J Syst Sci Complex (2021) 34: 314–338

Complex Systems in Economics and Where to Find Them*

GOMES Orlando · GUBAREVA Mariya

DOI: 10.1007/s11424-020-9149-1
Received: 30 April 2019 / Revised: 22 July 2019

Abstract The economy as a whole and most of its constituent parts, like markets, government institutions, firms, or households, are inherently complex conceptual constructions. Micro-level diversity, decentralized interaction, self-organization, adaptation and learning, emergence, and evolution, are some of the fundamental features that the above entities share and that allow to classify them as being complex entities. In a complex economic system, existing structures of interaction are in constant mutation as individual agents contact and influence one another and, by doing so, reshape the macro environment in which socio-economic relations unfold. Notwithstanding the observed pervasiveness of complexity in economics, there are a few areas of economic thought where the discussion on the theme has gained an exceptional relevance. In this article, six of such areas are identified and their complex nature is highlighted and scrutinized. These pertain to: (i) Knowledge interactions and technological innovation; (ii) Corporate design and organizational learning; (iii) Public policies directed at market regulation; (iv) Banking and financial markets; (v) Environmental economics, sustainability, and climate change; and (vi) income inequality.

Keywords Agent-based models, complex networks, complex systems, emergent phenomena, evolutionary nature, market regulation, public policies.

1 Introduction

Complex systems in Economics, we have to admit, certainly do not have much in common with the magical creatures of Harry Potter's enchanted world. However, in the same way as

GOMES Orlando
ISCAL - Lisbon Accounting and Business School, Instituto Politécnico de Lisboa, and CEFAGE - ISCAL/IPL Research Center, ISCAL, Av. Miguel Bombarda 20, 1069-035 *Lisbon, Portugal.* Email: omgomes@iscal.ipl.pt.
GUBAREVA Mariya (Corresponding author)
ISCAL - Lisbon Accounting and Business School, Instituto Politécnico de Lisboa; SOCIUS - Research Centre in Economic and Organizational Sociology, CSG - Research in Social Sciences and Management.
Email: mgubareva@iscal.ipl.pt.
*This research was supported by the Portuguese National Funding Agency for Science, Research and Technology (FCT), under the Project UID/SOC/04521/2020, and by the Instituto Politécnico de Lisboa as a part of the IPL/2019/MacroVirtu/ISCAL and IPL/2020/MacroRates/ISCAL Projects.
◇ *This paper was recommended for publication by Editor TANG Xijin.*

fantastic beasts can be searched for, discovered, identified, and catalogued, a parallel effort might be undertaken for the reality we want to address in this article. Economic relations, understood as the outcome of decisions that emerge from weighting benefits and costs of available alternative plans of action, acquire many different shapes; some are relatively unsophisticated transactions involving few agents in a trivial and predictable environment; others put together thousands of stakeholders with distinct preferences, decision capabilities, goals and expectations in an environment where they are compelled to constantly adapt, learn and evolve, giving place to emergent and complex phenomena. This paper identifies and highlights a few areas of economic research where complexity acquires special relevance. Thus, this is an article about complexity in Economics and about the economic habitats where its presence is apparently more acute and lively.

The idea that Economics is a science of complexity, i.e., a science that studies the complex nature of business relations and of economic agents' choices goes back to Alfred Marshall and his evolutionary understanding of market dynamics[1,2]. Although Economics has evolved to be a science of equilibrium, the idea that this equilibrium is a simplified and stylized representation of a sophisticated process of systematic interplay across self-interested agents has always remained latent. Mechanic economic models are, as highlighted by Marshall, a way to simplify and understand a reality that is, in itself, necessarily complex. Doubts exist on whether analyzing the economy as a complex system consists in an increment over the prevailing neoclassical economic thought or, in opposition, if it corresponds to a totally new paradigm that radically departs from the established theory[3,4]. In any case, few doubts remain on the complex nature of economic systems, systems that are formed by a multiplicity of interacting pieces that connect dynamically and that change behavior as interaction unfolds[5].

In this paper, we identify six areas pertaining to economic thought which have been subject to analysis and explored under the perspective of complex systems. After a discussion on the complex nature of the economy (Section 2), we collect evidence and debate the role of complexity on the creation and the diffusion of knowledge (Section 3), on organizational change and learning (Section 4), on market regulation (Section 5), on banking and financial markets (Section 6), on environmental policies and climate change (Section 7), and on inequality in the distribution of income (Section 8). In Section 9, we sketch a simple diagrammatic/analytical model to put into perspective how the six debated areas might be interconnected under a complexity perspective. Section 10 concludes.

2 Why is the Economy Complex?

Ecology is defined by scientists as the research field concerned with the interaction among living organisms and between communities of these organisms and their environment. Interaction processes of the mentioned type unfold in an ecological system or ecosystem[6]. Markets for goods and services, large production plants, governmental institutions responsible for the design of public policies, and even households occupied with consumption-savings decisions, are human socioeconomic ecosystems endowed with some peculiar features that allow to classify them as complex.

Typically, socioeconomic ecosystems are composed by agents that pursue their individual interests as they establish mutually beneficial transaction relations. Complexity emerges because of the heterogeneous nature of agents. Agents are not alike; they differ in their preferences, endowments, expectations, hierarchical position, degree of connectivity, and ability to engage in successful interactions, among other features. Furthermore, as the interaction takes place, agents learn, adapt and mutate, leading to a systematic and never ending evolutionary process where both the individual agents and the whole socioeconomic structure are subject to constant and perpetual change. Out-of-equilibrium dynamics are the rule and not the exception, and mechanistic notions of equilibrium that populate orthodox Economics lose relevance under the interpretation that economic relations take place in a complex ecosystem.

As emphasized by [7], people are not cogs in a machine. The behavior of humans coevolve with the environment; cooperation and competition, the formation and dissolution of alliances, the establishment of new relations and loss of others, introduce systematic changes in the intended goals and in the strategies followed to attain them. The changing nature of agents in a complex system preserves the micro-diversity and generates emergent phenomena that fuels the evolutionary dynamics of the ecosystem as a whole. Stability is not an inherent characteristic of the economy or any of its constituent parts; on the contrary, economic ecosystems are unstable, evolutionary and complex.

Recognizing that the economy is a complex system poses important challenges to economic policy. Public authorities must realize that the understanding one has on how the world works is always limited and constrained because reality is an ongoing process. There is no optimal static equilibrium to act upon; rather, policies must respond to an emergent reality where a multiplicity of tastes, goals, and intents coexist and coevolve.

Conventional economic thought implicitly assumes that markets function as a coordination device that mediates the relations between agents. Instead, a complexity perspective puts the emphasis on local and explicit direct contact, with the preferences, choices and actions of each individual being directly influenced by those with whom the assumed agent establishes contact[8]. Because of transaction costs and other market imperfections, the distance between agents (physical or social distance) is not negligible; i.e., networks are not complete in the sense that there is no possibility of exchanging information simultaneously and instantaneously with everyone else at no cost. Agents are asymmetric at a multiplicity of levels and therefore their ability to interact is subject to various constraints; the environment itself (and the way in which it is structured) functions as a constraint over which the actions of agents must conform with.

Economic networks are dynamic entities and the most important issue in their analysis is the formation and elimination of links. It is important to understand what determines the agents' choices and constraints that lead to a particular set of network liaisons and how the network configuration influences the economic outcomes. Complex systems correspond to a holistic view of reality, where even if one fully understands the characteristics of each component this is not enough to replicate the functioning of the system as a whole; relationships matter and the collective behavior is much more than the sum of the parts.

[9] and [10] highlighted the following characteristics of economic complex systems: These are systems with a large number of components that influence one another and provoke emergent phenomena (thus, constantly changing the shape of the underlying environment); feedback loops exist and, thus, any phenomenon can be amplified or damped; the system is decentralized and self-organized and, therefore, no central coordination is observable; the interactions have an emergent nature[11,12], in the sense that occurring phenomena are the result of unrepeatable series of events that are impossible to anticipate. This implies also that economic complex systems are path dependent; only the series of events leading to the current setting can explain this reality (history is relevant). The notion of emergence is associated with Hayek's concept of spontaneous orders that views markets as self-organizing entities[13].

