandelbrot (1987), who makes an explicit reference to Kondratiev. In the paragraph that Louçã (1999, p. 173) recommends to the reader, Mandelbrot (1987, p. 126) writes:

> For example, let an economic time series be generated by a stationary stochastic process *a* with a continuous spectrum and a smooth spectral density with no local maximum except for a pole at the frequency zero. Usually, the sample functions of such a process seem to exhibit long Kondriatieff-like cycles, upon which are superposed shorter cycles that recall ordinary business cycles, and so on down to short-period wiggles much like the speculative fluctuations.

Mandelbrot is a leading mathematician in this field of complex systems and, among his many seminal contributions, his investigations on economic dynamic are path-creating. His reflections on the specificities of economic dynamics are insightful for every researcher involved in complex systems research. One paper that could be very useful for our agenda is one in which he deals with nonperiodic cycles and evaluates the relationship between different processes: "Notably, economic time series tend to be characterized by the presence of clear-cut but not periodic 'cycles' of all conceivable 'periods', short, medium and long, where the latter means 'comparable to the length of the total available sample', and where the distinction between 'long cycles' and 'trends' is very fuzzy" (Mandelbrot, 1972, p. 260). In this paper, Mandelbrot mentions "pioneering remarks" by Adelman (1965) and Granger (1966): Adelman (1965) investigates long cycles using Fourier techniques,[4] and Granger (1966, p. 155) mentions "business cycles" of different amplitudes, from Kondratiev to Kitchin.[5]

Investigations on the superposition of different cycles may be traced to Kondratiev and the Moscow Institute of Conjuncture (Franco et al., 2022) – a line of investigation that might have been pursued by Slutsky while working there. In 1927, Slutsky published the first version of his classic paper on sources of cycles, research on how different cycles of different duration may compose broader cycles. Slutsky ([1927] 1937, p. 107) summarized this research question: "[t]he presence of waves of definite orders, the long waves embracing decades, shorter cycles from approximately five to ten years in length, and finally the very short waves, will always remain a fact begging for explanation".

As is well known, Kondratiev (1926) organizes his elaboration on long cycles by stressing the role of technical change as a source of those long-term fluctuations; "changes in technology" are a key determinant of those long cycles (p. 49). Schumpeter (1911) is among the references used by Kondratiev, showing that he had a formulation on how innovations were clustered and how the discontinuous nature of innovation is related to the cyclic patterns in capitalist economies. Possibly following that line of thinking, Kondratiev always lists different innovations as the technical changes behind each long cycle, innovations spread over a relatively long period of time. In the first long cycle, Kondratiev mentions "a series of significant technical inventions" introduced between 1764 and 1795, for the second long cycle he lists 19 inventions between 1824

[4] In the discussion of "empirical results", Adelman (1965, pp. 459-460) concludes that "[t]he evidence of the present spectral analysis is not at all inconsistent with certain other observations on the existence of long cycles".
[5] Granger (1966, p. 150) suggests that "power spectra" may be the "typical shape".

and 1848, and for the third long cycle there are 25 inventions between 1875 and 1898 (Kondratiev, 1926, pp. 39-40).

Each of those different innovations may interact among each other, giving rise to a superposition and an overlapping of different economic impacts that shape the larger waves. This type of overlapping is described by Rosenberg (1998, p. 180) in the context of the fourth long wave, from a theoretical approach related to the concept of general-purpose technologies (GPT): the rise of chemical engineering as a GPT is part of the growth of the automobile industry, being "inseparable from the history of petroleum refining" (ibid.). This type of overlapping has strong positive feedbacks that might compose a peculiar summation of technological causes in the making of economic cycles.

