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CHANGING LEVELS OF SELF-ORGANIZATION: HOW A CAPITALIST ECONOMY DIFFERS FROM OTHER COMPLEX SYSTEMS*

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SUMÁRIO

ABSTRACT

This paper investigates the specificity of a modern capitalist economy as a complex system. This investigation is based on a review of the literature to understand complexity in the physical and biological worlds, to learn the bases of complexity and self-organization, and to locate the tools used to identify and measure them. An economy has different layers and levels of organization, based upon human beings, agents that think, have intentions and change all the time. This paper presents a new model to replicate the workings of a capitalist economy that endogenizes the introduction of innovations and institutional change, and it runs a simulation. The analysis of those results indicate that a modern capitalist economy is a complex system, and that this complex system changes its level of self-organization over time. This finding highlights the peculiarity of a capitalist economy vis-à-vis other complex systems.

RESUMO

Este artigo investiga a especificidade de uma economia capitalista moderna como um sistema complexo. Esta investigação baseia-se em uma revisão da literatura para compreender a complexidade nos mundos físico e biológico, aprender as bases da complexidade e da auto-organização e localizar as ferramentas utilizadas para identificá-las e medi-las. Uma economia tem diferentes camadas e níveis de organização, baseados em seres humanos, agentes que pensam, têm intenções e mudam o tempo todo. Este artigo apresenta um novo modelo para replicar o funcionamento de uma economia capitalista, modelo que torna endógena a introdução de inovações e mudanças institucionais. A análise dos resultados de uma simulação indica que uma economia capitalista moderna é um sistema complexo e que esse sistema complexo muda seu nível de auto-organização ao longo do tempo. Esse achado destaca a peculiaridade de uma economia capitalista em relação a outros sistemas complexos.

Key words: rate of profit; technological revolutions; Marx; complex systems; metamorphoses of capitalism; simulation models.

JEL Codes: P160, O33, B510.

INTRODUCTION

Changing levels of complexity is a property that a capitalist economy has as a self-organized system. This property differentiates a capitalist economy as a complex system from other natural complex systems (i.e., physics, biology). This is the main finding of this paper, which is investigated through a new model of a capitalist economy as a complex system.

Our investigation is based upon conjectures put forward by Goldenfeld and Kadanoff (1999) and by Kaufman (1995). Goldenfeld and Kadanoff (1999) suspected that "complexity in biological and economic situations" would be different from the physical laws (1999, p. 87). Kaufman (1995) differentiates the biological and the technological evolutions: self-organization may be part of the explanation of evolution - from the first molecules to our species, with our brains - but those biological processes lack something specifically human: intentionality (1995, p. 192).[1]

The dialogue between the physics of complexity and economics has helped the economic discipline to understand our subject (Arthur, 1999), and it is one of the building blocks of an evolutionary economics (Dosi, 1997, p. 1531). Is this dialogue helpful for physics too? Is there a contribution that investigations in economy might help the understanding of complexity in general, given its (capitalist economies) peculiarities?

One key property of complex systems is the presentation of different organizations for different levels. The modern capitalist economy is the most sophisticated economic system created so far. It is composed by human beings, that are organized in households, firms, banks, governments, in a mosaic of institutions, in countries, that have different roles, that interact in networks. However, the properties of the economy as a whole are different from the properties of each of its components - firms, humans as consumers and producers, governments, etc. - in an analogue way to how properties of a cell are different from properties of the molecules that compose them. Furthermore, it shows a peculiarity, because it can be understood as a complex system based upon other complex systems - human beings with our brains, we are made of organs, organs are made of tissues, tissues are made of cells, cells are made of molecules, molecules are made of atoms. In other words, the basic component of an economic system – i. e., human beings – is also a complex system.

Our modelling is a tool to investigate the properties of the economy (capitalist economy) as a whole, as a complex system. We propose a new model that endogenously generates changes as specific economic conditions (a deep fall in the rate of profit) trigger innovations or institutional change that reshape the system. This model may help to evaluate the specificities of a capitalist economy vis-à-vis other natural complex systems.

This paper is organized in five sections. The first section reviews the literature on complexity to provide the context for our question - what is the specificity of a capitalist economy as a complex system, vis-à-vis the physical and biological worlds. The second section presents the theoretical background of our interpretation of a capitalist economy as a complex system. The third section introduces our new model and runs simulations. The fourth section uses the results from those

[1] Marx (1867, p. 284) stressed this difference: "...what distinguishes the worst architect from the best of the beesis that the architect builds the cell in his mind before it constructs the cell". According to Marx, "this is a purpose that he is conscious of".

simulations to investigate properties of a capitalist economy as a complex system. The fifth section concludes this paper highlighting what is peculiar to this complex system and discusses reasons and implications of this finding.

I. REVIEW OF THE LITERATURE: COMPLEXITY

I.1. Complexity as a Branch of Science

Complexity as a branch of science has a history. The origins of this branch can be grasped in a special issue of *Science* on complexity, where Goldenfeld and Kadanoff (1999) cite the pioneer studies of Turing (1952), Lorenz (1972), Anderson (1972), Mandelbrot (1977), Bak et al (1988) and Kaufman (1995). In 1995, there was also the launching of a new journal, *Complexity*, to work with this new line of research.

For Goldenfeld and Kadanoff (1999, p 87) "complexity means that we have structure with variations. Thus, a living being is complex because it has many different working parts, each formed by variations in the working out of the same genetic coding..... A complex world is interesting because it is highly structured".

Complexity is very widespread, as "[n]ature can produce complex systems even in simple situations, and can obey simple laws even in complex situations" (Goldenfeld and Kadanoff, 1999, p. 87).

Goldenfeld and Kadanoff (1999, p. 87) stress differences between physics and biology and economics. They talk about physicists: "[n]ature has been kind enough to have provided us with a convenient separation of length, energy, and time scales, allowing us to excavate physical laws from well-defined strata, even though the consequences of these laws are very complex. But we might not be so lucky with complexity in the biological or economic situations" (p. 87).

Kaufman (1995) "search for the laws of self-organization and complexity" basically in the world of biological evolution. In this world, Kaufman identifies the cell as a non-equilibrium system (p. 21), and all free-living systems as non-equilibrium systems (p. 21). This evaluation is in line with Gell-Mann (1994, p. x) for whom the jaguar "exhibits an enormous amount of complexity, the result of billions of years of biological evolution".

Kaufman stresses the role of self-organization for evolution (p. 19): “the origin of life as a collective emergent property of complex systems of chemicals”.