Economic systems are not closed systems. Their borders are difficult to define and establish. Furthermore, they tend to be scale invariant in the sense that there is typically a small number of hubs and a large number of individual agents weakly linked to the rest of the network. Allowing for a complex economy of simple minded individuals is also a recognition that agents are boundedly rational and that they use simple rules of thumb or heuristics whenever they have to make decisions. Intertemporal optimization is a fiction of the economic theory hardly compatible with what the human mind can achieve[14]. External coordination devices are useful and convenient from a modeling point of view, but they fail in representing the actual behavior of individuals[15].

In the following sections, we seek to survey and characterize the main complexity features found in various fields of economic analysis.

3 Complex Technological Change

Innovation is a fundamental source of economic growth and it can be associated, on one hand, with the individual effort of some illuminated and creative minds and, on the other hand, with the purposeful investment of firms in the development of new processes and products. The question that emerges is whether technical progress occurs independently of the ecology of economic relations. [16–20], among many other authors, sustain the view that creativity can only thrive in a complex economy where a systematic process of interaction and communication underlies the productive activity.

In a world of boundedly rational agents, firms, although creative, are also myopic and slow to react. Only when faced with events that deviate them from their intended equilibrium, will they react by searching for new competencies and by innovating. Thus, to innovate, a couple of conditions must be met: First, the incentive to innovate must arise from a necessity of the firm to survive and grow; second, the firm must be able to interact with its environment in search for the knowledge that it can recombine to arrive to new technological concepts.

In [17], innovation is interpreted as an emergent property of a complex system. Heterogeneous agents, who make decisions and pursue their own interests, interact within a given framework and are influenced by the structural features of this organized framework or system; the system, in turn, receives constant feedback from the individual interactions and is reshaped accordingly in a systematic basis. Individual decision-making and the architectural properties of the system in which decisions take place form a whole where one and the others are interdependent and influence each other.

In a complex system of social relations, innovation functions as the engine for everlasting change. Because agents are endowed with the capacity to learn and adapt to the constantly shifting conditions of the underlying environment, they create new ideas, processes, techniques and objects, i.e., they innovate. Thus, the creativity of agents is not, in this view of the world, a fruit of spontaneity; instead, it is the outcome of the system's organization and of the interplay across agents within the system. Creativity requires: (i) An individual incentive to change, which logically emerges whenever cost — Benefit analysis suggests that the status quo is not the best solution; (ii) An interaction scenario that promotes and favors change and evolution rather than simple adaptation; (iii) A feedback mechanism allowing for the perception that the best reaction to the events that take place is a creative one. This last feature introduces an element of path-dependence, that reinforces the notion that creation and innovation take place in a complex environment.

The creative response of agents to the dynamics of the complex world in which they interact turn technological change into an endogenous, recurrent and everlasting process, far from the vision of orthodox general equilibrium Economics, which interprets technology as exogenous and innovation as the outcome of extraneous perturbations over a pre-specified steady-state.

[17] also highlights that not all creative processes originating in a complex system culminate on an innovation. For the innovation to occur, two requirements should be met: Novelty and increased efficiency; although one might associate creativity with the generation of something new, one must also evaluate how the novelties are contributing to enhance the efficiency in production and to increase the utility of the agents. The emergence of innovation is, for the discussed reasons, a collective process where interaction and structure are the two fundamental pieces.

Interaction and structure are discussed, in the context of complexity-based innovation, by [21], under the designations dynamic interactionism and organization thinking, respectively. By dynamic interactionism this author means a class of ontological commitments, i.e., a series of choices agents make when deciding with whom to interact, how to interact, and which information to share. These commitments depend on history, reputation, credibility, and institutions, i.e., they depend on the conceptualization of social organizations. Again, it is the dynamics of local interactions in a complex world that create generative relationships, that is, relationships that give place to the emergence of something new.

The discussion offered in [21] on the complex nature of technological change builds upon the notion of exaptive bootstrapping. This notion is the foundation of a theory that pursues an explanation for the occurrence of innovation cascades, i.e., for the discovery of successive and intertwined new technological artifacts. The theory of exaptive bootstrapping assumes that innovation unfolds through a series of sequential steps: First, a new concept or object is developed in order to meet some social need; second, the organization of the system evolves and adapts to accommodate the innovation; third, the new concept or object and the new social structure induce change in the patterns of human interaction; fourth, new needs or functionalities emerge from the social change introduced by the innovation; fifth and back to the start, new concepts or objects are created to satisfy the needs or functionalities arising as described in the precedent step.

As characterized above, exaptive bootstrapping is a circular process that guarantees that innovation feeds itself as an ongoing process, leading to the mentioned innovation cascades. The relevant point when analyzing the proposed sequence of events is that innovation is an inextricably complex process: It changes the environment that created it and the nature of the interaction among agents, and these changes will constitute a force leading to further innovation. Moreover, new artifacts gain meaning through use, i.e., it is not always evident how an innovation will be implemented and how it will change the organization of society and the characteristics of human contact. One must wait for the dissemination of the innovation to unfold to fully understand its implications and how it will determine the course of future technological development. Again, technological change can only be understood as being path-dependent and historically determined.

In the above reasoning, the term exaptation signifies the emergence of new functionalities that can only emerge once the interaction relations within the system effectively unfold. The unpredictability underlying exaptation is evident; agents cannot predict with accuracy what new attributions of functionality emerge when a new artifact is generated. Nevertheless, there is some room for policy intervention, because agents and the society are in many cases capable not only of evaluating the generative potential of a new object, but also to act in the direction of increasing such potential. We call the generative potential of an innovation the capacity that the society has to develop interactions, which, in their turn, raise the usefulness of a new artifact and the possibility to create, from the new artifacts, other objects with social usefulness.

The generative potential of an innovation is intrinsically attached to the set of properties defining the complex structure allowing interaction to take place. [22] systematized these properties: (i) Aligned directedness — There must be some coincidence or points of contact on the goals pursued by the agents within the system; (ii) Heterogeneity — The previous property does not imply homogeneity; on the contrary, if agents are all alike there is no room to share ideas and create something new; (iii) Mutual directedness — Although different, there must exist some attractive feature that allows a link to be established between agents (without this, agents simply stay out of contact and no interaction occurs); (iv) Appropriate permissions — Wanting to stay in contact and share ideas may not be enough. The environment must be conducive to the existence of communication and share of ideas (organizations exist with this goal); (v) Action opportunities — Agents must have effective opportunities to interact and share ideas.

The process of innovation conceptualized as above is far from being deterministic. There is no pre-specified and predictable technological path that is independent of the actions of individuals and organizations and extrinsic to the course of history. In this perspective, innovation and technological change are necessarily cumulative, i.e., current innovation can be understood only by looking at the path taken to arrive to the current state of knowledge[23].

An evident setting to approach the propagation of technological knowledge is complex networks (e.g., the scale-free networks explored in [24]). Regardless of the structure of the network, the principles already mentioned above will apply, i.e., (i) innovation only spreads if agents locating in different nodes are heterogeneous and possess a willingness to interact to share ideas; (ii) links across nodes are established only if there is mutual understanding, that is, if there is some kind of affinity that triggers interaction (although technological proximity should not be too strong as well, because in this case there is not much knowledge to be exchanged); (iii) knowledge propagation (also in a network perspective) is an emergent phenomenon — The network is reshaped at every instant, as agents establish contact and create the opportunities to innovate. The network does not tend to an equilibrium position and, therefore, innovation can be interpreted as a disturbing rather than a balancing force[25−27].

4 Evolution and Learning Inside Firms and Other Organizations

The organization of firms, their culture and learning processes are also better explained under a complex systems perspective. Firms and other organizations are generators of innovation and technical progress; they exist to solve problems and their efficiency depend on how agents with different goals and skills are put together to learn, adapt to new circumstances, and coevolve.

Relatively to other social structures, organizations are oriented to promote maximum efficiency and, therefore, activities and procedures are arranged in order to optimize information flows. Hierarchies are typically well defined and known by all and competencies are also compartmentalized with well specified initial goals in mind. Emergent interactions in organizations are fundamental to understand the generation of wealth, and the success of agents and of the economy as a whole. This issue has been addressed by [28], [29] and [30], among others; these authors see complexity as the best tool to explore organizational routines, memory, performance, knowledge and hierarchies. It is the ensemble of patterns of organizational interaction that define the pace of technological advancement and development of new processes and products.