The elaboration of Kondratiev has important influence, starting with Schumpeter (1939) and reaching contemporary debates with Louçã (1999) and Freeman and Louçã (2001). Kondratiev's elaboration, beyond the ramification through Slutsky and Mandelbrot, has another influence on the approach to complex systems: Perez (2002, 2010) reinterpreted the roots of long waves and suggested a didactical tool to understand the influences of important and radical innovations – the big bangs at the root of each long wave. Arthur (2015, pp. 17-22), discusses how each technological revolution impacts the whole economy; "the economy in formation" is the title of this section and it makes an explicit reference to Carlota Perez, a reference that is repeated in Arthur (2021, p. 141). Arthur presents an "algorithm" that describes a "sequence of events" that transforms the whole economy.[6] This "sequence of events" involves, inter alia, various positive feedbacks among different and complementary technologies.

4. Capitalism, at the center, as a very peculiar complex system

As classical political economists (Smith, Marx), Kondratiev and Schumpeter, and evolutionary economists have put forward, capitalism – in its various structures and phases – is a system in permanent change. Furtado (2002) summarizes this understanding: metamorphoses of capitalism.

Metamorphoses of capitalism may be understood as multidimensional processes of institutional change, as new products, new processes, new firms, and new institutions appear and renew the system. All component institutions of modern capitalism change, driven by the relationship between innovation and profit, a key relationship that organizes the whole systems; here, it is the engine of self-organization in capitalism, a consequence of that dynamic at the heart of the system.

In this dynamic there is a combination between growth, new and more firms, and new markets – with changes in their overall dynamics – that makes the system different; "more is different" (Anderson, 1972) and more complicated (Arthur, 2015, pp. 144-157).[7]

Crises are part of the system´s dynamic, crises of adjustment (Freeman and Perez, 1988), moments of the system's transformation. The system is "robust" in the sense that it does not collapse, but after each crisis it resumes growth transformed. After each crisis, there are new institutions and new rules, leading to different phases and different varieties of capitalism over time: metamorphoses of capitalism.

[6] Possibly the first "algorithm" to describe a technological revolution starting at one single point and developing through forward and backward linkages to transform the whole economy was presented by Marx (1867, pp. 505-506).

[7] Although Arthur discusses the growth complexity over time, Ribeiro et al. (2017b) suggest that he is talking about complication, meaning "diversity" or "structural deepening".

These lessons from the history of economic thought originated the first investigations of our research group, focusing on the leading capitalist country, the United States (Ribeiro et al., 2017a, 2017b). The investigation on the USA begins with data from 1870, approximately the time when US GDP overtook British GDP (MPD, 2020). This focus, which helps to understand the dynamic of a leading capitalist country, misses one important feature: the US economy began assimilating technology and knowledge available from the leading country (Hamilton, 1791). The leadership of this complex system called capitalism is not static: the US had a long transition from imitation to innovation (Rosenberg, 1972). The previous leading country, the UK, also had a lengthy transition to hegemony, one that included a long process of learning from India, especially in textiles (Beckert, 2014, pp. 49-50). These comments highlight the fact that the interpretation of the development of countries, even developed countries, cannot be made in isolation. This is an important issue for the modelling strategy of our research group: how to include countries and the knowledge flows among them.

The data used in our investigation were prepared by Duménil and Lévy (2015), for the period between 1870 and 2010. The data on the rate of profit for the US were analyzed through analytical tools widely used in physics – the Fourier transform – to investigate their behavior in the long term (Ribeiro et al., 2017a). The rate of profit is a synthetic variable that can be interpreted as a key indicator of the overall behavior of the capitalist system, as it is a "synthesis of multiple determinations". Under an average profit rate, there is a turbulent process that involves a large population of firms with their individual profits, or losses, which aggregate as different rates of profit according to different economic sectors and industries (Bain, 1956; Schmalensee, 1989).