In the special issue of *Science* on complexity there is an article on nervous system, in which Koch and Laurent (1999, p. 96) stress how brains are complex systems and describe their complexity. Barabasi (2016) describes the brain as a network. Singer (2009) also describes brains as complex systems, highlighting their peculiar evolution: the role of neurons and of interaction with other brains (Singer, 2009, p. 328) - the evolution of brain is part of human evolution.

This evolution took long time, and those time-spans are important for our argument, as the speed of evolution matters for complexity in a modern capitalist economy. There is a slow and protracted evolution from the first particle to the first living organisms: first particle (10^{-32} seconds after the big bang - that was 13.7 billion years ago), first atomic nucleus (between 3 to 20 minutes after the big bang), first molecule (4 billion years ago), first living organism (3.5 billion years ago). Then, again, a slow evolution from those first living organisms to the first modern human being: first unicellular being (3 billion years ago), first eukaryotic cells (2 billion years ago), first pluricellular being (1.2 billion years ago), first *homo sapiens* (200,000 years)[2]. Those long time periods may be compared to the very short term of a modern capitalist economy - since the industrial revolution, there have only been 250 years. Those different speeds of change in systems organization are important clues to differentiate human society - and a capitalist economy - vis-à-via the physical and biological realms: the speed of changes. As we will see, under a capitalist economy its organization changes all the time.

The speed of changes might be related to a difference between human evolution and evolution in the physical and biological worlds, as Kaufman puts forward: human artefacts are products of intentional acts (1995, p. 192) - and human evolution is consequence of those acts.

I.2. Diversity, Variety, Structural Layers Of Organization: complication and complexity

A very important issue is how to evaluate changes in the level of complexity and self-organization. Arthur (2015, chapter 9) discusses "the evolution of complexity", reviewing biological evolution and commenting on a difference between complication and complexity (p. 145). Arthur suggests three mechanisms for the increase of complexity over time: diversity, structural deepening and capturing software. This chapter by Arthur is based on a paper from 1994 (p. 144), and since then the difference between complication and complexity, in physics, has been clarified. For our paper, to clarify this difference is important, because we will deal with complexity in a way that a system can become more complicated but not necessarily more complex (or more self-organized).

Over time, definitions of complexity have been developing, as Koch and Laurent (1999, p. 96) put forward: "[o]nly a decade ago, 'complex' simply meant made of many interrelated parts (the word derives from 'braided together'). Within mathematics and the physical sciences, the term 'complexity' has recently acquired a number of narrower but technical definitions". Their reference is a book from M. Gell-Mann (1994).

Gell-Mann (1995, p. 17) tries to explain what complexity is, providing clues for its differentiation from complication: "[e]ffective complexity can be high only in a region intermediate between total order and complete disorder". Gell-Mann (1995, p. 18) stresses the difference between "logical depth" and "effective complexity", highlighting that "[a]s the universe grows older and frozen accidents pile up, the opportunities for effective complexity to increase keep accumulating as well. Hence there is a tendency for the envelope of complexity to expand, even though any given entity may either increase or decrease its complexity during a given time period" ... "Different entities may have different potentialities for developing higher complexity" (p. 19).

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[2] Those aproximate dates are suggested by an exposition - *Origins* - *Espaço do Conhecimento*, UFMG (http://www.espacodoconhecimento.org.br/extratos-do-tempo-2/). Information on the first molecule from *Scientific American*. (https://www.scientificamerican.com/article/life-rsquo-s-first-molecule-was-protein-not-rna-new-model-suggests)

As a physicist, Gell-Mann's time horizon for those movements in the level of complexity is very broad: "[i]f, in a very distant future, virtually all nuclei in the universe decay into electrons and positrons, neutrinos and anti-neutrinos, and photons, then the era characterized by fairly well defined individual objects may draw to an end, while self-organization becomes rare and the envelope of complexity begins to shrink" (p. 19). Billions of years?

Other definitions of complexity and its origins adds new dimensions for its investigation: according to Schuster (2016) "[m]ost scientists will characterize complexity as the result of one or more factors out of three: (i) high dimensionality, (ii) interaction networks, and (iii) nonlinearity. ... Apparently, just one of the three factors in pure form is often not sufficient for complex features but in general additional criteria or combinations of two or more factors will do" (p. 7). For a diagnosis of the origins of complex behavior "[t]he most significant feature is weak predictability or unpredictability of future behavior" (p. 7).

Additionally, for Schuster (p. 7) "[a]nother feature of complex systems that can be easily diagnosed is the seeming lack of causal relations" For Schuster, "[w]e are accustomed to one dimensional causality in everyday life: We detect a failure and doing repair is targeted directly to removal or compensation of this particular defect. Observation and manipulation of ecosystems provided presumably the first clear evidence for 'network causality'. Repairing one defect may result in failures at some other sites, and in most cases there is no other general remedy than restoring the initial conditions. At present one most disputed lack of simple causality comes from pharmacology: There is no drug without side effects because the metabolic networks are highly complex". (pp. 7-8).

Finally, other origins of complexity: "lack of knowledge, lack of proper methods in problem solving, and embedding of a simple system in a complex environment" (p. 8).

In sum, beings may be more complicated but not necessarily more complex. More parts, more components, more variability, more diversity mean more complication, but not necessarily more complexity. Arthur (2015, chapter 9) discusses complication - more diversity, more variety, more layers, more functions, more organs -, focusing especially in biological evolution - that does not imply necessarily in more complexity.

To understand this differentiation is important as a precondition to evaluate changes in the level of complexity and self-organization.

I.3. How to Identify Complexity?

A system or problem is complicated if it is difficult to solve, but in general it can be split into small parts which are them solved independently or through small alterations of simpler systems/problems – perturbation theory. Complex systems are in turn formed by many interacting components and exhibit different organisations at different scales of observation, which lead to different behaviours at different scales (Goldenfeld and Kadanoff, 1999). In those systems, different scales of organization contribute differently - and unpredictably - to the global behavior of the system.

Technically, the identification of complexity and self-organization begins with the analysis of the functions that describe the phenomenon under investigation. A Fourier Transformation (FT) decomposes a function into is constituent frequencies. In more details, the transformation writes the original function as an infinite sum of other periodic functions (cos(...) + *i* sen(...)), each which a different period/frequency, until it sweeps all possible periods/frequency. This kind of decomposition might have implications for debates on long waves research, as a possible quantitative methodology (mathematical tool) to measure their duration and periodicity.

This decomposition of frequencies (through FT) that produces the behavior profile of a large variety of different evolutionary systems at low frequencies exhibits a Power Law 1/f relation. This 1/f behavior has been observed in wide range of systems, such as: condensed matter system, river discharge, DNA base sequence structure, cellular automata, traffic flow, economics, financial markets and other complex system with the elements of self-organization (Gontis et al, 2004; Gilden et al, 1995; Wong et, 2003; Kaulakys et al, 1998; Yamamoto et al, 1995; Maxim et al, 2005). Commonly, some parts of such systems are fractal and their statistics exhibit scaling. This universality of 1/f behavior suggests that it does not arise as consequence of a particular interaction, but it is a characteristic signature of complexity and self-organization (due to the contribution of different scales organization to the global behavior of the system).

