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WORKING PAPER SERIES

The Santa Fe Perspective on Economics: emerging patterns in the science of complexity

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The Santa Fe Perspective on Economics: emerging patterns in the science of complexity

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0. Introduction

The complexity approach to economics largely originated from the "Santa Fe Perspective": the view of a group of scientists working in the Economics Program (1988-2004) at the Santa Fe Institute for the Study of Complex Systems (hereafter SFI)[1]. This paper tells the story of the Santa Fe Perspective, traces its relation with other ideas that emerged at SFI in this seminal period, and concludes with some reflections on the current state of complexity theory in economics.

As a starting point, I divide the life of the Economics Program in three periods roughly corresponding to the three workshops (1987, 1996, 2001) dedicated to '*The Economy as an Evolving Complex System*'. Each of them reflects a stage in the development of the Santa Fe Perspective, characterized by a particular constellation of attitudes, ideas and objectives: the weakly heterodox, the strongly heterodox and the synthesis periods. These labels reflect the prevailing orientation towards neoclassical economics[2], which seems to be on the one hand, a core concern for the directors of the Economics Program, and, on the other hand, a central

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I wish to thank Kenneth Arrow, Brian Arthur, Sam Bowles, John Holland and David Lane for enduring my curiosity and for illuminating discussions on the issues covered in the paper. I am also grateful to Ronda K. Butler-Villa and to the staff of the Santa Fe Institute Library for their precious help in finding and gathering the material that grounds this research. The usual disclaimer applies.

[1] This term is introduced by W. B. Arthur, S. Durlauf and D. Lane (1997, p. 2-3). Other terms that have been used for defining the approach are 'The Complexity Perspective' and, to a lesser extent, 'the process-and-emergence perspective'. Many of the concepts discussed in the essay (agent-based modeling, inductive reasoning and increasing returns) were not first introduced at SFI; however the Institute acted as a catalyst for their synergy and consequent diffusion, and eventually got the credit for initiating them.

[2] I use the term neoclassical economics to define the mainstream of current economic thought which relies on market equilibrium as its organizing concept. This is the way the word was used by people during discussions at SFI and, in spite of the changes that the notion has encountered over the years, I believe it still captures the essence of orthodox economic thinking. Further details will be given in the paper.

issue for the relevance of complexity to economic theory.

1. The Weakly Heterodox Period (1984-1988): Economics and Emerging Syntheses

In 1983, George Cowan -- physical chemist, Manhattan Project veteran, and in this period Director of Research at Los Alamos National Laboratories -- assembled a group of senior scientists who were interested in creating an environment for "blue-sky" research on broad themes in science that crossed many disciplinary boundaries. One year later, these scientists formed the Santa Fe Institute,[3] with Cowan as its first president. The spirit of the Institute was illustrated later in the same year in a workshop significantly named "Emerging Synthesis in Science"[4]: the participants envisaged a transdisciplinary science, with no insular conception and the possibility of joining the hard science with the soft ones with in an attempt to bringing the rigor of the former into the latter (Pines 1988, Gell-Mann 1988, Cowan 1988).

In that workshop there were no economists, but it happened that the Institute's aim was to be put to its first test in the field of economics. On March 9, 1986, the meeting of the SFI Board of Trustees was dedicated to find funding. Robert McCormick Adams – anthropologist, Secretary of the Smithsonian Institution, and Board member -- reported that he had met with John Reed, CEO of Citicorp, who was annoyed by the failure of his economist colleagues and consultants to predict such large-scale economic phenomena as cascading failures in Latin American and credit card debt payments, and was therefore willing to fund research on a new kind of economics. The new Institute seemed to Reed an ideal place to carry out such research.

After some preparatory meetings[5], an exploratory workshop, 'The Evolutionary Paths of the Global Economy'[6], was organized. The idea was to open up a dialogue between physicists and economists on theories and methods: ten physicists and ten economists were invited to participate in a ten days workshop (September 8-18, 1987), which through lectures and discussions would try to find some common ground for productive interaction. The

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3 The institute was incorporated as "Rio Grande Institute" since the name "Santa Fe Institute" was already in use by a company. It got its current name more than a year later. The concept of the institute according to Cowan is to be found in an interview appeared in the SFI Bulletin 1988, 3, 2, p. 3-8.

4 October 6-7, November 10-11, 1984, School for American Research, Santa Fe.

5 August 1986 6-7, "International Finance as a Complex System", Rancho Encantado, Tesuque.

6 For an introduction to the workshop see also SFI Bulletin 1987,2, p.5. It also contains (p. 8-10) an illustration of complex adaptive systems by John Holland.

workshop was to be co-chaired by two Nobel Laureates, Philip Anderson and Kenneth Arrow, who were responsible for recruiting the other participants.

The choice of Kenneth Arrow[7], the grand man of the economic mainstream, to lead the effort to construct a new economics might appear paradoxical. On closer inspection, it is only partially so. On the one hand, the 1987 workshop had only a preliminary function: it was designed to put in evidence the current state of the respective disciplines, and, therefore, Arrow was fully entitled to act as the representative of economics. On the other hand, Arrow had long evidenced awareness of problems with the neoclassical approach and an openness towards discussing them (1962, 1964, 1982). The announced aim of the workshop was *"expanding the horizons of conventional economic theory so that it might eventually be able to deal with such complex macroeconomic problems as the global economy, rather than in applying pre-existing economic theories to this problem and so becoming a forum for conflicting views of causation and cure, based on manifestly incomplete theories.*" (Pines 1988, p. 4). The agenda for the economics side of the meeting was meant to initiate this process through a three-pronged strategy: to "teach" to physicists the fundamentals of orthodox economics to introduce them to the empirical side of the discipline and to outline some heterodox concepts. The latter point, in the team of economists (Waldrop 1992)[8] that Arrow charged to carry our this program had very little importance since the only non-mainstream representative was W. Brian Arthur

1. The Economy as an Evolving Complex System I: double track

The first workshop represents the inception of the emerging Santa Fe Perspective. In order to track it, I will not focus on the content of the single papers; rather, I will try to grasp the underlying model of economic theory and the expectations concerning the outcome of the workshop.

Arrow's summary (1998, p. 275-281) of the economics side of the workshop is illuminating. He depicts economics as steadily moving towards dynamic analysis, the theoretical side using nonlinear equations and the empirical side sticking to linear stochastic analysis. For both sides, the emphasis was on negative feedback, i.e. amplitude reducing behavior. The

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7 George Cowan had first invited James Tobin, who declined.