These data cover a long period, with important structural changes in the US economy, the country from which three big bangs have originated (Perez, 2010, p. 190): in 1882, electricity (Edison's Pearl Station); in 1908, the automobile (Ford's model T); in 1971, the microprocessor (Intel). The important structural changes are: the emergence of the multidivisional firm between the 1870s and the 1920s (Chandler, 1977); the transformations caused by changes during the First World War and after (Langlois, 2023, pp. 101-132); the Great Depression and the New Deal (Langlois, 2023, pp. 186-263); the Second World War (Langlois, 2023, pp. 264-314); and the subsequent transformations during the "Cold War" (Mowery and Rosenberg, 1993).

The application of Fourier techniques to investigate the long-term behavior of the US rate of profit uncovered three findings.

The first finding, as expected, is the identification by the Fourier analysis of the fingerprints of a complex system: the "power law regression" showing that the "profit rate curve is a fractal" and a $1/f^{\alpha}$ distribution (Ribeiro et al., 2017a, pp. 294-295).[8] These results from the Fourier analysis show that capitalism, at the center, is a self-organized system.

The second finding might contribute to discussions of long waves in capitalist development, as the analysis using the Fourier transform shows a more turbulent behavior in the cyclic dynamic of the US economy than the 50-year Kondratiev cycle or Schumpeter's three-cycle – combining 50-, 10-, and 3-year cycles. Ribeiro et al. (2017a, p. 296) show that there is an overlapping of cycles of many different frequencies, the more important being the 23-, 20-, 35-, and 70-year cycles.[9] Still more important than the 47-year cycle are many shorter cycles, with frequencies below 20-years. This second finding is very relevant for our research agenda, as it renews the interest in Slutsky's elaboration on cyclic patterns caused by the superposition of different oscillations.

[8] See Ribeiro et al. (2017a, figure 1, p. 294, and figure 2, p. 295).
[9] See Ribeiro et al. (2017a, figure 3, p. 295).

The third finding confirms the conjectures of Anderson (1972) and of Goldenfeld and Kadanoff (1999) on the peculiarities of complexity in economies. Ribeiro et al. (2017b) investigate if the levels of complexity in the US economy are the same in different periods. Using a technique that employs moving 50-year windows, the analysis through the decomposition of the Fourier transform shows that the exponents of the power law regression change over time.[10] These changes in the power-law exponents "indicate changes in the complexity of the system" (Ribeiro et al., 2017b, p. 56).[11] This third finding shows the very peculiar nature of capitalism, at the center, as a complex system, differentiating it from other levels: complex systems in the physical world do not show this property – at least, so far we have not found references that show changes in the level of complexity in complex systems of the physical and biological realms.

These three findings, related to the nature of complexity in a capitalist system at the center – the US capitalism – put forward new questions. One is about the self-organized nature of capitalist dynamics at the periphery. Another is about the nature of pre-capitalist economies: were they self-organized?

The first question was investigated by Cimini et al. (2020), using GDP per capita data from the Maddison Project Database to compare countries at the center (the US, Canada, Western European countries, Japan, Australia and New Zealand) and countries at the periphery (Latin American countries and India). Cimini et al. (2020) applied an analysis based on Hurst exponents, finding that "the Hurst exponent can separate the central countries from Latin America plus India" (p. 1243).[12] This result means that the trajectory of an economy at the periphery "tends to be quite random in the short-term" (p. 1252).

The second question is the finding of Melo (2023), that using data on wheat prices in the UK has found evidence of a transition from a random pattern to a self-organized pattern around the time of the industrial revolution.

These two preliminary findings on the behavior of the system before capitalism and at the periphery put forward the need to further investigations on the nature of the global system.

5. How to include the periphery

The inclusion of the periphery in an investigation on the global dynamics of capitalism – a complex system with peculiar features – may start with a suggestion of a theoretical framework, based on a dialogue among Kondratiev (1926), Furtado (1987), and Cohen and Levinthal (1989),[13] and a subsequent systematization of historical information and some preliminary data.