There are diverse self-organized systems. One of the most popular is the sandpile model (Maslov et al, 1999; Bak et al, 1988, Bak and Chen, 1991). This nonlinear model was introduced also for explanation of 1/f noise as result of the self-organized criticality. The great interest of research in this direction is related with the complex behavior that mimics a noise with fractal characteristics. In this model the noise, however, is originated from the nonlinear deterministic interactions.

It is also possible to define a stochastic model system exhibiting fractal statistics and 1/f noise. Furthermore, explaining the evolution of the complexity into a chaotic regime, the stochastic processes may be used for description of phenomena that occur as random sequences of events, exhibiting scaling of several statistics (Thurner, 1997). Considerable part of real stochastic sequences of events in physics, biomedicine, geophysics and economics are fractal (Kaulakys et al, 1998; Kaulakys et al, 1999; Gontis, 2001; Gontis, 2002).

The way to identify a Complex System comes from this definition because when the decomposition of frequencies is analyzed the contribution of different scales of the system to its overall behavior can be quantified. If a relation of 1/f is found for this decomposition, it is because there are relevant contributions of all scales to the overall system behavior. In this case, the correlation length of the system diverges – becomes as large as the whole system, i.e. the system behavior is defined by the behavior of each element, so perturbations on very few elements causes chain effects on its neighbors that changes the behavior of whole system. This way, it creates the huge variety of possible behavior the complex systems show.

I.4. How to Measure Complexity and its Variations?

The main interest here lies in the movement of the power law (PL) exponent, which conveys information about the complexity of the system. The PL exponent, as discussed in previous section, indicates the complex behaviour, so, it can be used to quantify the level of complexity. When the exponent is equal to -2, the analysed behaviour corresponds to Brownian motion, which is a random pattern of motion (Ivanova et al, 1999; Govindan et al, 2001; Costa et al, 2003). Therefore, as the exponent approaches -2 the system's behaviour becomes growingly random, i.e. it shows less self-organisation (control). Random fluctuations become more common, and the temporal correlation decreases. With increases in the PL exponent the system thus has a higher probability of randomly breaking with the previous behaviour. On the other hand, when the exponent approximants to 0 the analysed behaviour goes to a linear one, i.e., by becoming quite predicable therefore non-complex (Ivanova et al, 1999; Govindan et al, 2001; Costa et al, 2003).

Those are the tools that allow us to investigate how capitalist economy behaves as a complex system. The main question here is: does a capitalist economy have a specificity that differentiates it from other complex systems? Are there temporal variations in the complexity and self-organization of a capitalist economy as a complex system?

This question is relevant because, as far as we could review the literature, with this sense of complexity developed in physics in last decades, there is a lack of a literature that studies temporal variations of this complexity in natural systems. The closer study we found is Arthur (2015, chapter 9), discussing changes in biological systems. However, the changes addressed there are more related to the concept of complication than complexity. It also refers to the long time it takes - million years - for systemic changes to happen in biological systems.

Therefore, the tools described in this section are very important to our specific question.

II. A CAPITALIST ECONOMY: A PECULIAR COMPLEX SYSTEM

Is a capitalist economy a complex system? As we review the literature in section I, there are hints and clues suggesting that the answer may be yes.

Brian Arthur is one leading economist suggesting that economy is a complex system. This can be very intuitive for a researcher in economics. Arthur (2015, pp, 2-3) summarizes those intuitions: "[t]he economy is a vast and complicated set of arrangements and actions wherein agents - consumers, firms, banks, investors, government agencies - buy and sell, speculate, trade, oversee, bring products into being, offer services, invest in companies, strategize, explore, forecast, compete, learn, innovate, and adapt. And from all this concurrent behavior markets form, prices form, trading arrangements form, institutions and industries form. Aggregate patterns form". As we will argue latter, the rate of profit is an aggregate pattern that summarizes all those interactions.

For Arthur (2015, p. 3), "complexity, in other words, asks how individual behaviors might react to the pattern they together create, and how that pattern would alter itself as a result".

This section summarizes the components of a modern capitalist system, trying to pinpoint its different levels of organization, structures and patterns of interaction. Basically, we would like to identify the different layers of this economic system, as Arthur (2015, p. 3) presented them: humans, institutions as firms, markets, universities, governments, but also introducing countries and flows between countries, firms that are in all countries, national systems of innovation and even the beginnings of an international system of innovation. Furthermore, there are events such as wars and their huge economic impacts. In sum, several layers, changes in their organization, and interactions among them. Those levels of increasing diversity, levels of organization, scale, in sum, increasing complication, do they lead to specificities of complexity in economy?

II.1. Human Beings as Atoms of Economic Systems

The basic element of a capitalist economy are human beings, beings with brains, that we reviewed earlier as complex systems (Singer, 2009, p. 328). This is a very special basic element, as each brain is complex system (Barabasi, 2016). Human society as, inter allia, a network of brains, and this network shapes our brains (Singer, p, 328).

Human evolution is dependent upon human action, human inventions, human artifacts - outcome of intention (Kaufman, 1995, p. 192). Those human inventions, in their turn, shape further human brain development. An example is money: a human invention with roots in developments 2,500 years ago that had an important leap forward with the invention of coins (a Greek invention), with impacts on human ability of abstract thinking (Seaford, 2004). Later, the monetization of the economy, with the growing symbolic representation of money - under capitalism - was connected to an expansion of new intellectual abilities (Simmel, 1907, p. 152).

Human beings have brains (Singer, 2009), intentions (Kaufman, 1995; Simon, 1978), emotions (Freud, 1933; Kahneman, 2002), and beliefs (Arthur, 1995, p. 25).

According to Freud, "inclination to aggression" is a component of human psyche (1931, p. 69) and it may be at least part of explanation for wars (see the correspondence between Einstein and Freud on *Why War?*)[3]. Wars are part of the economic life of XIXth and XXth Centuries (Broadberry and Harrison, 2005; Harrison, 1998; Higgs, 1994) - and of earlier centuries (Tilly, 1993, p. 129). And wars – created by components of the system - change the organization of several layers of economic systems: Arrighi defines military power as a key element for the hegemonic country in his cycles of systemic accumulation (Arrighi, 1994).