8 The economists invited by Arrow were: W. B. Arthur (Stanford University), M. Boldrin (University of California), W. Brock (University of Wisconsin), H. Chenery (Harvard University) T. Kehoe (University of Minnesota), T. Sargent (Stanford University), J. Scheinkman (University of Chicago), M. Simonsen (Brazil Institute of Economics), L. Summers (Harvard University).

cornerstone of the entire building was the theory of general competitive equilibrium, with the injection of the rational-expectation hypothesis and the assumption of markets existing for all commodities at all times. He then expounds the problems with the neoclassical approach, thereby pointing out the possible areas of research for the envisaged interdisciplinary cooperation. In so doing, Arrow also reveals his own ideas concerning the relationship between the neoclassical approach and the new-economics-to-be: "*There was a generally held point of view, which indeed goes back to the origins of economics as a systematic discipline, that solutions that were not constant would tend to the constant solution or steady state. But more recent research [...] has demonstrated that there are solutions to the same equations with cycles and even with chaotic behavior. The multiplicity of solutions is itself an embarrassment, since it suggests that economic theory even if accurate, does not yield a unique pattern of dynamic behavior and hence its predictions are far from sharp*" (1988, p.278). And also: "*The general perspective of mainstream (the so-called neoclassical) economic theory had certainly had some empirical success. [...] But it is clear that many empirical phenomena are not covered well by either the theoretical or the empirical analyses based on linear stochastic systems, sometimes not by either*" (1988, p.278). In the light of these problems with the neoclassical theory, the collaboration between physics, biology and economic would be welcomed (1988, p. 280-1), with a particular focus on chaotic dynamics and learning.

Arrow's intervention as a whole shows that, in spite of the declared innovative aim of the workshop, he is not expecting the birth of an entirely new approach: the general framework should remain as it is, with the role for the 'new economics', enriched by cooperation with physicists and biologists, being to improve the *status quo ante*. In choosing to support an interdisciplinary approach to economics, he is probably playing the role of the captain in ferrying the mainstream towards new developments that would have overcome the criticisms to the neoclassical approach, which in the first half of the 1980s were multiplying and growing stronger. Arrow's idea is thus a sort of double track: SFI's effort must remain an addition, and not an alternative, to the neoclassical framework. According to him, the 'new economics' tools and theories have to be adopted only in specific cases when neoclassical economics fails.

This view is also reflected in the workshop results. The published discussions reveal a consensus on some primarily methodological issues, which do not imply a revolution with respect to the mainstream view: the use of statistical physics (especially spin glass) methods and genetic algorithms, and the possible relevance of chaos in economic dynamical models and econometric time series.

It has to be said that the very idea of putting together economist and physicists to work on a common –possibly long-term - project constituted a revolutionary approach in itself. Indeed, the premises were not at all encouraging: neither the intellectual hubris of both the physicists and the economists present at the meeting, nor the intellectual background of the chairmen seemed very promising for the search for common ground. For instance, Anderson in the early 70s had engaged in a fierce battle against reductionism (Anderson 1972), while reductionism was the very heart of Arrow's neoclassical economics. The "official" account of the workshop hints at some of the coordination problems between economists and natural scientists: "*Quite generally, the economists at the workshop were eager to learn as much as possible about the limits of applicability of the various kits of possible applicable complex systems tools provided by the non-economists, while the natural and biological scientists took every opportunity to inquire about the possible time dependence of models of the economy*" (Pines 1988, p. 5).

However, other sources give a different account. For instance, Colander writes that, at the first workshop, economists mostly attempted to defend their axiomatic approach, "*facing sharp challenges and ridicule from the physicists for holding relatively simplistic views*"[9] (Colander 2003, p. 8). Waldrop (1992, p.142) reports the reaction of Phil Anderson to the economists' account of the world: "*And you guys really believe that*?" Arrow (2009), questioned on the ease in interacting with physicists, agrees on the presence of some problems: "[*Was it easy to communicate with natural scientists?] Well, no, I would not put it that way. Simulated annealing was a figure of speech, I even did not know much about annealing. There were obviously a number of different aspects, and the truth is that we never really cohered to these days*".

The interaction, however, must have been convincing enough to justify funding the first residential program of the Institute, the Economics Program, which began the year after the founding workshop with Brian Arthur as first director.[10]

From the 1987 workshop onwards, Arrow has been a constant presence at the Institute.

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[9] Natural scientists perplexities on the economists account were by no means of small magnitude. They stressed their penchant at downplaying the role of non economic force, their acceptance of the Rational Expectation Hypothesis which is manifestly flawed, the impossibility of a system with a fixed number of variables to model novelty (Packard 1988, p.170)

[10] For the list of the initial participants in the Economics Program see SFI Bulletin 1989, 4, 1, p.6.

However his role has been more as a steersman, in the ambit of the Science Board, than as an active researcher: there are no SFI working papers by him and few interventions in the books of the SFI studies in the sciences of complexity (for instance, Arrow 1994). He intervenes only once in the SFI Bulletin, in 1989 (vol. 4 n.1), and, in that circumstance, he offers another glimpse into his way of thinking about the kinds of problem the Economics Program should address: "*We have a problem that the standard models require incredibly many markets, and the substitute model requires incredible recalculation. The suggestion, therefore, is that we have to emphasize a different kind of world, one in which people instead of optimizing and rationally forecasting the future, are engaged in much more limited operations more suitable to constraints on human reasoning and calculating abilities []. As a new point of view we turn to bounded rationality, a departure from the mainstream tradition*" (p. 10)[11].

Leaving aside his scientific contribution to the development of a complexity perspective in economics, Arrow has however had a crucial importance in raising the attention around complexity and in giving the economists' effort at SFI credibility and recognition in the academic world.

The publication of the proceedings (Anderson, Arrow and Pines 1988) received tepid but encouraging comments. For instance, Day's (1991) states " *it is a great mission on which the Santa Fe Institute has embarked. These essays, one hopes, are but early steps in a resolute march toward that better understanding of adaptive, dynamic forces in the world economy"*[12] (p. 80).

1.2. Sowing time

The choice of Brian Arthur[13] (1988-1990) as director of the Economic Program and the influence of and John Holland[14] were fundamental in determining the concepts and tools that would constitute the nucleus of the Santa Fe Perspective, and set the Economics Program in

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11 In 1994, however Arrow will criticize bounded rationality: *"I wouldn't say that it's a theory about how actual human beings solve problems. It's a theory of how you ought to go about solving problems. Where those rules come from, why are they used and not other possible rules, these things have numerical parameters that are quite arbitrary" (p. 455)*

12 Day is referring to John Reed's expectations concerning the 1987 meeting (Cowan, McCormick Adams, p.312)

13 W. Brian Arthur was Dean and Virginia Morrison Professor of Population Studies and Economics at Stanford University.

14 John Holland is Professor of Psychology and Professor of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor.

the direction increasingly divergent from the economics mainstream. Arthur, the only heterodox economist in the 1987 workshop, had developed a stochastic dynamic approach to increasing returns and technological lock-in, while Holland had for the past two decades pioneered a heterodox, biology-based approach to constructing computer algorithms, and had been a leader in abandoning traditional equation-based modeling of complex systems in favor of computer simulations.

