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A New Perspective for Fiscal Federalism: The NK Model

Marisa Faggini and Anna Parziale

Abstract: Economic models of fiscal federalism, according to different settings, are generally linear and static, offering unique and deterministic solutions starting with simplifying assumptions. This article stems from the idea of investigating how decision-makers, abandoning their traditional economic models and focusing on innovative components of evolutionary economics instead, can achieve better performance results in organizing and optimizing an economic system based on fiscal federalism. For this purpose, fiscal federalism must be understood as a dense network of economic relationships between different complex adaptive and co-evolving systems, the jurisdictions, linked by strong interdependencies. A better understanding of the links between interdependence will be provided by Stuart Kauffman's NK model. The relevance of the NK model in the study of economic organizations has been noted in the relevant literature. This literature, however, neglects the problem of co-evolution, which underpins our article.

Keywords: complex dynamic systems, evolutionary economy, fiscal federalism, NK model

JEL Classification Codes: H11, H30, H77

In the classical analysis of fiscal decentralization, the problem of assigning governmental functions to different levels of government have emphasized the importance of demand heterogeneity (Wallace Oates's "Decentralization Theorem"), the "technology" of public good provision (economies of scale, geographical spillovers), and fiscal competition for redistributive functions. From a complexity theory perspective, fiscal decentralization can be optimized by policy-making across a *patching algorithm* that we describe below and that confers system advantages for adaptability through diversity and coupling of policy-making jurisdictions. Such diversity and coupling is important for adaptability of the policy-making process itself by providing mechanisms for both experimentation and stability that are essential for the development of sustainable fiscal policies. In addition, as a co-evolving complex adaptive system, a decentralized regime evolves over time. Such evolution will require

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greater flexibility in the sharing of jurisdictional powers, as well as the utilization of new research tools to enhance the development of robust and adaptive policies.

More specifically, if public-sector and policy-making institutions are viewed as co-evolving and complex adaptive systems, then there are important implications for fiscal policy. One implication is that fiscal reform will have a diminishing capacity to achieve specifically desired outcomes, but will retain its influence over possible, usually unpredictable trajectories of sector performance. Instead, greater focus must be placed on how to design policies and policy-making processes that are more suitable for interacting with, interpreting, and responding to the public sector over time. In other words, greater attention must be paid to the adaptability of policies and the policy-making processes as they evolve with the public sector. These challenges reflect a fundamental shift in the governability of the increasingly complex system of public goods and services. This reality undermines the efficacy and appropriateness of the traditional policy analysis paradigm. Under the traditional paradigm, policy recommendations are developed based on the optimization of some measure of societal preferences reflected in an objective function, often a form of efficiency, using models that are essentially mechanic and deterministic. As Hongliang Liu, Enda Howley, and Jim Duggan put it:

> Complex nonlinear systems can generate a wide range of possible behaviors, and developing insights into the dynamics of a complex system has often been difficult. A key aspect that drives model complexity are interactions and feedbacks that occur across organizational boundaries … In terms of policy analysis, these nonlinear and feedback characteristics frequently surpass the capabilities of traditional analytical approaches, and therefore there is a clear need for automated and efficient search algorithms to support policy analysis. (Liu, Howley and Duggan 2012, 361)

In accordance with the growing recognition that policy-making systems are complex adaptive systems, and that they are involved in a co-evolutionary dance with other complex adaptive systems in society (including business and economic systems), to address these sources of unsustainability we need to modify our expectations of what policies can realistically be achieved. A first necessary step is the modification of expectations of policies (i.e., pairings of goals and rules/instruments) by shifting the emphasis from static optimization under constraints to adaptability. Policies should not be expected to achieve specific outcomes. Nor should they be expected to eliminate uncertainty because, as a complex system, markets have coexisting needs for change and stability. Instead, given the uncertainty and limited predictability of the economy, policy-makers need to accept the necessity of experimenting and closely monitoring the effects of adopted policies.

Consequentially, policy-makers also need to accept the inevitability of policy failures (Forrester 2013). As a result, policy goals, as well as the means of achieving them, should be expected to evolve over time. In addition to changes in expectations, policy-makers need to be willing to use and develop new research tools. Such tools include genetic algorithms, *fitness landscapes*, exploratory models, and simulations to anticipate potential long term consequences of policy options and their robustness over varying scenarios. In this article, we consider a *fitness landscape*, which is a powerful concept for describing the dynamic evolution and the performance of complex economic systems.

Under these assumptions, how can sustainable fiscal policies be created to enable the policy-making system and jurisdictions to move to higher points on their respective *fitness landscapes*? More specifically, for the purposes of this article, how should a policy-making system be designed to better enable the production of sustainable fiscal policies in its jurisdiction?

We structure the article as follows: In the next section, we propose a brief review of the latest literature on fiscal federalism. In the third section, we stress the innovative aspects of complexity theory by explaining the insights gained through framing economic phenomena in a complexity context. In the fourth section, we focus on a co-evolutionary approach and on the premises on which to base the analysis of fiscal decentralization in this perspective. In the fifth section, we introduce a patching theory to analyze economic dynamics across jurisdictions. In the sixth section, we describe the *fitness landscape* concept and the NK model of Stuart Kauffman (1993) as tools to analyze the evolutionary dynamics of complex systems. Accordingly, we stress the use of such tools in economics. Then, we proceed to model a landscape in which the jurisdictions, as complex systems of small size, must find the optimal path to organize the local tax planning and to optimize their local economy. We compare the properties of Kauffman's random exploration with a dynamic that reduces the randomness by introducing small constraints in the choice of fitness contributors. In the seventh section, we propose a simulation of optimizations across a *fitness landscape*, while in the final section we offer some concluding considerations.

Traditional Models of Fiscal Federalism and Their Limits

> *We need to understand which functions and instruments are best centralized and which are best placed in the sphere of decentralized levels of government.*
> *-- Wallace Oates (1972, 1120-1121)*

This is what some economists have been proposing since the 1970s, turning to the long debate on fiscal federalism with the aim of identifying the benefits of a public sector that has — in addition to the central government — even decentralized jurisdictions. Traditionally, the theory of fiscal federalism[1] (Buchanan 1965 Musgrave 1959; Oates 1972; Tiebout 1956) is concerned with three essential aspects: (i) the sharing of functions between the different levels of government, particularly at four levels of supply of public goods and services; (ii) macroeconomic stabilization as well as taxation and redistribution of income; (iii) the use of instruments of fiscal policy

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[1] For a review of the latest literature on fiscal relations between different levels of government, see Ehtoshad Ahmad and Giorgio Brosio (2006).

(particularly issues associated with taxation and inter-governmental transfers); and (vi) the identification of welfare gains resulting from fiscal decentralization (Spahn 2006, 182-199).

By using the analogy between clubs and local government, James Buchanan (1965) proposes to explain the behavior of local governments in order to determine the optimal level of size and activity. R.A. Musgrave (1959), however, considers federalism primarily in terms of the theory of public finance and suggests that there are three functions assigned to the public sector: macroeconomic stabilization, income redistribution, and resource allocation. The first two are the exclusive prerogative of central governments, while the third is the purview of decentralized governments. From these assumptions, we derive the theory of fiscal federalism, with the aim of maximizing an individual's utility function in regard to public goods and services by entrusting expenditure and revenue decisions to lower levels of government.

Wallace Oates (1972) shows that a centralized service can result in larger welfare losses than decentralized supply, and concludes that a multi-level system of government is superior to a system with only one level of government in terms of efficiency. This is Oates's (1972) decentralization theorem, holding that, in the absence of cost savings from centralization and interjurisdictional externalities, fiscal responsibilities should be decentralized. This argument implicitly assumes that the center is unresponsive to preference heterogeneity and thereby is only able to implement uniform policies. More specifically, "individual local governments are presumably much closer to the people … [as] they possess knowledge of both local preferences and cost conditions that a central agency is unlikely to have" (Oates 1999, 1123).

If the geographical scope of a jurisdiction falls short of the spatial pattern of spending benefits, the optimal assignment of policy tasks is deduced by trading off the welfare costs of policy uniformity against the welfare gains from internalizing spillovers in policy-making. Consider, for example, a country consisting of two regions that differ in their preferences for local public goods, which exhibit regional spillovers. In this setting, fiscal decentralization allows for a better matching of public good provision and local tastes, whereas under centralization, uniform provision ignores local taste heterogeneity but internalizes spillovers.

There are two main advantages to federalism: (i) increased efficiency of local governments in the provision of some public goods and services; and (ii) improved efficiency in resource allocation based on the assumptions that local governments, due to their possession of more information about the preference structure of the community, would be more capable of adjusting the supply of public goods and services and the management of policies related to the needs and local conditions than other institutions. At the same time, the greater proximity of citizens to local decision-making would give them a more effective control over public administrators, and public services could be funded through local taxation that best determines tax liability vis-à-vis benefits gained.

Oates's model not only suggests the absence of "spillover effects," economies of scale, and constant production costs, but also indicates the lack of uniformity of preferences within local government jurisdictions and heterogeneity of preferences among local jurisdictions. Oates achieves "unambiguous results" not just because he departs from these assumptions. Respect for the "correspondence principle" is made difficult by both the determination of the territorial scale of a single good and by the fact that, generally speaking, different public goods have different optimum dimensional areas. Oates's decentralization theorem has a clear rationale. Welfare is maximized when specific public goods are provided by local governments, whose jurisdiction corresponds to the subset of the national population for which the demand for specific public goods and services is homogeneous. Oates's assumptions on uniform provision of public goods by national governments do not reflect reality in any strict sense.

The homogeneity of preferences also characterizes Buchanan's (1965) model, to which are added such assumptions as the existence of a revelation mechanism of preferences and a population with the same income. Starting from the heterogeneity of preferences within the jurisdiction, C.M. Tiebout (1956) assumes that individuals can move freely between the different jurisdictions, offering different baskets of goods (government services) at a variety of prices (tax rates). Given that individuals have different personal valuations on these services and different ability to pay the attendant taxes, they will move from one local community to another until they find the best mix of services and taxes, which maximizes their utility. With enough variety among the jurisdictional offerings, each community will end up with people having identical preferences. Through this choice process, an equilibrium provision of local public goods in accordance with the tastes of individuals will be determined.

