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RESEARCH ARTICLE

The evolution of economies, technologies, and other institutions: exploring W. Brian Arthur's insights

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Abstract

Technology is a complex adaptive system that is both shaped by, and shapes, institutional arrangements. This critical insight, developed in depth by W. Brian Arthur – the father of complexity economics – is relevant to researchers interested in institutions. Arthur provides a method for capturing the underlying dynamics. He offers conceptual tools centred on the concept of increasing returns to make sense of some crucial challenges. He also suggests technical tools, including agent-based modelling, to tackle ill-defined economic, legal, and institutional problems. This article explores his body of work and derives some institutional insights from it.

Keywords: agent-based modelling; antitrust policy; complexity economics; complexity science; complexity theory; increasing returns; legal institutionalism; nature of technology; W. Brian Arthur

Bas du formulaire

Complexity science provides a general framework for approaching all fields of science. Unlike other scientific methods, complexity looks at how multiple interactions between agents (be they humans, insects, animals, companies, etc.) create a context to which they respond. Complexity does not see ecosystems in equilibrium. Agents face ill-defined problems to which they respond with not always optimal, fully rational behaviour. Ecosystems depend on time and history; complexity science looks at the messy vitality of ecosystems. Economists, lawyers, and, more generally, all scholars interested in systems and institutions, logically have much to gain from considering complexity science because they deal with lively ecosystems. Fortunately, they can build on previous research to guide their efforts, starting with the work of W. Brian Arthur.

W. Brian Arthur is an economist, engineer, and mathematician who obtained his first tenured position as a Professor of Economics and Population Studies at Stanford University after receiving his Ph.D. in Operations Research from Berkeley (50 years ago this year). From development economics and demography, Arthur moved to the Santa Fe Institute, where he led a research programme on complex systems applied to economics,[1] and while remaining there as an External Faculty Member, he became a visiting researcher in the Intelligent Systems Lab at PARC (Palo Alto Research Center; formerly Xerox PARC), where he currently conducts his research. He has received the Schumpeter Prize in Economics, the Lagrange Prize in Complexity Science, and two honorary doctorates. Against this

[1]About his experience at the Santa Fe, *see* (Arthur, 2010) ('The Santa Fe Institute had no students, and therefore no teaching. (…) It had no departments, and no set of colleagues with locked-in ways of thinking.'). W. Brian Arthur and John Holland were initially considered to run the program together, but John Holland turned the offer down as he wanted to stay in Ann Arbor, Michigan.

background, I would argue that being an Arthurian – I am Arthurian myself – implies several substantive and methodological interests.[2] I note three of them. First, it calls for approaching economies as systems in perpetual, evolutionary motion. Second, it sees technologies, including complex adaptive systems, as the driving force behind economic dynamics. And third, it employs inductive, almost instinctive methods. This article explores these interests in turn with the hope of contributing to the diffusion of W. Brian Arthur's ideas and inspiring others to embrace his research interest and scientific approach.

Economics in motion

Arthur's work exemplifies the potential of complexity science to address ill-defined economic and institutional problems. Over the years, he has developed some key concepts for understanding today's fast-moving economy, where increasing returns are the rule rather than the exception. These concepts are relevant across scientific disciplines.

A pioneering approach

Arthur pushed the boundaries of complexity science to uncharted territory. Arthur not only coined the term 'complexity economics' (Arthur, 1999b),[3] but he also significantly advanced research in the field (Axtell, 2007; Farmer, 2012; Kirman, 1989: 126).[4] This is not to say that all complexity economics is inherently Arthurian, given that, as we shall see, researchers have been working on the idea of complexity in economics for centuries. However, Arthur stands out as the main pillar of today's approach to complexity economics.

Arthur defines complexity 'not [as] a science, [but] rather [as] movement within science'(Arthur, 2021) that 'studies how elements interacting in a system create overall patterns, and how these patterns, in turn, cause the elements to change or adapt in response' (Arthur *et al*., 2020: 124). The fact that simple interactions between agents affect their environment (and, in turn, those same agents) informs much of Arthur's work.

Applied to economics, complexity relaxes the neoclassical assumption that agents are all equal, have perfect knowledge of other agents, and collectively arrive at optimal behaviour consistent, or in equilibrium with, the overall outcome caused by that behaviour (Arthur, 2018a). Neoclassical economists usually agree that these assumptions do not represent the 'real world', but maintain them to make economic theory workable.[5] Complexity economists instead turn 'to the question of how actions, strategies, or expectations might react in general to (might endogenously change with) the aggregate patterns these create' (Arthur, 1999b). Economic agents 'experiment, explore, adjust, readjust' (Arthur *et al*., 2020). Their behaviours are unrestricted; they evolve over time and self-reinforce.

Arthur's book 'Complexity and the Economy' (Arthur, 2015b) and his article 'Foundations of Complexity Economics' (Arthur, 2021) are very comprehensive explorations of complexity economics. Looking at complexity economics years after the emergence of the field, they present economic systems as adaptive, biological colonies that should be approached with a park ranger mindset (Arthur, 2023a). They connect complexity economics to earlier studies by Adam Smith, Joseph Schumpeter, Thorstein

[2]My view of what it means to be an Arthurian is necessarily informed and limited by my legal background. Economists and other scientists will hopefully complete the picture in the coming years.

[3]As W. Brian Arthur recalls, '[a]t the end of the decade, Science asked me to do a paper in the Science journal. The editor called me from London and asked, "What do you call this new approach?" I said, "I don't call it anything." He said, "No, no, you need to give me an answer". It went back and forth and eventually, I lost. I said, "All right, call it complexity economics".' (Arthur, 2023a, 2023b, 2023c).

[4]Although this article focuses on Arthur scholarship, other scholars have made important contributions to complexity economics, *see* (Axtell, 2007; Farmer, 2012; Kirman, 1989: 126).

[5]When discussing the validity of these assumptions with Kenneth Arrow, Arthur reported that Arrow agreed that they did not correspond to reality but believed that they were necessary to conduct a scientific analysis of economic phenomena.