1.2.1 Operative concepts and suitable methods

In the presentation given at the 1987 meeting (1988, p.117-24), Holland details the parallels between economies and other complex systems, which he referred to as "adaptive non linear networks," ANN. Up to that moment, discussion of complex systems, and the analogy between them and economies, had been vague, and the articulated definition of an ANN provided by Holland was the working concept needed by the Economics Program to get started. To my knowledge, in the brief life of the Institute, the only previous definition of complex systems was to be found in the SFI Bulletin in the preview of the workshop '*Complex Adaptive Systems*'[15]: *"Complex adaptive systems are systems comprising large numbers of elements the properties of which are modifiable as a result of environmental interaction [...] Complex adaptive systems process information, and can modify their internal organization in response to such information. In general, complex adaptive systems are highly nonlinear and are organized on many spatial and temporal scales*." (Cowan J. and Feldman, 1986, 1, 1, p.11). Cowan's and Feldman's concept is broad enough to recall the functioning of the market but gives no details on the underlying mechanisms.

For Holland, an economy has the following features, which qualify it as an ANN :

"*1. The overall direction of the economy is determined by the interaction of many dispersed units acting in parallel. The action of any given unit depends upon the state and actions of a limited number of other units.*

2. There are rarely any global controls on interactions. Instead, controls are provided by mechanisms of competition and coordination between units mediated by standard operating procedures, assigned roles, and shifting associations.

3. The economy has many levels of organization and interaction. Units at any given level behaviors, actions, strategies, products typically serve as "building blocks" for constructing units at the next higher level. The overall organization is more than hierarchical, with many sorts of

[15] A preliminary illustration (Non-Linear Systems Out of Equilibrium) of CASs had been given by Holland in 1986 in the same workshop.

tangling interactions (associations, channels of communication) across levels.

4. The building blocks are recombined and revised continually as the systems accumulate experiences – the systems adapts.

5. The arena in which the economy operates is typified by many niches that can be exploited by particular adaptations; there is no universal super-competitor that can fill all niches […].

6. Niches are continually created by new technologies and the very act of filling a niche provides new niches […]. Perpetual novelty results.

7. Because the niches are various, and new niches are continually created, the economies operate far from an optimum (or global attractor) […]". (1988, p. 117-8).

The list is introduced, in obedience to the spirit of the first meeting, as a 'substantial extension' of traditional economics (1988, p.118); however, in substance, the departure from orthodox thinking is sharp, both on the theoretical and the analytical side. Holland provides a framework in which economies and economic actors operate under hypotheses that are very different from the neoclassical economics ones, and he refuses a purely mathematical approach to economics in favor of a computational analysis.

Elaborating on the differences between an ANN and a neoclassical approach, Holland states that in traditional economics *"fixed rational agents […] operate in a linear, static, statistically predictable environmen*t" (1988, p.118); in contrast ANNs allow for *"intensive nonlinear interactions among large number of changing agents. These interactions are characterized by limited rationality, adaptation (learning), and increasing returns.*" (1988, p. 118). Moreover, ANN agents do not act in term of stimulus and response but try to anticipate the outcome of their courses of action and the changes in the systems. The models on which they do so are always imperfect. While in mainstream economics decision making models imply the computation of the best attainable option in given circumstances, Holland refers to a heuristic procedure in which the agents do not list and rank the all alternative courses of action but simply tries to figure out what should be done on the basis of available information (1988, p. 119).

Furthermore, according to Holland *"the global economy has features that, in the aggregate, make it a difficult subject for traditional mathematics"* (1988, p.117)[16]. The required mathematics should be able to model both the interactions among economic actors that generate the overall patterns, and the internal procedures that guide these actors'

16 "*The usual mathematical tools, exploiting linearity, fixed points and convergence, provide only an entering wedge when it come to understanding ANNs*" (1988, p.118)

anticipations and choices.

To sum up, the economy as ANN drops the assumption of perfect knowledge and rationality, introduces heterogeneity among actors and interaction modalities, and highlights the role of interaction, organization and hierarchy. The way in which neoclassical theory treats (or fails to treat) these aspects of economic phenomena have always been subject to criticism, in particular by such economists as Hayek, Simon, and Kornai, among many others. But those criticisms had been substantially ignored by the mainstream, on the grounds that there are no methods through which they could be investigated with the rigor of the mathematics employed in neoclassical theory. In this theory, the network of interactions that shapes the economy is simplified radically, mainly through the hypotheses of complete information and perfect knowledge. These hypotheses allow the theoretician to assume that each element of the economy can 'contact' and 'evaluate' all the other elements at no cost, so that the "real" network of connections is irrelevant to the functioning of the system. This is functional to the possibility of conducting an equilibrium analysis in mathematical form: links are akin to mathematical operators that must stay fixed if logical deductions concerning equilibrium outcomes are sought (Foster 2005, p. 884). In the same vein, the continuous variations taking place in connections due to adaptation and non- simultaneity of actions cannot be taken into account when using optimization techniques. Optimization is only practicable under the hypothesis of knowing all possible outcomes of the process under analysis and the probability associated with each of them, and this is not possible when dealing with complex systems.

To overcome such problems, Holland proposes use of the Genetic Algorithm (GA) in economic modeling. The GA is a tool that encompasses all the features of ANNs, including the generation of perpetual novelty. A GA manipulates a set of structures, called the population. Each structure is assigned a value (fitness) based on the result of its interaction with the environment. GAs operate on the population by producing new structures that form in the aggregate a new population; existing structures contribute to the formation of the structures in the new population in proportion to their observed fitness, i.e. the fittest ones have a higher chance to be represented in the new population.[17] In the processes through which a new population is formed from an existing one, not only are "old" structures reproduced (especially those with high fitness), but entirely new kinds of structures may emerge.

[17] Here, the discussion of the relationship between mathematics and computation is to be understood on purely qualitative terms (what is possible to obtain by applying computer simulation instead of mathematical models). Whether simulations can be considered different from mathematics in their essence remains a debated issue. See Fontana (2006).

With respect to the general ideas expounded in the 1987 meeting, Holland proposed a very well-organized framework of definition and tools. It is worth noting that, in Arrow's view, complexity science was almost overlapping with chaos. Holland's ANNs, with their 'perpetual novelty', extend the notion of complexity beyond mere non-linearity. Indeed, all complex systems have some degree of nonlinearity in their dynamics. At the same time, there are nonlinear systems that are *not* complex. Non-linearity is a necessary but not sufficient condition for complexity. Complex dynamics are processes that involve non-periodic fluctuations and switches in regime or structural changes (such as those implied by bifurcations and transitions to chaos) and perpetual novelty. The very act of adapting to other's unit behavior or exploiting the opportunities provided by a niche causes a reaction that spread in the system, thereby generating new adaptations and new behaviors. This feature escapes mathematical treatment even in non-linear or chaotic terms, since once a dynamics is embedded in the form of equation(s), there is no way for the system to endogenously change its own path (Packard 1988, 170).

Following Holland's account of ANNs[18], the new economics envisaged by John Reed should have different micro-foundations and methods from the neoclassical one. In the following years, Holland's account of ANNs becomes the basis of the shared definition of complex adaptive systems: the same features are reported –with few additions – in the introduction to the proceeding of the 1996 meeting (Arthur, Durlauf and Lane 1997) and it is used to identify the core of the Santa Fe Perspective.

