Bocconi

WORKING PAPER SERIES
ISSN 1973-0381

WORKING PAPER
N. 104
MARCH 2018

INSTITUTIONAL DYNAMICS IN AN ECONOMY SEEN AS A COMPLEX ADAPTIVE SYSTEM

Miguel Vazquez

Università Bocconi
IEFE
Centre for Research on Energy and Environmental Economics and Policy

Institutional dynamics in an economy seen as a complex adaptive system

Miguel Vazquez

IERES, George Washington University, 1957 E St NW, Washington, DC 20052.

Florence School of Regulation, RSCAS, European University Institute.
Via Giovanni Boccaccio, 121, 50133 Firenze FI, Italy.

IEFE, Bocconi University. Via Röntgen, 1, 20136, Milan, Italy.

Email address Miguel Vazquez: miguel.vazquez.martinez@gmail.com

Abstract

The primary objective of this paper is to study the role of institutions evolution assuming that economies are generally out of equilibrium. The focus is developing a logical framework that allows describing economies as complex adaptive systems. This will allow deducing the uncertainty inherent to the economy as a consequence of system characteristics (instead of assuming it as hypothesis). Thus, it will be possible to characterize adaptation from fundamental properties of the system. As institutions are mechanisms to facilitate adaptation, the paper will provide a fundamental description of the functioning and logic for institutions within complex adaptive systems.

Key words: Complex adaptive systems; Institutional dynamics; Algorithmic rationality; Uncertainty.

JEL: D8, D02, O3, B5.

1. Introduction

The primary objective of this paper is to study the role of institutions assuming that economies are out of equilibrium. To that end, the focus is developing a logical framework that allows describing economies as complex adaptive systems, and analyze the functioning and logic for institutions within this framework.

Complexity economics has been proposed as a conceptual framework for the study of out-of-equilibrium economies, e.g. (Arthur, 2014). However, complexity economics has no standard definition. This might be related to the fact that complexity itself has no standard definition. For instance, (Lloyd, 2001) provided a list of quantitative measures grouped according to the three broad headers, which suggest different definitions of complexity: difficulty of description, difficulty of creation and degree of organization, see also (Gell-Mann and Lloyd, 1996) and (Gell-Mann, 1995). Analogously, complexity science should not be considered as a single theory but a collection of conceptual tools proposed in the context of a range of disciplines, both in natural and social sciences, e.g. tipping-point models applied to sociological problems, (Schelling, 1978), or sand-pile models to describe self-organized criticality, (Bak et al., 1987). Correspondingly, the concept "complexity economics" is used in rather different manners. For instance, (Perona, 2007) noted that the term complexity economics does not imply a unified methodological approach: complexity is used in an ontological sense in some works, and in an epistemological sense in some others[1].

A first view on the objective of complexity science when applied to economics is presented in (Foxon et al., 2012). It proposes that complexity economics is closer to a research program, in the sense that it can be understood as a toolkit to study problems in different areas (physics, biology, economics…). Early works such as (Arthur, 1994) also aimed at applying concepts of complexity science to economic problems. In summary, this strategy, which can be called "complexity as a toolkit", consists of selecting one property typically observed and studied in physical or biological phenomena, and apply the models developed therein to explain certain economic phenomena. A typical example of this strategy is using the concept of positive feedbacks developed in control theory to explain financial bubbles, (Arthur, 1995). Closely related to the previous view, complexity science has also been considered as a tool to unify economics and other sciences. The rationale behind this approach is that if some phenomenon is common to several sciences (e.g. positive feedbacks), its study will have insight for all those sciences. For instance, (Rosser Jr, 2010) discusses whether a unification of several sciences (economics, physics and biology) can happen within the context of complexity (it concludes that such combination does not exist at the moment).

An alternative approach, which can be called "complexity as a framework", aims at developing a logical framework to describe economic systems based on complexity concepts. (Arthur, 2014) represents an attempt to build a general description of economic problems based on complexity concepts.

[1] (Dequech, 2004) shows that the term uncertainty is subject to the same variety of definitions.

(Foster, 2005) proposes a methodology that is similar to the one proposed in this paper, building from the definition of a complex system and then deducing its properties. This paper, nonetheless, uses the definition of complex adaptive systems proposed in (Page, 2010) and identify economies as complex adaptive systems, which are characterized by four basic properties: *i) interdependency; ii) connectedness; iii) diversity; iv) adaptiveness*.

Comparing the two previous approaches (complexity as a toolkit and complexity as a framework), one of the main differences is whether to define the characteristics of the outcomes of the system, or the characteristics of the system itself. In order to illustrate the difference, let me consider the following instance: the first approach (complexity as a toolkit) would define a complex system as one creating emergence (i.e. a type of outcome), whereas the second approach (complexity as a conceptual framework) would derive emergence from fundamental properties of the system (i.e. emergence is a consequence of system's diversity, connectedness, adaptiveness and interdependence).

One may identify two basic consequences of the above differences between the two approaches. First, it is more difficult to enumerate all possible characteristics of system outcomes (e.g. they are characterized by power laws, there is emergence, etc.) than the characteristics of the system itself (we used only four of them). More importantly, characterizing system outcomes does not help to explain the transition from the micro behavior to the macro behavior, in the sense of (Schelling, 1978).

In summary, this paper adopts the second strategy (complexity as a framework) and it defines an economy as:

> *A network made up of diverse entities, who interact among themselves, whose actions are interdependent, and who have the ability to adapt and to learn.*

The objective of this paper is to analyze the role of institutions within complex adaptive systems. Institutions are "the humanly devised constraints that structure political, economic and social interaction. They consist of both informal constraints (sanctions, taboos, customs, traditions, and codes of conduct), and formal rules (constitutions, laws, property rights)", (North, 1991).