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Veblen, Friedrich Hayek, John Maynard Keynes, and Ken Arrow.[6] Perhaps more fundamentally, they identify the main breakthrough of complexity economics: economic problems are ill-defined (Arthur, 2021: 137).[7]

Ill-defined problems are those for which there is no single optimal solution. Arthur defines economic problems as ill-defined precisely because agents are constantly adapting to what (temporarily) works. When they converge on a strategy, it creates opportunities to explore other strategies, which some agents do. Agents are constantly learning from the behaviour of other agents. They are in a state of perpetual novelty. Thus, one of Arthur's major contributions to economic theory is to provide 'a framework for studying the economy [which] involve agents that form individual beliefs or hypotheses – internal models (possibly several simultaneously) – about how to respond to the situation they are in' (Arthur, 2021: 137). More generally, his overall contribution to economics stands in contrast to the vast majority of publications in the economic field that is 'very much based on mathematics' (Arthur, 2023a).[8] Arthur rejects the 'highly mechanical' (Arthur, 2018a) perspective of the economy that often leads to 'prim dreams of pure order' (Venturi, 1966). Instead, he leans on the side of 'messy vitality' (Arthur, 2021: 137).

Beyond economics, Arthur's contribution to complexity science has important implications for the study of law and institutions as they also face ill-defined problems. Given the literature documenting the role of (legal) institutions in shaping markets and the pace of innovation, Arthur's impact in this area ends up being relevant to researchers interested in the design of institutions (Deakin *et al.*, 2021; Harper, 2018).

Generally, Arthur conceives institutions as social technologies – complex objects within the broader economic system (Arthur, 2009: 205). He posits that the structure of an economy consists of a network of interdependent arrangements, such as firms, means of production, and institutions, all of which can be viewed as technologies in a broad sense. This framework challenges the equilibrium view of institutions as stable and uniform belief systems that dictate the expected behaviour of members of society in different situations (Aoki, 2001; Kingston and Caballero, 2009). Instead, institutions are constantly evolving and adapting to the changing landscape of complex market dynamics (Arthur, 2023b). This perspective suggests that the task of designing institutions is inherently ill-defined; rather than seeking a static ideal, the focus should be on creating flexible, adaptive institutions capable of evolving with the economic and technological environments in which they are situated.

More specifically, Arthur's work informs three prospects. First, the legal system, like the economy, can be studied as a biological ecosystem. The combination of rules and standards exhibits a messy vitality that a complexity mindset can begin to comprehend. Using Arthur's methodology, scholars can document how small events trigger chains of legal responses, resulting in a complex network of laws, i.e. a complex adaptive institution. In a sense, Arthur's work on complexity economics informs the efforts of institutional scholars seeking to document the evolution of legal systems (Hodgson and Stoelhorst, 2014; Ostrom and Basurto, 2011).

Second, the legal system is part of a larger institutional ecosystem – including the market, norms and architecture – that constrains everyone's behaviour (Lessig, 2006). Scholars may be interested in studying how agents respond to and in turn influence the dynamics between these constraints (Schrepel, 2022). In a sense, Arthur's work on complexity economics provides a methodology for focusing on the evolution of institutional systems by looking at how agents' behaviour affects the combination of constraints (bottom-up). It nicely complements the more traditional institutional perspective used by policymakers, which typically focuses on how different arrangements within institutions shape the behaviour of agents (top-down).

[6]In other words, Arthur coined the term complexity economics and shaped the field, but the idea of looking at economic problems from a complexity perspective precedes him.

[7]Thorstein Veblen is also recognized as one of the founding fathers of institutional economics, which highlights the interconnectedness of complexity and institutional economics, *see* (Hodgson and Stoelhorst, 2014).

[8]Gérard Debreu and Samuelson were 'trying to reduce economics to a form of mathematics', (Arthur, 2023a). Sharing the same view, *see* (Akerlof, 2020).

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Third, given that agents' experimentation evolves over time in response to ill-defined problems, legal scholars might consider creating complex adaptive regulations that co-evolve with technology to document and respond to their experimentation (Schrepel, 2023a). Policymakers and regulators typically ignore the strategies and resources of the agents they regulate (Lourenço and Turner, 2019). But the ability to adapt to how agents respond to new regulations makes them more effective. It makes the law inductive rather than treating rules and standards as perfectly informed solutions to well-defined problems. To be clear, complex adaptive regulation does not make the initial state of regulation a bottom-up, agent-informed approach. Regulation remains top-down, but should policymakers go down the wrong path, leading to inefficiency or overreach, complex adaptive regulation corrects by responding to its own effects. Ultimately, this approach to the regulatory process helps address a phenomenon often observed by policymakers and legal scholars. Given the complexity of the systems they often regulate, rules and standards cannot repeatedly achieve a singular optimum using similar methods and provisions. Thus, instead of relying solely on experience to write new rules and standards, the introduction of complexity adaptive rules allows for more flexible regulations that adapt to current events and observations (Kupers and Colander, 2014).

For example, to decrease accidents, the speed limits for vehicles on the highway could dynamically adjust based on various factors such as the volume of traffic, the kinds of vehicles present, current weather conditions, the road type, and the time of day, among others (Pentland and Mahari, 2022). Alternatively, the speed limit could be changed every given month based on an assessment of its effectiveness in achieving a predefined, measurable goal (e.g. reducing car crashes or pollution). Either way, such adaptive regulations allow for real-time laws and standards rather than laws lagging behind or being ahead of technology. Building on the literature on epistemic game theory and social systems theory, real-time regulation effectively addresses ill-defined problems because it evolves based on effects that emerge from known and unknown parameters together (Lourenço and Turner, 2019: 617).

Increasing returns

There are two fundamental questions in the field of economics. The first revolves around 'allocation within the economy', wherein the focus is on determining quantities of goods and services, as well as their respective prices, both within individual markets and across various market domains (Arthur, 2018b). The other pertains to 'formation within the economy', encompassing the genesis of an economy, its subsequent development, and the evolution of its structural characteristics with time (Arthur, 2018b). Although the 'allocation problem is by now well understood and highly mathematicized, the formation question is less well understood' (Arthur, 2018b). Arthur's work in complexity economics helps with the second question (Petit and Schrepel, 2023). He seeks to answer, '[h]ow do economies come into being? How do they develop? How does innovation work? Where do institutions come from? How do institutions change things? What really is structural change, and how does it happen?' (Arthur *et al.*, 2020: 137).