While the model has the advantage of solving two major problems with a government provision of public goods — preference revelation and preference aggregation — it relies on a very restricted set of assumptions. Perfect mobility, perfect knowledge of the differences between the various local governments in terms of taxes to be paid and services to be used, large number of jurisdictions, limited relevance of spillover effects, and constant cost of services production, all allow for an efficient provision of public goods. The result of this is (what is now called) the first generation theory of fiscal decentralization. The final stream of the first generation theory derives from the public choice literature that reaches back to intellectual history. Under this approach (Brennan 1980, 29), central governments do not maximize social welfare and operate like monopolists (or leviathans) in order to increase their control over the economy's resources. Oates and Tiebout offer a theoretical framework in which fiscal decentralization can guarantee an efficient provision of public goods simply because local preferences are better satisfied as compared to the case of centralization. Both previous approaches assume a benevolent government, but the leviathan hypothesis is based on the opposite assumption, whereby decentralization is a means to reduce a government size in order to stem its inefficient behavior. The important contribution of the first generation theory is that it reveals that efficient levels of publicly provided outputs are more typically achieved through multi-level systems of government as compared to a unitary government. Welfare benefits from decentralization are likely to be greatest when there is a diversity of preferences for impure local public goods.

However, the limits of these findings, due to the restrictive assumptions used to derive the decentralization theorem, cannot be overlooked.

In the last twenty years, the classical approach and the theory of fiscal federalism have evolved in (what is often called) the second generation theory of fiscal federalism. The emerging second generation theory has been characterized by two motivating issues: (i) that incentives and knowledge incentives are required for subnational government to do a better job in avoiding outward migration of people and firms; and (ii) that knowledge of local preferences and tastes is crucial in achieving economic efficiency when local public goods and services are provided by subnational government. Both motivations have contributed to an increased economic efficiency. In this new literature, the effect of fiscal decentralization has been modeled to embody the political process and the possibility of asymmetric information across political agents. Contrary to the classical approach, governments are assumed to maximize their own objective function, which does not imply the maximization of social welfare. The new literature reconsiders the decentralization theorem in a political economy contest. Here, the main argument in favor of decentralization hinges on the inefficient outcome of the centralized decision-making process, rather than on the trade-off between preference matching and externalities typical of the original version of Oates's theorem. On the other hand, it studies the trade-off between centralized and decentralized provision in principal agent models of electoral accountability. The contributions of the second generation theory are mainly drawn from the economics of transaction cost, incomplete contracts, and principal/agent perspectives. Leading studies (which have been classed as part of the emerging second generation theory) are associated with Barry Weingast (1995), Paul Seabright (1996), Timothy Besley and Stephen Coate (2003), as well as Ben Lockwood (2006).

Complexity Theory

The modeling processes that have dominated economic theory on federalism share a common approach: the simplification and abstraction of the assumptions of generally linear and static models, capable of offering unique and deterministic solution across the board to simplify the described reality. If, however, it is true that the cognitive process is simultaneously a simplification process (because it does not perceive the reality of things, but its phenomenology), this does not mean that it has to destroy the layer of complexity that surrounds the nature of things. The principles imposed on economic theory by the Cartesian paradigm of simplification have created a separation between reality and its formal representation.

To overcome these limits, and in light of the growing interest in the dynamics of evolutionary systems, researchers from different disciplines (e.g., physics, biology, economics) have started to test the goodness of traditional theories and models. These efforts have proven that researchers are often unable to adequately capture the behavioral dynamics of systems, and they fail to explain the new principles that would provide a justification for such inadequacy, forming the foundation for the construction of a new interdisciplinary approach — the complexity theory (Arthur, Durlauf and Lane 1997; Bertuglia and Vaio 2005; Colander, Holt and Rosser 2004).

From the mechanistic and linear point of view that the whole is always equal to the sum of its parts, we are moving to a nonlinear complex view that the whole is more than the sum of its parts. A "complex" phenomenon is one that has not been completely framed in a linear, deterministic, and predictable context, which is different from what has dominated sciences that have blindly followed the principles of separation, reduction, and abstraction.

Complexity theory studies "complex systems." A complex system presents many elements that influence each other in a reciprocal way. Complexity depends on the number of influences and connections in the system. More connections equal more mutual influences, thereby determining a higher degree of complexity. But to ensure that the system is complex and not complicated it is necessary that these interactions are nonlinear. In a dynamic interaction, the constituent parts of the system influence each other by means of a feedback mechanism. The elements interact in a nonlinear way, and they are subject to environmental feedback that is also nonlinear. In such a system, the connections of each element to the other are too complicated or too concealed to be identified and isolated.

Within the category of complex systems, the complex adaptive systems (CASs) are the phenomena relevant to our analysis here. The Scholars Group of Santa Fe Institute has added a key feature to the set of features already describing complex systems: namely, that the CAS adapts to the environment and they learn. The purpose of the CAS system is thus adaptation. To accomplish this, CAS continually seeks new ways of doing things, hence learning and transforming themselves into highly dynamic systems, wherein small changes can have enormous consequences. In this new perspective, the systemic structure emerges not as the result of a simple process of sum of the behaviors of the parts in isolation, but as a result of the interaction processes that is not predetermined by the behavior of a single part of the system. These processes generate self-organization and emergence.

Despite traditional economic models that focus on static and linear patterns, our economy presents all the futures of a complex system. It is characterized by the presence of nonlinear dynamics, asymmetries, distortions, and discontinuities in the dynamics. It is a system that arises from interactions between agents in which micro-level interactions involve macro-level emergent behavior. In particular, economic systems are complex because they (i) have relations that exist between their heterogeneous parts, interacting locally in a certain environment; (ii) are subject to continuous adaptation through processes of evolution of the individual parts; (iii) have dynamics that are in states far from equilibrium and may have many equilibrium states; and (iv) when subjected to external forces, they react by creating endogenously new, completely unpredictable, and uncontrollable dynamics.

All this explains the need to analyze the economy like a complex adaptive system, characterized by constant evolution, disequilibrium, and change. The elements of a complex economic system are economic agents (consumers, firms, governments), and the dynamics within the system are not produced externally or predictably, but endogenously by nonlinear interactions between agents. Moreover, the relationships between agents change over time. Thus, the agent of a complex adaptive system adapts continually to the environment around him/her, interacting with others and adapting to their behavior.

Traditional economic theory assumes that agents are perfectly rational, use mathematical methods to make decisions, have complete information, exhibit the same preferences, and display no biases. In traditional economics, agents only interact indirectly, through static and closed market mechanisms. As a result, many of the connections within the economy are being ignored. However, reality is more complex than that because agents do not possess perfect rationality, but they are boundedly rational and make decision under asymmetric and imperfect information conditions. In a complex system, relationships change over time and the true power of an agent is influenced by his/her links to other agents and by continually adapting to the changes of the environment and to other agents' behaviors. The structure that arises from the connections between the parts of a system then define that system's distinctive and emergent dynamics features.

This can take place through the application of internal rules of the agents, which specify the strategy of interaction with other agents, as well as through rules of progress, organized in order to provide an agent that applies a model of evolution to the outside world. An agent of a complex adaptive system adapts to the world around him/her by interacting with it, and also adapts to the behavior of other agents through a process of continuous learning, based on feedback information the agent receives. Thus, each agent accumulates experience and tries to improve the outcomes of his/her actions, continuously shaping the rules of behavior and adapting these rules to the experience developed through the agent's own point of view. The linear view represents only one of many states in which a system can pass through. Chaos and order coexist and the key to understanding it all is to examine the degree of interaction between the various elements that comprise the system.

From Tradition to a Co-Evolutionary Approach

Economics is a complex system, but also a co-evolutionary one. The economic co-evolution describes the evolution of two or more agents that interact closely with one another and with the environment, reciprocally affecting each other's evolution. Moreover, because these agents are part of their environment, when they change, they also change their environment, and as the environment changes they need to adapt to it, thus creating constant state of flux. Each agent continually has to reorganize him/herself in order to achieve a sufficient level of performance (fitness) to survive. In other words, within this changing landscape, agents have to continually seek optimal positions, and with each strategic choice of a system there are position changes for other agents that occur in unpredictable and unplanned ways. But from these mass interactions, regularities emerge and start to form a pattern that feeds back into the system, informing the interactions between agents.

In biology, selection is the way in which nature chooses the subjects more efficiently. While nature chooses those best able to adapt to the environment, the economic competition model selects agents, individuals, or companies that are more efficient. The same analogy is present in the evolutionary theory of J.B. Lamarck (1809), which differs from Darwinian theory in its emphasis on adaptive capacity, the active role of experience, and the influence of the environment. Moreover Lamarck, in opposition to Darwin, asserts that selection is made between species, not between individuals, because the greater ability to adapt is transmitted hereditarily.

If the corresponding Darwinian gene in economics is the *homo economicus*, whose act is informed by a criterion of substantive rationality, the influence of Lamarck is evident in the definition of "agent" holding that for the realization of his/her objectives an agent draws from experience. This prpposition is in unison with Herbert Simon's (1957) definition of economic agent, who is a subject that draws from experience by planning procedures that allow him/her to control any problem, but is nevertheless a passive agent who suffers the impact of the environment without exploiting the possibilities available to him to prevent it.

Lamarckian and Darwinian theories have been overcome by the definition of macro-evolutionary theories (Gould 1981). In contrast to a position supported by both Darwin and Lamarck (1809) that evolution occurs gradually, macro-evolutionary theories assert instead that evolution occurs in jumps and it is not continuous. In economics, the macro-evolutionary approach postulates the abandonment of the determinist vision, which is also present in traditional evolutionary theories. This means that the system cannot be simply described by equilibrium relationships, but that it evolves through nonlinear relations and states of disequilibrium, and that economic units survive intact for relatively long periods, being finally replaced by other units or being totally modified in consequence of innovative drives and changing conditions.

If the competition model selection is determined by the efficiency of agents, in the theory of punctuated equilibrium, the foundation of biological macroevolution, the attribution of greater weight to environmental influences and historical factors mean that the differences in efficiency ensure survival and the exploitation of the most radical and varied processes informs the economic system. In this context, the concepts of niche and population become important, since different species coexist in a wide variety of environments. What is interesting for us is analyzing the behavior of the "system-model" located in the "environment-model" in order to understand how – through co-evolution – the system adapts to the environment and vice versa, from time to time resulting in different configurations (Merry 1999; Oliver and Roos 1999; Stacey 1995, 2003).