Human beings, the most basic unit of analysis in an economy, have brains - therefore they think -, have intentionality, introducing changes in the organization all the time - change the scale of the system, the components of the system, the behavior of the agents, the agents, the interactions, the rules of the action. And here there is an important difference: the atoms change the rules of their system.

[3] According to Freud (1932), in a letter to Einstein, there is a "destructive instinct which is seldom given the attention that its importance warrants" (http://www.public.asu.edu/~jmlynch/273/documents/FreudEinstein.pdf)

II.2. Firms and Markets as Changing Institutions

A second layer of organization in capitalist economies are firms. Those firms change all the time. There are innovations (Marx, 1867; Schumpeter, 1911): innovations are produced by entrepreneurs (that constitute new firms - Schumpeter, 1911) or by existing firms (Schumpeter, 1942; Chandler, 1992).

This key institution of a modern capitalist economy - firms - has been changing since the industrial revolution (Freeman and Soete, 1997, pp. 65-70). Huge changes in the structure of surviving leading firms: they have grown (Penrose, 1959), they have changed internal structures to allow that growth (Chandler, 1977), they became transnational (Dunning and Lundan, 2009), they grow by changing - towards new sectors and new regions (Chandler, 1992, pp. 92-93), their boundaries change all the time (Holmström and Roberts, 1998), mergers and acquisitions are part of those changes (Scherer and Ross, 1990, chapter 5; Holmström and Roberts, 1998, p. 91). Furthermore, there is the emergence of hybrid organizations (Holmström and Roberts, 1998, p. 92) and changing relationships between firms and their suppliers (Langlois. 2003, p. 327).

In this sense firms are not the same in two different points of time - see IBM, for instance, compare its structure in 1920, 1980 and 2010 (Britto et al, 2017). They are different between themselves - no single firm is equal to another firm (Nelson, 1991). Each firm is an outcome of human intention, human design, human interaction, and full of unintended results. Firms learn, invent and reinvent themselves (Teece, 2010, p. 698) - as the dynamics capability approach stresses, firms must transform themselves to create and capture value. Those ever-changing features might have implications for the system. Different firms by size and sector also interact among them creating a new layer of organization: market structures (Schmalensee, 1989): firms as a peculiar layer of a capitalist economy as a complex system. In this layer there is a core, there is a queue to join the core, there are marginal firms etc (Caves and Porter, 1977). In this process, diverse forms of turbulence affect the system as a whole: firms' turnover, natality and mortality (Caves, 1998).

Another layer of organization is composed by special kinds of firms: multidivisional and multinational firms. Those firms are networks - example: IBM with its more than 900 subsidiaries (Brito et al, 2017) - another window for complexity (Barabasi, 2016). And there are networks of firms with networks of suppliers and sub-contractors (UNCTAD, 2013, p. 140). This layer of a capitalist economy is different over time: compare the leading firm of British industrial revolution (Freeman & Soete, 1997, p. 65) with the leading firms today (all TNCs) - different firms, different networks of firms (UNCTAD. 2013, p. 140). TNCs are networks involved in networks, with those interactions leading to changes in the structure of TNCs themselves (Cantwell, 2013, pp. 20-21). Transnationals and their networks change patterns of competition that now are more global.

Firms interact with other firms - cooperation and competition (Richardson, 1972; Williamson, 1985). Firms interact with other institutions - innovation systems (Freeman, 1988; Nelson, 1993), innovation systems differ among them, and they shape differently firms and industrial structures. And those national systems have been eroding by international knowledge flows - by firms, universities and multifarious interactions between them (Ribeiro et al, 2018).

Composing another layer, markets are a selection mechanism that defines the survival of firms (Schumpeter, 1942, chapter 7). Markets change all the time (Swederberg, 1995, p. 273): Smith (1776) has pointed markets and division of labor as a positive feedback mechanism. Swederberg (2005, p. 238-241) and the historical formation of national markets. Markets could be decomposed in different sub-markets: labor, capital, consumer, industrial (Swederberg, 1995, p. 274) and financial, financial markets with their (mis)behavior - Mandelbrot and Hudson (2004). And the contemporary formation of international markets (Swederberg, 2005, p. 241) - see R. Freeman (2007) for emerging global labor market. The structure of markets changes as firms grow, acquire and merge with other firms, what was once a competitive market transforms into an oligopolistic or monopolist industrial structure (Chandler, 1992). Those changes mean changing rules of competition – different patterns of competition (Steindl, 1952). Langlois (2003, p. 376): movements in markets, thin or thick, thicker markets impacting the structure of firms and their boundaries

Markets change firms, firms change markets. Other non-market selection mechanisms change firms and markets (Nelson and Winter, 1982, pp. 268-272).

II.3. Self-Organized Criticality in a Capitalist Economy

Self-organized criticality is an important concept, formulated by Bak et al (1988). It is important because it explains how unpredictable changes might be in complex systems and how important phenomena might be generated by very simple and small changes. The sandpile model is an example of this phenomenon.

Is there a difference between a sand-pile model and a modern capitalist economy? According to Bak and Chen (1991, p. 53): "the various metastable stationary states of economics might correspond to the various metastable states of a sandpile or the earth's crust". There is an important difference: reaching the point of criticality the sand-pile leads to avalanche, but in a capitalist economy it leads to crises that reorganize the system (example: after the crisis of 1929, there was the *New Deal*). After an avalanche a sand-pile will have the same organization as before, but a capitalist economy will be different - a new phase. It is as if the sand-pile always return to a something like the initial structure, and the process will be repeated until the next avalanche, while a capitalist economy will resume its operation with a different organization, and this new process will go on until the next crisis. - almost certainly in a larger economy, with different leading sectors and eventually with a different leading country.

Furthermore, a capitalist economy, as discussed in sub-sections II.1 and II.2 (and in our previous work, especially in Ribeiro et al, 2017b, section 2), is permanently changing after the introduction of new commodities, new inventions, new production processes, new branches of production and new GPTs - perturbations with different impacts on the whole system. This is an important difference between a sandpile and a capitalist economy, because the sandpile receives new grains of sand while the economy generates changes receiving, therefore, new different entities.

The difference between an avalanche and a crisis is grounded on the nature of the agents in a capitalist economy - they think, the institutions formed by them react to those crises inventing new institutions and changing rules of the system. In an economy this is directed linked to metamorphoses of capitalism, as crises are moments of structural change in the system (Ribeiro and Albuquerque, 2016; Albuquerque and Ribeiro, 2016) - this capacity for change is inherent and embedded in the workings of the system.