Consequently, this paper is focused on the study of rules. I use the definition of rules provided in (Crawford and Ostrom, 1995): prescriptions of what agents involved "must" do, "must not" do, or "may" do, and the associated sanctions in case rules are not followed. There are two fundamental questions associated with the design of rules: who defines the rules, and what objectives rule-making processes pursue.

In order to investigate these questions, I propose the following reasoning. First, I will show what kind of outcome can be expected from a complex economy described through the four properties of complex adaptive systems. Second, I will deduce the way in which agents behave in complex adaptive systems, in order to analyze, on the one hand, the effects of rules on their decision-making process and, on the other, the logic for rule-making processes. Third, I will discuss the concept of adaptation introduced by complex adaptive systems, as adaptation plays a central role in the definition of rules, and the process to change them. Fourth, the relationship between this paper's approach and literature on institutions will be discussed.

The organization of the paper is as follows. Section 2 will deduce general kinds of phenomena that should be expected to be outcomes of economic systems from the four elementary characteristics defined in this introduction. Attention will be paid to the comparison of this approach to others found in the literature. Section 3 will use the four properties of complex adaptive systems to describe the individuals' behavior implied by them. Section 4 will analyze the concept of adaptation with respect to the representations developed in section 3. In particular, it considers different definitions of adaptation with respect to the different individual rationalities considered. Section 5 makes the connection between the complexity-based description and the Institutional Analysis and Development framework, in order to establish the role that institutions may play in an economy seen as a complex adaptive system. Sections 6 collects final remarks.

2. Fundamental properties of economies as complex adaptive systems

This section constitutes the first step of the reasoning developed in this paper. Its aim is analyzing several important implications of considering economies as systems characterized by diversity, connectedness, interdependency and adaptiveness. First, I check whether typical characteristics of outcomes in complex adaptive systems can be deduced from this fundamental system properties. Then I will investigate the relationship between these fundamental characteristics and the system outcomes. Finally, I will compare this approach to others found in the literature.

2.1 What kind of outcome should we expect of economies?

The aim of this subsection is to develop a review of the variety of phenomena that have been associated with complexity, in order to show how they are implied in the definition of economy as a complex adaptive system. The motivation for this description strategy is to prove that the previously defined minimal set of system characteristics allow deriving the rest without the need of further premises. All of those characteristics were associated with properties of the system as opposed to outcomes of the system.

In general, we can recognize several characteristics of system outcomes that are derived from the previous characteristics:

■ **They produce emergent properties**

Because they are connected, their elements are interdependent, and they adapt, economies produce phenomena that were not planned nor decided by a single agent. The main concept behind this characteristic of system outcomes is unpredictability. We will discuss this concept in more detail in section 3.1, when we analyze the definition of uncertainty implied in our definition of economy as a complex adaptive system. This property is fundamentally different of some of the definitions of complexity, namely those associated with the idea of "difficulty", (Page, 2008).

To illustrate this idea, consider the way in which engineers conceive a gas-fired power plant. It is a network of quite diverse interconnected entities. For instance, some of them have a gas turbine and a steam turbine that drive a common generator. They have condensers, pumps, heat-exchangers, etc. All these parts are also interdependent, which make three of the four characteristics required to be a complex adaptive system. But engineers decompose these parts in modules typically related to internal physical processes, and then they combine these physical processes to obtain the desired outcome (the design principles). In any case, once all these parts of the power plant are put together, and the corresponding tests are performed, these "difficult" systems are quite predictable. It is not difficult to know what is going to happen to the outcome of the power plant if one uses synthesis gas instead of natural gas, for example. This view is not far from the hierarchical complexity described in (Simon, 1962), which in turn can be related to the modularity ideas developed in (Langlois, 2002) and (Baldwin and Clark, 2000).

Complex adaptive systems do not behave this way. The nature of this difference stems from the adaptiveness property: they can modify the interconnections between the different parts of the network, thus creating a new configuration of the system. (Arthur, 2009) described technology using these reasoning.

■ **They produce large events**

Because they are diverse and they are interdependent and connected, sometimes all elements may react in the same way creating positive feedbacks. To illustrate the idea, consider the competition between Betamax and VHS to define the standard format for home videocassette recorders (VCR). Although Betamax was the first mover in the market, it started losing market-share already in 1978. At the end of the 1980's, Sony stopped producing Betamax VCRs.

A very simple model of this situation, which helps illustrating the idea of positive feedback, is to consider that the whole market for VCR is made up of one hundred people, all with different tastes. We consider that each person in the group has a behavior defined by the fact that they will adopt a certain standard for VCR if they observe enough people adopting that format. That is, if one person observe that the amount of people adopting VHS is above her threshold, she will adopt VHS as well[2]. Let us consider that each person of the group of one hundred has a threshold corresponding with her number. That is, person number one has a threshold of one (she will adopt VHS if she observes one person adopting VHS), person 98 has a threshold of 98, and so on. Note that the average threshold is fifty.

The previous model implies that if just one person chooses the VHS standard, the final result is that everyone will adopt the VHS format. The logic for that is if just one person decides to use the VHS format, everyone but one will decide to keep the format they are already using. But the person with the threshold one (she changes if she observes one person changing) will adopt the VHS. With the two people migrating to VHS, almost no one will react expect the

[2] We do not discuss whether this is because a direct or indirect network effect or other reasons, (Arthur, 1994).

person with threshold two. Continuing the reasoning shows that in the end, everyone adopts the VHS format.

This simplified model is not intended to describe reality accurately but to point at the main idea behind positive feedbacks: large systemic phenomena can be originated in a localized event (unstable system). This in turn has several consequences associated with the way in which we look at system properties. First, the average does not matter. Note that in the previous instance, the average threshold was 50, but it is enough that there is enough different people (in our extreme case, we had the complete range of possible thresholds). This points out the relevance of diversity: positive feedbacks require a certain level of diversity. Indeed, if each one of the one hundred individuals had the same threshold, the previous feedback mechanism would not exist.

