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Complexity Economics: An Introduction

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In September 1987, the then-nascent Santa Fe Institute (SFI) held a conference to look at the economy as an evolving complex system. It was organized by physicists Philip Anderson and David Pines and economist Kenneth Arrow. Out of that conference a year later came the Santa Fe Institute's first research program: The Economy as an Evolving Complex System. One of us (Arthur) headed that program, and another (Beinhocker) joined it in 1994, and from that program in turn came a different approach to economics—what many refer to as "complexity economics."[4] SFI has been associated with complexity economics ever since, and the approach has continued to develop and influence not just economics, but social science more broadly. In 2014 SFI devoted its annual symposium to complexity economics, and it did so again in 2019. The collection of talks in this volume provides a snapshot of recent thinking and examples of how the initial ideas have developed over the decades.

The Emergence of Complexity Economics

Complexity economics views the economy as a system not necessarily in equilibrium, but rather as one where agents constantly change their actions and strategies in response to the outcomes they mutually create. It holds that computation as well as mathematics is useful in economics, that increasing as well as diminishing returns may be present in an economic situation, and that the economy is not something given and existing, but forms from a constantly developing set of actions, arrangements, and technological innovations. The economy is thus comprised of evolving networks of interacting agents, institutions, and technologies—networks of networks. The macro-level patterns of the economy—growth, innovation, business cycles, market booms and busts, inequality, and carbon emissions—then emerge from these dynamic micro- and meso-level interactions. From the complexity economics perspective, change is largely an endogenous phenomenon, not simply the result of unexplained shocks from outside the system.

The complexity viewpoint has modern roots in pioneering work in the physical sciences conducted decades ago by groups in Brussels, Stuttgart, Ann Arbor, Los Alamos, and elsewhere.

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[4] The term "complexity economics" was first introduced by Arthur, 1999.

But the ideas have even earlier precedents in economics. Adam Smith had a deep, intuitive understanding of emergence and was arguably the first complexity economist. Smith and other early economists were aware that aggregate patterns emerge from individual behavior and interactions, and that individual behavior responds to these aggregate patterns. Smith's famous metaphor of the "invisible hand" of markets is popularly misinterpreted as a message that "greed is good" (something Smith did not believe), but in reality was a statement about emergence—how individual actions "without intending it, without knowing it" lead to collective outcomes which feedback to influence further actions.[5] There is thus a recursive, reflexive loop at the heart of the economy.[6] Complexity economics asks how this loop drives the behavior of the system over time, i.e. how will the pattern of the system today shape individual decisions which will then collectively create the pattern of the system tomorrow.

This is an obvious question, but a difficult one, and in the nineteenth century economists chose to ask a simpler question that was more tractable with the tools available at the time. They asked instead what individual behaviors (actions, strategies, expectations) would be upheld by—would be *consistent with*—the aggregate patterns they create. What patterns would call for no changes in micro-behavior, and so would be in equilibrium?[7] This equilibrium strategy was a natural way to analyze problems in the economy and render them open to mathematical analysis. But it placed a strong filter on what one could see. Under equilibrium by definition there isn't scope for exploration, or forming new structures, or creation; so, anything in the economy that takes adjustment—innovation, structural change, history itself—must get dropped from the theory. The resulting analysis may be elegant, but ever since its nineteenth-century origins, heterodox economists ranging from Joseph Schumpeter to Friedrich Hayek, Herbert Simon, Kenneth Boulding, and Elinor Ostrom have highlighted its limitations.

It was within this context that SFI's economics program started in 1988. After much discussion, the group at SFI decided to ask: what would economics look like if we allowed nonequilibrium? How do individual actors in the economy react, make decisions, anticipate, and strategize, in response to the pattern they have created? And what kinds of networks, institutions, technologies, artifacts, and patterns emerge and evolve?

How to answer these questions and what methods to use weren't obvious at first. Standard (neoclassical) economics assumes identical agents solving an identical problem using rational logic, knowing that other agents are identical and face the same problem. But in the actual economy this is rarely true. Different entrepreneurs starting up tech companies might not know how well their individual technologies will work, how the government will regulate them, or who their competitors will be. They would be subject to fundamental uncertainty, and so the problem they face is not well-defined. It follows that rationality is not well-defined either; there can't be a logical solution to a problem that isn't logically defined. There is no "optimal" move.

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[5] For a recent discussion see Norman, 2018, pp. 154-159.

[6] See the 2013 *Journal of Economic Methodology*, 20(4), symposium on reflexivity and the economy, notably George Soros, "Fallibility, reflexivity, and the human uncertainty principle," pp. 309-329.