In the 1987 workshop, Stuart Kauffman[19], a theoretical biologist, introduced a parallel between economies and self-organizing autocatalytic sets that became an important component of the Santa Fe Perspective (1993). Kauffman (1988, p. 125) notices that economics has no theory to explain the increasing complexity of the web of creation and transformation of products that constitutes the economy, while autocatalytic sets are able to endogenously create new structures, undergo phase transitions, booms and crashes exactly as economies do. By adopting the autocatalytic set hypothesis, whose basic idea is to start from an initial set of "molecules", some of them acting as catalysts, attracting new elements that, in turn, can grow more complex and reproduce, it was possible to generate endogenously

[18] See also Holland 1995 and SFI Bulletin 2000, 15, 1, p.10 for further details on ANNs, now called complex adaptive systems (CASs), and their implications for science in general.

[19] University of Vermont Complex Systems Center, adjunct Professor in the Department of Philosophy, University of Calgary. He has been faculty in residence at SFI from 1986-1997.

dynamics that can be interpreted as analogous to economic phenomena that escape traditional modeling, such as endogenous innovation, waves of innovation, new uses of already existing artifacts,[20] the existence of different kinds of economic systems and so forth. Notice that this view is different from Darwinian evolution, which had been already adopted in economics. In this view, there is no pretence of climbing a fitness landscape: agents, organizations and technology do not steadily proceed toward a global optimum, rather, they are linked to one another and their interactions create (and also ban) pathways for their future development. To use Kauffman's metaphor, they move around a fitness landscape made of rubber so that everything gets deformed each time a step is taken.

The reflection on whether these views can be considered as mere extensions to the traditional approach and whether the features they single out constitute a special case – as suggested by Arrow (1988) – permeates, often surreptitiously, the strongly heterodox and the synthesis period.

1.2.2 Brian Arthur and a New Economics

While Holland's contribution to the evolution of the complexity approach provides a common language for Economics Program's scientists, Arthur's relies on various theoretical and empirical findings (increasing returns, inductive rationality, agent-based and cognitive foundations) and on a constant attention to the methodological aspects of what was happening at SFI.

Brian Arthur's discontent with the traditional approach was well articulated long before the foundation of the Institute. As early as 1979, he had already elaborated a long list of criticisms to the mainstream approach and had a set of alternatives to propose (see Appendix A).

In the 1987 workshop he gave the most unorthodox presentation by an economist, with a talk on the effects of introducing increasing returns in the traditional economic view (Arthur 1988, p. 9-27). Increasing returns destroy some of the desirable properties of the general equilibrium approach: there are multiple equilibria whose process of selection is unpredictable, there is no guarantee that the competition would select the superior outcome and, once the market has settled on an outcome, it may get stuck in it, in spite of its (relative) inefficiency. The tone of the presentation is that of an impartial and even-handed survey of increasing returns; there are no claims for the need for a "New Economics" or the like.

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[20] This line of research will be very important in the Strongly Heterodox period and is still flourishing with some engaging interdisciplinary additions, as in Lane, Pumain, van der Leeuw and West (2009).

However, Arthur's terms as director of the Economic Program (1988-1990; 1994-1995) reveal a revolutionary agenda. He pioneered - together with Holland and others - the agent-based modeling technique as competitor of the traditional mathematical approach. With the popular "El Farol" bar example, he argued that when agents form their expectations, the resulting self-referential decision-making relies on induction rather than deduction. He used this argument as a springboard for an insistence on a plurality of views for the cognitive foundations of economics, in opposition to the mainstream's monofoundation of deductive optimizing rationality.

Arthur was aware that the Economics Program was going beyond the initial expectations of extending the neoclassical frame. It was moving toward a new economics. In a letter to Martin Shubik[21] he describes the direction of his leadership of the Economic Program:

"This shift—seeing the economy as an evolving, complex system—had three implications:

1. Because it included heterogeneous agents (differing consumers, banks, firms) together creating the patterns they reacted to, models could not easily be "solved" analytically. The natural approach was agent-based modeling

2. Because agents in most models attempted to formulate decisions in a problem where other agents (who differed in unknown ways) were trying to do the same, ill-defined decision problems resulted. Decision making in this context could best be seen as inductive, not deductive. Hence we focused greatly on issues of cognition in the economy, making heavy use initially of John Holland's ideas.

3. Because agents reacted to the patterns they co-created, by definition the problems we investigated started out of equilibrium (i.e. not at a static solution point). The appropriate research question in each problem was what patterns or outcomes would arise? Would the system find its way to a conventional equilibrium? Or would it find ever-new patterns, and produce perpetual novelty?" (Arthur 2003).

And again, later on in the same letter*: "From its start, the program had the objective of bringing a dynamic, evolutionary approach into economics. We decided this was best achieved by demonstration projects that reformulated some of the standard problems in economics in the new way. Hence for example the stock market model as our version of the classic asset-pricing problem. Our objective in 1988 was not so much to reform economics as to catalyze certain*

21 Martin Shubik is Seymour Knox Professor Emeritus of Mathematical Institutional Economics, University of Yale and an active presence in the SFI Economics Program from 1989.

changes that we saw as inevitable—in particular, the change from standard equilibrium economics to agent-based, out-of-equilibrium economics".

Brian Arthur was active throughout the life of the Economics Program. His papers (especially 1994b, 2005) provide an extremely useful account of the evolution of the complexity approach to economics. It was Arthur, together with David Lane,[22] who coined the term the Santa Fe Perspective, and to suggest that the kind of economics done at SFI was an autonomous approach detached from the neoclassical one.

2. The Strongly heterodox period (1988-1996): "An Emerging Paradigm"[23]

The Economics Program was anything but a unitary coherent project. The Institute Science Board favored a policy of quick turnover of resident researchers, so under the label of the program we find a lot of subprograms - sometimes only weakly interrelated- that were initiated at SFI and continued elsewhere. The direction of the program itself has been given to different scientists (Appendix B, List of Directors) who interpreted their mandates in quite different ways. In the period between 1988 and 1996, a lot of events took place (Appendix C, List of Seminars and Conferences); in what follows I will try to delineate some patterns and I will suggest an analysis. There is no doubt that the emergence of the Santa Fe Perspective has been itself an evolutionary adaptive process.

After Arthur's direction, the heterodox vein in the program was *dominant: "in contrast with the leading paradigm in economic theory, the Program's research is not directed to the search for equilibria, characterized statically as systems of production and consumption decisions at given prices under which all market clear. Rather, its object is to describe the dynamic processes operating under conditions of imperfect competition, and bounded rationality that lead to the creation of markets and prices, and evolution of the economic aggregates and institutions. The Santa Fe Economics Research program emphasizes the mathematics of stochastic processed computer simulation, instead of the traditional topological methods of neoclassical economics*"(SFI bulletin 1990, 5, 2, p.15)

In the strongly heterodox period the initial scope of the program (SFI Bulletin 1989, 4, 1 p.5) starts to broaden. Under the Lane-Geanakoplos[24] direction the program focuses on

[22] David Lane was Professor of Theoretical Statistics at the University of Minnesota.