In [31], the organization is interpreted as a collection of agents who establish formal and informal structures of interaction. These structures determine the distribution of authority, the communication channels, the allocation of incentives and responsibilities and, ultimately, the ability of the organization to fulfill its social or economic mission. The mentioned authors encounter in the agent-based approach, grounded on the idea that the organization is a complex system, the adequate framework to address the most meaningful questions about the existence and development of firms and other organizations. The questions are related with discovering how heterogeneous agents, endowed with distinct skills, capabilities, and traits of personality, interact in the organizational universe in order to achieve the organization's goals. The complex nature of the interaction process is evident: Individuals interact within the organization, and the firm is an interacting part of a broader environment. The components of the system coevolve and all of them adapt and learn, inducing the generation of emergent phenomena and the constant re-shaping of organizations in society, which do not tend to any kind of long-term institutional equilibrium. Under the complexity approach, it is not feasible to conceive a steady-state where, regardless from history and actual patterns of interaction, the same institutions, with the same degree of power and cohesiveness, will end up by thriving.

In the interpretation of [21], what distinguishes organizations from other kinds of entities, characterized by systematic interaction among agents, is a set of three main features: Structure, function and process. Every organization has a structure, i.e., a set of modules that have a predefined disposition inside the organization. These modules are linked to each other through hierarchies and information flows. Putting it simple, an organization is a structured network composed by nodes and links between these nodes. Function is the organizational feature according to which the actions and interactions that take place have a purpose to serve the initially established goals. Processes are associated with the procedures and interactions adopted in order to comply with the specified functions, given the existing structure. In a complex environment, structure, processes, and functions are not immutable and influence each other through the evolutionary process that underlies every complex system.

An interesting and curious aspect about organizational thought under a complexity view is that one of the main characteristics of organizations, the careful planning of their activities to achieve the best possible economic result, collides with the ever-evolving nature of the complex firm. This raises an important challenge for managers who, more than predicting the future, are compelled to formulate contingent strategic adaptation plans, i.e., to identify a series of probable scenarios and to update them over time as events take place. This updating process requires discarding obsolete plans and reacting to new scenarios that are forming. Furthermore, by realizing that the reality they face is complex, managers should be able to act upon the landscape, creating conditions for the most desirable scenarios to become probable and for the possibility of occurrence of the less desirable scenarios to be narrowed. Therefore, rather than worrying with 'sticking with the original plan', managers should attend to the signals that point to the transformations on the internal and external dynamics that affect the life of the organization[32,33].

Complexity in organizations possesses a holistic nature, i.e., one should approach it taking the organization and its multiple components as a unified system that can be evaluated as a whole. Notwithstanding, one can also approach various organizational functions in isolation under the same perspective. For instance, leadership, a key organizational feature, might be conceptualized as a complex interactive process where learning, innovation and evolution become fundamental ingredients. Complexity leadership theories, in the context of knowledge-producing organizations, have been proposed by [34] and [35]. A close subject has been addressed by [36], who focus on the notion of power. Power is defined as the capacity one agent has, in the context of the organization, to determine the set of actions that other agents can and cannot follow. Although this is apparently a rather deterministic process, it is embedded with a multiplicity of caveats that makes the interaction between those who exert authority and those who are subject to it also a complex process (historically determined and shaped by learning and adaptation).

A fundamental property of complex systems is, as already mentioned, path-dependence.

Are firms and other organizations path-dependent? The answer is undoubtedly yes. Although economists are used to consider that sunk costs and sunk benefits are irrelevant for current decisions and that firms are essentially forward-looking agents, there are many arguments that attach current decisions to past events. For example, [36] and [37] identified a few reasons why path-dependence is important in organizations; the most relevant are the following three: (i) Shared past experiences determine conventions and expectations for the future; (ii) The accumulation of past events is the source of the existing organizational culture and of the prevailing codes of communication; (iii) History consolidates roles, authority relations, information processing channels and eventually allows for increasing productivity as learning-by-doing or specialization processes consolidate.

From the complex network perspective, one may distinguish between the existence of a formal architecture, which is often portrayed in a company's chart, and an informal network that often departs in various respects relatively to the formal one. In any case, we are not far from the truth when asserting that firms can be defined as networks of interdependent decision makers[38]. Thus, firms and other organizations might be analyzed and interpreted under a connectionist view, in which the connections established among the various pieces are the engine determining the course of events and the attained outcomes. According to [39], the organization, interpreted as a network of relations, is a third vertex of a triangle where we also find markets and hierarchies. In the view of these authors, the complex organization is not a hybrid construction obtained by combining pure market relations and pure authority derived from institutional hierarchies. Networks are located on another dimension; they constitute a third attractor to which firms can be pooled into, an attractor in which informal transactions occur and the role of hierarchies becomes blurred.

5 A New Kind of Market Regulation

Typically, competitive markets are not complete markets. Given the multiplicity of involved agents and a series of obstacles that curtail the communication potential across the various players, at each period in time, market participants must be selective when choosing with whom to interact. This choice is, in principle, guided by rationality, but it is also subject to various constraints. If it is not feasible to interact with everyone participating in the market, options have to be taken. Geographical proximity, trustworthiness, and salience are some of the criteria commonly used to select business partners. In this perspective, markets are evolving networks where individual actions shape aggregate outcomes and where the system's structural evolution is also determinant for the adaptation of individual behaviors; in short, markets are the most fundamental prototype of what a complex system in Economics effectively is.

Although the incompleteness of markets is a debatable issue, with the neoclassical orthodoxy supporting the view that rational agents are capable of pervasively exploring market opportunities and of using the price mechanisms to identify the best possible potential outcomes[40], some of the complexity features involving the markets are worth exploring in order to better understand these entities and, above all, in order to acquire the possibility of designing policies that can enhance their performance, both in terms of efficiency and equity.

Identifying the complexity features of markets is not, or at least should not be, an end in itself or a mere conceptual exercise. As [41] pointed out, this identification process must have empirical meaning. Markets are better understood, and public authorities might act upon them, if some of the complexity traits are identified in practice. One should note that markets, as other complex entities, are markedly shaped by path dependence, since they are nothing else than the result of a series of unique and unrepeatable historical events. Furthermore, empirical analysis allows to recognize social interactions with specific features, allowing for identifying and cataloging the most frequently found types of market structures. This can be done in much more detail than the conventional alignment of market structures along a competition — Concentration scale. In particular, evidence shows that most markets are clearly shaped as scale-free networks, i.e., as networks where some players have a dominant and central position while the large majority occupies a relatively peripheral place. Typical contemporaneous markets, in many business sectors, exhibit a strong degree of concentration or centrality of a few agents. However, they allow for many other participants with a much smaller intervention, and thus, the distribution of agents within markets tends to approach a power-law configuration. A good example of this is the software industry, with Microsoft in the center and non-Microsoft surroundings; the centrality could also be multicentric if we consider Apple as the other focal point of the software industry.

The main issue to discuss in this section is how, under a complexity view, should public authorities intervene upon market relations, with the goals of fixing anomalies, managing externalities, providing public goods and fulfilling their role as gatekeepers of social well-being. The change of paradigm requires a modification in the approach followed by governments and other authorities. This is precisely the position of [10], who emphasize that the complex systems approach implies that economic policy, at a regulatory level, should shift its paradigm, moving from trying to control outcomes to aim at influencing them.

Because markets self-organize, the role of the public authorities should be to identify the formation of beneficial or harmful conditions that may lead to virtual cycles or to economic disasters, and to encounter the policies that best serve the purpose of dealing with the emergent phenomena that is gaining shape. This means, as well, that governments should be able to rapidly understand the early signs of relevant economic changes and to react with celerity taking the appropriate measures to influence behavior. Authorities must be able to identify which agents should be the primary target of their intervention, given the set of predictable propagation mechanisms. Well-conceived policies will desirably provoke changes in the behavior of key agents, changes that will then automatically spread throughout the network of relations.

[42] also indicated that under a complex system's interpretation of reality, regulatory policies acquire a completely new shape. Regulation is no longer, in opposition to the neoclassical view, an interference on market dynamics that injures efficiency in favor of promoting some sort of equity outcome. Instead, regulation is a necessary process to assure a sensible balance that the plain interaction among decentralized players does not allow for. Furthermore, public policies are, on their own, a complex structure that needs to be equated, adjusted and adapted to the

system it intends to regulate in the first place. [43] underlined that policy recommendations and measures acquire, in the complexity context, a more intuitive and less deterministic nature, as well as a capacity to adapt and change as implementation proceeds.