Kondratiev (1926), as presented in section 3, is a starting point. On the one hand, his elaboration places innovation as a determinant of long cycles. On the other hand, he articulates those technological changes with the inclusion of new regions in the global system (1926, p. 49); changes at the center are connected with the expansion of the whole system. Furtado (1987) adds to this theoretical framework a consequence of the first technological revolution – the industrial

[10] See Ribeiro et al. (2017b, figure 3, p. 55).

[11] These changes in the level of complexity, measured by changes in the power-law exponents, show that the complexity of the system was lower in the first and the last time intervals. However, during the whole period covered by the data analyzed in Ribeiro et al. (2017b) the US economy became more diversified, with more structures, more wealth, more firms, more institutions, and new layers of markets – in sum, a more complicated economy. Although more complicated, the self-organization process is capable of dynamically adjusting the whole system, a process that explains these changes in complexity.

[12] See Cimini et al. (2020, figure 7, p. 1243, and figure 8, p. 1244).

[13] This theoretical framework is presented in Albuquerque (2023, chapter 1).

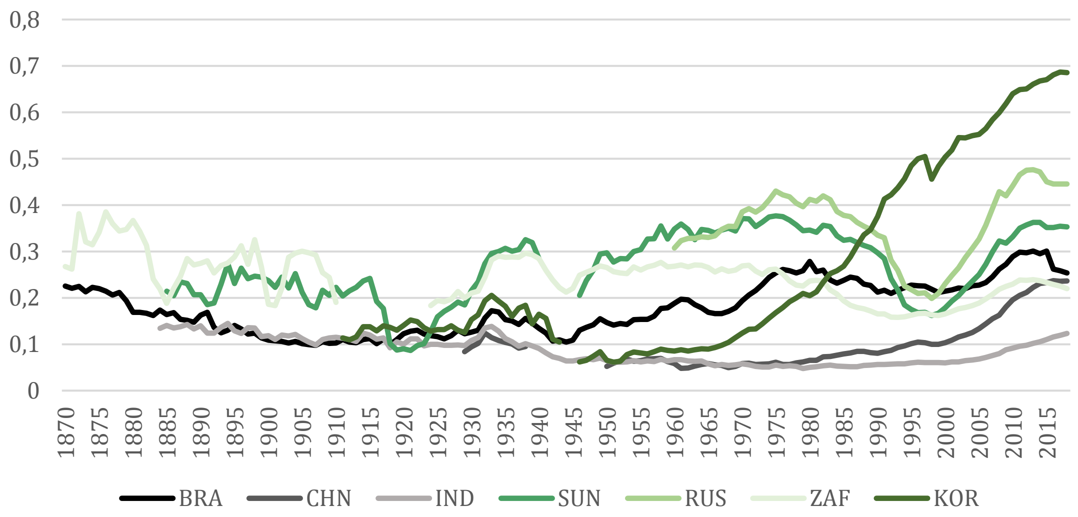
revolution – which is the reconfiguration of the center-periphery divide, a contribution to understanding the specificities of the economic dynamic at the periphery. Furtado (1987) stresses the lack of endogenous technological change at the periphery. Cohen and Levinthal (1989) bring to this theoretical framework their concept of absorption capacity, a key element for countries and regions outside the center to learn and to assimilate technology and knowledge generated abroad. The institutional bases for the creation of absorptive capacity at the periphery are processes of formation of innovation systems (Nelson, 1993).

This dialogue between the elaborations of Kondratiev, Furtado, and Cohen and Levinthal leads to a synthesis that identifies the interplay between expansionary forces emerging from the center and assimilatory forces created at the periphery as a driver of global dynamics.

This interplay defines turbulent patterns that show further evidence of capitalism being a peculiar complex system, an even more complicated system vis-à-vis its dynamic at the center.