History provides examples for this dynamic. In 1866, there was an important crisis in the leading country, United Kingdom, triggered by the bankruptcy of a bank - Overend and Gurney. The way that the Bank of England operated during the crises created a new function in the banking system - lender of last resort -, a structural change with deep implications, especially the emergence of a modern central bank (Paula et al, 2016). In 1929, another important crisis, with its epicenter in the United States, triggered by a stock exchange and its shares. The reform implemented by the New Deal in 1933, in reaction to that crises, reshaped the nature of capitalism, with new institutions, regulations and a new interaction between markets and public sector (Albuquerque and Ribeiro, 2016).

Therefore, self-organized criticality is a very important concept for complex systems, because it is related to the capacity of the system to absorb the huge perturbations created by avalanches or crises – the system does not collapse after them. However, in a sandpile those perturbations do not change its organization – the organization of the system is very similar before and after an avalanche, but in a capitalist economy those perturbations trigger institutional answers that reorganize the system.

III. INVESTIGATING METAMORPHOSES OF CAPITALISM

To investigate the implication of changes in organization in the different layers of a modern capitalist economy, we propose a model that captures change in systems' complexity triggered by its own inner dynamic.

Our model[4] investigates the economy as a whole (at least for one country), therefore including all sub-systems and other layers, that have been more commonly investigated - see Mandelbrot and Hudson (2004), for financial markets, for example. And this adds complication and complexity to the system; we are investigating a complex system composed of parts that are complex systems. This form of composition was already identified by Gell-Mann (1995, p. 19): "Clearly, complex adaptive systems have a tendency to give rise to other complex adaptive systems".

III.1. Rate of Profit: summarizing interactions between differents layers of a capitalist economy

The starting point of our model is an understanding that profit is a key driver of capitalist economies and that its movements - ups and downs - summarize multiple and variegated phenomena that in the diverse layers and organizational levels discussed in section II.[5] The movements of the rate of profit may be interpreted as emergent phenomena.

[4] Goldenfeld et al (1999, p. 88) has three suggestions for modelling: 1) "use the right level of description to catch the phenomenon of interest. Don't model bulldozers with quarks"; 2) "... The inclusion of too many processes and parameters will obscure the desired qualitative understanding"; 3) "Every good model starts from a question. The modeller should always choose the correct level of detail to answer the question".

[5] Ribeiro et al (2017a) review the classical and modern economic literature that put forward profit as a key driver of modern capitalist economies.

The search for profits may be the invariant in this system.[6] Firms search for profits, and leading firms search for super-profits (Teece, 2010, p. 680, p. 710). A well-known regularity in industrial economics is the inter-firm, intra-industry and inter-industry differences in the rate of profit (Schmalensee, 1989). The well-known behavior of the rate of profit in the long term (Duménil and Lévy, 2015) shows the ups and downs of the rate of profit in an economy as the USA, and under this national moving average there is differentiation and turbulence (Ribeiro et al, 2018).

A national average rate of profit expresses movements of millions of firms - some with high rates of profit, some with low rate of profits, some going bankrupt, some being created. As we have presented in the previous section, there are several layers of organization and the elements of each layer interacts and suffers the effects of the elements from all other layers. Universities interact with firms, banks provide credit, clients buy, governments collect taxes that feed the state that support infrastructure essential for firms - and sometimes help to contain crises. Firms are *loci* of capital accumulation (Guimarães, 1982). From this ocean of sometimes conflicting actions, emerge a national average rate of profit. In a capitalist economy, the rate of profit summarizes multifarious phenomena and all the forces behind those movements. That is why this variable might be useful for investigations of the economy.

Movements of the rate of profit might signal long term dynamics of economies. As discussed in Ribeiro et al (2017a, 2017b), those movements go hand-in-hand with growth, structural changes, crises, restructuring, technological revolutions reshaping the economic dynamics, crises bring institutional changes as answers to them.

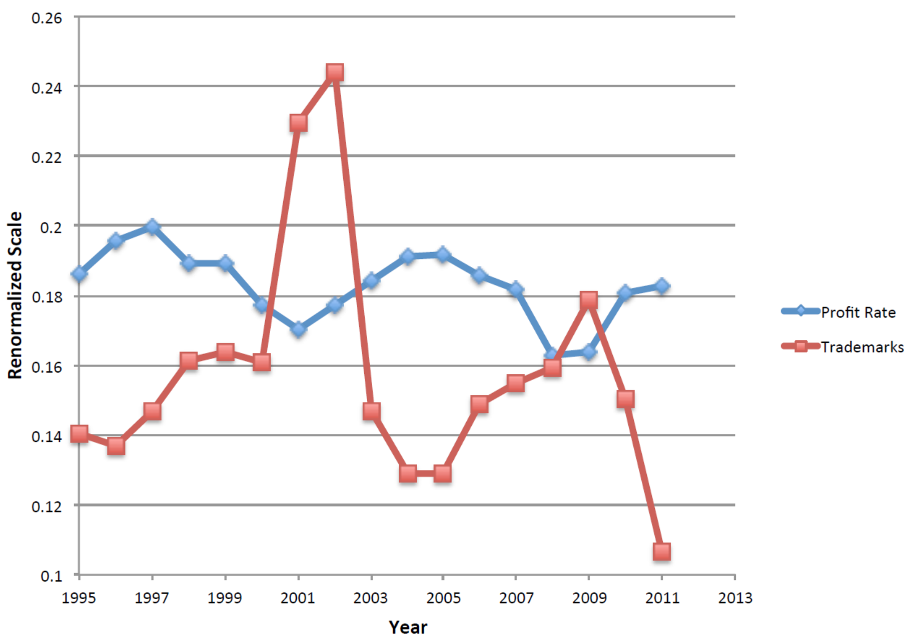
Insights from Marx (1894) offer line of investigation: the behavior of the rate of profit after a contradictory and simultaneous operation of tendencies and counter-tendencies to the fall of the rate of profit. Marx's insight is a starting point for our modelling (Ribeiro et all, 2017a, 2017b).

So far, our modelling was built upon the strategic role of countertendencies to the fall of the rate of profit (Ribeiro et al, 2016). One examples of a countertendency is technological innovation - source of super-profits for Marx. But countertendencies are much broader than those strictly economic factors - they involve, as discussed in sub-section II.3, institutional changes that are provoked by crises, and crises are always connected (correlated) to big decreases in the rate of profit. Those important changes - institutional changes related to actions to, at least, contain further deterioration in the rate of profit - see the Bank of England exercising the role of lender of last resort in 1866, New Deal in 1933 and the coordinated actions of the major central banks in October 2008. All those actions have in common an answer to a strong deterioration in the rate of profit - and intentional and unintentional post-crisis impacts, that reshaped capitalism, sometimes shaping a new phase.