[7] General equilibrium theory asks what prices and quantities of goods produced and consumed would be consistent with—would pose no incentives for change to—the overall pattern of prices and quantities in the economy's markets. Classical game theory asks what strategies, moves, or allocations would be consistent with—would be the best course of action for an agent (under some criterion)—given the strategies, moves, allocations his rivals might choose. And rational expectations economics asks what expectations would be consistent with—would on average be validated by—the outcomes these expectations together created.

People of course do act in ill-defined situations all the time. They form individual hypotheses—internal models—about the situation they're in and continually update them. They constantly adapt or discard their hypotheses, strategies, and the actions as they explore.[8] They proceed in other words by induction.[9] As it happened, John Holland, a superb computer scientist and cognitive theorist, was part of SFI's early program and had developed methods by which computer programs could "learn" in games by creating hypotheses and adapting or discarding or mutating them. We could use this idea, we realized, as the basis for a general method to investigate situations in economics that weren't well-defined and weren't in equilibrium.

Several things came out of this approach. In problem after problem we saw a world where beliefs, strategies, and actions of agents were being "tested" for performance and survival within an "ecology" that these beliefs, strategies, and actions together created. The behaviors themselves were adapting to the ecology they together created and that ecology in turn evolved as the behaviors changed. A distinct biological evolutionary theme emerged (another area in which the SFI community had deep expertise). While economic systems have important differences from biological ones, they share some deep commonalities—notably, both use energy to create islands of order, stability, and local equilibrium (or homeostasis) in larger seas of disorder, but those islands of local stability are by necessity evolving as their environment evolves, meaning that the system as a whole is highly dynamic and far from equilibrium.[10] Modelling such a world requires tools that are different from the standard economic approaches and our team at SFI began to put together computational methods to look at economic problems.[11] These models were built "bottom-up" around agents' individual behaviors, and so they used an early form of agent-based modeling. This is now a well-known method that has been applied to a variety of economic problems.[12]

But computers aren't the only way to understand complex adaptive systems, and the desire to understand the messy reality of human social systems drove innovation in other methods as well. For example, a community of researchers centered at SFI has, over decades, integrated results from laboratory behavioral experiments, field experiments, cross-species studies, archeological and anthropological data, models of cultural evolution, and innovations in game theory to generate deep insights into the role of human prosocial behaviors and cooperative norms and institutions in the creation and evolution of economies.[13] Such multi-method, interdisciplinary work, while a core part of SFI's *raison d'être*, was not typical of economics as a field at the time and still remains relatively rare.

From Crises to Opportunity

Max Planck famously remarked that science advances one funeral at a time, but as Thomas Kuhn observed, it also advances one crisis at a time. While the rational-actor, efficient-market,

[8] See for example Hommes, 2011.

[9] See Holland et al., 1986; Sargent, 1993; Arthur, 1994.

[10] Beinhocker, 2006.

[11] The early work on computational economic models at SFI was led by economists, including Brian Arthur, Blake LeBaron, with help from computer scientist John Holland, statistician David Lane, and physicist Richard Palmer. Early on the approach was called "element-based modelling" and then later the more descriptive "agent-based modelling" came into use.

[12] For other early examples of agent-based modeling in economics see Epstein and Axtell 1996; Amman, et. al. 1996, and Tesfatsion and Judd, 2006.

[13] See for example Gintis, Bowles, Boyd, and Fehr, 2005, Bowles and Gintis, 2011, Bowles, 2016, and Gintis. 2017.

equilibrium view of economics traces its roots to the nineteenth-century work of figures such as Léon Walras, its modern ascendency in academia and policymaking has its origins in the economic crises of the 1970s. The collapse of the postwar Bretton Woods regime, a series of currency crises, high inflation, recessions, and high unemployment in many Western countries caused policymakers to lose faith in Keynesian analyses and prescriptions. This created an opening for the ideas of monetarists, led by Milton Friedman, and neoclassical economists such as Robert Lucas, Thomas Sargent, Eugene Fama, and Gary Becker. Their ideas had a profound influence from the 1970s to 2000s, shaping not just academic research, but also what many historians refer to as the neoliberal policy consensus of the period. That intellectual consensus in turn drove agendas on de-regulation, market liberalization, free trade, financialization, increased reliance on economic incentives to shape behavior, and attempts to scale back the role of the state.[14]

While this academic and policy consensus held for several decades, the first crisis of the neoliberal era appeared early on and provided the motivations for the founding of the SFI economics program. Following the neoliberal recipe book, many Latin American countries opened up their economies to international capital flows, but by 1982 found themselves gripped by a cascade of currency crises and debt defaults. One of the banks with the greatest exposure was Citicorp, and its then-chairman and CEO, John Reed, began a quest to understand what had caused the crisis and how future crises could be prevented. Reed consulted widely with leading economists, but the rational-actor, efficient-market theories espoused at the time offered little insight into the formation and bursting of such a massive bubble—debt crises are a profoundly disequilibrium phenomenon. Reed's quest eventually brought him to SFI, and Citicorp provided funding for the 1987 founding workshop and the 1988 start-up of the SFI economics program. One can thus say that complexity economics was born out of crisis.