The contemporary periphery is heterogeneous – one dynamic feature of this interplay between expansionary and assimilatory forces during the 20th century is the increase in its heterogeneity (Chaves et al., 2020). For the discussions of this section, which countries and regions could be considered to be at the periphery? Figure 1 presents data for 1870 to 2018 from the Maddison Project Database (MPD, 2020) on the income gap of selected countries vis-à-vis the leading country, the United States. From 1870, all countries presented in figure 1, with the exception of South Korea,[14] could be considered to be in the income traps – or the historical trap that is underdevelopment (Furtado, 1992, pp. 37-59).

Figure 1 – *Income gap between USA and selected countries, defined as US GDPpc/country i GPPpc, India, China, former Soviet Union, Russia, South Africa, South Korea, and Brazil, 1870-2018*



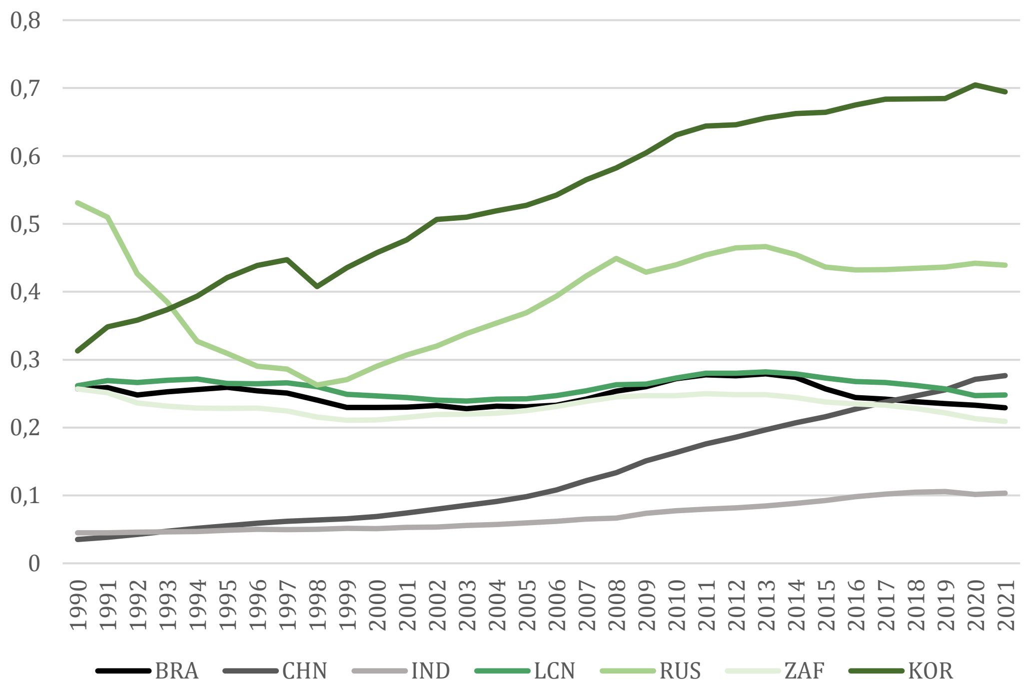
Source: MPD (2020).

[14] The South Korean catch-up has been well discussed by Amsden (1989) and Lee (2013, 2019).

Figure 1 shows that the results for India, China, Russia (or the former Soviet Union, with a longer availability of data from the Maddison Project), South Africa and Brazil,[15] from 1870 to 2018, oscillate, with ups and downs below the threshold of 43% of US GDP per capita (*The Economist*, 2023); Russia, with 44% of US GDP per capita in 2018, would be at that threshold, a situation mentioned by *The Economist* (2023).

Figure 2 uses data from the World Bank for 1990 to 2021, including data on Latin America, to show that the region is near the Brazilian position, slightly above and with very similar movements.

Figure 2 – *Income gap between USA and selected countries, defined as US GDPpc/country i GPPpc, India, China, Russia, South Africa, South Korea, and Brazil, 1990-2021*



Source: World Bank (2023).