To answer these questions, Arthur first slowed the economic selection processes 'down and look[ed] at them step-by-step' in order to identify how small events induce partial equilibrium (Arthur, 2018a). His approach contrasts with that of neoclassical economics. In 'Complexity and the Economy' (Arthur, 1999b: 107 & 108), Arthur observed that conventional economic theory opts not to investigate the dynamic development of patterns engendered by its agents. In short, neoclassical economic theory assumes that 'individual behavior produces an outcome that doesn't give that behavior any incentive to change' (Arthur *et al.*, 2020: 134).[9] It does not ask how things of economic value are created but which strategy is consistent with the outcome that the things cause. This approach has substantial implications because 'if everything is the same over time, time disappears and there's no

[9]He adds that 'this particular way of looking at the economy – it may be mechanistic; (…) was borrowed in the late 1800s from physics' (Arthur *et al.*, 2020: 126).

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history' (Arthur *et al.*, 2020: 126). By contrast, complexity asks how heterogeneous agents react to their created outcome. Complexity economics looks at changing behaviours.

Arthur's focus on the formation question led him to uncover several key mechanisms of today's fast-moving economy. He theorized them in publications initially rejected by the profession but are now widely celebrated across ideological lines. Complexity, evolutionary, and institutional economists are particularly fond of studying formation in recent literature (Brette and Chassagnon, 2021; Choi and Storr, 2022; Van Bavel, 2020).

Inspired because of his background as an electrical engineer and his readings of Ilya Prigogine,[10] Arthur started working on the concept of positive feedback loops in 1983. Alfred Marshall previously explained that sectors of the economy can benefit from increasing returns – without naming them – but failed to derive all consequences from his observation. In 'Competing Technologies, Increasing Returns, and Lock-in by Historical Events' (Arthur, 1989) and 'Positive Feedbacks in the Economy' (Arthur, 1990a), Arthur popularizes the fact that economies with increasing returns (i.e. 'the whole high-tech sector', (Arthur, 2018a)) 'magnif[y] the effect of small economic shifts' (Arthur, 1989: 92). It follows that random events can decide market outcomes.[11] These events can be rationalized *ad hoc*, but the multiplicity of small economic events makes prediction illusory. This, in short, is the main contribution Arthur made to the concept of increasing returns. He approached them as random (stochastic) processes with multiple possible outcomes.[12]

Several editors first contested his work's scientific grounding. It took Arthur six years to publish his increasing returns paper (Arthur, 2018a). As he recollects, Arthur submitted his working paper to the American Economic Review, a publication he believed would be a suitable fit given the significance of the topic of increasing returns in economics. The editors answered that his article was not economics. Same with the Quarterly Journal of Economics and the Economic Journal in England (Arthur, 2018a). The paper was eventually published in the United Kingdom. It is now widely accepted in the literature (Ades and Glaeser, 1999; Antweiler and Trefler, 2002; Schmitt-Grohé, 2000; Wang, 2015).

The U.S. editors disapproved of the articles' main findings that economic theory can face a lack of predictability when there are increasing returns and that market processes do not necessarily lead to the most efficient outcome. As Arthur explained, increasing returns does not yield a state of equilibrium but rather engenders instability within a system. An initial advantage due to chance or astute strategic decisions could be amplified by increasing returns and result in a lock-in (Arthur, 1996). The lock-in is then typically intensified by path dependency, i.e. the 'autocatalytic' or self-reinforcing outcomes or structures under increasing returns (Arthur *et al.*, 1987). '[H]istorical "small events" are not averaged away and "forgotten" by the dynamics – they may decide the outcome' (Arthur, 1989: 116). Arthur describes that phenomenon as an expression of 'non-ergodicity' (North, 1999).

Arthur's findings cannot be easily used to feed ideological preferences. As a New Yorker journalist recalls, the article's publication drew a predominantly negative reaction. Richard Zeckhauser, a Harvard economist, went as far as to object, 'if you are right, capitalism can't work'. Several months later, when Arthur presented the same paper at a gathering in Moscow, an equally distinguished Russian economist vehemently declared, 'your argument cannot be true!' (Cassidy, 1998) because it made the top–down control of the economy illusory (Arthur, 1996). Applied in practice, Arthur's theory was unsurprisingly used by both defendants and plaintiffs in the U.S. Microsoft antitrust case (Cassidy, 1998).[13]

[10]Arthur was motivated to focus on increasing returns after reading the Nobel laureate Ilya Prigogine's work on non-equilibrium thermodynamics. (Arthur, 2023b).

[11]Several authors explain institutional inertia in the same way, emphasizing that randomness plays a rule in institutional change, *see* (Kingston and Caballero, 2009: 164).

[12]Note that in a defamatory article published on January 15, 1998, Paul Krugman accused Arthur of falsely claiming that he 'came up with the idea of increasing returns.' But Arthur did not claim this. In fact, Arthur's article entitled 'Competing Technologies, Increasing Returns, and Lock-in by Historical Events' refers to earlier publications on the subject. Instead, Arthur built on the earlier literature and greatly developed the concept.

[13]Microsoft argued that increasing returns benefit consumers while the U.S. Department of Justice argued that increasing returns result in lock-ins that hurt consumers.

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Yet, Arthur's concepts are not recipes for the status quo. First, Arthur's work opens up space for legal enforcement to unfreeze markets stuck in inferior outcomes (Cassidy, 1998). It gives legal institutions an important role to play, unlike the Chicagoans and Schumpeter's work, which does not.

In fact, Arthur's work informs what policymakers can do. Under constant and diminishing returns, the evolution of a market is primarily shaped by predetermined factors such as initial endowments, individual preferences, and available transformation possibilities. In such scenarios, minor events or perturbations hold little sway over the ultimate outcome. While this predictability may offer a sense of comfort, 'it reduces history to the status of mere carrier – the deliverer of the inevitable' (Arthur, 1989: 127). If they intervene to avoid the inevitable, policymakers must first choose 'which technologies to bet on' (Arthur, 1989: 127) and second, do more than inject a random event into the ecosystem. Arthur warns that 'because a superior planning authority cannot know in advance which technology will turn out to be best, chance may lock in inferior technologies' (Arthur, 2018a). The best policymakers can do is provide access to business opportunities for several competing technologies, e.g. by reducing legal barriers to entry or development. They can help enable entrepreneurship (Foster, 2015: 41).