There are a considerable number of related phenomena that have been described within the complexity science literature. For instance, several models put forward within the physics literature have been applied to study economic phenomena (e.g. tipping points). We will not develop this reasoning in detail. From the point of view of this paper, the logic is that the underlying rationale for these models is the mechanism of positive feedback.

Related to the previous feedback effect is the idea of path dependence. In addition to the previously commented positive feedback, there may be negative feedbacks. They are related to more intuitive ideas in systems in equilibrium. For instance, if the market price increases, demand decreases and thus the price decreases. The point is that the combination of positive and negative feedbacks create a situation where the system is highly dependent of the previous state. That is, the net effect of positive and negative feedbacks create path dependence.

Mathematically, this means that the most important effects take place in the tails (as “the average does not matter”). Consequently, the relevant probability distributions are not Gaussian but power laws, see for instance (Mitzenmacher, 2004). These characteristics are closely related to the systems that are extremely dependent of initial conditions (oftentimes called chaotic systems). Although there is a variety of applications, from the viewpoint of this paper the most important result derived from chaos theory is that very unpredictable systems can arise from rather simple rules. We will comment in detail this idea in section 3.1.

■ **They are robust to unexpected changes**

Because they are diverse and they adapt, they can reconfigure themselves in the presence of single random events even when they are relatively catastrophic, as in financial crises, so that they do not lose functionality.

The rationale behind the discussion on robustness is more controversial, so let me show schematically the reasoning of the following analysis. The first step is to define precisely the meaning of diversity, as it may have different interpretations depending on the context. In this paper, diversity encompasses the measure of several dimensions, both changes along the same numerical category (as represented by statistical measures) and changes across types (as represented by entities with different functionalities). From a complex adaptive systems' point of view, the direct consequence of diversity in a system is that it allows innovation[3].

Nonetheless, diversity also may favor robustness. The basic mechanism behind this is that diversity provides the capability to have a response for unforeseen circumstances. As before, this concept includes both "variation" (as measured for instance by the standard deviation), which can be related to the traditional diversification of portfolio theory, (Markowitz, 1952), and diversity of types, which is closer to the idea of variety in evolutionary systems.

2.2 Meso-levels: the balance between too complex and too simple

One of the most discussed ideas within the context of complexity economics is the idea that systems can be studies in different levels of aggregation: micro, meso and macro, see for instance (Cantner and Hanusch, 2005). The main advantage of this view is that it allows identifying a type of phenomenon that takes place only at the meso level. That is, it does not happen at the individual particle level nor at the aggregate system level. As expressed by (Arthur, 2014), it happens in-between.

On the other hand, the previous standpoint may suggest that complexity can be avoided by working at different levels of aggregation. However, the approach adopted in this paper is that the view of complex adaptive systems is general. In that sense, our framework assumes that, when looked with enough detail, individual particles are complex adaptive system by themselves.

An alternative explanation consists in considering that the four properties (interdependence, connectedness, diversity and adaptiveness) can take different values, see (Page, 2009). That is, one may consider a certain scale (1 to 100 for instance) to represent the level of interdependence of a system. The same with the rest of properties. Consider for instance diversity. Regardless the way in which one defines the scale, large values will represent that the system is very diverse, and low values will represent that diversity in the system is low.

This representation allows a different interpretation of meso-levels: they are intermediate values of the four properties. In that sense, the phenomena described in 2.1, which are specific of complex adaptive systems, will happen for intermediate values of the four properties. When values are very large or very low, the system tends to regular behaviors, either statistical regularity (pure chaotic behavior) or equilibrium behavior, see (Page, 2009).

Hence, this representation allows circumvent several difficulties associated with the application of evolutionary theories to economic problems. On the one hand, we can place traditional microeconomics, for instance equilibrium theory, as a particular case of properties' values. For instance, perfect competition in a partial equilibrium model can be understood as a situation where interdependency and connectedness is very high (the rationale behind "infinite number of players") and adaptiveness is very high as well. Indeed, if we understand adaptiveness as learning, perfect competition implies that

[3] We will not discuss this observation in detail, as it is essentially the same role played by variety in evolutionary theories.

market participants learn fast enough to respond always with the best response. I will discuss adaptation in detail in section 4.

More importantly, this representation allows understanding the extension of evolutionary ideas to economics, where human design plays a role, see for instance (Vromen, 2003), (Nelson, 2006) or (Possas, 2008) for discussions on the challenge. From this paper's point of view, following (Page, 2009), human design can be viewed as a specific way of creating diversity. In particular, i) new entities created by design means that the differences with existing entities can be larger than in the evolutionary case; ii) designed entities do not need to be always viable; and iii) evolution is path dependent.

From the description above, one may observe that designed systems are more diverse than evolutionary ones. The trade-off is precisely the lack of constraints: because designed systems need not interim viability, and they leap only as a result of the designer's imagination, they are constrained by that. Evolutionary systems, on the other hand, can potentially create maximum diversity, except that the process is slower.

2.3 Comparison to other approaches

In order to organize the comparison, it is important to highlight that one important characteristic is that the approach avoids taking as primitive properties of system outcomes. Much of the literature dealing with complexity economics consider as elementary units of the analysis emergence, dependency of initial conditions, path dependency, etc. As this paper defines just four properties from which outcomes can be characterized, it is significantly easier to generalize. Along the same lines, this paper also avoids considering prototype models intended to show an effect, as tipping point models, self-organization, etc. Although these models are important, this paper understands them as consequences of fundamental properties of complex adaptive systems.