These two figures introduce the countries/regions evaluated in this section, based on previous work (Albuquerque, 2023), where India, China, Russia, Sub-Saharan Africa and Latin America are investigated to understand some elements of the propagation of technological revolutions throughout the periphery, a dynamic that is shaped by the interplay between expansionary and assimilatory forces (Albuquerque, 2023, chapter 8).

[15] A discussion focused on the ups and downs of the data on Brazil, interpreted as a long oscillation between periods of limited catch-up (ups) and limited lagging behind (downs), is presented in Albuquerque (2019b). Similar investigations connecting the economic history of different countries with those series shown in figure 1 would be very interesting.

The interplay between expansionary and assimilatory forces can be summarized using as a starting point Carlota Perez's systematization of the five big bangs that triggered technological revolutions (Perez, 2002, p. 11; 2010, p. 190). Additionally, a sixth big bang is suggested – the invention of WWW or the World Wide Web in 1991 (Albuquerque, 2019a). Each big bang triggers initial movements of expansionary forces emanating from the center. The arrival of each technology of these six big bangs at the periphery is dependent on the assimilatory forces created in its five different countries/regions, a foundation of the uneven propagation of technological revolutions through the global system – and a source of the increasing heterogeneity of the periphery.

The interplay between expansionary and assimilatory forces is discussed in a previous work, *Technological Revolutions and the Periphery* (Albuquerque, 2023), an elaboration presented in chapter 8, based on systematization presented in chapters 3 to 7. Each chapter investigates one big bang and how it spread throughout the five regions of the periphery. Table 8.1 in chapter 8 (Albuquerque, 2023, p. 194) summarizes those findings.

That table complements Freeman's scheme (1987, pp. 69-75), which describes the main characteristics of each long wave and adds new information: the arrival of the radical innovations related to each big bang (Perez, 2010) in the periphery. Table 8.1 investigates 5 different regions: India, China, Russia, Sub-Saharan Africa and Latin America. Thus, Table 8.1, a matrix with six rows corresponding to technological revolutions and five columns relating to the five regions, informs the date of arrival of the innovation in each region, in addition to presenting an indicator of its initial diffusion intensity.

The table highlights how the propagation of these technological revolutions and the inclusion of new regions in the global system are processes that add new elements of turbulence to the global economic dynamic.

First, the propagation of technological revolutions is not instantaneous. On the contrary, there are important – and long – time lags in this diffusion. These time lags differ among the five regions/countries, and they also show differences according to each technological revolution.

Second, the arrival order of these technological revolutions at the periphery does not follow the same sequence of the big bangs at the center. As illustrated by the cases of India and China, the second big bang – the railways – reached them earlier than the first big bang – textile mechanization.

Third, assimilatory forces are the main drivers of those arrivals. Given the sensitivity of these forces to political institutions, complicated chains of events are behind the creation of preconditions for assimilation. These processes are related to institutional building – to formation of national innovation systems – at the periphery, and further illustrate the limitations of pure expansionary forces to diffuse new technologies.

Fourth, the initial operation of assimilatory forces impacts the operation of expansionary forces, changing the way that technologies propagate. This phenomenon is illustrated by the first movements of local initiatives to install textile machines, initiatives that strengthened the machine-producing industry of the UK, originating changes at the center that moved the country from exporting textile goods to exporting textile machinery.

Fifth, since the initiative to reconfigure the international division of labor comes from the region that is the technological leader (Furtado, 1987, p. 219), the role of countries/regions at the periphery is rearranged under that external pressure; the timing of the introduction of different innovations is a product of the dynamics at the center, as discussed in sections 3 and 4. This hierarchical dynamic is translated to a peculiar form of propagation through the periphery. On the one hand, once new assimilation processes begin – by definition, with some time lag– there might not be time enough to allow a more complete diffusion of an older technology. For example, in 1909, a year after the big bang of the automobile industry, the diffusion of textile machinery – measured by the number of spindles – was very limited in all five countries/regions, with a large gap vis-à-vis the UK. The region that came closest to the UK, Russia, had only 15% of the UK's stock of spindles (Albuquerque, 2023, p. 194). During the initial process of assimilation, a newer technology may emerge that can result, on the other hand, in different superposition of different technologies, in different combinations of different technologies – foundations for different varieties of peripheric capitalism.