The fall of the rate of profit pushes the economy to search for new avenues, to new ways of doing business, to innovations etc. Probably a stronger driver towards innovation in all meanings than in normal times. Figure 1 shows an inverted relationship between the average rate of profit in the USA and innovation - using deposits of trademarks as proxy (Ribeiro, Santos et al, 2017).

[6] Mandelbrot and Hudson (2004, p. 241) ask for "invariance" in the system.

FIGURE 1
Rate of profit for the United States and USPTO trademarks evolution
(1995-2013)



Source: Duménil and Lévy (2015) and USPTO, authors' elaboration.

The combination of the data shown in Figure 1 with the historical knowledge that connects big institutional changes with answers to big drops in the rate of profit (a signal of crises) illustrate our interpretation of Marx's insights in relation to the role of countertendencies to the fall of the rate of profit in the metamorphoses of capitalism. Those processes that involve all layers of organization discussed in section I change systematically the capitalist economy, probably establishing a complex system that behaves differently from a sandpile and its avalanches. Those observations are new building blocks for the model suggested in the next subsection.

III.2. The Model

This model is built in three steps, each step representing a feature of the complex system that we would like to replicate.

The first step organizes the basic equations of the model. In this step Marx's insights presented in section three of Volume III of *Capital* are translated into a three-equation system. Those equations summarise the operation of the tendency of the rate of profit to fall (as discussed in chapter 13), the countertendencies to its fall (as discussed in chapter 14) and the interaction between tendencies and countertendencies (as discussed in chapter 15). The proposed system of equations is:

(1) $D(t) = \alpha_D * \xi + \beta_D * I(t\text{-}1) * \xi$;[7]

(2) $I(t) = \alpha_I * \xi + \beta_I * D(t\text{-}1) * \xi$;[8]

(3) $RoP(t) – RoP(t\text{-}1) = I(t) – D(t)$.[9]

The terms $\beta_D * I(t\text{-}1) * \xi$ and $\beta_I * D(t\text{-}1) * \xi$ correspond to the "simultaneous and contradictory operation" (Marx. 1894, p. 357) of tendencies to the fall of the rate of profit and their countertendencies, coupling equations (1) and (2).

The solution of this system replicates the long term behavior of a capitalist economy (Ribeiro et al, 2017a), with the ups and downs of the rate of profit, expressing expansions and crises - critical and supercritical states generated by the system. However, in this step the coupling between tendencies and counter-tendencies is always the same, i. e., it does not generate broader changes in the economy.

The second step makes explicit the factors that leads to ups and downs of profit rate, adding a level of concreteness: factors that lead to increase or decrease of the rate of profit are represented as nodes in a network, with the links between them corresponding to their interaction. Those interactions between the factors can be of two types. Suppressor interactions decrease the intensity of the interacting factors, which occurs when the factors are of the same type (both tendency or both countertendency). Excitatory ones, conversely, increase the intensity of the interacting factors, occurring when factors are of different types.

The intensity of the factors is given by four components:

a) Due to the excitatory interaction between two factors: in this case, the interacting factors are intensified, as modelled in equation (4) below. To maintain correspondence with the second term of equations (1) and (2), this means the randomly selected value of the ξ that multiplies β is greater than its previous one. The variation of the intensity of both interacting factors is governed by:

(4) $F_i(t) – F_i(t\text{-}1) = \delta Fi = \delta F_j = \beta_I * F_i * F_j$

b) Due to the inhibitory interaction between two factors: in this case, the interacting factors are diminished, as modelled in equation (5) below. To maintain correspondence with the second term of equations (1) and (2), this means the randomly selected value of the ξ that multiplies β is lower than its previous one. The variation of the intensity of both interacting factors is governed by:

(5) $\delta F_i = \delta F_j = -\beta_D * F_i * F_j$

---

[7] $D(t)$ is the intensity of the factors that pull the profit rate down at time (t); ξ is a random number uniformly distributed between 0 and 1 (generated as many times as used in the equations – i.e., the several terms are not equal). The term $\alpha_D * \xi$ varies between 0 and α_D. That is, α_D is their maximum

[8] $I(t)$ is the intensity of the factors that push the rate of profit up, at that same moment (t); ξ is a random number uniformly distributed between 0 and 1 (generated as many times as used in the equations – i.e., the several terms are not equal). The term $\alpha_I * \xi$ varies between 0 and $\alpha_{D,I}$. That is, α_I is their maximum.

[9] The difference between the intensity of the factors that push the rate of profit up ($I(t)$) and the counteracting factors that pull it down ($D(t)$).

c) Due to external processes that are not modelled as factors of the network, which positively influence the factor in question. This item corresponds to the first term of equations (1) and (2), when the value randomly selected for the ξ that multiplies α is greater than the previous value:

(6) $\delta F_i = \alpha_I * F_i$

d) Due to external processes that are not modelled as factors of the network, which negatively influence the factor in question. This item corresponds to the first term of equations (1) and (2), when the value randomly selected for the ξ that multiplies α is greater than the previous value:

(7) $\delta F_i = -\alpha_D * F_i$

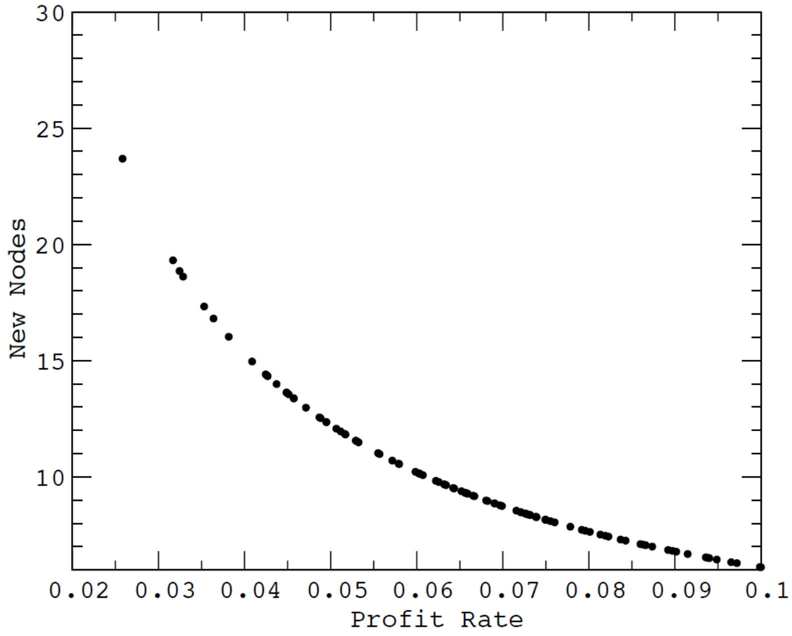
These two types of interactions represented by equations (6) and (7) are exogenous, i.e. they are processes that are not modelled as other factors in the network.