With hindsight, the 1980s Latin American and 1990s Asian debt crises were just warm-ups for the big crisis to come. The 2008 global financial crisis effectively ended the period of neoclassical/neoliberal intellectual dominance. In an interview after the crash, US Treasury Secretary Hank Paulson was asked whether economics had been of any help during the crisis and bluntly replied, "The economic models were worthless."[15] Likewise, Jean-Claude Trichet, president of the European Central Bank at the time said, "we felt abandoned by the conventional tools," and called for "inspiration from other disciplines: physics, engineering, psychology, biology," where "scientists have developed sophisticated tools for analyzing complex dynamic systems in a rigorous way."[16]

Such calls from policymakers gave a new impetus and urgency to the complexity economics research program. Significant effort by multiple research groups was invested in applying complex systems techniques to better understanding issues of financial system stability and contagion.[17] This work opened doors to new collaborations with policymakers, and complexity economics ideas were actively debated, and experimented with inside institutions that had once been bedrocks of neoclassical thinking, including major central banks as well as international institutions such as the

[14] See Burgin, 2012.

[15] Tapper, 2010.

[16] Trichet, 2010.

[17] For example, see the EU funded Project CRISIS led by Domenico Delli Gatti (Project Director), J. Doyne Farmer (Scientific Director), Jean-Philippe Bouchaud, Mauro Gallegati, Cars Hommes, Giulia Iori, Fabrizio Lillo, Stefan Thurner, and Eric Beinhocker. See the *Journal of Economic Dynamics & Control*, 50, 2015, special issue on "Crises and Complexity" for a collection of papers.

International Monetary Fund and World Bank.[18] The Organisation for Economic Cooperation and Development launched a major effort called "New Approaches to Economic Challenges" (NAEC) with the explicit mission of bringing complexity-economics thinking into policymaking.[19] One of the biggest casualties of the 2008 crisis was confidence in the equilibrium, micro-founded, macroeconomic models often used by policymakers (so-called dynamic stochastic general equilibrium, or DSGE, models).[20] A number of initiatives were launched to explore alternatives, including those offered by complexity economics.[21]

Other policy challenges have provided motivations for advances in complexity economics. The remarkable pace of technological change and its impacts on society have prompted fundamental explorations into the nature of technology, innovation processes, and the co-evolution of technologies and institutions.[22] A complex-systems perspective has also been increasingly applied to questions of economic growth, development, and inequality.[23] And finally, it is becoming increasingly clear that the existential question facing humankind—how to create an economy that delivers human well-being without causing planet-wide ecological collapse—can best be understood through an interdisciplinary, complexity-economics perspective.[24]

Science is always a work in process, and complexity economics still has much maturing to do, but over the thirty-three years that separates the first SFI economics workshop and the symposium summarized in this volume, much progress has been made. The complexity-economics community has grown well beyond its origins at SFI, with individual scholars pursuing this approach around the world, and highly active research groups in the US, UK, Italy, France, the Netherlands, Switzerland, Austria, Singapore, and other countries. There have been numerous advances in theory, modeling, data, and methodologies, drawn from across a large range of disciplines. While complexity economics is still a new perspective in economics, many of its key ideas have entered the mainstream of the field. Most economists now accept the need for more realistic assumptions in economic theory; and methodologies such as network analysis, heterogeneous agent models, evolutionary game theory, and economic lab experiments are becoming standard. Understandably, there still remains a reluctance to let go of the equilibrium framework, embrace ideas of evolution and emergence, and make full use of modern data and computational tools. But in our view, if economics is to be relevant to the challenges we face—from pandemics, to economic inequality, technology acceleration, and climate change—it will have to embrace the complexity of the phenomena it seeks to understand.

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[18] For examples of the application of complexity economics to Bank of England policymaking see Baptista, Farmer, Hinterschweiger, Low, Tang, and Uluc, 2016, and Farmer, Kleinnijenhuis, Nahai-Williamson, and Wetzer, 2020.