Under increasing returns, policies geared towards success in high-tech production and international trade take on a distinctive character (Arthur, 1989). Arthur's findings on increasing returns bear relevance to institutions in charge of innovation policy. Policymakers need not choose which technologies to bet on. Still, they must be prepared for unpredictable outcomes – to address the negative externalities generated by changes in the technical environment (Arthur, 2018b). Their interventions would require little interference if they act early or stronger remedies that unlock positive feedback loops if they intervene late.

Arthur's findings on increasing returns also inform the work of institutions in charge of competition policy. In the short run, these institutions should see positive feedback loops as generating economic uncertainty (i.e. competition) because they change the business environment and thus force agents to 'cognize' (Arthur, 2009)[14] – rather than rationally devise – new strategies (Petit and Schrepel, 2023). In the medium to long term, institutions in charge of competition policy should see that positive feedback loops have the potential to lead to lock-ins and path dependency, i.e. to a frozen ecosystem, especially when increasing returns are not bounded (Arthur, 1990b). The role of antitrust agencies becomes to ensure (or even encourage) the emergence of positive feedback loops in the short and long term.

To achieve this goal, Arthur's findings suggest that firms within a given industry should cooperate and pool resources through joint ventures. These joint ventures would facilitate the sharing of upfront costs, the creation of marketing networks, the exchange of technical expertise, and the standardization of compatibility conventions. Additionally, such policy may extend to the realm of strategic alliances, fostering cooperative endeavours among companies spanning multiple countries, particularly in situations where entering a complex industry proves insurmountable for any individual entity in isolation. Finally, Arthur's work on increasing returns suggests that competition agencies target anti-competitive practices that reduce the ability of third parties (i.e. competitors) to benefit from those returns. The theory of harm would be as follows: in industries with increasing returns, agencies would identify the source of those returns (e.g. users, computing power, etc.) and find harm when strategies are implemented to corner companies out of that source.

Overall, Arthur's work on increasing returns supports one of the central tenets of legal institutionalism: regulation can help create dynamic markets (Deakin *et al.*, 2017). However, regulation can only contribute to dynamism if two conditions are met. The first condition is for regulation to be adapted to the nature of the market. The presence of decreasing or increasing returns varies with the type and timing of the intervention required. The second condition derives from Arthur's views on complexity: policymakers should be concerned with how firms respond to these rules (Lourenço and Turner, 2019; Schrepel, 2022). As he points out, economic agents react to the context (legal, economic, etc.) in which

[14]Note that the term 'cognizing' implies deciding in ill-defined situations, whereas the term 'bounded rationality' does not.

they evolve. They adapt to it, which means that regulation can only bend inefficient monopolies if it adapts to how agents interpret the rules, play with the rules, and eventually bend the rules.

Technology in motion

Arthur's interest in economic creation led him to question the engine behind it, namely, technology. Departing from a strictly Darwinian approach, his writings explore the emergence of new technologies through combinations. He describes technology as 'what separates us from the Middle Ages' (Arthur, 2009: 10), the force that 'creates our wealth, our economy, our very way of being' (Arthur, 2009: 10). Arthur's appreciation for technology naturally tempted him to use it in his own work.

The nature of technology

Arthur's work on the nature of technology is foundational. Although Arthur describes his work on technology and complexity as separate topics, at the very least, they are interrelated: technologies evolve within the ecosystem of other technologies. Arthur's work on technology complements his work on complexity theory, which, as he notes, does not 'tell us usually about the formation of tastes, or of technologies, or of structure' (Arthur, 2006: 1554). Technology is also a driving economic force: 'the economy [is] not so much a container for its technologies, as I had been implicitly taught. The economy arose from its technologies' (Arthur, 2009: 3). Technologies play the role of 'Lego pieces to build new organizational models' (Arthur, 2017). Arthur's research in complexity economics naturally led him to focus on technology, its nature, evolution, and disappearance.

Departing from a strict Darwinian approach that 'only' explains how established technologies evolve, Arthur documented a different form of evolution. He published his findings in a book entitled 'The Nature of Technology: What It Is and How It Evolves' (Arthur, 2009), in which he derived some organizing principles for the emergence of new technologies. This book, which he began researching in 1997, builds on earlier lectures (Arthur, 2009: 4) and articles such as 'The Evolution of Technology Within a Simple Computer Model' (Arthur and Polak, 2006) and 'The Structure of Invention' (Arthur, 2007).

Seeking to document and analyse *how* an economy forms out of technologies, Arthur first observes that 'when we face the key question of how radically novel technologies originate – the equivalent of Darwin's question of how novel species originate in biology – we get stymied. Darwin's mechanism does not work' (Arthur, 2009: 18).[15]

His interest in the emergence of new technologies led him to question the process of invention – as truly innovative technologies result from invention (Arthur, 2018c). Arthur read historians of technology but found no satisfactory explanation for the 'act of insight' they only mentioned when describing the appearance of new inventions (Arthur, 2007). Instead of starting with a pen (or computer), Arthur started in the field. He went on to study 'about 20 technologies' with the goal of knowing 'about a dozen extremely well' (Arthur, 2009). More specifically, his engineering background led him to study aircraft, radar, spark radio, vacuum-tube radio, jet engines, the steam engine, railroads, computers, the cyclotron, the mass spectrograph, the polymerase chain reaction, penicillin, and others (Arthur, 2009). He did this for 12 years before finally putting his first word on paper (Arthur, 2009).

A pattern emerged: invention is problem-solving, and the problem is solved thanks to what he calls 'combinatorial evolution' (Beinhocker, 2007; Schumpeter, 1911; Silverberg and Verspagen, 2005). As he summarizes it: '[n]ovel technologies must somehow arise by combination of existing technologies' (Arthur, 2009: 19). Contrary to Darwinian evolution, which proceeds by variation and selection,

[15] Although Arthur often describes his approach as different from Darwin's theory, one can appreciate how complementary they are. Arthur explains how innovations emerge, while Darwin's theory is useful for understanding how innovations are selected once they are in the marketplace.