In this step changes in the coupling between tendencies and countertendencies are created by the insertion of new factors in the economy, i.e., represented by the insertion of new nodes in the model network.

Due to the interactions, the creation and change of factors causes perturbations in the system, more specifically in the factors that interact directly with those created or transformed in the first moment. These impacted factors then perturb those that that interact with them and so on, establishing a chain of events that may reinforce changes through positive feedbacks and cause a broader effect on the system as a whole (Ribeiro et al, 2017b).

The third step is the definition of a mechanism, endogenous to the system of equations, that causes the insertion of new factors to be triggered by the behavior of the own system. Supported by the empirical relation between US trademarks registration and US profit rate that shows a negative correlation between them (Figure 1, subsection III.1) and supported by the theoretical background related to creation of countertendencies when profit rate falls (subsection III.1), in this model the endogenization of new factors creation is done through a very simple rule. The rule articulates the size of the fall in the rate of profit to the probability of creation of new factors, as discussed in the second step. The same rule states that when the rate of profit increases it decreases the probability of new factors creation. There is an inverse relation between them the movement of the rate of profit and the endogenous introduction of new factors in the system. Figure 2 shows this inversely proportional relation proposed, in which X-axis represents the rate of profit rate and Y-axis represents the number of new factors being created.

FIGURE 2
Rate of profit and probability of new nodes creation



Source: Authors' elaboration.

This paper presents a new model because it suggests and includes this simple rule. With this simple rule this third step endogenize the introduction of new factors, that can be translated as an endogenous creation of innovations and institutional changes as answers to crises - movements that causes large falls in the rate of profit. Furthermore, this third step completes and rounds the model as we may have now both critical and supercritical states, producing both minor events and catastrophes (or crises). And the "mechanism that leads to minor events is the same one that leads to major events" (Bak and Chen, 1991, p. 46). However, in our model, minor and major events will trigger different answers.

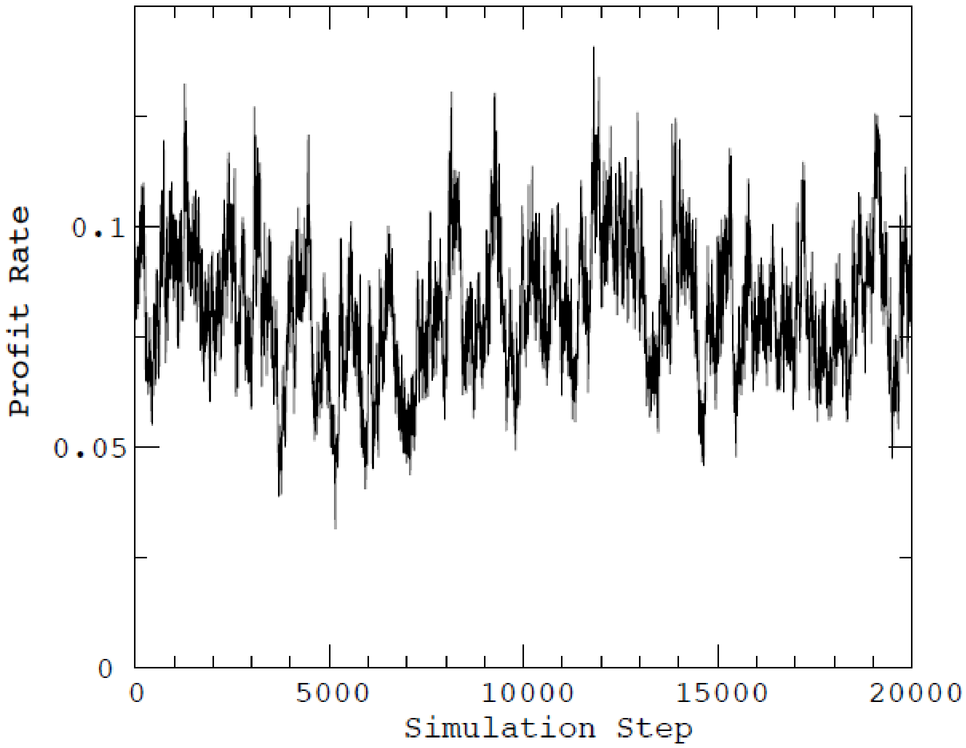
III.3. A Simulation and its Results

For the simulations, a free-scale network containing N_{nodes}=4,000 nodes was generated and the link types (suppressor or excitatory) were randomly distributed with probability *p*=0.5. Monte Carlo simulations were performed (Metropolis et al, 1949; Swendsen et al, 1992), in which for each simulation step N_{nodes} neighbour pairs are randomly selected and their intensity is updated according to the interaction rules. The simulation waits until the system becomes thermalized to begin – i.e. its configuration becomes independent of the initial one – and consecutive simulations steps wait until the configuration becomes uncorrelated with the previous one.

So, following the relation presented in the previous section to calculate the number of new nodes (factors in the model) at each 1,000 simulation steps and then insert those nodes following the free-scale rule to maintain its structure.

Figure 3 shows the movements in the rate of profit obtained in the simulation during 20,000 simulations steps - for reasons of improving the visualization of the graph was not presented the evolution during the whole simulation that involved 1 million simulation steps.

FIGURE 3
Simulation results – rate of profit evolution (20,000 simulation steps)



Source: Authors' elaboration

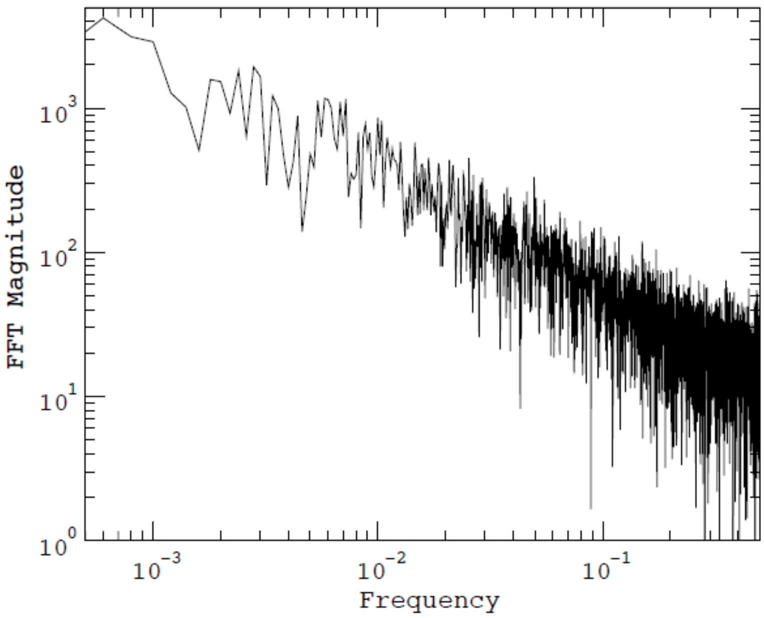
Those movements show that our new model replicates the workings of a modern capitalist economy (see Ribeiro et al, 2017a, sub-section 4.2).