[23] SFI Bulletin 1988, 3, 2, p.11

[24] John Geanakoplos, a previous Arrow's PhD student, was Professor of Economics at Yale with specialization in general equilibrium theory and incomplete markets, game theory

technological innovation, chaos in financial series, and on the theory of money. Geanakoplos was investigating the reason why certain markets were missing in collaboration with Eastern Europe economists and anthropologists, while Lane worked on artificial societies and information contagion (Lane 2003). The agent-based methodology pioneered in Arthur's and Holland's (Arthur, Holland, Le Baron, Palmer 1996) artificial stock market was extended and applied to other themes. Technological innovation[25] was treated as endogenous to the system and studied in an artificial economy and, as for the theory of money, a simulated strategic market game was developed, with money and loans of various periods, in order to observe the emergence of structure for interest rates [26]. William Brock[27] and Blake Le Baron[28] were engaged in showing that financial series were not random walks, but exhibited a chaotic behavior or other non-linear regularities.

Le Baron's (1993) steers the program toward a more empiric approach in developing methods to detect underlying patterns in time series. Transversal to these researches,[29] it is worth noting the work of Doyne Farmer and others on prediction in financial market.

From 1993 onward, references to the Economic Program in the Bulletin of the Institute become less and less frequent. Meanwhile, ideas developed within the Program started to spill over to other areas of research, and the Institute began to attract scientists with similar interests. The "Sugarscape" agent-based model, which J. Epstein and Axtell (1996) had developed outside the Institute is increasingly incorporated into Institute presentations and activities, as are the modeling platforms Swarm, developed by a group coordinated by Chris

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and mathematical finance.

[25] The research group was composed by: Holland, Lane, G. Dosi, M. Lippi, F. Malerba, L. Orsenigo.

[26] The research group was composed by: Shubik, Miller, Lane, Geanakoplos, Sudderth and Karatzas.

[27] William "Buz" Brock is Professor of mathematical economics at the University of Wisconsin Madison.

[28] Blake Le Baron is the Abram L. and Thelma Sachar Chair of International Economics at the International Business School, Brandeis University.

[29] Although Farmer was not actively doing research in economics during 1987-91 he had lots of contacts with the participant in the program. He then (1992-8) devoted his efforts to the creation of the Prediction Company trying to transfer his researches in the business field. He is in full time residence at SFI from 1999. (From a letter of D. Farmer to M. Shubik 2003).

Langton in the Institute's Artificial Life program,[30] and Echo, initiated by John Holland and developed in the context of the Adaptive Computation program (SFI Bulletin 1993, 8, 2, p. 13-19). In addition, a few excellent economists with backgrounds in the neoclassic paradigm, most notably Alan Kirman,[31] began to frequent the Institute and collaborate with SFI scientists (Lane 2003).

The interaction of these projects and people led to the formation of the Santa Fe Perspective, whose contours took shape in 1996, during the second workshop dedicated to the Economy as an Evolving Complex System.

2.1 The Economy as an Evolving Complex System II: The Santa Fe Perspective

The task of the 1996 workshop was to provide an overview of the contribution of complexity research to economics. This was evaluated in contrast to two defining elements of mainstream economics: (1) 'equilibrium, in which "*the problem of interest is to derive, from the rational choices of individual optimizers, aggregate-level "states of the economy" (prices in general equilibrium analysis, a set of strategy assignments in game theory with associated payoffs) that satisfy some aggregate level consistency condition (market-clearing, Nash equilibrium) and to examine the properties of these aggregate level states"* (Arthur, Durlauf, Lane 1997, p. 3); and (2) 'dynamical systems', in which "*the state of the economy is represented by a set of variables, and a system of difference equations or differential equations describes how these variables changes over time. The problem is to examine the resulting trajectories, mapped over the state space.*" As the authors of the conference proceedings volume went on to note, *"the equilibrium approach does not describe the mechanism whereby the state of the economy changes over time – nor indeed how an equilibrium comes into being. And the dynamic system approach generally fails to accommodate the distinction between agent – and aggregate – (levels except by obscuring it through the device of representative agents. Neither accounts for the emergence of new kinds of relevant state variables, much less new entities, new patterns, new structures"* (Arthur, Durlauf, Lane 1997, p. 3).

As for the complexity view, it was harder to find a pattern in the mix of programs and researches sketched in the previous section carried out under the auspices of the Economic Program. The editors of the book however, while acknowledging the diversity in the

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[30] The SWARM platform was to be released in 1996 (SFI Bulletin 1995-6, 11, 1)

[31] Alan Kirman is Professor and Director of Studies at the Groupement de Recherche en Economie Quantitative d'Aix –Marseille.

Economics Program set forth the perception of a unity and the dawning of a unitary view on economic phenomena: "*the authors of the essays in this volume by no means share a single coherent vision of the meaning and significance of complexity in economics. What we will find instead is a family resemblance, based upon a set of interrelated themes that together constitute the current meaning of the (Santa Fe) perspective in economics"* (Arthur, Durlauf, Lane 1997, p. 1-15).

In order to find out what these 'interrelated themes' are, I begin by highlighting some differences with the 1987 meeting. Then, there was a strict alternation between largely mainstream economics presentations and methodological presentations from physics, biology or computer science; in the 1996 workshop, all the papers treated economic themes, and the envisaged integration of these themes with methods from biology and physics seemed to have been accomplished (see Colander 2003, p. 8). In addition, the range of economic phenomena discussed was larger (e.g. cognitive foundations, interaction networks) and changed in their relative importance (e.g. the interest on chaos has diminished). Most importantly, it was possible to discern a single new core concept pervading almost all the work presented: Holland's ANNs, now referred to as complex adaptive systems.

In the introduction to the second workshop proceedings, Holland's 1987 definition (see section 1.2.1) is re-proposed and now identified as the hallmark of the Santa Fe Perspective. Holland's general statements have been provided with labels (dispersed interaction, no global controller, cross-cutting hierarchical organizations, continual adaptation. and out-of-equilibrium dynamics) [32] that recur in the Santa Fe Perspective jargon and summarize the lines of thought at the Institute.

Moreover the introduction highlights two novel organizing themes, presented in sharp contraposition with neoclassical thought: cognitive and structural foundations. Instead of the unitary cognitive foundation of rational optimization (with all its attachments of common knowledge, probabilistic uncertainty, Bayesian updating and deductive reasoning) the Santa Fe Perspective holds to a pluralistic view. The process of transforming data into knowledge is shaped by experience and action as a result of adaptation, interpretation and anticipation of future developments (Shubik 1997, Santa Fe Bulletin 11, 2 p. 14-5, Arthur 1994a). Moreover, as CASs continuously change, it becomes impossible even to compute a global optimal course of action: "*it follows the deductive rationality of neoclassical economic agents occupies at best a marginal position in guiding effective action in the world"* (Arthur, Durlauf and Lane 1997, p. 5)

32 Arthur, Durlauf and Lane 1997, p. 3-4.

Instead of the social vacuum of neoclassical models, the Santa Fe perspective supports the study of social interaction and networks, whose structure is believed to shape the overall behavior of the economies. Networks and social rules are seen as both constraining and carrying social interaction (Lane 1995, Tesfatsion 1997).