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radical innovation proceeds by combination and selection. W. Brian Arthur just developed a comprehensive theory of the emergence of new technology (Thurston, 1878),[16] which he calls 'a vast system that creates itself out of itself constantly' (Arthur, 2018c). That theory is now commonly cited in the literature published by complexity and institutional economists (Beinhocker, 2011; Kalthaus, 2020; Koppl *et al.*, 2023). It helps to further define the label 'Arthurian' as scholars who are not only interested in approaching economics from the perspective of complexity science but also focus on the key role that technological emergence and evolution play in driving these dynamics.

Echoing the views of Joel Mokyr (Mokyr, 1992). Arthur further emphasizes that combinatorial evolution is increasingly the result of the accumulation of knowledge in a deep, systematic way (Arthur, 2009: 65). The production of modern inventions is thus in stark contrast to earlier technologies, which were often developed through empirical methods or common sense. This suggests a central role for institutions, both public and private, in making knowledge widely organized and accessible. Such accessibility can be facilitated through the development and promotion of open-source solutions and the creation of incentive programmes, digital libraries, and open-access repositories. As shown in the most recent literature, these initiatives significantly accelerate the emergence of new technologies, leading to what Arthur describes as combinatorial evolution (Wright *et al.*, 2023).

Overall, Arthur's work on the nature of technology provides legal institutions (law enforcement agencies and policymakers) with several insights. For one thing, Arthur's work urges enforcers to think of new technologies as combinations of existing technologies. This means that the regulation of one component can affect (positively or negatively) all the others (Schrepel, 2021b, 2023b: 6). For example, regulating blockchain immutability affects all Web3 applications. The same is true for encryption (Department of Justice, 2023; Schrepel, 2021a). This co-evolving ecosystem view leads to a preference for regulating use cases or individuals (e.g. users, developers, companies) rather than technical features (Schrepel, 2021a).

Second, Arthur's suggestion to think of technology as Legos leads to the identification of critical pieces, i.e. technologies that are key to the development of others. Policymakers may want to (more) closely monitor the practices around these critical technologies, impose mandatory or fair, reasonable, and non-discriminatory ('FRAND') terms on licenses, etc.

Third, if one takes Arthur's reminder of the overall positive impact of technology on our modern world seriously, one needs to enact pro-innovation policies and regulations (Arthur, 2009).[17] He writes: 'more than science, more than our legal system, more than philosophical or political ideas, it's technology that has created our modern world' (Arthur, 2009). If indeed technology is a crucial institution shaping our modern life, regulation should first and foremost seek to ensure the survival of technology and a global environment conducive to the emergence of new technologies. To this end, regulation should not freeze the development of technology, favour specific characteristics, seek to 'govern' technology from above, remove incentives to combine existing technologies, create unnecessary barriers to entry, impose heavy regulatory burdens on open-source ecosystems, etc. Regular studies can and should be conducted to list and remove such regulations. To be clear, this does not mean that regulation should not address the problems created by technologies and consider banning the technologies that have only adverse effects, but it does mean that policymakers should be concerned with creating a thriving environment as a rule and that researchers could help keep track of that effort.

Realistic agent-based modelling

In addition to pioneering the use of agent-based modelling ('ABM') in economics, Arthur has developed a unique methodology for creating these models (Arthur *et al.*, 2020: 124). This was years in the

[16] Arthur is the first to have developed a complete theory on the subject, even though he observes that 'the actual process of invention varies greatly from historical case to historical case, so that universalities appear not to exist', (Arthur, 2007: 275).

[17] As Arthur notes, pro-innovation policies do not come naturally, '[w]e trust nature. When we happen upon a technology (…) [we] immediately ask how natural this technology is' (Arthur, 2009: 11).

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making. As early as 1988, Arthur discussed his desire to simulate a stock market with John Holland (Arthur, 2015b).[18] Holland had published a book entitled 'Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence' (Holland, 1992), in which he deployed the process of adaptation by natural selection across the fields. Holland and Arthur relied on this pioneering approach to move from rule-based simulations to agent-based ones.

On the methodological side, W. Brian Arthur has published articles expressing his preference for inductive reasoning (Palmer *et al.*, 1994). As he puts it, '[i]f you want to crack anything, first comes the idea, then comes the technique' (Arthur, 2018a). In 'On Learning and Adaptation in the Economy' (Arthur, 1992), he emphasized that inductive reasoning revises hypotheses by importing new data (Arthur, 1994). Four years later, in 'Inductive Reasoning, Bounded Rationality and the Bar Problem' (Arthur, 1994), Arthur linked his preference for inductive reasoning to ABM. His simulation featured 'many rules per agent' (Arthur, 2018b), with '[a]gents [that] "learn" over time which of their hypotheses work'. He adds: 'from time to time they may discard poorly performing hypotheses and generate new "ideas" to put in their place' (Arthur, 1994). In other words, the rules that prove accurate are noticed and used by the agents, while the ones that are not 'go down the chute' (Arthur, 2018b).

Continuing his work in this area, Arthur and his co-authors developed the idea he first discussed with John Holland ten years earlier in 'An Artificial Stock Market' (Palmer *et al.*, 1999). Instead of creating a simulation in which 'almost everything is decided at time zero' and agents 'work out how the whole future should be, and then the world just plays itself out', Arthur's stock market ABM opposed neoclassical economics à la Samuelson and Debreu. His simulation featured dynamics, learning, and co-evolution (Palmer *et al.*, 1994), with agents adapting to an 'environment created by other agents' hypotheses' (Arthur, 1994).