IV. PROPERTIES OF A CAPITALIST ECONOMY AS A COMPLEX SYSTEM

Figure 4 shows the result of applying the FT to the profit rate from the simulation. The horizontal axis is the frequency of the periodic function and the vertical one is the coefficient that multiplies this function, which means the weight of the frequency in the original function.

The resulting power law regression in Figure 4 indicates the behavior of a complex system (see section I.3 for a more detailed discussion).

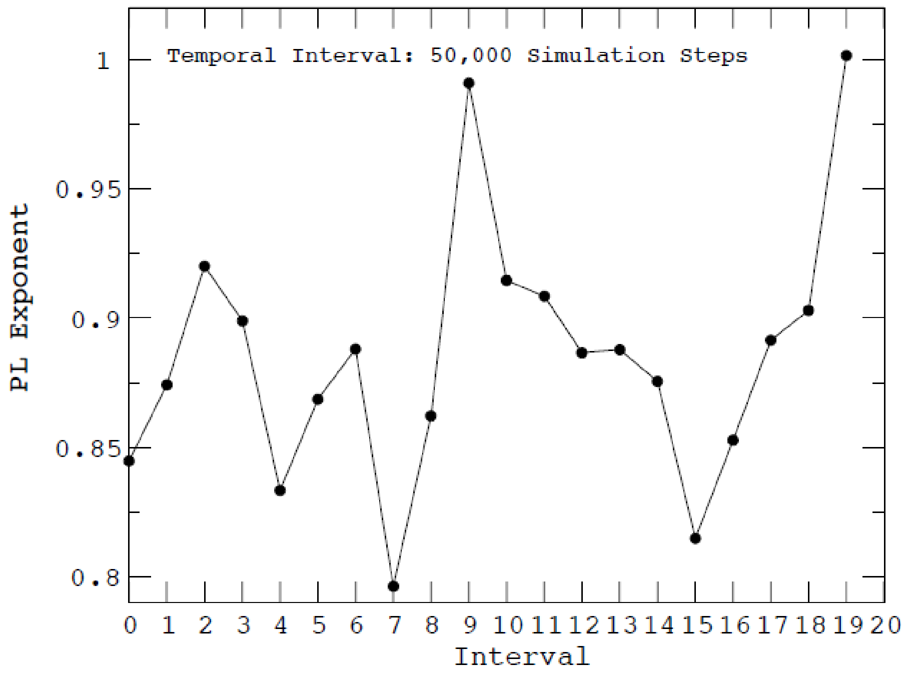
FIGURE 4
Fourier transformation of simulated rate of profit



Source: Authors' elaboration

Discovering the capitalist economy represented in Figure 3 is a complex system, the next step is to evaluate whether its level of complexity changes over time. For this evaluation, as suggested in sub-section I.4, the results presented in Figure 3 are processed by a DFT, performed in a moving 50,000 simulation steps window, and the respective exponents of the power law were calculated. Figure 5 shows the exponent's evolution during the simulation.

FIGURE 5
Changes of power law (PL) exponent



Source: Authors' elaboration

Figure 5 shows that the exponents change over time, an indication that the level of complexity change over time. This result hints a very special feature of a capitalist economy as a complex system - movements in the level of complexity, therefore changes in the level of self-organization.

V. A COMPLEX SYSTEM THAT CHANGES ITS LEVEL OF SELF-ORGANIZATION

The new model presented in section III.1 endogenizes mechanisms that lead to changes of organization in different layers of the system. It replicates a long-term dynamic of a capitalist economy - countertendencies to the fall of the rate of profit at work. The simulation results in a long-term dynamic with ups and downs in the rate of profit, combined with structural changes including the growth of the system over time - the system becomes more complicated by introduction of nodes representing those innovations and new institutions. Analyzing its properties, this model leads to an economy that not only works as a complex system but also changes its level of complexity over time.

The results of our new model offer a new line of interpretation of previous works. Ribeiro et al (2017b) analyze empirically data for the USA and finds similar indication of changing levels of complexity (Ribeiro et al, 2017b, Figures 3 and 4) and run a simulation model (Ribeiro et al, 2017b, section 5) - with exogenous changes - that replicates those changes in the level of complexity (Ribeiro et al, 2017b, Figure 5). The variations in complexity and self-organization found in the analysis of the rate of profit in the USA (Ribeiro et al, 2017b, Figure 3) show that although the level of complication of the economy grows steadily - more people, more commodities, more GPTs, more firms, more institutions, etc -, the level of complexity and self-organization oscillates. Those data and analyses show that in a capitalist economy the level of complication of the system is not correlated to the level of complexity.

This variation in the level of complexity and self-organization shown by a modern capitalist economy might be grounded in three different bases.

First, a modern capitalist economy is structured by different layers and levels of organization - human beings, their creations such as commodities, firms, institutions, that by their turn build networks, subsystems -, and many of those layers are complex systems build upon other complex systems. Differently from complex systems in the physical and biological worlds, in a capitalist economy each of those components think and act with intentionality, leading to actions that impact the whole system, with intentional and unintentional consequences.

Second, a modern capitalist economy and its components change all the time, given its composition and its main drive, namely the search for profits. Their components have actions, as they change beliefs, invent new commodities, create new firms, new and old firms grow and transform themselves, expand and create institutions - from universities to governments. This system shows that everything changes all the time.

Third, the dynamics of a modern capitalist economy shows self-organized criticality, as that ever-changing environment may generate minor and major events that initiate chain reactions that will eventually lead to catastrophes - crises. However, a capitalist economy has an important difference vis-à-vis other systems: in capitalist economies reaching the critical state triggers institutional answers that reshape the economy. This chain of events shows that, in a capitalist economy, something occurs that does not happen either in the physical or in the biological worlds: the rules of the system change over time.

Those three bases for complexity in economies might explain why we can find this very specific feature in our empirical and simulated worlds: changes in the level of complexity, although the level of complication is increasing.

Since we have not found this pattern of change in other complex systems, this finding might be a contribution that investigations in economy may bring to the understanding of complexity in general, given its (capitalist economies) peculiarities.

This paper leads to an agenda for further research, whose first topic can be an extension of this modelling beyond one national economy, an attempt to build a model that includes economies in different levels of development, probably a more accurate description of a complex system that has been expanding since the industrial revolution.

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