In the process of its shaping, the Santa Fe Perspective has increased its distance from mainstream economics. The initial idea was to complement the neoclassical approach, which had to remain the reference point, but – as it is shown by the above description - it ends up as a competing view.

In the first decade of its life, the Economic Program has inverted the initial relationship between orthodox and unorthodox thought: initially, complexity economics was conceived as a small add-on to neoclassical economics, whereas by 1997 some researchers were proposing quite a different relation between the two: *"In short, Santa Fe economics had an unmistakable theme, an approach that instead of assuming homogeneous agents allowed heterogeneous agents; instead of assuming deductive decision-making allowed inductive decision-making; instead of assuming equilibrium allowed out-of equilibrium. In this context standard-equilibrium economics became a special case, and we often used it for a benchmark."* (Arthur 2003, p.11).

In the parabola of the Economics Program, the second workshop is characterized by the self-perception as a research community and by the maximum distancing from traditional economics. The publication of the proceedings in 1997 received favorable reviews. For instance, Silverberg (1998) pointed out that the Santa Fe Perspective was having considerable academic recognition and slowly penetrating leading journals (e.g. Arthur 1989, Arthur 1994, Holland –Miller 1991). While he believed that much work remained to be done before one could speak of a new paradigm, Silverberg praised the high quality of research conducted in the Economics Program.

While the proceedings volume presented the 1996 workshop as a starting point towards a new economics (Arthur, Durlauf and Lane 1997, p. 6-7), in the following years the Economic Program went off in a different direction. The Santa Fe Perspective played an ever more minor role in the Program research, which increasingly drew its themes and even methods from mainstream economics.

3. The Economy as an Adaptive Complex System III: the Synthesis Period (1997-2004)

Immediately before and - with more intensity - after the second workshop, the Economics Program was becoming less important within the Institute, as more researchers with other interests came aboard and new programs reflecting these interests were funded. Institute policy encouraged the turnover of scientists and programs[33]; as for the program itself, discontinuities in its leadership had probably hindered the coalescence of the Santa Fe Perspective as the Program's unifying element and principal research direction. Under the co-directors Lawrence Blume[34] and Steven Durlauf[35] (1995-1998), the Program steered sharply back to the mainstream.

The proceedings of the third workshop of the series The Economy as an Evolving Complex System, held in November 2001, provides the last snapshot we need to sketch the evolution of the Economics Program. This volume provides many interpretative difficulties. According to its editors (Blume and Durlauf 2006), it demonstrates that the merger between economics and complexity science has matured (Blume and Durlauf 2006, p.1) and the workshop represents the fulfillment of the initial expectations of the Economics Program: the injection of new methods in the mainstream theoretical body.

The clear theoretical opposition between neoclassical economics and the Santa Fe Perspective has disappeared. Indeed, it has been relegated to the role of an unsuccessful endeavor: "*the volume reflects some of the way is which [...] some of the early aspiration were not met. The models presented here do not represent any sort of rejection of neoclassical economics. One reason for this is related to the misunderstanding of many non-economists about the nature of economic theory; simply put the theory was able to absorb SFI-type advances without changing its fundamental nature. Put differently, economic theory has an immense number of strengths that have been complemented and thereby enriched by the SFI approach. Hence, relative to the halcyon period of the 1980s, this SFI volume is more modest in its claims, but we think much stronger in its achievements*" (Blume, Durlauf 2006, p. 2).

The change of direction is surprising, especially if one considers that Durlauf had signed together with Arthur and Lane the Introduction of the second volume in which the unorthodox spirit of the Santa Fe perspective was in center stage and that Blume was in the list of the contributors to that volume[36]. It has to be noted that Blume and Durlauf in 2001 had

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33 These policies have been clearly re-enunciated in 1995. See SFI Bulletin 1995, 10, 1, Message from Bruce Abell vice President.

34 Lawrence Blume is Goldwin Smith Professor of Economics and Professor of Information Science, Cornell University.

35 Steven Durlauf is Kenneth Arrow Professor of Economics at the University of Wisconsin-Madison.

36 Barkley Rosser suggest a hypothesis: "*the editors are naturally inclined towards some kind of consensus accommodation with the mainstream establishment of economics, perhaps*

already stated that a discussion on methods was unnecessary since the complexity approach was only a language for scientific research, whose usefulness resided in the ability to simplify the analysis under some specific and particular conditions.

The interaction within the Economics Program had led to the emergence of a new synthesis between the cautious spirit of the first meeting and the revolutionary claim of the second. However, on closer inspection, it seems that there is a discrepancy between the tone of the Introduction (Blume, Durlauf 2006, 1-4) and the content of the contributions. As compared with the previous workshop there seems to be coherence concerning the themes discussed (learning, patterns in individual and aggregate data and social interaction, some traditional evolutionary problems).

As for the content of papers, there is considerable difference of opinion about their novelty. One reviewer (Hanappi 2007) claimed that the papers were 'subtly subverting the traditional approach under many respects (e.g. communication as an infection process, learning from past subjective experience, scaling), while another. (Rosser 2006) noted the fact that the papers are extensions of works already published on leading journals and therefore squarely in the mainstream.

In my opinion, the family resemblance that grounded the Santa Fe Perspective has not disappeared in the third workshop, rather it seems to me that the family had been just considerably enlarged: some contributors (e.g. Peyton Young, Samuel Bowles) come from the mainstream but still their methods and issues are not easily inserted into the neoclassical frame. From a different viewpoint it can be said that the Santa Fe Perspective was attracting scientists from the traditional approach to economics. This process could be interpreted as the inception of a Lakatosian change according to which new ideas are generated from outside the mainstream and than they come to be accepted in it and gradually switch from heterodoxy to orthodoxy[37].

If one accepts that the papers presented in the 2001 workshop are both heterodox and mainstream then the change of emphasis from the revolutionary claims of Arthur, Durlauf and

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because of their roles as editors of the forthcoming Revised New Palgrave Dictionary of Economics." (p. 6).

[37] Colander's (2004) distinction between mainstream and orthodoxy can be useful in understanding the contradiction. 'Mainstream' is a sociological concept that refers to the kind of economic research conducted by leading scientists in the profession, whereas 'orthodoxy' is an intellectual concept that refers to a consistent system of knowledge that has been codified in textbooks. It follows that mainstream economics need not to be entirely orthodox,

Lane's Introduction (1997) to the reconciliation mood of Blume and Durlauf's (2006) cannot be entirely explained in terms of a switch in the set of ideas and methods concerning complexity, rather it is better understood as a change in the set of people and objectives in the Economics Program.