Arthur followed Tom Sargent's suggestion to start with a neoclassical model and make the agents non-identical to increase realism (Arthur, 2018b). He and Holland did this using Robert Lucas' stock market model from 1978, in which agents could not differ. They added multiple small computer programs, each representing an agent that learned by trial and error. Their approach led to the creation of ABM in which problems are not well defined, i.e. situations where agents ignore what other agents are doing and thus cannot find an optimal equilibrium solution. Arthur's ABMs help understand systems that are alive. To quote John Holland, '[i]f it's in equilibrium, it must be dead'.[19]

Arthur eventually published the results of his experiment in 'Designing Economic Agents That Act like Human Agents' (Arthur, 1991). As he recalls, he observed market crashes that mirrored the dynamics of real financial markets (Arthur, 2018b). His agents found what worked temporarily, leading to bubbles that Robert Lucas' simulation did not find.

In more recent years, Arthur has applied ABM outside of economics. In 'The Evolution of Technology Within a Simple Computer Model' (Arthur and Polak, 2006), he modelled the apparition of new technologies by constructing what he called an 'artificial world within the computer' (Arthur and Polak, 2006: 24).[20] His conclusion rested on the premise that new technologies invariably emerge from the amalgamation of existing assemblies and components, with pre-existing technologies providing a foundational substrate or repository of building blocks for future technologies (Arthur and Polak, 2006: 30). In 'All Systems will be Gamed: Exploitive Behavior in Economic and Social Systems' (Arthur, 2015a), he used ABM to simulate the exploitation of social and economic systems. He showed that 'exploitive behavior within the economy is by no means rare (…); [and] that policy studies can be readily extended to investigate the possibility of the policy's being "gamed"' (Arthur, 2015a). In the end, Arthur's approach to ABM 'is not that different from what really good playwrights have done

[18]W. Brian Arthur describes John Holland as 'an inspiration' (Arthur, 2023c). The cooperation between Arthur and Holland first led to use of 'genetic algorithms' for simulating agent behaviour, *see* (Beinhocker, 2011: 398).

[19]A quote attributed to John Holland, *see* (Arthur *et al.*, 2020).

[20]Arthur described ABM as 'what happens when Darwin gets a computer' (Arthur, 2023b).

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(…) many very good writers don't have an idea how it's going to come out' (Arthur, 2023c). Plays and ABMs unfold in unexpected ways.

Although Arthur's contribution to agent-based modelling is widely recognized in today's economic literature, it is also relevant when applied to the realm of legal institutions (Ahrweiler, 2017; Bertani *et al.*, 2021; Haldane and Turrell, 2019; Koppl *et al.*, 2023). Realistic ABM à la Arthur can indeed be used to (better) anticipate the effects of new rules, standards, policies, and enforcement actions. There are three reasons for this.

First, ABM can allow policymakers, regulators, and enforcers (i.e. legal institutions) to document the *robustness* of the problems they seek to regulate. In particular, ABMs, in which agents learn over time which of their hypotheses work in their (new) environment, help anticipate the evolving response of agents to new regulations and how their response, in turn, will change their environment. If an ABM leads to different outcomes each time it is run, the simulation indicates a fragile ecosystem that can be disrupted by regulation (i.e. a change in the institutional environment). If policymakers are still willing to intervene, regulation does not require significant changes in the environment to be effective. Conversely, if ABM leads to a consistent result each time it is run, the ecosystem's robustness indicates the need for a major change in the (regulatory) environment if policymakers want to address an issue effectively.

Second, Arthur's type of ABM, in which agents do not respond to tradeoffs in the same way, shows a path to more *granularity* than relying on the idea of the 'average consumer' or general concepts like 'companies', 'businesses', and so on. Realistic ABM could be used to document the different responses of all kinds of different agents and the dynamics that emerge from this vibrant ecosystem. For example, antitrust authorities could simulate how privacy-sensitive and quality-sensitive agents respond (differently) to the implementation of data protection regulation. In this sense, ABM informs the tradeoffs legal institutions have to settle.

Third, realistic ABM can help policymakers document something they often struggle with: the *timing* of regulation, especially the timing between different regulations. For example, the order in which privacy, competition, and financial regulations are introduced into an area can have a major impact on the state of the ecosystem. Taking a step back, ABM could also show the effect of introducing regulations before or after the emergence of certain market events (e.g. the emergence of new competitors). This means that ABM can help to optimize the timing of regulatory institutions as they introduce new rules and standards.

Science in motion

There are as many ways to approach science as there are ways to skin a cat. Arthur took a somewhat unique path by rejecting economic orthodoxy. His research approach led to academic endeavours such as running the Santa Fe Institute's economics programme rather than keeping his university chair.

Science from the outside world

Arthur's approach to science is unique in (at least) three ways. First, one of Arthur's notable strengths is his ability to derive research ideas from personal experience rather than relying solely on the literature.[21] He advised that 'it's a good idea at the start of a research project to ignore everything that's been written and simply think for yourself' (Arthur, 2017). For instance, he drew inspiration for his well-known El Farol article (Arthur, 1994) from a real-life experience at a Santa Fe bar named… El Farol. The bar featured Irish music on Thursday nights. The enjoyment of the evening depended on the bar's crowd size. It was pleasant when not too crowded but less enjoyable when overly crowded. Arthur

[21] Arthur shared that his temperament leans towards artistic expression rather than strictly-defined scientific endeavours: '[u]ntil about 10 or 15 years ago, I realized that my temperament all my life has been more like an artist than a scientist' (Arthur, 2023c).

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realized that if everyone anticipated a large crowd on a particular night, they might decide not to go, thus invalidating that prediction. Conversely, if everyone expected a small crowd, they might decide to attend, again rendering that prediction inaccurate (Arthur, 2015b).

This approach to research allowed Arthur to avoid researching problems that others had preconceived. This led him to big questions such as what is technology, which technology will succeed (Arthur, 1999a: 108; Arthur and Polak, 2006), how do economic systems evolve (Arthur, 1990a), are economic agents rational (Arthur and Polak, 2006: 30), is the information revolution dead (Arthur, 2002: 65), how to simulate markets with computers (Palmer *et al.*, 1994), and how inventions come about (Arthur, 2007).