In a similar vein but in a more general perspective, various authors (e.g., [3, 44]) argued that once a complex system view is adopted, the way in which economic policy, namely fiscal policy, is interpreted and implemented must change. This is because in traditional economic models there is an implicit assumption that markets tend to equilibrate themselves what leads to the dominance of the laissez-faire liberal approach, in which the intervention of the government should be minimum if the goal to achieve is increased efficiency and long-term growth. Complex systems, however, explain circumstances in which out-of-equilibrium situations persist and, in this case, public policies may be necessary to pull the economy into good or virtuous basins of attraction. Moreover, in a complex economy, both the long-run attractors and their basins are moving objects given the evolutionary and emergent nature of the system. This makes public policy extremely hard to implement and maybe the best practice consists in trying to anticipate emergent phenomena in order to place the economy in the direction of the basins that are supposed to exist in the future, given the expected and predictable dynamics.

As [44] argued, government policies should change their nature: Deterministic top-down measures should be replaced by a decentralized intervention, one more of influence than control and where localized actions may be more effective to deal with the multiple feedbacks that are present in the interaction agents establish in a complex world. If, in a complex system, self-organization does not necessarily lead the economy to a desirable equilibrium, economic policy is always relevant. Governments must stay vigilant in order to identify and predict abrupt changes in the status-quo that necessarily occur, sooner or later, in a complex setting.

In recent literature, one can find several attempts of approaching the impact of fiscal policy through the exploration of agent-based computational models and respective simulation[45–47]. In particular, [47] devised a comprehensive agent-based artificial economy, populated by households, firms and government agencies, which are organized in markets for goods, labor and real estate, with the goal of addressing the impact of fiscal policies over the welfare of citizens. These authors integrated the mentioned components in a relatively simple and not too computationally demanding framework to arrive to results with relevant policy implications. Fundamentally, they seek to investigate whether and how the reorganization of administrative regions and the consequent modification of fiscal policies impact on the quality of life of individuals, both in terms of the taxes they pay and the public services they have access to.

6 The Complexity of the Financial System

One of the areas of the economic literature where the complex systems' approach abounds is the one concerning the structure and organization of the financial system. [48–50] are some representative studies in this area.

In the view of [51], financial markets are the prototypical example of a complex system in the economy. In these markets, the micro–macro interaction is evident; the decisions of individual investors are strongly determined by the evolution of aggregate indices and these are directly influenced by how investors decide to act. Furthermore, the networks formed in financial markets are relatively easy to identify, following the patterns of investment that the players in the market adopt (see [52], for an empirical analysis of the complex web of relations generated by the global operations of large banks).

In reality, in financial relations, we encounter most of the features already discussed in previous sections: Agents are heterogeneous and boundedly rational, market outcomes emerge from the will of the agents and their ability to create business opportunities in a competitive decentralized environment, and observed phenomena are necessarily generated from past history without any possibility of conceiving any pre-specified equilibrium state. Moreover, as stated above, the feedback effect from individual behavior to the global structure and vice-versa is clearly present in financial markets.

[53] argued that the complexity degree of the financial system has risen over time. As a consequence, the financial system became more fragile. If the financial system is complex, it shares the mentioned properties of complex systems, namely the absence of a well-defined equilibrium to which the system eventually tends in the long-term. Therefore, borrowers and lenders must at every moment reexamine their conditions, and the risk of default must not be ignored in any circumstance. Optimal solutions in an intertemporal perspective may not be adequate in a complex scenario where short-run unpredictability dominates.

A benchmark idea in Economics about financial markets concerns accepting the efficient market hypothesis, according to which market failures are absent and forces of demand and supply are enough to impose self-regulation and an inescapable ability of the system to return to equilibrium after any given disturbance. The efficient market hypothesis, though, involves strong assumptions on agents' rationality and absence of frictions that we do not encounter in practice. Therefore, a finer analysis is undoubtedly required. This analysis is necessarily associated with the detailed inspection of the specific local interactions taking place in markets where financial assets are traded. Financial markets, as any other trading structure in the economy, are far from being complete and the degrees of information and skills held by the participants vary significantly.

A prototypical example of a strand of literature where heterogeneity and interaction are the building blocks of a theory of non-trivial financial outcomes is the one developed by the Dutch economist Cars Hommes and his coauthors. [54] explained that financial systems should be interpreted as complex adaptive systems where agents are heterogeneous because they can adopt different investment strategies. Agents interact, learn and adapt over time preventing a unique investment strategy to become dominant. The purely rational outcome is, in this framework, often dominated by simple rules-of-thumb that offer better short-run outcomes. In this view, market psychology is important and agents taking investment decisions based on market fundamentals will coexist with technical analysts who look at patterns and past trends seeking for simple heuristics to apply to their decisions. This simple scenario, with a degree of complexity associated with heterogeneity and interaction, deals with market anomalies (e.g., speculative bubbles) endogenously, giving an intuitive explanation for a reality that conventional theory avoids considering as emerging from purely economic events.

The recognition that financial markets are complex bodies poses, in the perspective of [55], significant obstacles to the definition of regulatory policies for these markets. A 'one-size-fits-all' kind of policy will be ineffective, because it will be incapable of dealing with unique structures of interaction, unique profiles of investors and other market participants, and unique dynamics of evolution and innovation. Despite the hardship imposed to policy design by the recognition of the complex nature of the financial system, the acceptance that policy design is in fact complex is fundamental to advance in terms of understanding and of the ability to act upon financial markets.

Above all, the complexity of financial markets offers a relevant clue to the first step of an effective regulatory policy. This first step consists in identifying and possibly stylizing the network of relations that the specific financial system under evaluation involves. This means highlighting the nodes of the financial network, the links relating them to each other, and the respective strength, that connect each of the nodes. Once the main regularities of the financial network are captured, policies might be designed and implemented for the specific network, guaranteeing from the beginning a higher probability of success than those policies that are implemented in the financial system regardless of the identification of the main network properties.

The nodes in a financial network are all the players involved in financial transactions, including households and firms, and all the institutions for which lending and borrowing constitute their main activity (banks, insurance companies, investment funds). The links connecting these nodes are the financial claims and obligations that emerge from the established financial transactions. Note, in particular, the dynamic nature of this kind of network. More than many other networks of economic relations, the financial network changes, adapts and evolves very fast, as financial ties weaken, get stronger, disappear or are formed at every instant. This makes the financial system not only a complex system but also a system where the corresponding complexity is systematically changing and, most of the times, increasing.

The everchanging nature of the financial network in an economy results in a fundamental challenge for policy. This challenge is to define how to manage systemic risk and avoid systemic crises. Typically, a financial network involves a large amount of links across nodes, meaning that these nodes are almost all linked to one another, even if only indirectly. If an important player in the web of financial relations (e.g., a large bank, highly connected with the rest of the network) for some reason defaults on its obligations towards the other nodes, this will provoke a chain reaction that may trigger an overall incapacity of the system to perform its role. Network analysis unveils how easily a financial system may disrupt, but also furnishes a tool for policy guidance; if the authorities have a comprehensive notion of the network they are dealing with, it will be easier to identify the links to be carefully repaired in order to contain the spread of a possibly damaging financial crisis.

The complexity perspective to financial markets also suggests that no credit contract can be assessed only from the perspective of the lender-borrower relation. There are evident externalities that imply that no financial transaction can be interpreted as an exclusively private business. These externalities involve information and the credibility of the financial system (the failure of a financial institution to meet its obligations may conduct to a generalized loss of confidence in the financial system as a whole), and also balance-sheet interconnections (banks and other financial institutions are linked through a tight web of lending relationships, turning a solvability problem of an institution to rapidly become a solvability problem of the whole system). Understanding the nature of the externalities, present in financial transactions, is another essential element of the flexible policy proposal that the complexity approach brings to finance; being able to identify these indirect links across nodes in a financial network allows monetary authorities to undertake accurate fine-tuned policies that achieve results, containing the propagation of potentially damaging events, with relatively low costs for society.

The adoption of the complexity view in finance allows for the interpretation of the financial system as being inherently fragile. The constant change in network topology makes these networks hard to control, especially when negative unexpected events take place[56]; financial networks are prone to panic episodes and to rapid contagion given the high degree of connectivity. The policy challenges are relevant, but once understood the complex nature of financial relations, monetary authorities may build the required instruments to deal with financial challenges and financial distress.