Sixth, as assimilatory forces develop at the periphery, new reconfigurations of the international division of labor take place – another form of delayed interaction between expansionary and assimilatory forces.

Seventh, the perturbations emanating from the technological revolutions at the center, seen as exogenous to peripheric countries/regions, may be one source of the random patterns found by Cimini et al. (2020). The systematic shocks coming from abroad, rearranging the role of peripheric countries in the international division of labor while still processing older technologies, may define the random nature of economic processes at the periphery.

Eighth, the resulting overall picture that combines the dynamic at the center and at the periphery – a global dynamic of a global system – that seems to be self-organized as a whole, apparently has parts – important parts – that follow a random pattern of economic behavior.

6. Conclusion: preliminary steps for the inclusion of the periphery in a simulation model

Our research effort has prepared three initial simulation models to investigate the capitalist dynamic. In this line of investigation, our group follows the methodological advice from Nelson and Winter (1982); commenting on "the nature of fruitful theorizing in economics", they suggest a combination between "appreciative theory" and "formal theory", as improvements on one side may contribute to better understanding on the other side (Nelson and Winter, 1982, pp. 45-47).[16]

Three steps have been taken so far in the preparation of simulation models.

The first (Ribeiro et al., 2017a) is a model built following Marx's insights on the long-term behavior of the rate of profit (Marx, 1894, section III). In Marx's elaboration, there are three moments, each transformed into a chapter in Engel's edition. The first shows the operation of forces that push the rate of profit down, the tendency of the rate of profit to fall; the second witnesses the operation of forces that pull the rate of profit up, counter-tendencies to the fall of the rate of profit; and the third introduces the simultaneity of the operation of tendency and counter-tendency. These insights from Marx were transformed in a system of equations, which is the basis of the simulation model. Running the simulation model, we got results that replicated the behavior of the rate of profit in the US economy (Ribeiro et al., 2017a, pp. 300-301).

The second model (Ribeiro et al., 2017b) introduces technological revolutions in the system, through an automatic introduction of nodes – representing new technologies – after 10,000 steps in the simulation process. This model was able to replicate the dynamic of the rate of profit in the US economy (Ribeiro et al., 2017b, p. 59) and also replicate the changing levels of complexity captured through the Fourier transform (Ribeiro et al., 2017b, p. 60).

The third model concludes the effort related to developed countries, with a preliminary exploration (Ribeiro et al., 2018) that basically endogenizes the trigger of technological

[16] The research that led to the book *Technological revolutions and the periphery* is my contribution, from the side of "appreciative theory", to the collaborative effort of our group.

revolutions. The strategy for this modelling, which has support from different approaches in the literature (Schumpeter, Mensch, Langlois), is based on the understanding of innovation efforts as reactions to big problems and adversity, expressed in the fall of the rate of profit. This third model introduces a triggering mechanism that is activated every time that the rate of profit falls consistently.

After these three models, which focus only on the center, our group plans to start the preparation of models that include the periphery. In a workshop in CEDEPLAR (3 April 2023), Leonardo Costa Ribeiro presented preliminary thoughts on how to combine a self-organized system at the center with a random system at the periphery. This initial combination would feed another model that explores how a transition from a random behavior to a self-organized pattern could take place.

Given the very peculiar operation of global capitalism, which is apparently a complex system that has a dynamic center operating with self-organized properties and a periphery with random patterns – possibly because it is permanently undergoing perturbations that emerge from the center – these new models would help to translate the "appreciative theory" summarized in section 5 to "formal theory" in new simulation models. This research question is our specific "challenge for research in development".

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