Second, Arthur's training as an engineer made a strong impression on his later work. Most of his publications are informed by his technical understanding of the subjects he studies – Arthur often refers to the example of light-water reactors versus gas-cooled reactors (Arthur, 1989: 126; 1990a). As a result, W. Brian Arthur's work is technically deep and relevant across the political spectrum.[22] His writings are used by the public and private sectors, corporations and governments, sometimes in the same cases. To that technical side, Arthur adds social science approaches by considering bounded rationality, influences and dynamics among agents on the market, etc. (Arthur, 2018a).[23] These concepts allow Arthur to get even closer to the reality of the markets and escape what he calls 'economics using stick figures' (Arthur, 2023c). In short, Arthur combines the technical analysis of non-conscious entities such as technology with that of living beings, resulting in a unique blend in the field of economics.

Third, Arthur shows interest in the scientific instruments made available outside of his own field of research. As he explains, '[s]cience proceeds as much by its instruments – its technologies – as it does by human thought' (Arthur, 2023b: 638). Arthur identifies three major shifts in the language of science: the emergence of geometry, then algebra, and now algorithms (i.e. computation). He describes computation as the language of biology, emphasizing that algorithmic expression is crucial in understanding how variables and events lead to new ones; in other words, algorithms help address ill-defined problems (Arthur *et al.*, 2020: 124).[24] He also stresses that computation is not as limited as algebra, which can only express balanced quantities (the left part of the equation *must* equal the right part of the equation) and is limited by the human ability to keep track of complicated formulas. Arthur suggests using computational thinking to approach complexity because with 'algorithms or computation, you can model agents acting, (…) you can directly use verbs: agents can buy, sell, change their minds, throw things out, create new things' (Arthur, 1999a). Algorithms enable the understanding of processes. In other words, Arthur links what he observes in economics to a new scientific method. This method does not necessarily require the use of computers (Arthur, 2006) but a new approach that integrates processes and actions. Computation emerges as a central concept in complexity economics. In fact, complexity economics would not be possible without computation, which is why complexity economics was formalized in the late 1980s after computational power was democratized.

Applied to legal issues and institutions, Arthur's reality-based approach calls for research to begin with the 'outside world', that is, with what happens outside the legal system. To be sure, this does not mean that doctrinal research focused on legal sources (e.g. court decisions, policies, academic publications, etc.) is not important. Legal scholars can contribute to society by increasing the relevance of legal sources. But, Arthur's work suggests that research questions should come from outside the legal system itself. Legal scholarship does little to advance the common good by studying sources for their own sake. As Arthur suggests, a good rule of thumb for anticipating the impact of legal

[22]'I didn't see it was up to me to go on a crusade' (Arthur, 2023c).

[23]'I believe science is shifting away from its grounding in the Enlightenment ideas of formalism, determinacy, rationality, and stasis. It's shifting to a new grounding in organicism, indeterminacy, contingent behavior, and evolutionary openness' (Arthur, 2018a).

[24]Algebra is convenient when one can keep the object still while examining it but is not well suited in other situations.

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scholarship on society is to formulate research questions based on experiences (i.e. lived experiences such as his El Farol moment and learned experiences such as reading interviews with regulated agents, etc.) rather than legal sources.

Arthur suggests that a deep technical understanding of the subject is more than just a nice feature to have when answering research questions related to technical fields. It is a necessity. When addressing digital issues, this means having a (self-made) background in computational thinking. More specifically, when it comes to AI-related challenges, it means having a technical background in machine learning to, at the very least, be able to understand, communicate, and collaborate effectively with computer scientists. Indirectly, Arthur's work also suggests exploring legal subjects with computational tools. These tools, as he shows in economics, allow scientists not only to understand better the subject they study but also to change the substance of the subject itself. Lawyers who study computational law should rejoice at their ability to influence the nature of new rules and norms (Schrepel, 2021c, 2023b).

Entrepreneurship

Two of Arthur's character traits have persisted throughout his career. First, Arthur is a risk-taker.[25] Despite being the youngest person to hold an endowed chair at Stanford University at the age of 37, despite being a colleague of Ken Arrow and other great names in the field, Arthur decided to leave Stanford because, I quote, he was 'bored'.[26] He took a full-time position at the newly formed, and at that time not yet prestigious, Santa Fe Institute. There, Arthur decided to work on complexity economics, nonlinearity, disequilibrium, etc. With his research agenda, Arthur made a conscious decision to forgo publishing in the top five economics journals that were not open to theories other than neoclassical, despite having strong credentials in both mathematics and economics.[27]

Second, Arthur is an academic-entrepreneur. I have discussed his contribution to science through the many concepts he has developed. But more than that, Arthur also contributed to the emergence of the Santa Fe Institute (founded in 1984) as a leading academic institution (Waldrop, 1992). At Kenneth Arrow's invitation, Arthur travelled to New Mexico in 1987 to participate in a meeting Kenneth had convened with Philip Anderson. As Arthur recalls, the gathering included a contingent of 10 theoretical economists (including Tom Sargent and Larry Summers) brought by Arrow and an additional group of 10 physicists and mathematicians (including John Farmer and John Holland) brought by Anderson. A year later, Arthur became the head of the Santa Fe Institute's economic programme. His group was funded by John Reed, the chairman of Citibank, with a single mandate: '[d]o anything you like, providing it is at the foundations of economics, and is not conventional' (Arthur, 2023a). Arthur hired 25 people that first year. He then developed a unique research programme. As he recalls, 'there were no orthodox departments, no orthodox people, and so unconventional ideas could thrive and conventional ones could be held up to the light and examined for what they were. This was a different world' (Arthur, 2018a). For the rest, 'Complexity Economics: Proceedings of the Santa Fe Institute's 2019 Fall Symposium' nicely relates how the Santa Fe Institute came to be (Arthur *et al.*, 2020). Today, the SFI's economics programme is one of the most prestigious in the world.

As Arthur's professional life illustrates, being a risk-taker means pursuing one's own interests regardless of what universities, (funding) institutions, and group pressures may want to see. It means pursuing what excites scholars most, regardless of trends and calculated moves. It means taking a bottom-up, emergent, and flexible approach to research rather than following a top-down, long-term agenda. This approach is compatible with professorships, as many have proven. The only

[25]When Arthur left Stanford, Kenneth Arrow told him he was taking a big risk. Arthur answered it was a bigger risk to stay (Arthur, 2023b).