[19] See www.oecd.org/naec. SFI external faculty member Alan Kirman has played a key role as an advisor to the OECD NAEC initiative.

[20] See for example *Oxford Review of Economic Policy*, vol. 34, issue 1-2, spring-summer 2018, special issue on Rebuilding Macroeconomic Theory.

[21] See for example the UK Economic and Social Research Council (ESRC) Rebuilding Macroeconomics initiative, rebuildingmacroeconomics.ac.uk.

[22] See Arthur, 2009. In 2017 and 2018 SFI hosted workshops on the co-evolution of physical and social technologies, see Farmer, Markopoulou, Beinhocker, and Rasmussen, 2020 for a summary and eudemonicproject.org for more information.

[23] See for example Hidalgo and Hausmann, 2009, Hausmann and Hidalgo, 2011, and Banerjee and Yakovenko, 2010 [also cite Axtell new book on firms]

[24] See for example Farmer et. al. 2015, 2016, 2019; Brand-Correa and Steinberger, 2017; and O'Neill et. al. 2018.

The Symposium

The November 2019 conversations in Santa Fe that follow were not intended to be a comprehensive review of the current state of complexity economics. Rather they cover a diverse array of topics, viewpoints, and ideas on future directions for research. The participants include members of the SFI academic community as well as SFI's Applied Complexity Network (ACtioN), which brings together the worlds of business, finance, technology, and government. Thus, what follows in the volume are edited transcripts of the talks and panels rather than more traditional academic papers. We hope that this format makes them accessible to a wide audience.

In his introductory remarks (Chapter 1), SFI President David Krakauer sets the stage tracking developments in the core themes in economics from the Enlightenment into the twenty-first century, from the mechanics of Newton to concepts of agency, adaptation and purpose brought in by Adam Smith and Charles Darwin, to the impacts of economics on the real world, exemplified by the work of John Maynard Keynes. As Krakauer notes, the concern of economics is now "the global stability of the planet" and the stakes are high.

Eric Beinhocker, picking up on Krakauer's historical theme, traces the development of the discipline of economics and how its core theoretical insights regarding the imagined reality of a self-regulating market economy were translated into the ideology of neoliberalism, which has become destructive for both humans and nature. Neoliberal ideology has supported a "greed is good" popular and political culture based on an overly simplistic, pseudoscientific view that self-interested action would, through the magic of markets, automatically produce societal betterment and human flourishing. Beinhocker argues that it is not atomistic competition in markets that has made societies prosperous, but rather human cooperation and prosocial behaviors in an evolving ecology of market and non-market institutions. True prosperity comes from "solving human problems", and solving complex problems requires sustained cooperation at scale. The state, business, and civil society all have roles to play in creating the inclusion, fairness, and trust necessary for sustaining cooperation at scale. Furthermore, Beinhocker argues in Chapter 2, the environment is not an "externality" but deeply intertwined with human social systems, and solving the problem of creating a zero-carbon, sustainable economy is not a "cost" to be traded off with future "benefits" but an existential necessity that also is a historic opportunity to increase human and non-human well-being. Beinhocker and his collaborator Nick Hanauer see the potential for complexity economics to underpin a new economic ideology they call "market humanism," an ideology that reinforces rather than undermines the ties that bind humans together in the cooperative enterprise of civilization.[25]

In Chapter 3, Allison Stanger considers the impact of neoliberal understandings of the global political economy on the American loss of faith in the efficacy of government. When government is assumed to be an obstacle to economic growth, the privatization of what were previously inherently governmental functions follows. The hollowing out of government blurs the demarcation between the public and private sectors, undermining the capacity of government to serve all of its citizens. When elites benefit at the expense of the majority, the obsessive focus on efficiency blinds the powerful to the political ramifications of growing social inequality and mass loss of trust in government. Technological innovation has accelerated these trends, so that the very Enlightenment values that produced spectacular prosperity are now increasingly seen as rationalizations of domination. Whatever new national story Americans together construct must

[25] Beinhocker and Hanauer (forthcoming).

speak to the realities of both the winners and the losers of economic development and value the contributions of care for others as well as unbridled self-interest.