Being mainstream involves a series of benefits, Blume and Durlauf's attempt to catch up with the established thought is a reasonable attempt at conquering them. In addition, it must be recalled that the Economics Program has stemmed from Arrow patronage. As already said, he agreed on enlarging the boundaries of the neoclassical domain so as to encompass the incorporation of complexity theory, but he was not very willing to accept a paradigm shift. As more and more people that were in closer connection with him were appointed in leading positions within the Economics Programs (for instance, Durlauf is Kenneth Arrow Professor of Economics at the University of Wisconsin-Madison) it must have been increasingly difficult to reject his legacy, which, in fact, is strongly emphasized in the introduction to the third volume: "*Kenneth Arrow has served as the intellectual leader for the SFI Economics Program ever since its inception. Whatever success the program can claim very much derive from the brilliance and the wisdom he has provided"(Blume and Durlauf 2006 p. 4)*

To sum up, the 2001 workshop can be seen, in substance, as the attempt at hybridizing the Santa Fe Perspective non-mainstream heterodoxy within the mainstream neoclassical view[38] and, in form, as the abandonment of the Santa Fe Perspective in favor of mainstream thought.

In the following years, during the directorship of Samuel Bowles[39] (2000-2003), the Program sailed straight for the mainstream [40]and, to a great extent, successfully arrived there. The idea of maintaining such an Economics Program at the Institute was fading. It was anomalous there, since the Institute was increasingly interested in transdisciplinary research, and economics was, after all, an established discipline. Bowles himself took the initiative in

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38 The feasibility of such an operation will be discussed in the following section.

39 Samuel Bowles is Professor Emeritus at the University of Massachusetts, Amherst and Professor of Economics at the University of Siena

40 "*Economic analysis must become more social and psychological in its treatment of the human actor, more institutional in its description of the exchange process, yet no less analytical in its model-building and no less dedicated to the construction of general equilibrium models".* (2000, p.1412).

scuttling the Program and replacing it with a Behavioral Sciences Program, which he currently leads and which aspires to a transdiciplinary perspective merging themes usually treated by such separate disciplines as anthropology, sociology, economics and psychology. The new program is less inspired by ideas and methods from statistical mechanics and biology than those from other social sciences, in ways that might be considered mainstream but unorthodox.

4. Viral Diffusion, the Complexity Approach to Economics and Concluding Remarks

The Economics Program has been governed by a sort of Wienerian servomechanism: a mix of negative and positive feedbacks that have fostered and then controlled the innovative upsurge, the initial emphasis on risky long-time horizon programs substituted by more mainstream research, the current idea of complexity at SFI relying more on transdisciplinarity than on Holland's CASs. But what happened to the Santa Fe Perspective?

Since its foundation, SFI's philosophy has been to act as a catalyst for scientific change. Differently from traditional universities, it initially hosted researchers for short periods of time, using seminars and workshop to generate and circulate ideas, which were then developed elsewhere.

The Santa Fe Perspective followed this trajectory. The researches by Arthur, Holland, Kauffman, Lane, Brock, LeBaron and other protagonists of the Strongly Heterodox Period have been adopted as central elements of the wider and flourishing complexity approach to economics. Recognition of the Santa Fe Perspective legacy is sometimes explicit (e.g. Matthews 2000 p. 63; Rosser 1999, Ehrentreich 2008, p.15, Ward 2003) while other times it lies between the lines (Markose 2005, Foley 2003, Albin 1998, Arthur 2009).

Three streams of research have developed from the Santa Fe Perspective and currently represent the complexity approach to economics (Foster 2005, Fontana 2008). The first one, 'dynamic complexity' is essentially a mathematical one that reflects the first narrower notion of complexity in the Economics Program, in that it includes bifurcation analysis and chaos, trying to identify their consequences for economic theory. For instance, sensitivity to initial conditions implies unpredictability; while indecomposability implies that it is not possible to derive implications on the behavior of the system's subcomponents by analyzing them separately.

The second research stream, 'computational complexity', recalls the Santa Fe Perspective emphasis on cognitive foundations, in that it refers to the computational and cognitive skills of decision makers. They may face problems that are undecidable, so that no mind or computer can devise a computational procedure able to solve them in a finite time. A typical example of such a problem is self-reference is discussed by Arthur (1994). An agent has to form conjectures about the conjectures of the other agent(s); assuming that each decision maker tries to foresee what the others' conjecture would be and to adjust her own on that basis, this leads to a procedure that never settles on a solution. Decision makers also encounter problems that are in theory decidable but for which the cost of an optimal solution can be so high as to deprive the optimal choice of any possible advantage for the decision maker (Albin 1998, p. 46). This line of research includes contributions on bounded and procedural rationality and on cognitive models.

The third stream, 'connective complexity', descends from the Santa Fe Perspective's emphasis on social interaction, in that it investigates the links existing between the elements forming a system and the generative properties that derive from them, as in Kauffman's autocatalytic sets. It is the kind of relationship that links the elements of the system to one another that shapes their behavior, and it is the changes in such relationships that cause the system to evolve. The hallmark of this kind of complexity is the emphasis on forces that act to maintain the order of the system and on countervailing forces that drive it towards disorder. The struggle between the two generates novel elemental kinds and relations, and leads to the disappearance of other structures (Foster 2005; Lane, Pumain, van der Leeuw, West 2009).

At a higher level of generality, the debate that took place within the Economics Program is now replicated within the discipline. In the face of the weakening of a shared and demarcated notion of mainstream, the complexity approach to economics has sparked a widening interest. The issue is whether the neoclassical paradigm, which since WWII had been able to absorb the contributions (such as bounded rationality and experimental economics) that critically challenged its assumptions and results, would now be able to incorporate the insights, problems and methods associated with the complexity approach. As happened at SFI, the latter is now considered by many as a new paradigm (Beinhocker 2007, Markose 2005), by others a mere addendum to neoclassical theory (Kirman 2005, p. 18, Lesourne 2002)

The synthesis between the neoclassical view and the Santa Fe Perspective, can be interpreted both as a sign of neoclassical theoretical imperialism[41] and as a symptom of a paradigm shift

[41] See, for instance, Paul Krugman (1997, 1996) on increasing returns and economic geography and Tom Sargent (1993) on transition dynamics, rational expectations and bounded rationality.

in economics. To a certain extent, the two overlap in that in enlarging itself, the neoclassical paradigm had to blur its boundaries and doing so necessarily engage in a certain degree of dissolution.

Can the neoclassical imperialism win over the Santa Fe Persperctive/Complexity Economics? In order to address this question, let me leave aside the mainstream/non-mainstream and the orthodoxy/heterodoxy dichotomies, and concentrate on the coherence between ontology and methods.

Complex adaptive systems are very different from neoclassical economies. If we subscribe to the view that the economic phenomena that we observe are epiphanies of complex adaptive systems, then the crucial question becomes whether neoclassical economics' ontology can deal with such phenomena[42].

The neoclassical economy, even after the inclusion of bounded rationality, the acknowledgement of the violations of the EUT axioms and some concessions to computer simulation and learning algorithms, remains a system whose functioning is much more similar to general equilibrium models than to complex systems.

Neoclassical theory cannot deal with heterogeneity, out-of-equilibrium behavior, non linearity, unpredictability, irreversibility, learning, endogenous change, (i.e. it cannot handle complex phenomena) without '*changing its fundamental nature'* (Blume and Durlauf 2006, p. 2), without becoming the kind of science envisaged by the Santa Fe Perspective.