Out-of-equilibrium systems are also the object of evolutionary studies within economics, e.g. (Nelson and Winter, 1982), and specifically of generalized Darwinism, (Hodgson and Knudsen, 2010). In evolutionary economics, the aim is describing economies as the result of the principles of evolution, namely diversity, accumulation (or heredity) and selection. This proximity can be observed in (Beinhocker, 2011), who identified evolutionary principles as well as self-organization (a characteristic outcome of complex systems) with computational search of agents interacting in a complex environment. The paper is based on the idea that information aggregation would play a central role, thus placing the complexity definition closer to the ones associated with "difficulty of description", (Gell-Mann and Lloyd, 1996), which is a more restricted definition than the one considered in this paper. On the other hand, literature also contains efforts to separate the use of evolutionary principles from the study of economic systems. For instance, in (Foster, 1997), self-organization is proposed as a substitute for evolution, arguing that evolutionary principles lead to invalid analogies to biological systems. Hence, there is not a consensus on whether complex adaptive systems will always fulfill evolutionary principles. Differently put, it is not clear whether evolutionary principles are the only ones deriving from systems that are diverse, connected, interdependent and adaptive.

Finally, this paper pursues the same strategy as (Foster, 2005). In it, the initial step was a characterization of complex adaptive system based on the following properties: a) maintains complexity; b) the connections are forged to allow emergence; c) hierarchical development creates irreversibility. Although we pursue the same strategy, we have developed an alternative description of complex adaptive systems. As we discuss in section 2.1, properties b) and c) can be deduced from our four fundamental properties. Regarding property a), we have avoided, as noted above, the use of complexity as an observable property, because of the difficulty in defining complexity. In any case, property a) is essentially a consequence of our definition of complex system: it will adapt in order to maintain minimum levels of diversity, connectedness and interdependency. Property c) is again a property of the outcome under this paper's definition: because of the four properties that we have used to describe complex systems, they will be path dependent.

In the next section, I will deduce the consequences of considering the previous definition on the characterization of agents' decision-making processes.

3. Decision-making within complex adaptive systems

An important question in the study of market players' behavior is the characterization of the way in which agents decide. In traditional microeconomics (see (Kreps, 1990) for the contents included in my use of the vague term "traditional microeconomics"), the characterization is done through a two-step procedure: one first describes the environment in terms of time and uncertainty, and then develops a formalization of rational preferences. In the particular application of utility under uncertainty, one would first describe the formalization of uncertainty (for instance, by von Neumann-Morgensten lotteries) and then describe rational preferences (correspondingly, by expected utilities). To facilitate the construction of this paper's reasoning, I will follow a similar two-step procedure with decision-makers within a complex system. I first deduce what uncertainty in a complex system is, building on the properties of complex adaptive systems described in section 2, and then I describe rationality when individuals decide within the context of a complex system. One of the main objectives of this section is to discuss algorithmic rationality and the consequences of defining it on the definition of uncertainty. In this regard, we will tackle topics discussed in (Page, 2008).

3.1 Definition of uncertainty

One of the main elements in our description of agents' behavior, and hence their adaptation characteristics, is the definition of uncertainty. Literature uses a wide range of definitions of uncertainty, even varying in whether it is a property of the world or a property of the mind, (Dequech, 2004). This sub-section discusses the concept of uncertainty that follows from our definition of a complex adaptive system based on the properties of interdependency, connectedness, diversity and adaptation. To that end, we will compare our conclusions to the typology of uncertainty concepts developed in (Dequech, 2011). I reproduce the typology in Table 1

	Weak uncertainty	Strong uncertainty
Substantive uncertainty	"uncertainty about which state will obtain"	ambiguity: predetermined list of states
		fundamental: unknowable list of states
Procedural uncertainty		Difficulty related to limited capabilities

Table 1. Typology of uncertainty developed in (Dequech, 2011).

This paper's reasoning consists in deducing properties of economic systems from the four fundamental properties of complex adaptive systems that were defined in the introduction (variety, connectedness, interdependency and adaptiveness). Consequently, according to the reasoning, one should be able to deduce uncertainty from them. In that view, one would be answering the question: where does uncertainty come from? In this sense, we do not consider uncertainty as a fundamental property but as a consequence of the characteristics of a complex system.

To answer the question, consider first uncertainty as perturbation. That is, uncertainty is some external disturbance to some process. This is typically related to the description of the perturbation through some probability distribution. From this point of view, this definition would be "weak uncertainty", as defined in (Dequech, 2011). Note that this is a description but it is not a justification of its source, as one may ask infinitely: where does the disturbance come from? Differently put, this alternative would mean answering uncertainty is caused by uncertainty.

Another possibility is to consider uncertainty as a fundamental property of the environment. This is done with success in quantum mechanics, where it is proven that uncertainty is a fundamental property of nature. In terms of the typology of (Dequech, 2011), this would be "fundamental uncertainty". As before, anyway, it does not show where uncertainty comes from, but it shows that no matter how small the scale we choose, uncertainty does not disappear.

The two first views on uncertainty provide descriptions of uncertainty, and in the latter case, a justification that uncertainty is inescapable. However, none of them provides a mechanism by which uncertainty is generated (without an external agent).

One possible approach to the problem is to try to build a machine that creates uncertainty. It is possible to design very simple sets of rules that result in completely random outcomes, i.e. they are impossible to predict. One useful example was developed in (Wolfram, 1986). The simple explanation I use in this paper was developed in (Page, 2009). The experiment consists of a string of lights (in general, a class of models called cellular automata), where each light is connected to a neighbor on the right and a neighbor on the left. In this situation, we define the rule that one certain light is going to be off in the next period if:

- the light and its neighbor to the left are both on
- the light is off and both its neighbors are off
- the light is off and both its neighbors are on

In any other combination, the light is going to be on in the next period. We begin with just one light on in the center of a long string of lights. This situation is going to generate a sequence of lights that will propagate through the string, creating complex patterns. In particular, if we observe the pattern of the light initially on, we find that it is completely impossible to predict whether it is going to be on or off in the next period.

This means that interdependency creates randomness. In that sense, we would be characterizing as what is called "ambiguity" in (Dequech, 2011), and such ambiguity is generated from a set of relatively simple rules. In this context, ambiguity means that it is impossible to know the probability of a certain event, but the set of all possible events is knowable ex ante. In this case, the events would be the possible combinations of on and off lights in the string. As the rules are fixed, the set is knowable ex ante (possibly very large).