Ole Peters (Chapter 4) introduces the non-initiated to "ergodicity economics," which postulates that individuals do not optimize their expected utility value over a set of well-defined possible probabilistic outcomes, but instead consider their decisions over time in the face of uncertainty. This has profound and underappreciated implications for modeling economic decision making and systems as a core assumption of standard economics is that the time average and the expected (ensemble) value of an observable are one and the same. In real-world situations they often are not, and human decision making has evolved to help us make decisions in a world where outcomes are path dependent and where we only get to live in one future (in contrast the standard expected utility model can be interpreted as one where history doesn't matter and where we can probabilistically live in multiple future universes). Peters has applied this thinking to a range of problems including optimal levels of debt, market efficiency, and inequality.

Matthew O. Jackson's work on markets and social networks, a collaboration with the Nobel Laureates Abhijit Banerjee and Esther Duflo, highlights the importance of being attentive to the ways in which economic and social systems interact (Chapter 5). Studying economic relationships in a manner that detaches them from lived experience in particular communities can producing misleading inferences about what development interventions are effective and why. Jackson partnered with BSS bank in India, who was interested in securing better participation in their microfinance, Grameen Bank–style loans given to women aged eighteen to fifty. The bank's strategy was to target well-connected individuals to maximize the likelihood of diffusion. Jackson considered different measures of this centrality that might be used to predict outcomes. He found that informal networks made a difference in spreading information about opportunities, but that once the loans were dispensed, and people were the recipients of microfinance, it changed the structure of their social network and interactions. This suggests that while human relationships can be exploited to expand markets, the spread of markets can also spawn unintended consequences for the social fabric, potentially increasing inequality rather than ameliorating it.

C. Mónica Capra (Chapter 6) considers the collective action problem of protests, where an individual does not benefit from a particular action unless others act in similar fashion. Social media would seem to transform the dynamics of this interaction, since a human with anger and grievances can easily find like-minded compatriots. Narratives can be generated through online relationships that may or may not be products of the fact-based world. Using Amazon Mechanical Turk, Capra's team generated two communications experiments, one in which a single human subject is communicating with four bots, and a second comprised of five humans. Three types of communication were studied in each experiment—no communication, wall communication, and bilateral communication, all under different local network conditions. Bilateral communication improved the decisions of individuals, in that it was most conducive to developing a common narrative that is a necessary condition for successful coordination.

Brian Arthur's closing talk provides a firsthand account of the founding of the Santa Fe Institute and of complexity economics from someone present at the creation of both. Traditional equilibrium economics assumes that stasis, rather than adaptation and change, is life's predominant condition, and that the economy is comprised of identical hyper-rational agents. Based on a set of assumptions that enable mathematization of the core problems of economic life, it facilitated elegant solutions, fine for presentation in a textbook but not always appropriate for characterizing the realities of economic life. Complexity economics lets go of these restrictive assumptions. It assumes differing agents who are forced to make decisions in the presence of not knowing what other agents will do—in the presence therefore of fundamental uncertainty. They thus explore and adapt constantly, and this renders non-equilibrium as the norm in the economy, not the exception.

It is a bottom-up approach that incorporates both space and the reality of events triggering further events in the unfolding of the economy. Arthur encourages us to see the economy not as a well-oiled machine but instead as an ecology of mutually adapting beliefs, strategies, and actions.

The second day of the workshop, documented here in Chapters 8 through 12, featured lively and engaging interdisciplinary discussion of both complexity theory and its past and future deployment in grappling with challenging real-world financial and socioeconomic problems. The offerings commenced with discussion of computational approaches to complex economies and moved on to an exploration of the leverage that physics might provide in apprehending economic systems. SFI President David Krakauer moderated both panels. Biology's contributions to our understanding of the economic organism and the insights of the social sciences for appreciating the significance of economic architectures were next on the docket. SFI Vice President for Applied Complexity William Tracy guided these conversations. *Wall Street Journal* reporter Paul J. Davies oversaw the final panel, comprised of successful practitioners who considered the impact of complex adaptive systems thinking born at SFI on the evaluation of investment alternatives.

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Shortly after the symposium, the first cases of COVID-19 were detected in Wuhan, China, and the world soon plunged into a crisis unprecedented in modern times. The pandemic has vividly illustrated the need to understand the complex, dynamic, and highly interconnected nature of our economic, social, and bio-physical systems. [26] Other major challenges, from the climate crisis, to fracturing democracies, accelerating technology change, and future issues that we aren't yet aware of, will require the insights that only a complex-systems perspective can bring. Complexity economics has made much progress over the past three decades, but the work has only just begun.

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[26] Interestingly, epidemiologists were relatively early adopters of agent-based modelling and other complexity approaches; see Epstein, 2009. For an example of how a bottom-up complexity-based approach can be applied to integrated economic and epidemiological modelling of COVID-19 policy questions see Pichler, et. al. 2020.

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