Central banks might have a word to say about the nature and shape of the financial network. [57] suggested that the monetary authority may promote one of two types of network structures (or some structure in between). On one hand, we may have a vertically integrated system with low exposure to systemic risk; on the other hand, a decentralized strongly connected system may be promoted. The latter has the advantage, over the former, in respect to efficiency in liquidity circulation, but it allegedly increases the risk of systemic crises. Although real-world financial systems are currently closer to the (de)centralized option, the choice is pertinent: How much risk is the monetary authority willing to bear in order to guarantee that in 'normal times' financial resources flow with few frictions. Again, the answer seems to be in the ability to react and adapt. In the presence of potential systemic risks, central banks must have the tools to promote a quick change on the network's configuration, suppressing the links that could be harmful for the system under a given event. In simple terms, this means that in face of financial risk the decentralized financial structure must be transformed in a much more controllable environment in a short time span. And when the threat is gone, the flexible network structure should be restored.

In technical terms, the study of financial networks and of cascade or domino effects within them has been subject to intense research, namely under the simulation of agent-based computational models (see [49, 58, 59]). These models contain some pervasive features, namely (i) the existence of a few key players (large banks or funds) that serve as the vehicle for the fast propagation of contagion effects, (ii) a set of behavioral rules that allow to distinguish across players (e.g., agents may hold different associated levels of risk), (iii) the definition of a typology of policy regulatory actions and of policy transmission mechanisms, and (iv) the pre-specification of initial conditions and of the origin of the shocks that disturb the regular contact among financial agents.

7 Climate Change — A Complex Economic Problem

One area where complexity science has been particularly useful in addressing pressing issues is environmental economics[60]. [61] identified several topics for which a complex systems approach is especially useful. These are climate and pollution negotiations, the macroeconomic impact of climate change, the functioning of energy markets, and the propagation of technologies that are environmentally beneficial. A fruitful debate on all these topics requires taking an ecosystem where heterogeneous agents interact in a decentralized manner generating out-of-equilibrium dynamics.

The complex systems view is of special relevance because of the eventual catastrophic impact of climate change. This approach allows for a richer perspective on possible sudden and abrupt changes in the ecosystems and for a better assessment of alternative policy responses. There is a wide consensus in the academic community agreeing that traditional economic models are inadequate to address climate change. Specifically, [62] identified four key issues why this is so; first, these models do not deal adequately with uncertainty; second, there is also an inability to tackle aggregation and heterogeneity; third, as a consequence of the previous point, typical models also struggle with an effective explanation for innovation and technological change; fourth, there is a difficulty in devising realistic damage functions, i.e., functions that assess the economic impact of the consequences over the environment of global warming and other climate change phenomena. All this can, effectively, be better understood under a complexity view. Namely, damage functions might be constructed endogenously as individual actions are assumed to have specific effects over the assumed ecosystem. The correct delineation of the damage functions is important to assess the social and economic costs of the actions leading to climate change and to better understand the policies that need to be implemented to fight this problem.

[63] highlighted that the complexity approach allows for good results in other areas of economic thought (like the financial sphere) and, therefore, these authors predict that relevant results will also be obtained when adapting this approach to study environmentally related problems. One of the important virtues of complexity is that it is an approach well equipped to deal with extreme events occurring with a non-predictable periodicity; events such as these can be easily identified when looking at the earth's environmental history along the last few decades.

The economic approach to complex systems offers a new look over some issues that relate to economic and environmental sustainability. For instance, a complexity view, linked with the understanding of path-dependence and with the dynamics of interaction and emergence of new phenomena, might provide possible answers to promote the substitution of technologies for more efficient ones in the presence of strong lock-in effects. A closer look to agents' interaction might as well provide the required answers for finding more sustainable patterns of resource use by firms and also by consumers. These issues are discussed in detail in [64]. Sustainability is associated with maintaining living standards with a more balanced and judicious use of resources; a complex system, where agents are realistic boundedly rational agents with the capacity to learn, adapt and evolve, might furnish the scenario to understand the emergence of macro realities in which we live in.

Particularly important in today's world is the view that the high-carbon economy that exists is historically determined and that, despite the difficulties, it is possible to implement the policies that may overturn this reality, breaking the lock-in effect that prevents the economy to advance to an environmentally sustainable state of affairs.

In [65], environmental sustainability policy is discussed from a conceptual point of view. These authors claim that the typical representative agent optimal control problem is inadequate to address sustainability issues, because it does not account for path-dependency, emergent phenomena, behavioral heterogeneity, and decentralized interaction. The complexity approach, in turn, is well equipped to provide the tools that are essential to address the most relevant issues in sustainability policy, which comprise, according to the mentioned article, (i) the adoption of environmentally friendly technologies, (ii) the design and implementation of measures aiming at reducing carbon emissions, and (iii) the development of scenarios fostering the compatibility between the natural environment and the socioeconomic system.

Sustainability policy demands a flexible framework in which to think about environmental change. An agent-based complexity setup furnishes such framework, where the idiosyncrasies of agents, their adaptation and evolution mechanisms and the feedback from micro to macro and to micro again are well captured. Challenges for an effective sustainability policy arise from the fact that uncertainty exists on the compatibility between environment protection and economic growth. A complex system modeling device may help in quantifying the positive and negative effects of environment protection over growth and of growth over environment protection, offering thus additional tools for public authorities to decide. The complex systems approach to environmental issues is much more than a theoretical exercise; it involves explaining the evolution of the environment, given natural, social and economic constraints, in a way that helps public authorities to make educated and conscientious policy choices.

As already discussed in previous sections, once again complexity raises an enormous challenge for policy-makers. One-size-fit-all policies are particularly ineffective when it comes to environmental issues. Ignoring complexity can be extremely painful in a long-term perspective if this means maintaining ineffective environmental policies. Although complexity models might be hard to manage by policy practitioners, they bring a degree of realism to the discussion of environmental subjects that is required to implement high quality policies capable of tackling environmental problems that, by definition, are evolving and emergent.

Climate change, environmental damages and sustainability issues have huge implications over life on earth, and particularly on the ways of living of human beings. For instance, agricultural practices must change, adapt and evolve (see [66], for a discussion about how agent-based computational models may help in informing public authorities on the adaptation of agricultural practices to perturbations on environmental conditions). Other environmentally related subject in which the complexity approach may be fruitful is in equating the role of environmental degradation and climate change over human conflict; [67], [68] have assembled an agent-based model to evaluate the impact of increased resource scarcity over the potential for predatory behavior and increased conflict. Their fundamental conclusion is that in a complex scenario, where agents are capable of learning, adapting and evolving, progressive resource scarcity is not necessarily linked with increased predatory behavior. The complex system setting is adequate to show this because it provides a natural scenario for perceiving dynamic evolution: predatory behavior does not increase because agents can adapt (those being predated increase protective efforts; those predating understand that an increase in the intensity of predation is not cost-effective).

8 Income Inequality

The economic orthodoxy is particularly inappropriate to deal with income distribution and income inequality issues. Such issues require a setting where agent heterogeneity not only exists from the beginning (e.g., concerning agents' endowments) but where the assumed evolution process implies a strong propensity for such heterogeneity to persist and eventually to be amplified. Again, the complex systems approach is apparently an appropriate framework to launch a more appropriate discussion on the issue.

In the perspective of [69], network dynamics tend to promote income inequality because there is a natural tendency of networks, economic networks in particular, to turn into scale-free networks where a few agents acquire a central position, while a large majority of agents stay at the margin (with few links connecting them to the network and thus having few opportunities in the market economy). Resources will then have the tendency to accumulate in the hands of few people as connections concentrate around a small number of nodes. A power-law income distribution is then generated by a natural process of concentration that underlies network dynamics. This natural process is associated with the notion of preferential attachment.

Preferential attachment emerges from a boundedly rational decision that consists in choosing the business partners that are more prominent and closer and not necessarily those that would emerge from an optimal intertemporal decision. In this setting, those who are already big in the sense of concentrating power, clients and income, will tend to get bigger, in a process that feeds itself and conducts to ever increasing inequality. In this view, income inequality is a complexity phenomenon because individual interaction choices promote a given macro scenario that in turn decisively influences again individual choices. The outcome is not a desirable equilibrium solution, from a sensible social welfare point of view, but it is the one that individual choices lead to. In this respect public policies might have a relevant role in preventing cumulative causation from imposing an economy of extremes.