So interdependency is able to create strong uncertainty from simple rules. But (Dequech, 2011) identifies a different kind of uncertainty when events are not knowable ex ante: "fundamental uncertainty", which is strongly related to creation. Can we deduce this kind of uncertainty from the definition of complex adaptive systems? One way of introducing the existence of this kind of uncertainty in our context is to consider that systems adapt. In our simple example with the string of lights, this means that the rules that govern whether lights are on or off change over time. In this situation, the process of the initial light becomes non-stationary (which is sometimes called path dependent). Consequently, each time rules change, new potential combinations of lights on and off may appear. Events are not knowable ex ante. It is worth noting that, as pointed out in sub-section 2.1, the combination of interdependent rules can create diversity (at the system levels), which allows innovation, which in turn creates fundamental uncertainty.

The last kind of uncertainty considered in (Dequech, 2011) is procedural uncertainty. As this is related to the description of agents' rationality, I will tackle the subject in the next sub-section.

3.2 Description of rationality

From this paper's point of view, reckoning the kind of uncertainty implied by the characteristics of complex adaptive systems means that agents in those systems cannot be perfectly rational. In fact, a key point of our representation is considering that agents do not decide using deductive, rational reasoning. Instead, we represent that agents, in a context of significant complexity, understand reality through simplified models that are then used to perform deductions (possibly through algorithms). Such models may be interpreted as beliefs. Agents then obtain feedback from the complex environment, which allows them to modify decisions according to their beliefs (their simplified models), (Arthur, 1991).

In order to investigate the decision-making processes of these agents, let me consider one image used frequently within complex systems literature: the fitness landscape, (Kauffman and Johnsen, 1991). This kind of model was originated within the evolution literature. In it, higher elevations mean better results in terms of evolution (often the ability to replicate). In the application to our economic problem, the agent (e.g. a firm) located at a high point of the landscape would have better economic results than one agent located at a lower point.

Much of our discussion on the fundamental properties of complex adaptive systems can be cast in terms of fitness landscape. Besides, it allows illustrating quite directly the kind of agents' rationality that can be derived from the consideration of economies as complex adaptive systems.

Consider that our agents are firms, and that each firm is facing a specific landscape. The simplest landscape would be characterized by a single peak, so the best result for the firm would be going to that peak. The other extreme would be the chaotic landscape: many peaks and valleys with similar relative fitness. As shown in section 2.2, this paper is concerned with landscapes with intermediate properties: neither too simple nor too complex. These landscapes would be "rugged", in the sense that they would have several peaks, but not too many.

The question is how agents behave in such landscapes, how they search. Most of search algorithms can be described by means of two elementary strategies, exploration and exploitation. (March, 1991) describes these strategies in the context of organizations as the relation between the exploration of new possibilities and the exploitation of old certainties. In terms of the landscape image, exploration strategies would represent movement through the landscape, whereas exploitation strategies correspond to agents remaining in a specific location in the landscape.

Each firm faces a landscape, and the strategy to move through it depends on the kind of landscape. Thus, if the landscape has a unique peak, the firm will move quickly to the peak and then remain there, i.e. exploitation strategies are dominant. Analogously, if the firm faces a chaotic landscape, it is likely that the firm chooses not to move, as the gains of other locations are relatively small. Exploration is more important in multi-peak landscapes.

All previous search algorithms pursue the idea of optimization, even if they face different problems. One significant hypothesis of our representation above is that firms' landscapes are independent. However, one central aspect pointed out in coevolutionary studies is that landscapes might be interdependent. That is, a certain firm's decisions may change the rest of the firms' landscapes. In that context, optimization strategies might not be the best strategies for interdependent landscapes.

From this paper point of view, the most important consequence of the previous analysis is that agents in a complex system control almost nothing but affect almost everything. We will use this idea to discuss the concept of adaptation in complex adaptive systems.

4. Individual adaptation and system adaptation

One of the main purposes of our characterization of economies as complex adaptive systems is to be able to reason from individual behavior to system properties. We will do this with respect to the concept adaptation. Three concepts in economic theory have been used to characterize adaptation.

4.1 Adaptation as response to signals

This view probably originates in (Hayek, 1945), in the context of the study of price signals as coordination mechanisms for economic activities. It is useful, in order to refer to the many models that have been proposed within this context, to cast its ideas in terms of Game Theory, (Rasmusen, 1989). Looking at coordination problems as games, the design of efficient trading rules would mean to build, for each economic environment, rules of a game that result in efficient outcomes when agents play equilibrium strategies. Note that equilibrium strategies must be associated with the definition of solution of the game, (Kreps, 1990).

This is the objective of the theories of mechanism design and implementation (see for instance (Wilson, 1993) for a very general problem formulation). The setting considered involves an economic environment that is characterized by private information —information observed only by a subset of players, and the objective is to design rules that obtain efficient results. In that sense, the relevant concept of adaptation is the agent's equilibrium response to the rules of the game.

4.2 Adaptation as response to conflict

The second one is response to the conflict associated with unforeseen situations. This view is heavily influenced by the view proposed in (Barnard, 1938). The adaptation described in this literature is not the one performed by individual players responding to changing prices, but the one implemented through hierarchies. Transaction Cost Economics, particularly (Williamson, 1975) or (Williamson, 1991), argued that whether to use the first kind of adaptation (decentralized) or the second one (hierarchical) depended on the kind of transaction. When the prospect of conflict is not relevant (as in impersonal transactions), adaptation can be performed through price mechanisms. On the other hand, when identity matters and future events are uncertain (or when players decide under bounded rationality), the prospect of conflict is relevant and hierarchies should be preferred.