Systems and environment are often studied under a separated perspective, but not by considering their interdependences and the reciprocal nature of their interactions in time and space in the context, for example, of co-evolution. "The co-evolutionary approach offers an additional, powerful dimension to policy exploration ... The distinction from normal optimization methods is that, with co-evolutionary optimization, individual sectors in the model can be optimized to their own fitness functions, and because of this a fuller range of policy responses can be investigated" (Liu, Howley and Duggan 2012, 362). Speaking of co-evolution then implies the need for a dual and contextual perspective of investigation – the perspective of systems and of the environment — in which the economic and the anthropological variables are strongly represented and interdependent.

It is a contextualized system in time and space, whose features include the fundamental variability of the environment (landscape) and the ability to use the environment as a source of competitive advantage (survival skills, fitness levels, etc.).[2] Therefore, to study the characteristics of the system-environment relationship, one must take into account the fact that, because of the interaction, any evolutionary change of a system can lead to evolutionary changes in another system, and that improvements in a system will provide competitive advantages for another system in the context of co-evolution. Thus, the increased fitness of a system is due to the decreased fitness of another system. The only possible alternative for a system involved in this kind of competition is to adapt continuously as fast as possible in order to maintain its fitness level as compared to that of other economic systems, and alternately to change its configuration.

Since the environment in which systems operate is continuously changing as a result of co-evolution, the purpose of each system is to optimize its level of fitness in order to survive by following typical adaptation mechanisms of natural selection.[3] This is important since the majority of economic activities involves the integration and coordination of interdependent resources. These interdependencies imply that an element of the system needs other elements to perform its function, or at least it can perform well its function if other elements are also present. It is, therefore, helpful to think of an economic system (enterprise, firm, production system, jurisdiction, etc.) as a network of connected elements by virtue of a dense and complex web of interdependencies.

We consider the public sector as a big complex adaptive system in which different forces (that are hardly compatible) act, with a multitude of human beings, variables moods, and continuous changing political and economic scenarios. The fiscal decentralization as a prerequisite for organizing the fiscal structure leads to the creation of local jurisdictions with fiscal autonomy. These jurisdictions are economic systems with many dimensions, characterized by complexity at different hierarchical levels. In this sense, they are complex systems of connections between different levels and sizes of jurisdictions through communication network. Economic agents are the nodes of this network, who produce knowledge by processing the information (Barabasi 2002). For all those reasons, jurisdictions are complex adaptive systems that focus on the role and capacity of a government to maximize the welfare of all citizens (i.e., the benevolent state).

Thus, jurisdictions play a very important role in the development of a state's competitiveness in economic development. That is why, it stresses the need to develop

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[2] The theory of fitness has been proposed in evolutionary biology to represent the relationship between the number of genotypes of a certain class found in the present generation and the number of the same class of genotypes identified in the previous generation (Wright 1932).

[3] The economic science has translated the concept of fitness in an evolutionary theory, according to which heterogeneous organizations are selected on the basis of their ability to develop different levels of fitness within the territory they operate in (Nelson and Winter 1982).

an integrated and coordinated strategy (based on the use and development of new research tools, such as genetic algorithms, exploration models, and simulations) in order to analyze the potential long-term consequences of fiscal policies, and their adaptability and robustness in different environment contexts.

Patching Theory and Jurisdictions

Patching theory proposes to divide a complex adaptive system (and its problems) in several non-overlapping parts, or *patches*. These patches, however, are not independent of each other. Each agent of each patch pays attention only to what happens within his/her proximity, thereby losing sight of the unity of the system and the problems that need to be solved. It is important to remember that the aim is always the efficiency and survival of the global system, wherein the original sub-systems (dating to its division) constantly have to exchange information and co-evolve together:

> Co-evolutionary algorithms typically employ genetic algorithms (GA) to model the evolution of each species. GAs are inspired by Darwin's theory of evolution ... The key operators for the GA are selection, crossover and mutation, and these transform the solution information that is stored in a "chromosome." Therefore, each chromosome has a fitness that captures the overall solution quality of the SD model. As part of the optimization process, the selection operator is used to select two solutions (parents) from the population, using methods such as roulette wheel selection or rank selection. The crossover operator selects "genes" from parent chromosomes and creates two new offspring. It involves first randomly choosing some crossover point and then swapping the values according to this point. Finally, the mutation operator randomly changes the values of offspring in order to promote diversity in the overall solution space. These models of evolutionary processes are found to be effective analogues of economic agent strategic learning. (Liu, Howley and Duggan 2012, 362-363)

Therefore, the patching algorithm searches for improvements in the local fitness inside the patch, rather than global improvements. Instead of adopting changes that have a positive impact on the entire system, the patching algorithm produces changes that have a positive impact on the system's subsets.

This process seems to be particularly suitable for studying social systems today, because individual solutions are not enough for resolving various conflicts that people create. In particular, Kauffman (1993) argues that, for systems with different local autonomies, the analogy with the patches can be used for understanding the evolution of economic and cultural systems. A system moves around its *fitness landscape* through various mechanisms: the adaptive walk that estimates the effects of individual changes on the entire system and the patching that estimates the effects on sub-system levels. Thus, the theory of fiscal decentralization and the patching theory propose to analyze complex economic-financial issues of a complex economic system/ state in the same way — by equating jurisdictions with patches. Using the patching theory, one can also addresses the question of possibility (during the "adaptive walk") of entering the *fitness landscape* with low efficiency and low fitness value. To avoid such mishaps, it should let the patches evolve individually and freely and to auto-organize themselves.

As with other complex adaptive systems, "problem of this sort are computationally intractable, incapable of true solution by any known methods" (Post and Johnson 1998, 1059). D.G. Post and D.R. Johnson (1998, 1059) assert that "legal theory would be enriched ... by paying attention to the study of various algorithms derived from the study of 'complex adaptive systems' that can successfully operate on problems of this kind." From the complexity theory perspective, there are several kinds of problem-solving algorithms, two of which are relevant here. One is a simple trial-and-error method known as the simple "adaptive walk." The adaptive walk is an effective algorithm for finding the highest point on the *fitness landscape* for systems with no interconnections or spillovers between elements. "In systems with substantial spillover effects, however, the algorithm performs progressively less and less well. On these more rugged *fitness landscapes*, the adaptive walk is increasingly likely to become trapped on local fitness peaks — places on the *fitness landscape* from which there are no steps leading upwards at all" (Post and Johnson 1998, 1076).

The presence of spillovers across jurisdictions has long been noted by economists. Inter-jurisdictional spillovers decrease the efficiency with which public goods and services are provided. Spillovers usually occur because the benefits of a locally provided goods or services spill beyond the local jurisdiction to benefit those not contributing to the cost (e.g., benefits from control of air and water pollution, and locally educated students who relocate, or because nonresidents come to the locality to enjoy the public services provided, such as parks, cultural, recreational, and transportation facilities, state universities, state welfare and healthcare systems, etc.).

For systems with substantial spillover effects, there is a different algorithm — patching[4] — that is a variant of the adaptive walk.[5] In a patching algorithm, each element in the system is assigned to a single group of elements, or a patch. As an element is "flipped," the fitness of the patch is recalculated. An individual element is permitted to move from one state to another if, and only if, the effect of the move is positive on the aggregate fitness of the members of its patch. Thus, "the patching algorithm seeks local, within-patch improvements in fitness rather than global improvements ... Each patch is allowed to maximize its own fitness, independent of any effects on the fitness of non-members or on the aggregate fitness of the system as a whole" (Post and Johnson 1998, 1078). Thus, patching is an adaptive walk over a patched system. Complexity theorists have recognized this similarity in expressing the

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[4] The patching algorithm is described in-depth by Kauffman (1995), and was discovered by Kauffman and his colleagues at the Santa Fe Institute.

[5] In a system of spillover effects, "an element's 'spillover set' consists of those elements whose fitness contribution is a function of that element's state" (Post and Johnson 1998).

same phenomenon with federalism, described as a patching algorithm for solving public-policy problems. Post and Johnson (1998) provide an exemplary discussion linking the same concept with interjurisdictional relationship, decentralized decision-making process, and complexity theory. The implications of their work for fiscal decentralization may come as a small surprise to those familiar with theories of competitive federalism:

> A greater understanding of the patching algorithm described here may shed some light on these mechanisms. Patching may be more than merely a metaphor for decentralized political decision-making structures (though it is that, and no less interesting because of it); those structures may, in a sense, be instantiations of the patching algorithm in the political realm. Federalism may "work," in other words, because it is a "patching algorithm," a means for solving public policy problems defined over a most complex "social welfare landscape." As such, an understanding of the factors that determine the effectiveness of the algorithm cannot help but have an impact on our understanding of these political decision-making institutions. (Post and Johnson 1998, 1090)

Post and Johnson's (1998) analysis, highlighting the role of inter-jurisdictional spillover in patched systems, suggests that the efficiency of dispersed decision-making processes is not a simple inverse function of the magnitude of inter-jurisdictional spillovers. The effective functioning of the patching algorithm does not necessary depend on configuring the boundaries between jurisdictions in such a way that all inter-jurisdictional externalities are internalized. The systems with high congruence "appear to be more efficient at finding system-wide fitness peaks than those with more inter-patch spillover" (Post and Johnson 1998, 1091). In the systems Post and Johnson (1998, 1091) examine, "perfectly congruent systems with no inter-group externalities was often less effective at finding system-wide optima than systems with somewhat lower degree of congruence." The authors' (1998, 1091) results suggest "that search efficiency may decline if congruence is too low or too high, that there may be an intermediate congruence 'sweet spot' causing systems with an intermediate level of congruence to be better at finding higher points on the *fitness landscape* than both those in which spillovers are only weakly internalized within patches (low congruence) and those in which spillovers were perfectly internalized within patches (high congruence)."

Therefore, similarly to biology studies, the competitive or cooperative decentralization could be described as a complex system, composed of parts that jointly determine the national welfare. Only when some combinations of system parts occur that are complementary would the result be a high national welfare. Conversely, if the combinations of system parts are incoherent, the result would be a lower level of national welfare. Searching for a good fit between policy parts of the system is difficult as a mutation in one policy (even if it yields improvements in some functions) may well be detrimental to the overall performance of the political socio-economics system.