Neoclassical theory is a mathematical one in which explanation of the economic facts is derived from theorems and proof rather than observation and experimentation, in which linearity and homogeneity are, at the same time, a theoretical underpinning and a modeling necessity, in which the successful prediction is the parameter that establishes the goodness of a theory.

That economics is undergoing a transformation is widely acknowledged. Arthur states: "*there are signals everywhere these days in economics that the discipline is losing its rigid sense of*

[42] For a detailed discussion of this topic see Fontana 2008.

determinism, that the long dominance of positivist thinking is weakening and that economics is opening itself to a less mechanistic, more organic approach"(1994b, p. 1). Rosser (2004, p. IX) echoes that sentiment and adds that "*awareness of the ubiquity of complexity is transforming the way that we think about economics*." Hahn (2001) complains "*not only will our successors have to be far less concerned with general laws than we have been, they will have to bring to the particular problems they will study particular histories and methods capable of dealing with the complexity of particular contexts, such as computer simulation. Not for them […] the pleasure of theorems and proofs. Instead, the uncertain embrace of history, sociology and biology*" (2001, p. 50). The process of change is in course, its outcome not easily predictable. The future is ahead.

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APPENDIX A

Brian Arthur's new economics (Colander 2006, p.6-7)

Old Economics	**New Economics**
Decreasing returns	Much use of increasing returns
Based on marginality and maximizing principles (profit motive)	Other principles possible (Order principles)
Preferences given, Individual selfish	Formation of preferences becomes central individual not necessarily selfish.
Society as a backdrop	Institutions come to the fore as a main decider of possibilities order and structure
Technology as given or selected on economic basis	Technology initially fluid, then tends to set
Based on 19th-century physics (equilibrium, stability, deterministic dynamics)	Based on biology (structure, pattern, self organization, lifecycle)
Time not treated at all (Debreu) or treated superficially (growth)	Time become central structure, pattern, self organization, lifecycle)
Very little done with age	Individuals can age
Emphasis on quantities, prices and equilibrium	Emphasis on structure, pattern and function (of location, technology, institutions, and possibilities)
Elements are quantities and prices	Elements are patterns and possibilities; Compatible structures carry out some functions in each society (cf anthropology)
Language: 19th-century math, game theory and fixed point topology	Language more qualitative; Game theory recognized for its qualitative uses; Other qualitative mathematics useful
Generations not really seen	Generational turnover becomes central; Membership in economy changing ad age- structure of population changing; Generations carry their experiences
Heavy use of indices; People identical	Focus on individual life; people separate and different; Combined switching between aggregate and individual; Welfare indices different and used as rough measure, Individual life-times seen as measure
If only there were no externalities and all had equal abilities, we'd reach Nirvana	Externalities and differences become driving force; No Nirvana, System constantly unfolding
No real dynamics in the sense that everything is at equilibrium. Cf. Ball on string in circular motion. No real change happening; just dynamic suspension	Economy is constantly on the edge of time; it rushes forward, structures constantly coalescing, decaying, changing, All this due to externalities leading to jerky motions, increasing returns, transaction costs, structural exclusions
Most questions unanswerable. Unified system incompatible	Question remain hard to answer; But assumptions clearly spelled out
'Hypothesis testable' (Samuelson) assumes laws exist	Models are fitted to data (as in EDA); A fit is a fit; No laws really possible, laws change
Sees subject as structurally simple	Sees subject as inherently complex
Economics as soft as physics	Economics as high complexity science
Exchange and resources drive economy	Externalities, differences, ordering principles, computability, mind–set, family, possible lifecycle and increasing returns drive institutions, society and economy

APPENDIX B Directors of the Economics Programs and areas of research and methodology (my elaboration on Shubik 2003, p. 2-3)

YEAR	DIRECTOR	THEMES	METHODS
1988-90	**W.B. Arthur**	Increasing returns, path dependent processes and lock-in, cognitive modeling, an agent based stock market with heterogeneous evolving rules.	Stochastic processes, analysis, agent based modeling, essay.
1990*	**D. Lane**	Artificial economy project, foresight complexity and strategy; Methodology	Stochastic processes, analysis, agent based models, essay
1990*	**J. Geanakoplos**	Missing markets, common knowledge, and predictions,	Stochastic processes, analysis
1991	**J. Sheinkman**[43]	Urban systems	
1992	**M. Shubik**	Theory of money and financial institutions, emergent minimal institutions, resource allocation in economics and biology, trust, money, credit and net.	Stochastic processes, simulation, gaming, institutional study essay.
1992-93	**B. Le Baron**	Empirical investigation of economic time series	Econometrics, simulation
1993-94	**Vacant**		
1994-95	**W. B. Arthur**	Same as above with more emphasis on cognition	
1995-98	**S. Durlauf** **L. Blume**	Social interaction, evolution of scientific knowledge, evolution of preferences, evolutionary games study.	Statistical mechanics approaches to socio - economic behavior, analysis.
1998-2000	**Economics Board**		
2000-3	**S. Bowles**	Origins, nature and consequences of human sociality; insiders, outsiders and the dynamics of groups; emotion and cognition in human behavior; the understanding of the persistence of economic and social inequality; coevolution of institutions and preferences.	Behavioral social sciences approach, institutional analysis

*** Co-direction**

43 Jose Sheinkman is Theodore A Wells '29 Professor of Economics, Princeton University.

Appendix C List of Seminars and Conferences of the Economic Program (Shubik 2003, p. 7-8)

1987
Evolutionary Paths of the Global Economy

1989
Adaptation and Learning in Economics
Learning in Games and Markets
Environmental Issues, Economics & Public Policy
The Economy as an Evolving Complex System
1990
Summer Study Group in Economics

1991
Learning in Economics, Psychology & Computer Science
Missing Markets & Emergence of Market Structure
Rationality
Prediction & Pattern Recognition/Financial Markets

1992
Theory of Money and Financial Institutions
Increasing Returns
Biology and Economics: Overlapping Generations

1993
Economics Annual Meeting

1995
Economics Annual Meeting

1996
Economy as an Evolving, Complex System II
Economics and Cognition Study Group
Fundamental Limits to Economic Knowledge
Inferential Problems/Analysis of Treatment Effects
Social Interactions and Aggregate Economic Behavior

1997
Empirical Analysis of Individual Decision-Making
Interactions-based Models & the Social Sciences
Sustainability, Inequality, and Growth-Mac Arthur Grp.

1998
Adaptive and Computable Economics
Economics Working Group

1999
Institutions: Complexity and Difficulty
Empirical Analysis of Social Interactions

2000
Co-evolution of Institutions and Preferences
Beyond Equilibrium and Efficiency
Groups, Multilevel Selection & Evolutionary Dynamics

2001
Co-evolution of Institutions and Preferences
Strong Reciprocity: Modeling Cooperative Behavior
Poverty Traps
Economic Inequality and Economic Sustainability
Intergenerational Inequality
Economy as an Evolving Complex System III

2002
Co-evolution of Institutions and Behaviors
Globalization and Egalitarian Redistribution