4.3 Adaptation as a learning process

The concept of adaptation used in this sub-section follows from the idea of algorithmic rationality described in section 3.2. We build on the idea that agents understand reality through models, which are imperfect representations of the world. In that sense, the importance of adaptation is not just related to misalignment of incentives, but to interdependent landscapes, which in turn implies the constant need to learn.

Consider first the exploration/exploitation strategies that were described above in independent landscapes. Each agent, e.g. each firm, will search the peak of its corresponding landscape and, once it is found, the firm will remain there. This can be identified with an equilibrium.

However, when landscapes are interdependent (that is, there is coevolution), search strategies of each firm affects the landscape of all others. Consequently, all firms will need to adapt, which in turn will cause all landscapes to vary. The previous equilibrium situation disappears. Note that the equilibrium does not exist because landscapes are interdependent, which is a basic property of our definition of complex adaptive systems. That is, when we consider that the economy is a complex adaptive system, there is, in general, no equilibrium (it can always exist as a particular case).

In that context, we represented individual rationality as built on models that processes information, the algorithms. Consequently, adaptation within this framework will be related to the adaptation of the algorithms used to process reality. This can be understood in the context of (Simon, 1959): agents follow 'satisficing' routines, and they will only change routines in case outcomes are no longer satisfactory. The study of those algorithms is closely related to the work summarized in (Kahneman, 2003), and the subsequent program on behavioral economics, e.g. (Thaler, 1980). In this context, the complexity approach implies the consideration of algorithmic rationality, which is along the lines proposed in behavioral economics. As shown in section 2.3, there is a close relationship also to evolutionary approaches. In this context learning is a consequence of interaction through interconnection.

From this paper point of view, it is important to highlight that system adaptation is seen as an emergent property derived from the interaction of individual agents in the system. That is system adaptation cannot be explained just by observing how individuals adapt. Differently put, the study of economies as complex adaptive systems focus on the transformation of individual adaptation (the algorithms) into system properties. Pointing at the fact that adaptation is an emergent property can be identified as the main difference with respect to the two other concepts of adaptation (sections 4.1 and 4.2).

Table 2 represents a summary of the different definitions of adaptation discussed in this section.

Response to what	Principles	Rationality considered
Prices	Revelation Principle	Rational
Conflict	Asset Specificity	Transaction-costs minimizers
Learning	Evolution and Satisficing Routines	Algorithmic

Table 2. Typology of adaptation.

5. Complex adaptive systems and the Institutional Analysis and Development framework

As shown in section 4.2, one typical way of motivating the analysis of institutions is using the idea of coordination among players in a certain industry. The typical case studied within this field is how to manage long-term, bilateral relationships imposed by the characteristics of asset-specific transactions. We will call this first kind of problem “conflict” situations. Nonetheless, as highlighted in (Langlois and Robertson, 2002), another critical functions to be performed is the coordination of resources, not only of incentives (thus involving what was called learning in section 4.3). To perform those functions, entities (frequently firms) create a set of productive routines, which constitutes their capabilities. Hence, the second kind of problem, which describes the previous decision-making process, will be called “cooperation” situations. The set of the two problems will define the coordination of agents.

From this paper’s point of view, we are interested in showing how these two streams of institutional studies can be combined within the framework of complex adaptive systems. The link will be done using fundamental characteristics of complex adaptive systems, and the Institutional Analysis and Development framework defined by (Ostrom, 2009). In this sense, the exercise may be viewed as an application of the ideas developed in previous sections.

Let me begin with the first kind of problem: conflict situations. To that end, I analyze this situation with a concrete example. Consider the situation described in (Bajari and Tadelis, 2001), where a certain authority is procuring the outcome of a certain project, which is normally difficult to develop. In order to be specific, let me consider that the case is the procurement of a project to build a highway.

This problem has been looked at from different standpoints, each of them generating knowledge regarding particular phenomena involved in the procurement problem. First, mechanism design, (Laffont and Tirole, 1993), is concerned with the study of how to provide incentives for the revelation of proprietary information possessed by the firm building the highway. Within the context of this paper, the situation described by that theory involves a system very connected and very diverse. The system is relatively non-interdependent, in the sense that the situation considers just two players[4]. The main insight of mechanism design is that if there is no uncertainty (only risk), there may be an equilibrium and hence adaptation is not necessary after the design of the contract (adaptation mechanisms are included in the contract at the signature time). In that sense, the adaptation considered in the one described in section 4.1. The output is typically an equilibrium (when it exists).

We may complicate the previous situation as in (Bajari and Tadelis, 2001) by introducing uncertainty in the outcome of the project. In this case, the message of the study is that it is not efficient to include too many clauses in the contract (i.e. incentives) because, due to uncertainty, those clauses will need to be renegotiated, which is costly. So the system remains very diverse and very connected, it is still not interdependent, but the adaptation concept has moved from the one in section 4.1 to the one in section 4.2: adaptation as a part of a conflict situation with uncertainty.

The two previous situations are complicated but reasonably predictable, in the terms we have set in this paper. The contract is signed, and then renegotiation

[4] Different versions of this models may consider many players. In those cases, in order to keep the system “simple enough”, diversity is drastically reduced (transactions are anonymous, in the terms of Transaction Costs Theory).

takes place each time something unexpected happens (only possible in the second conflict situation). The situation considered above is a conflict situation: incentives must be aligned for agents decide to engage in a long-term, bilateral relationship. In case that conflict still is unresolved, they may change the contract and even introduce a third party to enforce it. But we cannot consider it as a complex adaptive system, because it is not adaptive: the objective and the characteristics of the players do not change over time. It is "just" a difficult situation[5], in the sense introduced above.