Obviously, the interdependencies of policy jurisdictions, depending on interjurisdictional agreements, indicate that the choice of one strategy cannot be made independently from the choice of others. The existence of interdependencies thus provides a rationale for the coordination of search activity at a centralized level. Under a regime of decentralized standard-setting, every jurisdiction may pursue conflicting goals of adopting legal standards that, on one hand, fit its own local conditions, and are synchronized with the legal standards of other jurisdictions deemed of particular economic importance, on the other hand. The jurisdictions are choosing their respective legal standards (non-)cooperatively and under (in)complete information about the local conditions prevailing in other jurisdictions

The relative importance that jurisdictions assign to matching their legal standards to their own local conditions versus synchronizing their legal standards with other jurisdictions, depends on the extent of jurisdictional interdependence. More of these independent actions of system elements can be handled using genetic algorithms to approach search problems.[6] In this way, the algorithm attempts to find a single solution to a complex problem by mutating and selecting bit-strings that represent individual solutions to the problem. In fact, the main idea is that, if the best solutions are selected in a number of iterations, the algorithm would converge into a single very powerful solution in the end. However, algorithms often get trapped in a poor solution and several runs can generate different solutions. This outcome has striking similarities to natural evolution, whereby the ultimate complex problem is self -replication, resulting in greater diversity of species.

Regarding the fiscal decentralization, autonomous local jurisdictions organize their fiscal structure toward the efficient allocation of resources. However, this needs to happen within the limits set by the national legislation which must coordinate the process of adaptation of individual geographical areas in order to reach the highest peak of the *fitness landscape* for the entire state. In this situation, the increase in efficiency can be spread with a proper management of externalities in order to erase the negative ones and to encourage positive ones. Dividing up a complex system into independent self-optimizing decision-making patches can increase the efficiency of the search for optimal system-wide configurations. In fact, dividing a decision-making policy into sub-units may be subject to fewer inefficiencies of information transfer. Therefore, local governments and consumers will be more likely to make better (welfare-maximizing) decisions. Optimization across a *fitness landscape* involves using optimizing search algorithms not only to control for a direction, but also to test the fitness of different system-component combinations as well as to adapt to the results continuously. Moreover, the system's optimization algorithm must be adaptive, because the systems with which it interacts are evolving in their own searches for the best solutions. Complex adaptive evolutionary systems incorporate algorithmic decision-making tools that allow for an adaptive long-term fitness optimization through repeated reevaluation of the system design.

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[6] A detailed explanation about the algorithm's operation is offered by Post and Johnson (1998).

To allow a complex system to move in the landscape by patching it can clarify the problems within the system that when the system is oversized, it has difficulties in exploring its entire territory in order to design and test new evolutionary paths. Dividing the state into local units of government provides the entire tax system with the degree of flexibility needed not only to adapt to socio-economic changes, but also to find and exploit all facets of the local microcosm. For this to happen, it is essential that the size of local jurisdictions is just right. (We saw earlier how Buchanan [1965] resolved the matter.)

From an economic point of view, it is also important to take into account the magnitude of the externality effects, the preferences of citizens, administrative costs, and economies of scale. These constraints are added to those deriving from the patch theory. The patches should not be too large because the complex system is likely to crystallize in a single configuration and hang in one area of the landscape, or too small because chaos reigns supreme.

These new restrictions are necessary to ensure that the financial structure of a country has an appropriate process for future development in place, which is aimed at achieving the goals of fiscal decentralization. For example, to find out what the right size of jurisdictions is, we can use the *fitness landscape* in the following way. In modern states, there usually are three levels of government: a central, intermediate (e.g., regions, Länder, cantons, state), and local (municipality, province, districts) government. Each level corresponds to a different dimension, taking into account economic and political considerations. The intermediate level, which is often in conflict with the central level, mostly concerns the system of territorial government. Consequently, local units have very few skills. Considering these circumstances and leaving aside the central government (whose dimensions are not the subject of study of the fiscal decentralization theory), we can construct graphs for two landscapes. The first shows the fitness value of the various regions and the second of the municipalities.

Each region and municipality, in each case providing a degree of autonomy, is responsible for its own internal organization, with a configuration somewhat different from all others. So, the graphs represent the solutions offered by the intermediate and local levels of government to address the problems of federal taxes. In this way, one can understand what the current level of efficiency (such as possible future development) is, and what the process of adaptation at all levels is. Obviously, efficiency should be measured on the basis of subjects, where all levels of government have responsibilities, whether shared or not. Therefore, the *fitness landscape* of regions and municipalities are compared by taking into account the efficiency of the bureaucracy, the capacity for local development, the efficiency of collecting and spending resources, and so on. This provides guidance on what is the right size of jurisdictions that ensures better solutions of different issues, and what level of government should be entrusted with a particular domain of public administration.

The entire system must be flexible so as to monitor the behavior of all patches of every size, and to change its organizational and space structure in order to facilitate and encourage more efficient jurisdictions. It may also be that the optimal size of jurisdictions is a cross between the regional and local levels. Patching and *fitness landscapes* can also be used to find the best size for every possible configuration. As mentioned earlier, each patch can organize its own management structures and obtain different results. Both regions and municipalities have preference for the more efficient level, tending to occupy the highest peak of the landscape. By taking into account the socio-economic differences, such a level can serve as a model for all other levels of government to guide them to the final step of the adaptive walk.

Using the NK Model in Economics

Although there are several equivalent models for analyzing the effects of interdependences on the complexity of a system, for the purposes of this article, we deal with the theoretical core of *fitness landscapes*, associated with Stuart Kauffman (1995), and the NK model whose basis is the *fitness landscape*. The NK model means the search for optimization of problems characterized by a large number of variables that are in conflict with each other.

We consider a system composed of *N* elements that can have different states (0 and 1). These elements may also have different degrees of interdependence. We do not get into the details of these interdependencies, but we treat them as if they were determined randomly. The only thing that we check in detail is the "degree of interdependence" in the system — i.e., the average number of other elements with which each element is interdependent.

K denotes the measure of interdependence and has values between 0 and $N-1$. We define each possible combination of states of individual components as system configuration and the measure for the system performance as fitness. Each possible configuration of the elements of the system will have its own degree of fitness, more or less dependent on the exploitation of complementarity[7] and the greater or lesser effects of conflicts between systems. The set of fitness values associated with different configurations of the system provides a "surface" for the fitness of the system called *fitness landscape*.

The NK model is composed of two distinct components: a specific problem and an algorithm searching for possible solutions. As we have said, the problem is a set of possible solutions represented as binary strings, each associated with a value of fitness that is the pay-off of that solution. The NK model analyzes the evolution of a single string, which represents the state (or configuration) of a system and it is important (albeit preliminary) for the construction of more elaborate models that suggest possible avenues for self-organization in situations of co-evolution.

The relevance of the NK model for the study of economic organizations has been noted in the literature (e.g., Frenken 2001; Frenken and Valente 2004; Levinthal 1997; Pagano 1998; Westhoff, Yarbrough and Yarbrough 1996). Following Kaufmann's NK model theory, Koen Frenken (2001) and Koen Frenken and Marco

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[7] Complementarity, in this case, means that the elements must be used and act together in order to maximize the degree of fitness of the system, to which they belong.

Valente (2004) suggest a formalization of network organizations in search for a complex *fitness landscape* of technological artefacts and innovations characterized by conflicting constraints due to the interdependencies of complex system's constituting elements. The central question is: What modes of organization can be distinguished in designing a complex system and how can their performance of a search activity in complex systems be compared? These authors distinguish three types of organizational modes: a centralized organization, a decentralized organization, and a network organization. These studies, however, neglect the problem of co-evolution, on which we focus here.

Kauffman (1993) restricted his analysis of complex systems to particular types of architectures, expressed by parameter K, which stands for the number of elements. This parameter is an indicator of a system's complexity, with $K=0$ being the least complex architecture and $K=N-1$ expressing the most complex architecture.

In our case, a low value of K indicates little interaction between policy choices of different jurisdictions, so the *fitness landscape* is smooth or highly correlated. Therefore, a change in one policy has little impact on the fitness contribution of other jurisdictional choices. By contrast, a high value of K implies that a change in one jurisdiction policy has a large impact on the fitness contribution of other jurisdictional choices. Therefore, given an initial setting of incremental change in the vector of N, policy jurisdictions may substantially change the overall payoff level. As a result, the *fitness landscape* becomes less correlated, or equivalently, more rugged, with a higher K value. When there are significant interaction effects among policy variables, there may be a number of local peaks.

While Kauffman's work exploits the simulation of large complex systems, we pursue an analytical approach to the presentation of the main qualitative properties of the models, as far as possible. To clarify our intent, we consider a process of co-evolution between jurisdictions, which is induced, for example, by the need to reorganize the economic system of these jurisdictions as a result of tax reform. For optimal fitness, it is necessary to adjust K, depending on co-evolution. In the fiscal policy context, the value of co-evolution is determined by the extent to which the policies of an opponent directly affect one's own policies. Co-evolution cannot be controlled, but the value of K can be modified by adjusting the extent to which some sets of rules cancel out or modify the effects of other rules within the organization.

Co-evolution in a landscape model deals with rules. A jurisdiction's tax planning is generally tax rule-following. Public expenditure reflects the implementation of tax rules established at a prior point in time rather than resulting from the novel solution of an optimization problem. Tax rules are not constant — they change either as a result of catastrophic failure, or as a matter of course — but they change slowly, except in unusual situations like crises. Low K systems improve their performance very slowly, since rules must be changed one by one, without synergistic effects. High K systems can be changed more rapidly because the change in one tax rule can affect a large number of other rules.

The reorientation of the possibilities for tax planning and opportunities for economic growth, starting as a direct consequence and given the scarce resources, generate competition between jurisdictions. This is a phase of substantial uncertainty, caused by the fact that new opportunities are still ill-defined and can evolve rapidly. This situation gives rise to new dominant solutions for the tax planning of jurisdictions due to the extensive process of co-evolution influenced by interdependence.

Our choice to present the concept of co-evolution tends to emphasize that a change in the tax planning of a jurisdiction creates new and different opportunities or disadvantages for other jurisdictions. In other words, a movement of a jurisdiction along the *fitness landscape* can deform the *fitness landscape* of other jurisdictions. We present the *fitness landscape* of a jurisdiction as a map that associates each possible variant of the state (configuration) of a jurisdiction with its fitness level, interpreted as a measure of its efficiency in a given environment and at a given time. If the effects of interdependence between jurisdictions are strong enough, the results of co-evolution in each jurisdiction are disturbed based on the systematic deformation induced by simultaneous evolution of the *fitness landscape* in the remaining jurisdictions.