In [70], a macroeconomic agent-based model is devised with the objective of explaining the market mechanisms that promote the progressive concentration of wealth among the richest. By assuming that financial investments lead to a positive income, often larger than the growth rate of the economy, the dynamics of the model clearly point to the formation of asymmetric income distributions, which typically assume the form of distributions with a power-law tail. The mentioned authors explicitly conclude that extreme income and wealth concentration are unintended by-products of the organization of the economic system under the form of a complex network of heterogeneous interacting agents.

Other studies that develop agent-based models with heterogeneous agents endowed with different income levels at a given starting date abound in the literature. For instance, [71] and [72] established causality relations from increasing inequality to slow growth. Their complex system models imply that shocks that raise inequality in income distribution cause an increase in the fraction of credit-constrained households, what lowers consumption. Therefore, a recession can be caused, under this interpretation, as the result of some event in the economy that promotes increased inequality (e.g., the imposition of some regressive tax). On the contrary, a more progressive tax system is likely to have a stabilizing effect.

In the same vein, the agent-based model of [73] highlights that policy measures such as increased tax progressivity and promotion of increases in the wages of the less skilled workers create positive effects both over economic development and mitigation of income inequalities. This is not a completely evident outcome; opposite measures that benefit profits over wages may boost investment and promote growth. However, a sensible agent-based framework of the macroeconomy points out that such effect is overtaken by the polar argument, namely the idea that higher wages mean higher expenditure levels that stimulate production, employment and growth in the short-run.

In [74], a similar type of agent-based framework is directly used to assess the impact of labor market reforms over unemployment and inequality. The model reveals that labor market reforms aiming at reducing real wages, lowering the bargaining power of workers, suppressing employment protection, and reducing unemployment benefits, tend to increase unemployment and the economy's income inequality. This is not an obvious result as well, since the conventional wisdom is precisely the opposite, i.e., this type of labor market structural reforms is supposed to increase flexibility, or decrease rigidity, and therefore should contribute to eliminate the constraints that exist, namely in Europe, to the creation of jobs. Because this logical argument does not encounter much empirical support on the economic history of the last decades, the complex system model developed by these authors reveals that the complexity approach may be a better guide for policy than the conventional economic theory recipe.

Income inequality is not circumscribed to household's differences on disposable income; it can be discussed, as well, under the regional perspective, and also in this regional set-up the complex system approach has been applied. The study by [75] employs a large-scale agent-based model to assess income inequality across European Union regions. The main aim is to evaluate how cohesion policies that are technology-oriented might help in promoting convergence of per capita income across regions. Heterogeneity of households and firms reveals the existence of different degrees of absorptive capacities across regions.

In some empirical studies, [76], [77], the degree of economic complexity of a nation is measured, taking into account the country's level of industrialization and exporting profile. These studies conclude that highly complex economies (which produce and export a relatively large variety of sophisticated goods and services) have lower levels of income inequality. The explanation for this relationship between complexity and income inequality relies on the learning and job opportunities that arise in diversified industrialized economies, which allow for a leveling of income. In economies with a low level of diversification and production of low value-added goods, unemployment crises are more likely to set in and low paying jobs tend to persist. Complexity is, in this perspective, associated with tacit knowledge that allows the economy to innovate and evolve, bringing more opportunities to narrow the wage and wealth gaps. Although logically acceptable, and empirically validated in given circumstances (e.g., in the case of developing countries), the mentioned reasoning is not completely in line with the observation of income trends in the developed world, where highly complex and globally integrated economies have also become extremely unequal economies regarding their income distribution.

9 Wrapping Things Up: Intertwined Complexity

In the above sections, we have separately discussed a series of economic issues for which complexity features naturally emerge. These topics are not separable blocks; they are pieces of an integrated general structure of analysis, a structure that we now briefly discuss. Taking such a general structure implies privileging comprehensiveness over detail; therefore, the brief analysis in this section should be interpreted as a basic reference guide to model interconnected complex economic features, rather than a formal complexity framework.

The basic entity in economic analysis is the agent. As remarked in Section 2, agents are heterogeneous and might be distinguished from one another by, among others, the following features: Preferences, endowments, expectations, hierarchical position, degree of connectivity, and ability to engage in successful interactions. Let $a^j(\boldsymbol{h})$, $j \in J$ represent agent j; agent j is distinguishable from any other agent in set J because she is endowed with a series of features, as those mentioned above, which are unique for this agent and that are included in vector $\boldsymbol{h}$.

Elements in vector $\boldsymbol{h}$ are not static endowments; they change and evolve through interaction. Therefore, a second step in our general structure consists in defining a network allowing for decentralized interaction. In this network, regardless of the specific phenomenon under scrutiny, agents establish contact with one another in order to exchange ideas, information, goods, assets, and other tangible and intangible entities. To define the network, we focus on its outmost relevant feature, namely its connectivity properties; let $P(k)$ be the degree distribution of the network, i.e., the distribution of the probabilities of one node being linked with other k nodes. Economic networks are typically scale-free networks, where the majority of the agents (each represented by a node) have relatively few connections, and where there is a small number of highly connected agents (hubs). As it is evident, characterizing connectivity in such a stylized way prevents accessing important information, namely the strength of each link; however, it is sufficient to make the point that markets (and economic relations in general) are not complete: No one has the possibility of systematically being in contact with everyone else in the economy at the same time.

The network represents the macro-system that emerges under a bottom-up perspective from the interaction among the heterogeneous micro-units. This interaction systematically shapes and reshapes the environment and the macro changes will force the individual agents to continually adapt, learn, and evolve. Because each agent $a^j(\boldsymbol{h})$ is under systematic evolution, establishing and breaking ties with others, this creates emergent aggregate phenomena that once shaped feeds back again to the individual units. This process continues in an everlasting irregular loop that maintains the economy permanently out of equilibrium and implies that its performance is historically determined by how agents have behaved in the past and how such behavior led to aggregate results.

Figure 1 schematizes the above straightforward complexity interpretation of the economy.

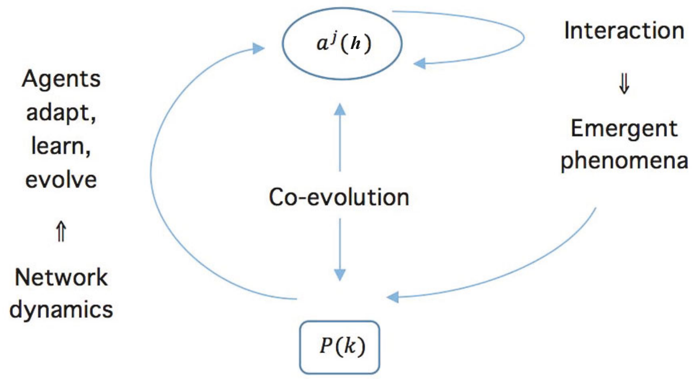

Figure 1 The economy as a complex system

By sketching the above general framework, one can identify where the several pieces of our discussion fit in. This is done through Figure 2. The figure displays a scheme where the various assumed dimensions involve complexity, but at different scales.

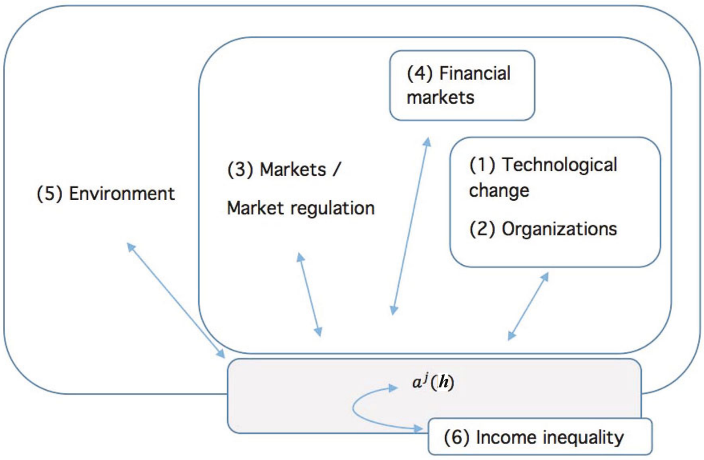

Figure 2 Complexity phenomena in Economics and their interrelations

In Figure 2, the environment, and associated climate changes, are displayed as being the main macro-structure or macro-network: Every behavior of the heterogeneous micro-units in the economy (households, firms, public institutions, financial intermediaries, and so on) has an impact in the environment as a whole. Still on a macro level, the actions of agents shape markets and the policies that assist in regulating them; the evolution of markets is decisive for the shaping of the profile of the micro units. Within the overall notion of markets acquires special relevance, as described, the role of financial institutions and how these shape and are shaped by the various agents (who, in this context, have different saving and investment profiles). Income is generated in firms, which have an obviously relevant role in markets. As characterized in Sections 3 and 4, they are also complex environments, where self-interested agents interact generating evolving value-added activities, both from the point of view of organizational structure and change and from the perspective of innovation and technological advancement. The last discussed issue, in Section 8, might be interpreted at a relatively distinct level. Income inequality does not constitute per se a complex system; in turn, the respective dynamics are the result of how individual agent profiles evolve as they participate in the various complex environments one has highlighted.