Let me consider the second kind of problem, the cooperation situation. As an instance, it is interesting considering a different product of the long-term relationship: the one created in a market for capabilities, (Langlois, 1992). In the example of an authority procuring a difficult project, the idea is that authorities typically know the required characteristics of the project, but lacks certain relevant capabilities to implement it, e.g. the ability to develop technology to facilitate or lower the costs of the project. Symmetrically, the firm has technological capabilities, but lacks the capability to define the characteristics of the project. And as consequence, there is capability/information that neither of them has, e.g. the technology to solve a specific challenge of the project. When one considers the new element in the situation, the coordination problem goes beyond the opportunistic behavior that generate conflicts. The coordination problem also includes the problem of the capabilities that did not exist before the interaction. This inexistence of capabilities adds a new perspective, because there are some capabilities that cannot be acquired. Without the relationship, at any given point in time, the capability does not exist. The ability of any of the two parties to behave opportunistically then is limited.

The "complexity" of the previous situation comes from the fact that the objective of the two entities do change over time and are interdependent. If one firm decides to behave opportunistically, the ability to develop the project disappears, and hence the objective changes. For instance, the authority needs to define a different project, and the firm needs to find other useful capabilities that it can sell. In this sense, adaptiveness responds to the one defined in section 4.3. Hence, the situation corresponds to the ones described by complex adaptive systems, because depending on the evolution of the system, or more precisely, on each agent's perception of system evolution, the value of the cooperation will change so the institution (the contract, the project, etc.) must adapt.

Furthermore, the kind of adaptation described in this paper creates a specific logic for institutional dynamics. When rule-makers are considered also agents deciding within the complex adaptive system, they also update their algorithms according to their evaluation of the environment. This process of updating is one of the main insights provided by the Institutional Analysis and Development (IAD) framework, (Ostrom, 2009). In fact, evaluative criteria

[5] We can have games that allow players to change the strategy according to what happened in the past. However, the possible players' behaviors (typically common knowledge) are established before the game starts. The initial conditions (of possible behavior) does not change. So there is no accumulation of new capabilities and possible strategies.

guide institutional adaptation IAD, which in turn can be connected to the idea of algorithmic rationality developed within complex adaptive systems. In that sense, one can see the IAD as a framework to include institutions within the logic of complex adaptive systems. This means that macro-dynamics of institutions emerge from the adaptation process of rule-makers when they evaluate the outcomes of the economic environment.

Moreover, the IAD also studies institutional dynamics as a multi-layered decision-making process, which is closely related to the idea of complexity as a fundamental property. To illustrate this idea, consider two sets of multi-level group of processes: i) the institutional one as identified by (Williamson, 1998) and ii) the technological one, defined by (Künneke, 2008) building on (Dosi, 1982). The two sets of levels are coherent with the levels defined within the IAD.

In the first column of Table 1, we represent the different levels of action situations [6], as defined by (Ostrom, 2009). This general framework can describe both the institutional levels developed in (Williamson, 1998) and the technological levels developed in (Künneke, 2008). The correspondence is represented in Table 1.

Situation type	Institutional level	Technological level
Operational-level situations	Resource allocation	Operation management
Collective-choice situations	Governance	Routines
Constitutional-level situations	Institutional environment	Technological trajectory
Metaconstitutional-level situations	Embeddedness	Technological paradigm

Table 3. Relationship between action situations and institutional and technological levels. Source: Own elaboration, based on (Ostrom, 2009), (Williamson, 1998) and (Künneke, 2008).

One of the most important insights of the IAD is that, even if the decision-making process of the four situation levels is nested (e.g. decisions at the operational level are framed by decisions at the collective-choice level), level-shifting strategies are crucial to understand the evolution of institutions. That is, an agent chooses a level-shifting strategy at a certain level, e.g. changes in terms of technological trajectories, when she begins to consider the change of the constraints at the immediately lower level, in this example constraints on productive routines. Consequently, agents deciding at a lower level (e.g. collective choice situations) may engage in level-shifting strategies to change the rules at the higher level (e.g. constitutional-level situations). This process is coherent with algorithmic rationality, in the sense that agents decide based on their evaluation of the outcomes, and hence the institutional dynamics (the rule-making process) can be identified with a complex adaptive system as well.

[6] The basic idea behind an action situation is very close to the definition of transaction in (Williamson, 1998).

6. Final remarks

This paper builds on a fundamental description of complex adaptive systems to understand the dynamics of institutions assuming that economies are generally out of equilibrium. Complex adaptive systems are entities characterized by connectedness, diversity, interdependency and adaptiveness, and this paper considers that economies can be represented by complex adaptive systems.

From these properties, the paper deduces that agents in such an economy decide, in general, subject to fundamental and procedural uncertainty. Only in particular configurations of the system the uncertainty reduces to other forms as weak uncertainty. These configurations can be described as equilibrium states. In addition, agents' decision-making processes are described by algorithmic rationality: agents process the environment and decide using algorithms, and then observe outcomes and update such algorithms.

This description generates a logic for adaptation based on such learning process (algorithms update). In particular, system adaptation is shown to emerge from agents' learning processes. In that sense, we show the mechanisms by which micro-adaptation translates into macro-behavior.

More importantly, the kind of adaptation described in this paper creates a specific logic for institutional dynamics. When rule-makers are considered also agents deciding within the complex adaptive system, they also update their algorithms according to their evaluation of the environment. These evaluative criteria, which are a central element of the Institutional Analysis and Development framework, guide institutional adaptation. Consequently, macro-dynamics of institutions emerge from the adaptation process of rule-makers when they evaluate the outcomes of the economic environment.

References

Arthur, W.B., 2014. Complexity and the Economy. Oxford University Press.

Arthur, W.B., 2009. The nature of technology: What it is and how it evolves. Simon and Schuster.

Arthur, W.B., 1995. Complexity in economic and financial markets: Behind the physical institutions and technologies of the marketplace lie the beliefs and expectations of real human beings. Complexity 1, 20–25.

Arthur, W.B., 1994. Increasing returns and path dependence in the economy. University of michigan Press.

Arthur, W.B., 1991. Designing economic agents that act like human agents: A behavioral approach to bounded rationality. The American Economic Review 81, 353–359.