In this scenario, the constraints of interdependence play a selective role because they affect the likelihood that the systems will be well adjusted. This occurs because the interdependence constraints increase the probability of evolution toward a stable configuration (despite the fact that the configuration may not be optimal *ex post*) by limiting the set of advantageous movements in the space of representation of the possible solutions. In this way, the interdependence constraints help to reduce uncertainty and disorder in a system, considered as a set of evolving complex systems.

We assume that the possible levels of public spending of jurisdictions are uniformly distributed in space K, where K is the measure of interdependence. To take a systematic relationship between interactions and contributions means that every *fitness landscape* is drawn from a distribution such that the degree of interaction of an element is correlated with its contribution fitness. A stronger interaction leads to stronger constraint of complementarity. On this premise, more integrated *fitness landscape* is even more rugged on average. Then, as evidenced by Kauffman's results in a rugged landscape, the number of local optima grows, although their average fitness value may decrease. In addition, routes to the local optima involve fewer steps. These properties can be used to prove that, at every stage of a co-evolutionary process, evolving systems on a rugged landscape are more likely to be simultaneously on a landscape's peak, and then to move toward a local optimum.

If the systems have a sufficiently large number of N elements, there is a trade-off between the probability that a process co-evolves toward a stable local peak and the average fitness of a peak. So, it turns out that systems with an intermediate degree of interaction have a selective advantage against competitors with very high or low complementarity constraints. These properties are always true, no matter whether evolution proceeds by random exploration of such trial and error (as assumed by Kauffman 1993, 1995), or by imposing constraints that help to identify optimal choices within a set of local choices. Once the systems are simultaneously at peak fitness, co-evolution tends to decrease. In what follows, we try to show how Kauffman's model can be used to construct a formal model of the co-evolution.

A Landscape for Jurisdictions

We indicate[8] the level of per capita public expenditure $ai(t)$ in jurisdiction i at time t. The level of public spending is strictly correlated to the tax planning of that jurisdiction. The information on the level of public spending are coded in a number of binary elements, each of which may have the value of 0 or 1. We can think of the string as a way of encoding a specific combination of supply of public goods and services. In each stage of a research, the number of potentially available combinations tends to grow over time, thus extending the length of the string. Pointing out that the suggested approach has little to do with determining magnitude of the problem, we assume that the length of all strings is finite and fixed. The efficiency of the chosen level of per capita public spending, represented by the fitness value, defines the competitive strength of the jurisdiction vis-a-vis the other jurisdictions.

There are G jurisdictions in a country. The level of public spending in jurisdiction $i(i=1, ..., G)$ is a string of N binary elements $(x_{i1}, x^{i2}, ..., x_{iN})$, where each x_{ij}, $j=1, ..., N$ can take value of 0 or 1. There are 2^N possible levels of public spending for the jurisdiction, corresponding to the number of different states in the space $\{0,1\}^N$ that define the set A_i. For reasons of simplicity, we assume that, at the initial moment, the level of public spending is the same in every jurisdiction. The configuration (planning) of the tax jurisdiction is defined by the level of public spending in i. Let x_i and x'_I, then N-strings in A_i. The distance between x_i and x'_i is defined by the number of components having a different value with respect to the corresponding components of the neighbor strings:[9]

$$d(x_i, x'_i) = \sum_{j=1}^{N} (x_{ij} - x'_{ij})^2 \tag{1}$$

The neighborhood of x_i is the set of strings in A_i with distance from $x_i \leq 1$, and it is composed of x_i and its N neighbors. The fitness function of the jurisdiction is the map $F_i: A_i \longrightarrow R$ that associates each configuration of jurisdiction i with its fitness value (real number).

The fitness value of a string is the sum of the fitness contributions of its N elements:

$$F_i(x_{i1}, x_{i2}, ...x_{iN}) = \sum_{j=1}^{N} F_{ij}(x_{i1}, x_{i2}, ...x_{iN}) \tag{2}$$

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[8] For the original model, see Mauro Caminati (1999). Here, we propose an adaptation consistent with the aim of our analysis.

[9] We define two or more neighbouring combinations that differ for a single element, $d=1$.

In equation (2), $F_{ij}(x_{i1},x_{i2}, ..., x_{iN})$ is the fitness contribution of the string element x_{ij}, given its configuration ($x_{ij}=0$ *or* 1). F_{ij} is treated as a random real number in a unit interval. We use this equation to formalize the concept of interdependence since the fitness contribution of x_{ij} may depend not only on the configuration of this element, but also on the configuration of the other elements of the string.

$K_{ij} \leq N-1$ is the number of string elements that are interdependent with respect to x_{ij}, so $K_{ij}+1$ is the number of the no redundant argument of $F_{ij}(x_{i1},x_{i2}, ..., x_{iN})$. For simplicity, we assume that K_{ij} is constant in all jurisdictions:

$$K_{ij}=K=,\ j=1, ..., N_i=1, ..., G \tag{3}$$

In the absence of interdependence, $(K=0)$, $F_{ij}(xi1, x_{i2}, ..., x_{iN})$ can be written as:

$$F_{ij}\left(x_{ij}\right)\ e\ \ F_{ij}\left(x_{i1}, x_{i2} \dots x_{iN}\right)=\sum_{j=1}^{N} F_{ij}\left(x_{ij}\right) \tag{4}$$

The level of public expenditure with the highest fitness in A_i is then identified by the string, such that the configuration of each element x_{ij} maximizes the fitness contribution $F_{ij}(x_{ij})$ of that element. The *fitness landscape* of jurisdiction *i* can be represented with the function F_i on A_i. A walk that combines x_i to x'_i is a sequence of strings, such that x_i and x'_i are the first and last elements of the sequence, respectively, and the distance between each pair of adjacent elements of the sequence is $d=1$. An adaptive walk joins x_i to x'_i and is minimal if the distance to x'_i is strictly decreasing on this "walk." x'_i is a local maximum of $F_i(x_{i1}, x_{i2}, ..., x_{iN})$ on A_i if and only if on every walk that joins x'_i to a string y_i (such that $F_i(y_i)>F_i(x'_i)$), there is y'_i, such that $F_i(y'_i)<F_i(x'_i)$ and $d(x'_i, y'_i)<d(x'_i, y_i)$.[10]

Suppose that $K=0$. If x_i is a global maximum of F_i on A_i, and y_i is an arbitrary string in this set, then F_i does not diminish during the shortest walk joining x_i and y_i. The proposition is self-evident. Because the walk is minimal, there must be many steps along the path as there are elements of y_i, which differ in their configuration from the corresponding element of x_i. At every step along the path, the distance from x_i decreases, since there is another element of y_i that has the same value of the corresponding element of x_i. This value maximizes the fitness contribution of the element because x_i is a global maximum, without reducing the fitness contribution of

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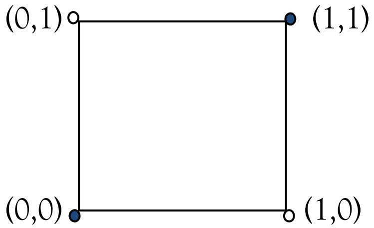
[10] With reference to the case of $K=0$, it is important to remember that a change occurring between 0 and 1 (or vice versa) in the configuration of a single string element does not affect the fitness contribution of the other components.

the other elements (because $K=0$).[11] If $K=0$, the *fitness landscape* of jurisdiction i has at most one local optimum of F_i on A_i, which corresponds to a global optimum.[12]

We suppose that $K>0$. The choice of configuration to maximize the fitness contribution of element x_{ij}, given the configuration of the other $N-1$ elements of the string, cannot positively contribute to the general fitness level of public spending in jurisdiction i. The reason is that interdependence implies the possibility of a feedback of uncertain sign, stemming from the new configuration of x_{ij} to the fitness contribution of the other elements. This is equivalent to the possibility that there may be more local optima. The situation is illustrated in Figure 1 with reference to the simple case of $N=2$ and $K=1$.

Figure 1. Landscape N=2, K=1



In this example, the set A_i of possible levels of public spending in the jurisdiction is composed of four strings. Strings (0.0) and (1.1) are the local optima. The path that joints the strings follows the sides of a square, but not its diagonal because the diagonal steps involve simultaneous changes of many elements, not just one. By construction, we know that in each path joining (0.0) and (1.1), the fitness function does not have a monotonic behavior.

Finally, we consider the greatest interdependence ($K=N-1$). The *fitness landscape* is random in the sense that the fitness values of the neighbors are totally uncorrelated. A change (i.e., from 0 to 1, or vice versa) in the configuration of a single element — say, element j of the level of public spending of a jurisdiction — not only assigns a new random fitness contribution to F_{ij}, but also a new random contribution F_{hi} to each

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[11] The probability that a randomly chosen string in a landscape $K=0$ is a local peak is $1/2^N$. Let $F^*(N,K)$ be the expected fitness of a local peak. $F^*(N,0)$ is independent of N and can be expressed as:

$$E\left[\sum_{j=1}^{N} Max\left(a_j, b_j\right)\right] = 0.666$$

where (a_j,b_j) are N couples of real random numbers uniformly distributed in the unit interval.

[12] This is easily demonstrated by supposing the contrary. If x_i is a maximum of F_i on A_i, there may be in the same space an isolated maximum (local or global) $y_i \neq x_i$ of the fitness function F_i. By construction, F_i has a non-monotonic behavior on every minimal path joining y_i and x_i.

component of $h(h=1, \ldots, N)$.[13] The reason is that now x_{ji} is not a redundant argument of $F_{hi}(h=1,N)$.[14]

The statements are based on the following assumptions: Since $K=N-1$, the fitness values are not correlated. Each string in a landscape has a probability $1/(N+1)$ to be a local optimum and the expected value of local optima is $2N/(N+1)$. In each landscape the lower local optimum has a higher fitness value than the fitness value of the other N strings. The fitness value of the local optimum can be understood as the maximum in a set of $2N$ fitness values.[15] On average, a higher K implies that the higher the number of local optima, the shorter the minimal path that connects a random string in A_i to the nearest local optimum, and the lower the correlation between fitness values F_i of neighboring strings x_i and y_i.