10 Conclusion

The features insistently mentioned along this text as being the characteristics that define and shape a complex system might be intuitively found in any decentralized socio-economic system composed by self-interested interacting individuals. The relevant question is whether, to explain relevant socio-economic phenomena, one can abstract from complexity and take a stylized view of reality that is more effective in offering a simple, robust and cohesive explanation of how things truly work. In many areas of Economics stylized representations of the reality proved to be useful for the understanding of fundamental issues (e.g., the demand curve — Supply curve apparatus to explain the basics of price formation). However, in many areas of study and sub-disciplines of Economics, the science can only evolve, from the point in which now it stands, if the complexity view is no longer avoided. In this paper, six substantial areas where complexity analysis and mainstream Economics have merged have been discussed in some detail. These are areas where a full understanding of the underlying phenomena can only take place if one recognizes the existence of heterogeneity, bounded rationality, evolution, learning, and emergence. The quest for complexity in Economics has led us to reflect upon the issues of technological progress, organizational learning, market regulation, financial markets, the environment, and income inequality; these were the themes where we found a more pronounced presence of complexity analysis in Economics.

A central issue of the pursued discussion concerns the design and implementation of public policies. In any case, one has concluded that the complexity view introduces a degree of adaptability and evolution into the systems under scrutiny that prevents any inflexible policy rule to be effective. The main virtue of the complexity approach is that it should allow for a dynamic representation of a network of relations over which public authorities should act upon. The implementation of policies over an ever-evolving complex network is comparable with shooting a moving target; it is an extremely demanding task, but there is no real alternative to it. In the same way a stopped watch gives the correct time twice a day, an unchangeable policy rule may be effective from time to time, but it will hardly be the expected and desired solution for problems as market deregulation, climate change, or increasing inequality.

References

[1] Hodgson G M, Come back Marshall, all is forgiven? Complexity, evolution, mathematics and Marshallian exceptionalism, *Eur. J. Hist. Econ. Thou.*, 2013, **20**: 957–981.

[2] Caldari K, Marshall and complexity: A necessary balance between process and order, *Cambridge J. Econ.*, 2015, **39**: 1071–1085.

[3] Colander D and Kupers R, *Complexity and the Art of Public Policy: Solving Society's Problems from the Bottom Up*, Princeton University Press, Princeton and Oxford, 2014.

[4] Heise A, Whither economic complexity? A new heterodox economic paradigm or just another variation within the mainstream?, *Int. J. Plural. Econ. Edu.,* 2017, **8**: 115–129.

[5] Faggini M and Parziale A, More than 20 years of chaos in economics, *Mind & Society*, 2016, **15**: 53–69.

[6] Odum E P and Barrett G W, *Fundamentals of Ecology*, 5th Edition, Thomson, Brooks/Cole, Belmont CA, 2005.

[7] Allen P, Complexity, uncertainty and innovation, *Econ. Innov. New Tech.*, 2013, **22**: 702–725.

[8] Bargigli L and Tedeschi G, Interaction in agent-based economics: A survey on the network approach, *Physica A*, 2014, **399**: 1–15.

[9] Cilliers P, Biggs H C, Blignaut S, et al., Complexity, modelling, and natural resource management, *Ecol. Soc.*, 2013, **18**(3): article 1.

[10] Bruno B, Faggini M, and Parziali A, Complexity modelling in economics: The state of the art, *Economic Thought*, 2016, **5**: 29–43.

[11] Foster J and Metcalfe J S, Economic emergence: An evolutionary economic perspective, *J. Econ. Behav. Organ.*, 2012, **82**: 420–432.

[12] Gallegati M and Kirman A, Reconstructing economics: Agent based models and complexity, *Complexity Econ.*, 2012, **1**: 5–31.

[13] Rosser J B, Emergence and complexity in Austrian economics, *J. Econ. Behav. Organ.*, 2012, **81**: 122–128.

[14] Kao Y F and Velupillai K V, Behavioural economics: Classical and modern, *Eur. J. Hist. Econ. Thou.,* 2015, **22**: 236–271.

[15] Tesfastsion L S, Agent-based computational economics: Modeling economies as complex adaptive systems, *Inf. Sci.*, 2003, **149**: 263–269.

[16] Frenken K, Technological innovation and complexity theory, *Econ. Innov. New Tech.*, 2006, **15**: 137–155.

[17] Antonelli C, The economic complexity of technological change: Knowledge interaction and path dependence, *Handbook on the Economic Complexity of Technological Change*, ch.1: 3–59, Ed. by Antonelli C, Edward Elgar, Cheltenham, 2011.

[18] Krafft J and Quatraro F, The dynamics of technological knowledge: From linearity to recombination, *Handbook on the Economic Complexity of Technological Change*, ch.7: 181–200, Ed. by Antonelli C, Edward Elgar, Cheltenham, 2011.

[19] Antonelli C and Scellato G, Complexity and technological change: Knowledge interactions and firm level total factor productivity, *J. Evol. Econ.*, 2013, **23**: 77–96.

[20] Maggitti P G, Smith K G, and Katila R, The complex search process of invention, *Res. Policy*,

2013, **42**: 90–100.

[21] Lane D A, Complexity and innovation dynamics, in *Handbook on the Economic Complexity of Technological Change*, ch.2: 63–80, Ed. by Antonelli C, Edward Elgar, Cheltenham, 2011.

[22] Lane D A and Maxfield R, Ontological uncertainty and innovation, *J. Evol. Econ.*, 2005, **15**: 3–50.

[23] Colombelli A and von Tunzelmann N, The persistence of innovation and path-dependence, *Handbook on the Economic Complexity of Technological Change*, ch.4: 105–119, Ed. by Antonelli C, Edward Elgar, Cheltenham, 2011.

[24] Barabási A L and Albert R, Emergence of scaling in random networks, *Science*, 1999, **286**: 509–512.

[25] Cantner U and Graf H, Innovation networks: Formation, performance and dynamics, *Handbook on the Economic Complexity of Technological Change*, ch.15: 366–394, Ed. by Antonelli C, Edward Elgar, Cheltenham, 2011.

[26] Ormerod P, Rosewell B, and Wiltshire G, Network models of innovation process and policy implications, *Handbook on the Economic Complexity of Technological Change*, ch.19: 492–532 Ed. by Antonelli C, Edward Elgar, Cheltenham, 2011.

[27] Saviotti P P, Knowledge, complexity and networks, *Handbook on the Economic Complexity of Technological Change*, ch.6: 141–180, Ed. by Antonelli C, Edward Elgar, Cheltenham, 2011.

[28] Chiva R, Ghauri P, and Alegre J, Organizational learning, innovation and internationalization: A complex system model, *Brit. J. Manage.*, 2014, **25**: 687–705.

[29] Dosi G and Marengo L, The dynamics of organizational structures and performances under diverging distributions of knowledge and different power structures, *J. I. Econ.*, 2015, **11**: 535–559.

[30] Dosi G and Virgillito M E, In order to stand up you must keep cycling: Change and coordination in complex evolving economies, *Struct. Change Econ. D.*, 2017, in press.

[31] Chang M H and Harrington Jr J E, Agent-based models of organizations, *Handbook of Computational Economics*, Eds. by Tesfastsion L and Judd K L, 2006, **2**: 1273–1337.

[32] Anderson P, Complexity theory and organization science, *Organ. Sci.*, 1999, **10**: 216–232.