Bajari, P., Tadelis, S., 2001. Incentives versus transaction costs: A theory of procurement contracts. Rand journal of Economics 387–407.

Bak, P., Tang, C., Wiesenfeld, K., 1987. Self-organized criticality: An explanation of the 1/f noise. Physical review letters 59, 381.

Baldwin, C.Y., Clark, K.B., 2000. Design rules: The power of modularity. MIT press.

Barnard, C., 1938. 1.(1938). The functions of the executive. Cambridge/Mass.

Beinhocker, E.D., 2011. Evolution as computation: integrating self-organization with generalized Darwinism. Journal of Institutional Economics 7, 393–423.

Cantner, U., Hanusch, H., 2005. Heterogeneity and Evolutionary Change–Concepts and Measurement. Economics, Evolution and the State: The Governance of Complexity 13.
Crawford, S.E., Ostrom, E., 1995. A grammar of institutions. American Political Science Review 89, 582–600.
Dequech, D., 2011. Uncertainty: a typology and refinements of existing concepts. Journal of economic issues 45, 621–640.
Dequech, D., 2004. Uncertainty: individuals, institutions and technology. cambridge Journal of Economics 28, 365–378.
Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Research policy 11, 147–162.
Foster, J., 2005. From simplistic to complex systems in economics. Cambridge Journal of Economics 29, 873–892.
Foster, J., 1997. The analytical foundations of evolutionary economics: from biological analogy to economic self-organization. Structural Change and Economic Dynamics 8, 427–451.
Foxon, T.J., Köhler, J., Michie, J., Oughton, C., 2012. Towards a new complexity economics for sustainability. Cambridge journal of economics 37, 187–208.
Gell-Mann, M., 1995. The Quark and the Jaguar: Adventures in the Simple and the Complex. Macmillan.
Gell-Mann, M., Lloyd, S., 1996. Information measures, effective complexity, and total information. Complexity 2, 44–52.
Hayek, F.A., 1945. The use of knowledge in society. The American economic review 35, 519–530.
Hodgson, G.M., Knudsen, T., 2010. Darwin's conjecture: The search for general principles of social and economic evolution. University of Chicago Press.
Kahneman, D., 2003. Maps of bounded rationality: Psychology for behavioral economics. American economic review 93, 1449–1475.
Kauffman, S.A., Johnsen, S., 1991. Coevolution to the edge of chaos: coupled fitness landscapes, poised states, and coevolutionary avalanches. Journal of theoretical biology 149, 467–505.
Kreps, D.M., 1990. A course in microeconomic theory. JSTOR.
Künneke, R.W., 2008. Institutional reform and technological practice: the case of electricity. Industrial and corporate change 17, 233–265.
Laffont, J.-J., Tirole, J., 1993. A theory of incentives in procurement and regulation. MIT press.
Langlois, R., 1992. External Economies and Economic Progress: The Case of the Microcomputer Industry. https://doi.org/10.2307/3117052
Langlois, R.N., 2002. Modularity in technology and organization. Journal of economic behavior & organization 49, 19–37.
Lloyd, S., 2001. Measures of complexity: a nonexhaustive list. IEEE Control Systems Magazine 21, 7–8.
March, J.G., 1991. Exploration and exploitation in organizational learning. Organization science 2, 71–87.
Markowitz, H., 1952. Portfolio selection. The journal of finance 7, 77–91.
Mitzenmacher, M., 2004. A brief history of generative models for power law and lognormal distributions. Internet mathematics 1, 226–251.
Nelson, R., 2006. Evolutionary social science and universal Darwinism. Journal of evolutionary economics 16, 491–510.
Nelson, R., Winter, S., 1982. An evolutionary theory of technical change. Cambridge, Ma, Beknap Harvard.

North, D.C., 1991. Institutions. Journal of economic perspectives 5, 97–112.
Ostrom, E., 2009. Understanding institutional diversity. Princeton university press.
Page, S.E., 2010. Diversity and complexity. Princeton University Press.
Page, S.E., 2009. Understanding complexity. Teaching Company Chantilly, VA.
Page, S.E., 2008. Uncertainty, difficulty, and complexity. Journal of Theoretical Politics 20, 115–149.
Perona, E., 2007. The confused state of complexity economics: an ontological explanation, in: Complexity Hints for Economic Policy. Springer, pp. 33–53.
Possas, M.L., 2008. Economia evolucionária neo-schumpeteriana: elementos para uma integração micro-macrodinâmica. Estudos avançados 22, 281–305.
Rasmusen, E., 1989. Games and Information: an Introduction to Game theory.
Rosser Jr, J.B., 2010. Is a transdisciplinary perspective on economic complexity possible? Journal of Economic Behavior & Organization 75, 3–11.
Schelling, T., 1978. Micromotives and macrobehavior. Nueva York. WW Norton & Company.
Simon, H.A., 1962. The architecture of complexity. Proceedings of the American Philosophical Society 106, 467–482.
Simon, H.A., 1959. Theories of decision-making in economics and behavioral science. The American economic review 49, 253–283.
Thaler, R., 1980. Toward a positive theory of consumer choice. Journal of Economic Behavior & Organization 1, 39–60.
Vromen, J.J., 2003. Economic evolution: an inquiry into the foundations of the new institutional economics. Routledge.
Williamson, O.E., 1998. Transaction cost economics: how it works; where it is headed. De economist 146, 23–58.
Williamson, O.E., 1991. Comparative economic organization: The analysis of discrete structural alternatives. Administrative science quarterly 269–296.
Williamson, O.E., 1975. Markets and hierarchies. New York 2630.
Wilson, R.B., 1993. Design of efficient trading procedures, in: The Double Auction Market: Institutions, Theories and Evidence. Daniel Friedman.
Wolfram, S., 1986. Random sequence generation by cellular automata. Advances in applied mathematics 7, 123–169.