Fully vs. Constrained Randomness in a Landscape Exploration

So far, we have given a formal description of what could be a *fitness landscape* of a jurisdiction. Let us see how the concept of jurisdiction can precede this exploration. Here, we compare the properties of Kauffman's random exploration with a dynamic one that reduces the randomness by introducing small constraints to be respected in the choice of fitness contributions. The choice rises by the assumption that the

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[13] Footnote 9 above implies that $F^*(1,0)=0.666$. If $N>1$, then $F^*(N,N-1)$ first grows above 0.666 and then decreases to 0.5. Moreover, if $K=N-1$, then $F^*(mN,K)=F^*(N,K)$ for any $m\geq 1$. This suggests that $F^*(N,K)$ remains approximately constant as N grows to infinity and K is fixed at $N-1$.

[14] The fitness value of each element on a landscape $K=N-1$ is a random number, uniformly distributed between 0 and 1. The probability that a randomly chosen element of the landscape is a local peak (its fitness value is higher than its N neighbors) is $1/(N+1)$. Then, there are $2^N/(N+1)$ local peaks on average on a landscape $K=N-1$.

[15] This involves lower and upper bounds to $F^*(N,N-1)$:

$$E[Max(\alpha_1, \alpha_2, \ldots, \alpha_m)]<F^*(N, N-1)<E[Max(\beta_1, \beta_2, \ldots, \beta_m)]$$

In this equation, each α_m and β_m is an average of N random numbers in the unit interval $m=N+1$, $M=2^N$. Since the expected fitness value of the intermediate local optima is uniformly distributed between the lower and upper bounds above, we have:

$$F^*(N, N-1)=\{E[Max(a_1, a_2, \ldots, a_m)]+E[Max(b_1, b_2, \ldots, b_M)]\}/2$$

Order statistic shows that:

$$\{E[Max(\alpha_1, \alpha_2, \ldots, \alpha_m)]+E[Max(\beta_1, \beta_2, \ldots, \beta_M)]\}/2\approx 0.7 \text{ for } 4\leq N\leq 10$$

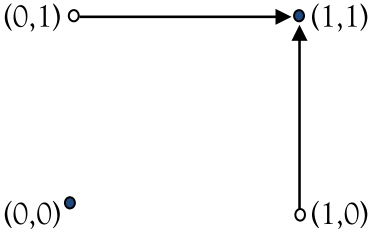
Consequently, $F^*(N,N-1)$ decreases as N increases, and it converges to 0.5 as N grows to infinity, because each single sample average α_m and β_m must behave accordingly. Moreover, we consider $K=N-1$ and $F^*(N,K)$, where $N=mN$ and $K=K$. Through a possible reordering of elements, every string of length N can be composed of m segments with N elements each. Within each segment, each element is connected to K other elements. Thus, the fitness contribution of each component depends on its configuration (0 or 1), and on the configuration of every other component of the same segment. Thus, the expected fitness value of each segment is an average of N random numbers in the unit interval, and is identical to the expected fitness contribution of every other segment. This holds true independently of the size of m.

introduction of some qualitatively and quantitatively important information in a totally random model increases the effectiveness of the use of complex tools. At each time *t*, jurisdiction *i* does not have a perfect knowledge of A_i because the perception of a potentially profitable combination of elements $x_i \epsilon A_i$ — and even more, the information on its fitness $F(x_i)$ — is available only if x_i is in the neighborhood of the string that defines the tax configuration of jurisdiction *i* at time *t*. The information, even when it can be codified, does not immediately translate into knowledge that can be exploited for useful purposes. The transformation of information into knowledge requires understanding, learning, and adaptation.

We can assume that this not-encoding of information can be gained through experience. Unlike sectors where every change is always associated with a random mechanism, here we try to figure out how the research can proceed through the combination of random and more targeted explorations designed to achieve pre-selected goals. According to the dynamic of the NK model, induced by random exploration on a *fitness landscape*, the neighbor element x'_i of the current state x_i is randomly selected at any time.[16] The fitness value $F(x'_i)$ is then examined, and a movement toward x'_i occurs if $F(x'_i)>F(x_i)$.

A greater focus on the intentional components of research generates the assumption that, at any moment, a system moves one step from some predetermined state to the state identified by the string with the highest fitness value in a given neighborhood. This modeling strategy produces a slightly different dynamic on A_i. This comes out when the sequence of a neighbor x_i of x'_i uses combinations of intentional and random choices. Each time, $n<N$ components of x_i with relatively low contributions to fitness are intentionally selected, one of which is randomly chosen and its configuration modified. Again, a move towards x'_i occurs if $F(x'_i)>F(x_i)$. Figure 1 shows the dynamics of a single jurisdiction on the *fitness landscape* $N=2$ and $K=1$. Black points identify the local peaks of the *fitness landscape*. String (1.1) is the global optimum F_i on A_i. String (0.0) is a degenerate basin of attraction, which coincides with the string itself. Figure 2 clarifies how the landscape in this example is robust in the sense that each neighbor of a string that is not a local optimum is a local isolated peak.

Figure 2. Local Optimum



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[16] This amounts to a random selection of one element of x_i and a change of its configuration (from 0 to 1, or vice versa).

It may be instructive to compare the asymptotic average properties of the NK model of Kauffman's random exploration and the dynamics of the model with bounded randomness on the *fitness landscape* randomly generated for the extreme cases of absence and complete interdependence. The main difference from the comparison is: When $K=0$, the full random exploration and the bounded randomness exploration both reach the global optimum of the landscape at the end, and the number of steps required is smaller in the bounded randomness because every step is taken toward a pre-selected direction.[17] The $0<K<N-1$ dynamics of random exploration converges to the average of global optimum of the landscape. The average fitness value $F^*(N,K)$ of a local optimum changes with N and K. For finite values of N, the asymptotic deterministic dynamic on a landscape $0<K<N-1$ climbs a local optimum of fitness, which is surely above average. If $K=N-1$, the fitness of the highest optimum drops to 0.5, on average, when N tends to infinity. The same is not true if N grows to infinity, but K remains constant.

The Effect of Co-Evolution of Interdependence

We consider pairs of public spending levels in G jurisdictions of a country. We also consider the hypothesis that a single level is evolving in each jurisdiction. Therefore, the efficiency of public spending here refers to the level of public spending of jurisdiction $i(i=1, \ldots, G)$. On any given landscape, the dynamics are assumed to have reduced randomness, but — in line with the conclusions of the preceding paragraph — the same qualitative results are obtained when exploratory dynamics are considered totally random. The optimization of a tax system that is based on the interdependence of the elements implies that, in general, the fitness of the $2N$ states of i, depends on the current state of the other G−1 jurisdictions. Following Kauffman (1993), we can predict certain effects like deformities of the *fitness landscape* of jurisdiction i, triggered by changes in the other $G-1$ jurisdictions. More precisely, we consider the changes in fitness levels of public spending in jurisdiction $i(i=1, \ldots, G)$. The changes in the landscape can be local or global. If the interdependence relationships between jurisdictions are limited to small segments of the string, the change of a single element does not induce a change in the global *fitness landscape* of another jurisdiction. However, because the country is composed of many jurisdictions, a multiplicity of individual changes takes place simultaneously. Hence, G is larger than N, and the probability of a global change of the landscape is greater. If G is very small relative to N, deformation is based on the assumption that the global interdependence across jurisdictions is pervasive. Situations of complete interdependence are defined by the fact that each component of each string is connected to every other component in every other string. A single change in a state of an element, therefore, is sufficient to set up an entirely new landscape for any other jurisdiction. We use this rather extreme hypothesis because it suggests an approach that takes into account the co-evolution,

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[17] The average fitness value $F^*(N,0)$ of a global optimum is 0.666.

from which the general qualitative effects of complementarity are more easily detected. So, we define C, which is the number of co-evolving systems.

The economic dynamics of G jurisdictions are determined by their interdependences. Tables 1 and 2 describe the list of fitness values of each element corresponding to each state of public spending level in the remaining jurisdictions. The first element of the list has the highest fitness value. The possibility that adjacent elements in the list have the same fitness value is excluded because the event could be an irrelevant fluke. Below we give two examples for of $N=2$ and $C=2$. The two jurisdictions are called α and β, and $\alpha 00$ is the state of public expenditure (0,0) in jurisdiction α. Table 1 refers to the case of $K=0$, while Table 2 refers to case of $K=1$.

Table 1. Interdependence with K=0

Se β00 :α10	α11	α01	α00
Se β01 :α11	α10	α01	α00
Se β10 :α01	α00	α11	α10
Se β11 :α00	α10	α01	α11
Se α00 :β11	β10	β01	β00
Se α01 :β10	β00	β01	β11
Se α10 :β00	β10	β11	β01
Se α11 :β01	β11	β00	β10

Table 2. Interdependence with K=1

Se α00 :β00	β11	β01	β10
Se α01 :β00	β11	β10	β01
Se α10 :β11	β00	β10	β01
Se α11 :β11	β00	β01	β10
Se β00 :α00	α11	α01	α10
Se β01 :α00	α11	α01	α10
Se β10 :α11	α00	α10	α01
Se β11 :α11	α00	α01	α10

Time is discrete, and at each time t, every configuration moves from its present state to a fittest neighbor through simultaneous changes. The representation space of the dynamics induced by a given interdependence pattern between G jurisdictions, given the co-evolution, is the hypercube $\{0.1\}$ NG. Each hyper-row or hyper-column of this representation space consists of an ordered series of 2^N elements, where each element or point $(x_1, \ldots, x_G)$ is an ordered list of tax configurations (strings of N binary codes), one for each jurisdiction.

The neighbor of a point in the configuration's space is an ordered list $(y_1, \ldots, y_g)$, such that each y_i is a string of N binary codes N and $d(x_i, y_i)<1$. A point in the state space has *N*G neighbors. Each element of a hyper-row (or hyper-column), therefore, is a configuration of a jurisdiction and moves on the same hyper-line (or hyper-column) on which all the possible states of jurisdiction *i* are situated, while the state of other G *–1* jurisdictions is unchanged. Recall that for *K*=0, each *fitness landscape* has one peak and that, by construction, each hyper-row (or hyper-column) refers to the *fitness landscape* of a given jurisdiction. Suppose that the level of interdependence is given. A rest point in the state space corresponding to this model is that all jurisdictions are simultaneously on a peak of fitness. If and only if *K*=0, on every hyper-row (or hyper-column) in the state space, there is at most one rest point in which the co-evolution slows down, as Figures 3 and 4 show. Figure 3, in fact, expresses associated dynamics in the representation space of possible solutions *{0,1}4*, determined by the model of interdependence indicated in Table 2.