[33] Dosi G, Faillo M, Manara V C, et al., The formalization of organizational capabilities and learning: Results and challenges, *LEM Papers Series* 2017/08, Sant'Anna School of Advanced Studies, Pisa, Italy, 2017.

[34] Schneider M and Somers M, Organizations as complex adaptive systems: Implications of complexity theory for leadership research, *Leadership Quart.*, 2006, **17**: 351–365.

[35] Uhl-Bion M, Marion R, and McKelvey B, Comlpexity leadership theory: Shifting leadership from the industrial age to the knowledge era, *Leadership Quart.*, 2007, **18**: 298–318.

[36] Dosi G, Marengo L, and Nuvolari A, Institutions are neither autistic maximizers nor flocks of birds: Self-organization, power, and learning in human organizations, *LEM Papers Series* 2016/38, Sant'Anna School of Advanced Studies, Pisa, Italy, 2016.

[37] David P, Path dependence and predictability in dynamic systems with local externalities: A paradigm for historical economics, *Technology and the Wealth of Nations*, Eds. by Foray D and Freeman C, Pinter, London, 1992, 208–231.

[38] Ioannides Y M, Complexity and organizational architecture, *Math. Soc. Sci.*, 2012, **64**: 193–202.

[39] Elsner W, Hocker G, and Schwardt H, Simplistic vs complex organizations: Markets, hierarchies, and networks in an organizational triangle — A simple heuristic to analyze real-world

organizational forms, *J. Econ. Issues*, 2010, **44**: 1–30.
[40] Durlauf S N, Complexity, economics and public policy, *Polit., Philos. Econ.*, 2012, **11**: 45–75.
[41] Durlauf S N, Complexity and empirical economics, *Econ. J.,* 2005, **115**: 225–243.
[42] Elsner W, Policy and state in complexity economics, *A Modern Guide to State Intervention*, Eds. by Karagiannis N and King J E, Edward Elgar Publishing, Cheltenham, 2019, 13–48.
[43] Velupillai K V, The impossibility of an effective theory of policy in a complex economy, *Complexity Hints for Economic Policy*, Eds. by Salzano M and Colander D, Springer, Milan, 2007, 273–290.
[44] Kirman A, Complexity and economic policy: A paradigm shift or a change in perspective? A review essay on David Colander and Roland Kupers's complexity and the art of public policy, *J. Econ. Lit.*, 2016, **54**: 534–572.
[45] Dawid H, Gemkow S, Harting P, et al., Labor market integration policies and the convergence of regions: The role of skills and technology diffusion, *J. Evol. Econ.*, 2012, **22**: 543–562.
[46] Dosi G, Fagiolo G, Napoletano M, et al., Income distribution, credit and fiscal policies in an agent-based Keynesian model, *J. Econ. Dyn. Control*, 2013, **37**: 1598–1625.
[47] Furtado B A and Eberhardt I D R, A simple agent-based spatial model of the economy: Tools for policy, *J. Artif. Societies Soc. Simul.*, 2016, **19**(4).
[48] Tabak B M, Cajueiro D O, and Serra T R, Topological properties of bank networks: The case of Brazil, *Int. J. Mod. Phys. C*, 2009, **20**: 1121–1143.
[49] Grilli R, Tedeschi G, and Gallegati M, Markets connectivity and financial contagion, *J. Econ. Interact. Coor.*, 2015, **10**: 287–304.
[50] Russo A, Riccetti L, and Gallegati M, Increasing inequality, consumer credit and financial fragility in an agent based macroeconomic model, *J. Evol. Econ.*, 2016, **26**: 25–47.
[51] Kenett D and Havlin S, Network science: A useful tool in economics and finance, *Mind & Society*, 2015, **14**: 155–167.
[52] Cetorelli N and Goldberg L S, Organizational complexity and balance sheet management in global banks, *NBER Working Paper*, 22169, 2016.
[53] Kitt R, Economic decision making: Application of the theory of complex systems, *Chaos Theory in Politics*, Eds. by Banerjee S, Ercetin S S, and Tekin A, Springer, Amsterdam, 2014, 51–73.
[54] Hommes C H, Interacting agents in finance, *The New Palgrave Dictionary of Economics*, Eds. by Durlauf S N and Blume L E, 2nd Edition, Palgrave MacMillan, Basingstoke, 2006, **4**: 402–406.
[55] Gaffeo E and Tamborini R, If the financial system is complex, how can we regulate it?, *Int. J. Polit. Eco.*, 2011, **40**: 79–97.
[56] Cruz J and Lind P, The dynamics of financial stability in complex networks, *Eur. Phys. J. B*, 2012, **85**: 1–9.
[57] Giocoli N, Network efficiency and the banking system, *Int. Rev. Econ.*, 2014, **61**: 203–218.
[58] Ramanauskas T, Agent-based financial modelling: A promosing alternative to the standard representative agent approach, *Bank of Lithuania Working Paper*, 2009, **3**.
[59] Bookstaber R, Using agent-based models for analyzing threats to financial stability, *US Department of the Treasury*, Working Paper, 2012, 12–03.
[60] Gubareva M and Gomes O, On the edge of climate change: In a search of an adequate agent-based methodology to model environmental dynamics, Eds. by Sequeira T and Reis L, *Climate Change and Global Development, Contributions to Economics*, 2019, 37–57. https://doi.org/10.1007/978-3-030-02662-2_3.
[61] Balint T, Lamperti F, Mandel A, et al., Complexity and the economics of climate change: A

survey and a look forward, *Ecol. Econ.*, 2017, **138**: 252–265.

[62] Farmer J D, Hepburn C, Mealy P, et al., A third wave in the economics of climate change, *Environ. Res. Econ.*, 2015, **62**: 329–357.

[63] Farmer J D and Hepburn C, Less precision, more truth: uncertainty in climate economics and macroprudential policy, *Bank of England Interdisciplinary Workshop on the Role of Uncertainty in Central Bank Policy*, 2014.

[64] Foxon T J, Kohler J, Michie J, et al., Towards a new complexity economics for sustainability, *Cambridge J. Econ.*, 2013, **37**: 187–208.

[65] Mercure J F, Pollitt H, Bassi A M, et al., Modelling complex systems of heterogeneous agents to better design sustainability transitions policy, *Global Environ. Chang.*, 2016, **37**: 102–115.

[66] Berger T and Troost C, Agent-based modelling of climate adaptation and mitigation options in agriculture, *J. Agr. Econ.*, 2014, **65**: 323–348.

[67] Hassani-Mahmooei B and Parris B W, Why might climate change not cause conflict? An agent-based computational response, MPRA Paper, 2012, 44918.

[68] Hassani-Mahmooei B and Parris B W, Resource scarcity, effort allocation and environmental security: An agent-based theoretical approach, *Econ. Model.*, 2013, **30**: 183–192.

[69] Markey-Towler B and Foster J, Understanding the causes of income inequality in complex economic systems, *University of Queensland Discussion Paper*, 2013, 478.

[70] Desiderio S and Chen S, Why the rich become richer: Insights from an agent-based model, *Int. J. Comput. Econ. Econometrics*, 2016, **6**: 258–275.

[71] Cardaci A and Saraceno F, Inequality, financialisation and economic crises: An agent-based model, *Sciences-Po Publications,* 2015, 2015-27.

[72] Palagi E, Napoletano M, Roventini A, et al., Inequality, redistributive policies and multiplier dynamics in an agent-based model with credit rationing, *Sciences Po publications*, 2017, 2017-06.

[73] Caiani A, Russo A, and Gallegati M, Does inequality hamper innovation and growth? An AB-SFC analysis, *J. Evol. Econ.,* 2019, **29**: 177–228.

[74] Dosi G, Pereira, M C, Roventini A, et al., The effects of labour market reforms upon unemployment and income inequalities: An agent based model, *Socio-Econ. Rev.,* 2018, **16**: 687–720.

[75] Dawid H, Harting P, and Neugart M, Cohesion policy and inequality dynamics: Insights from a heterogeneous agents macroeconomic model, *J. Econ. Behav. Organ.*, 2018, **150**: 220–255.

[76] Hartmann D, Guevara M R, Jara-Figueroa C, et al., Linking economic complexity, institutions and income inequality, *World Development*, 2015, **93**: 75–93.

[77] Sbardella A, Pugliese E, and Pietronero L, Economic development and inequality: A complex system analysis, *PLoS ONE*, 2017, **12**(9): e0182774.