Figure 3. Dynamics with K>0

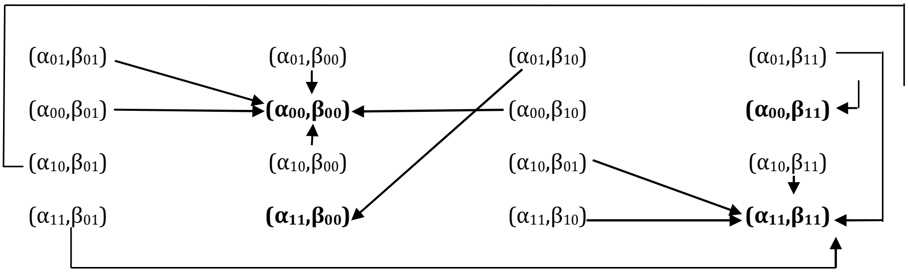
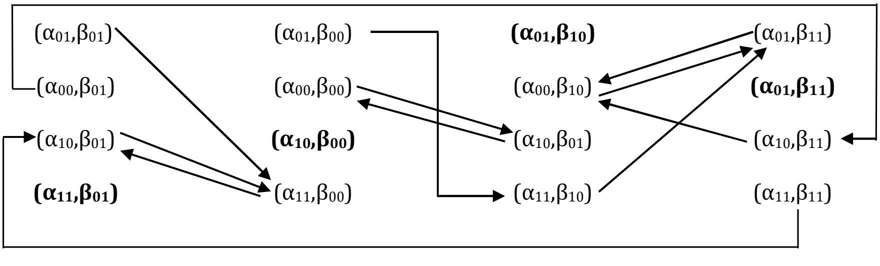


Figure 4. Stationary Points of Co-Evolution



When *K*>0, when the co-evolution begins to decrease, not all jurisdictions are necessarily on a global optimum of their landscape (see, for example, the state (*α11, β00)* of Figure 3). Some may be at the global peak, while others may be at a strictly local peak. The number of admissible patterns of interdependence depends on the parameters N and K and on co-evolution. Since there are *2N* different states of a given jurisdiction, there are *2N!* reorderings of these different strings based on their fitness value. When *K*=*N–1*, each of these reorderings is admissible. However, if *K*=0, two adjacent strings differ based on only one element in every admissible reordering.

Since every configuration of jurisdiction $i(i = 1, \ldots, G)$ can be coupled with $2N(G-1)$ different states of the remaining jurisdictions, we obtain $[(2N!)2N(G-1)]S$ possible patterns of interdependence for the case of $K=N-1$, where the parameter S identifies the degree of co-evolution, and a considerably lower number of possibilities for $K=0$. Any admissible model gives rise to an evolutionary dynamics in phase space, which is a set of $2NS$ trajectories, each starting from a different initial condition in phase space (see Figures 3 and 4).

A Simulation

In this section, we provide a simulation that covers the identification of the optimal configuration of fiscal decentralization. We consider the financial relations between all units of various levels of government. These relationships, as we have previously said, can be articulated in various ways by regulating the relations between rich and poor parts of a country and the degree of competitiveness and cooperation between units of state government. We assume that this variability gives sixteen possible configurations of fiscal decentralization that we obtain considering four critical features ($N=4$), which can assume two modes. Each configuration is identifiable with a string of four binary variables, each of which has a value of 0 or 1, according to the methods by which it presents its character. The features are: (i) competition vs. cooperation, (ii) inter-jurisdictional agreements, (iii) vertical fiscal equalization, and (vi) horizontal fiscal equalization:

Feature I
Cooperation value 0
Competition value 1
Feature II
No inter-jurisdictional agreements value 0
Inter-jurisdictional agreements value 1
Feature III
No vertical fiscal equalization value 0
Vertical fiscal equalization value 1
Feature IV
No horizontal fiscal equalization value 0
Horizontal fiscal equalization value 1

1. Competitive or cooperative federalism, with units of government that, in the second case, are in competition with each other, having the freedom to change tax rates and establish new and different taxes and exemptions. In the case of cooperation, all levels of government have in common a unique and direct goal of maximizing the benefit of smoothing the national spatial inequalities.
2. Presence or absence of inter-jurisdictional agreements.
3. Presence or absence of vertical fiscal equalization.
4. Presence or absence of horizontal fiscal equalization.

Binary values of 0 and 1 are assigned in the following way: The configurations are represented in a *fitness landscape* to measure their ability to achieve the goals of fiscal decentralization, including to develop local areas, to enforce more efficient spending, to improving the system of financial resources, to empower all levels of government, to reduce waste, to speed up decision-making processes that involve multiple levels of government, to reset the collusion between politics and bureaucracy and between center and periphery, and to provide services that meet most people's needs. Greater efficiency in the achievement of these purposes will correspond to a higher fitness value. This value is the result of the arithmetic mean of four fitness contributions. The *K* parameter indicates whether the contributions influence each other. If there are relationships between them, this would indicate the presence of a correlation among all or some of the *N* variables.

With K=0, the mode of a character provides a precise contribution that remains the same in all possible combinations. The mutation of the contribution of another character corresponds to the change of a single feature $K=l$. This continues until the contributions to the efficiency of all variables are changed with $K=N-1$ for each variation, including the fully correlated ones. In this case, each mode has different fitness contributions for each configuration, and the efficiency of each feature depends on the way in which it combines with others. The value of the parameter *K* models the morphology of the *fitness landscape*. In the sense that K=0, it is easy to find a configuration with the highest level of fitness that corresponds to the global optimum.

K can also be the index of the correlation between different portions of the landscape. A high value of *K* corresponds to a lower correlation between areas of high peaks and valleys, without following a linear ascending or descending trend. This happens if we consider an entire landscape, but if we divide it into multiple regions instead, each of which includes multiple configurations, we can perform restricted walks that show different degrees of correlation for each region valid only inside these regions. When a CAS has difficulties during its adaptive walk, it can divide itself — as well as its landscape — into parts, as seen with the patching, in order to attain the maximum fitness value for each region. This is equivalent to a spin-off of both the problems and the goals of a CAS.

The use of this model reveals the complex nature of each system and its ability to bind order and disorder. The disorder is represented by the evaluation of the fitness contributions, whose values are chosen randomly within the range [0,1]. The order is given by a coherent structure, produced by the model and comprised of configurations, an adaptation walk, a *fitness landscape*, and a fitness value. This structure, by itself, is not able to give definite answers about how to solve problems, but it can provide information about adaptation processes, proven and probable interactions between variables, and alternative scenarios that are not always known or taken into consideration in analyzing the behavior of a social organization embedded in a given environment. The knowledge about alternatives, even the unthinkable ones, can reinforce decisions made using traditional tools of study (linear and deterministic), or may suggest an alternative approach to problems, looking for new and different solutions. In any case, one has the advantage of widening the horizons of exploring and becoming more sensitive to signals that can capture and observe any system, be it natural or man-made.

The choice of giving random values to fitness contributions is also based on the fact that it is extremely difficult to know with certainty all events in a complex system and on a reluctance to overcome this difficulty with oversimplifications. It is better to trust in randomness than to have models with partial data collected in the field, from which emerges a description of reality that is far too removed from the world as we perceive it. However, the influence of such a case can be reduced by placing constraints and restrictions to be observed in the choice of fitness contributions. With the theory of complexity, these variables become endogenous. For fiscal decentralization, the randomness can be identified in historical and environmental factors. In fact, the fitness contributions indicate that each mode of every feature takes into account the history and socio-economic equilibrium of a nation-state. These factors are often disrupted by exogenous shocks, whose interactions with the elements of the tax system are not knowable with certainty and precision. All differences — which are due to historical events that have occurred and continue to exist in part because the story of every economic phenomena is self-determining — causes path-dependence and lock-in cultural phenomena. Economic agents are self-determining in the sense that they are proactive and free to choose and they are not guided only by environmental forces or innate impulses. From this theoretical perspective, the story of economic phenomena itself is self-determining. It is seen as the product of mutual dynamic actions between economic factors, agent behavior, and the environment.

We proceed with illustrating our simulation. We have random fitness contributions N=4 and K=3. Table 3 lists sixteen combinations of possible systems of fiscal decentralization, the fitness contributions (between 0 and 1) of each feature considered, and the final values of the fitness function. These are also shown in Figure 5 which presents the profile of the *fitness landscape*. We highlight the best combinations that correspond to peaks, and the worst ones that correspond to deep valleys. There is a global optimum for the combination (8)0111 which corresponds to a system characterized by cooperative federalism, networking between jurisdictions (vertical and horizontal equalization), and there are two minima corresponding to the string (6)0101 and (4)0100. The remaining peaks, highlighted by Figure 5, represent configurations of local optima. To verify whether it is true, we have to analyze the hypercube in Figure 6.

The distance between strings d measures the number of different elements between the strings. We also define two or more neighboring strings that differ in only one way, thus having d=1. With N=4 configurations, each configuration has four neighbors. The margin of the hypercube that separates two vertices connects two adjacent strings. In our case, the string 0000 needs to make a shift along one edge in order to reach string 0100, string 0010, or string 0001. Considering the hypercube and Table 3 (where the combinations are ordered according to the corresponding values of fitness), we note that there are two points of local optimum: that it is identifiable for string 0001 starting from string 0000 and its neighbors, while string

1101 has the highest fitness value in the area comprising the configurations 1100, 1001, 0101, and 1111. The hypercube is also important in tracing the adaptive walk of the system and in identifying the path that a system, whose configuration is not optimal, should take to reach an optimum peak. In our case, it represents the number of features to modify in the configuration of a tax system in order to increase its efficiency.

Table 3. Configurations with Random Fitness Contribution

No.	Configurations	Fitness contributions				Fitness value
(1)	0000	0.3	0.6	0.7	0.1	0.425
(2)	0001	0.5	0.4	0.9	0.7	0.625
(3)	0010	0.3	0.6	0.7	0.2	0.450
(4)	0100	0.9	0.2	0.2	0.1	0.350
(5)	0011	0.7	0.1	0.4	0.6	0.450
(6)	0101	0.2	0.6	0.2	0.4	0.350
(7)	0110	0.1	0.4	0.3	0.7	0.375
(8)	0111	0.5	1	0.8	0.6	0.725
(9)	1000	0.1	0.8	0.2	0.8	0.475
(10)	1001	0.9	0.1	0.3	0.4	0.425
(11)	1010	0.4	0.1	0.7	0.7	0.475
(12)	1100	0.5	0.7	0.1	0.6	0.475
(13)	1011	0.3	0.8	0.4	0.7	0.550
(14)	1101	0.4	0.4	0.6	0.9	0.575
(15)	1110	0.6	0.1	0.4	0.4	0.375
(16)	1111	0.6	0.7	0.1	0.8	0.550

Figure 5. Fitness Landscape with Full Randomness

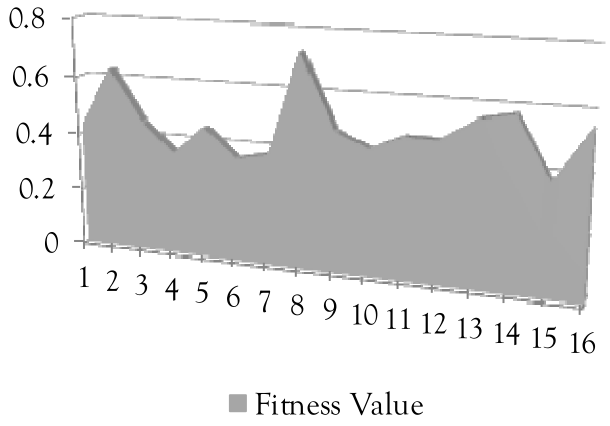
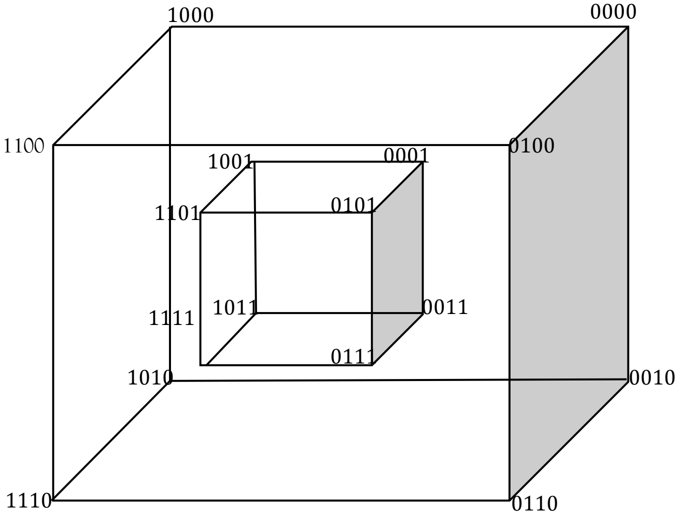


Figure 6. Hypercube of the Adaptive Walk



There are configurations that can climb only on local optima. String 1001 can achieve a level of efficiency equal to 0.625 (0001) (see Table 4), but fails to reach the peak of string 0111. The same is true for strings 1000 and 1100. The adaptive walk can be taken with a single movement, but it can also require numerous movements, culminating in the achievement of local or global optimum. In our case, the paradoxical situation is that, in order for the worst combination of string 0101 to reach the optimal one of 0111, the former must simply move a single side along the hypercube, modifying only the character of vertical equalization. The other minimum, 0100, must pass before 0110, adopting a structure of vertical equalization, and it can then proceed to the point of highest fitness value through a horizontal equalization.

Two clarifications are in order here. First, the point of the *fitness landscape* associated with the absolute highest fitness value is reachable from any configuration, provided that the systems pass though the less efficient configuration and, therefore, to temporarily hamper the performance of the system. Second, combinations near local optima can reach global optima, but only if they undertake adaptive walks that consist of at least two stages. The decisions on how to move through the landscape depend on the length of the period of transition from one configuration to another. The advantage of having a final optimal position should compensate for the temporary disadvantage to pass through a valley in the landscape. If, however, the organizational and legislation processes take a long time (for bureaucratic, political, or other reasons), then the losses suffered over the years can stop any change. This model, therefore, generally emphasizes the absolute importance of a network presence.

Table 4. Fitness Value in a Descending Order

Configurations	Fitness value
0111	0.250
0001	0.625
1101	0.575
1011	0.550
1111	0.550
1000	0.475
1010	0.475
1100	0.475
0011	0.450
0010	0.450
1001	0.425
0000	0.425
0110	0.375
1110	0.375
0101	0.350
0100	0.350

Conclusions

This article was inspired by the idea of investigating how new tools, provided by the complexity theory, may offer interpretative solutions to the optimization of an evolutionary economic complex system. In fact, we present complexity theory as an opportunity to better understand reality, and not to *a priori* neglect all phenomena that cannot be pigeonholed and explained according to preconceived theses. Even complex, the economy is a system that "evolves." Normally, we think of evolution in biological terms, but modern evolutionary theory — as a branch of complexity theory — perceives evolution as something much more general. Evolution is an algorithm, a formula that, through its special brand of "trial and error," creates new projects and solves difficult problems. Evolution concerns not only the DNA "substrate," but also each system that has the ability to process and collect information. In short, the simple function of evolution "to differentiate, select and amplify" creates information, knowledge, and growth. An economic system then is the way in which an ecological niche, with different "species" of players and agents, engages in a struggle for the "survival of the fittest." (Paul Krugman [1996] calls this metaphorical comparison of the economic and biological systems "biobabble.")

The efforts to understand modern economics as an evolutionary system negate such metaphors, focusing instead on understanding how the universal algorithm of evolution is literally and specifically implemented in the substrate of information processing of human economic activities. Having shown that fiscal federalism is to be understood as a dense network of economic-financial relationships between different co-evolving complex and adaptive systems that are linked by strong interdependencies, we endeavored to study fiscal federalism from a dynamic and evolutionary perspective, seeking solutions to problems posed by traditional economic theory with the tools of complexity theory. The solution of a problem, built on an adaptive complex system, cannot be searched as if we were solving a simple problem with no interdependencies.

In fact, identifying a single optimal solution for a problem — which is the purview of a simple system — is not for a complex system. Only on the basis of its numerous connections is it possible to determine the process by which different solutions to a problem may emerge. Taking into account the existence of multiple solutions, the same research can be done through a searching algorithm on a *fitness landscape* — a dynamic landscape in which complex adaptive systems are moving in search of optimal conditions. The configuration of this landscape is strongly conditioned by the presence of co-evolution and interdependencies. Moreover, jurisdictions can be regarded as evolving complex systems in the context of fiscal decentralization, albeit smaller systems. From these assumptions, and on the basis of evolutionary dynamics, we analyzed the behavior of jurisdictions in order to develop a model that identifies their optimal fiscal configurations by using the NK model.

The NK model includes two distinct components: a specific problem and a searching algorithm in the space of possible solutions. A problem is a set of possible solutions represented as binary strings, each associated with a fitness value that is the pay-off of that solution. The searching algorithm consists of repeated mechanism that scans the solution space from a (usually randomly chosen) initial string, or a binary *N*-dimensional space. The ongoing search is defined in terms of rules for how to move from one point to another. For example, the typical search, originally proposed by Kauffman (1993), calls for randomly choosing a string, changing one bit of which determines its acceptance or rejection based on whether the changed string has fitness value higher than its current one or not.

The repeated application of the algorithm generates a pattern in the space of possible solutions. The pattern ends when the rule reaches a string, from which all possible strings within the space of solutions are rejected. Two aspects make the NK model particularly attractive. The first aspect is determining the whole solution space, or the *fitness landscape*. Building a landscape with few or no interactions (represented by the value of *K*) means generating the equivalent of a simple problem, and increasing *K* generates a complex problem. The second aspect is the representation of the NK-model's searching algorithm. The NK model assumes a local search. It is local because the search involves a difficulty in observing the space beyond the immediate goal of improving present condition of the systems. These two aspects — complexity through interaction and local search — paradoxically lead to simplified and manageable solutions to many real situations.

It is an interesting tool because it provides the opportunity for researcher to represent and control the two aspects of problem-solving: the complexity of the problem and the degree of expertise for finding a solution. It is possible to use the NK model to generate and evaluate the space formed by these two dimensions in order to represent them as real-world phenomena on a small scale. The use of the NK model arises from the possibility of establishing a relationship between the skills of decision-makers and the difficulty of intervention in economic policy. In this case, it is no longer relevant that the modeled problem is much simpler than the real one, since the solution strategies are modeled in a much less sophisticated way. By controlling both aspects, we can expect that the properties of the set that includes the solutions generated in the model are similar to the set of real solutions generated in real systems with an equivalent ratio of task-to-skills difficulty in finding a solution.

Dividing a complex system into independent self-optimizing decision-making patches can increase the efficiency of the search for optimal system-wide configurations. These theories reflect a broad consensus regarding two underlying benefits of decentralized decision-making procedures of this kind. First, decentralized decision-making can function as an efficient sorting mechanism, and mobile individuals can efficiently match their preferences for different local public goods via migration into (and exit out of) different decision-making units. Second, dividing a decision-making polity into smaller and local decision-making subunits may be subject to fewer inefficiencies of information transfer because information about local conditions and local preferences is imperfectly distributed and tends to be concentrated locally. Therefore, local governments and consumers are more likely to make better (welfare-maximizing) decisions. There is an equally broad consensus on the "cost" side of the decentralization equation as well. Decentralized decision-making is not favored where jurisdictions are not "congruent," i.e., where there are significant intercommunity interdependencies or spillovers.

Fiscal decentralization may "work," in other words, because it is a "patching algorithm," a means for solving public-policy problems defined in the context of a complex "social welfare landscape." As such, an understanding of the factors that determine the effectiveness of the algorithm cannot help, but have an impact on our understanding of these political decision-making institutions. With adaptive management, the decision-making process is open to continuous change and based on a continuous input of information and analysis. This, in turn, will require the use of tools that include adaptive optimization algorithms.

Optimization across a *fitness landscape* involves using optimizing search algorithms not only to control for the direction, but also to test the fitness of different system-component combinations and adapt to the results continuously. Moreover, the system's optimization algorithm must be adaptive because the systems, with which it interacts, are evolving in their own searches for the fittest solutions. Complex, adaptive, evolutionary systems incorporate algorithmic decision-making tools that allow adaptive long-term fitness optimization through repeated evaluation of the system design. Such tools need to be interdisciplinary, they require extensive and reliable information, and they utilize parameters that are interrelated and co-evolving over time.

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