[26]'I didn't leave for any reason except boredom, I suppose.' (Arthur, 2023c). Arthur also confessed: 'I got tired of academia… I just felt it was just one battle after another' (Arthur, 2023b).

[27]Arthur published two articles in the American Economic Review (Arthur, 1991, 1994).

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drawback, in Arthur's words, is that this approach 'ignores other things like how much money is in [your] bank' (Arthur, 2023c). Being an entrepreneur means creating research projects, groups, institutes, taking part in young, nascent initiatives in which one can play a decisive role rather than always preferring well-established, initially more prestigious groups.

Concluding thoughts

Arthur's contributions to (complexity) science have far-reaching applications. From Silicon Valley to Singapore and research labs around the world, the relevance of Arthur's insights continues to grow (Arthur *et al*., 2018; Tetzeli, 2016). Because of its cross-disciplinary relevance and focus on dynamics, Arthur's scholarship is particularly well suited to informing institutional challenges.

His work on emerging new technologies through combination and selection is the cornerstone of his contribution to institutional economics. Arthur explains that the economy emerges from its technologies, which means that the study of economic dynamics cannot be separated from the study of technology and the conditions under which radical innovations emerge. These conditions are not only economic, legal, and technical, but also social: technology is a social institution whose evolution depends on the accumulation, application, and exchange of codified knowledge. Technology is a complex adaptive system shaped by and shaping institutional arrangements.

Arthur's contribution to the study of institutions is not limited to describing their complex dynamics but also to providing a method for understanding them. First, Arthur highlights the importance of treating economic challenges as ill-defined. Second, Arthur offers conceptual tools centred on the concept of increasing returns to make sense of these challenges. He also suggests technical tools, namely realistic agent-based modelling, and algorithmic expression, i.e. economics in nouns and verbs. Third, Arthur suggests an inductive use of these tools to approach ill-defined problems, even if this precludes simple policy implications. In other words, Arthur's scholarship suggests embracing economic, technical, legal, and institutional complexity rather than discounting it.

References

Ades A.F. and Glaeser E.L. (1999). Evidence on growth, increasing returns, and the extent of the market. *The Quarterly Journal of Economics* **114**(3), 1025–1045. Available at http://www.jstor.org/stable/2586890

Ahrweiler P. (2017). Agent-based simulation for science, technology, and innovation policy. *Scientometrics* **110**(1), 391–415. https://doi.org/10.1007/s11192-016-2105-0

Akerlof G.A. (2020). Sins of omission and the practice of economics. *Journal of Economic Literature* **58**(2), 405–418. https://doi.org/10.1257/JEL.20191573

Antweiler W. and Trefler D. (2002). Increasing returns and all that: A view from trade. *American Economic Review* **92**(1), 93–119.

Aoki M. (2001). *Toward a Comparative Institutional Analysis*. Cambridge, MA: MIT Press.

Arthur W.B. (1989). Competing technologies, increasing returns, and lock-in by historical events. *Economic Journal* **99**, 116–131.

Arthur W.B. (1990a). Positive feedbacks in the economy. *Scientific American* **262**, 92–99. Available at http://www.jstor.org/stable/24996687

Arthur W.B. (1990b). 'Silicon valley' locational clusters: When do increasing returns imply monopoly? *Mathematical Social Sciences* **19**(3), 235–251. https://doi.org/10.1016/0165-4896(90)90064-E

Arthur W.B. (1991). Designing economic agents that act like human agents: A behavioral approach to bounded rationality. *American Economic Review* **81**(2), 353–359.

Arthur W.B. (1992). On Learning and Adaptation in the Economy. *Queen's University, Department of Economics, Working Papers* [Preprint], (854).

Arthur W.B. (1994). Inductive reasoning and bounded rationality: The El Farol problem. *American Economic Review* **84**, 406–411.

Arthur W.B. (1996). Increasing returns and the new world of business. *Harvard Business Review* **74**(4).

Arthur W.B. (1999a). Competing technologies and economic prediction. *Options* April 1984, 10–13. Reprinted in D. MacKenzie and J. Wajcman (eds), *The Social Shaping of Technology*. Buckingham, UK: Open University Press.

Arthur W.B. (1999b). Complexity and the economy. *Science* **284**, 107–109. https://doi.org/10.1126/science.284.5411.107

https://doi.org/10.1017/S1744137424000067 Published online by Cambridge University Press

Arthur W.B. (2002). Is the information revolution dead. *Business* **2**, 65–72.
Arthur W.B. (2006). Chapter 32: Out-of-equilibrium economics and agent-based modeling. *Handbook of Computational Economics* **2**, 1551–1564. https://doi.org/10.1016/S1574-0021(05)02032-0
Arthur W.B. (2007). The structure of invention. *Research Policy* **36**(2), 274–287. https://doi.org/10.1016/j.respol.2006.11.005
Arthur W.B. (2009). *The Nature of Technology: What It Is and How It Evolves*. New York: Simon and Schuster.
Arthur W.B. (2010). Complexity, the Santa Fe approach, and non-equilibrium economics. *History of Economic Ideas* **18**(2), 149–166.
Arthur W.B. (2015a). All systems will be gamed: Exploitive behavior in economic and social system. *Complexity and the Economy* [Preprint].
Arthur W.B. (2015b). *Complexity and the Economy, Complexity and the Economy*. New York: Oxford University Press.
Arthur W.B. (2017). Where is technology taking the economy? *McKinsey Quarterly*.
Arthur W.B. (2018a). Berkeley, increasing returns, and silicon valley. *Singapore*.
Arthur W.B. (2018b). Complexity and the beginnings of the Santa Fe Institute. *Singapore*.
Arthur W.B. (2018c). Technology and combinatorial evolution. *Singapore*.
Arthur W.B. (2021). Foundations of complexity economics. *Nature Reviews Physics* **3**(2), 136–145.
Arthur W.B. (2023a). *Complexity Economics*. YouTube.
Arthur W.B. (2023b). Economics in nouns and verbs. *Journal of Economic Behavior and Organization* **205**, 638–647. https://doi.org/10.1016/j.jebo.2022.10.036
Arthur W.B. (2023c). Private conversation.
Arthur W.B. and Polak W. (2006). The evolution of technology within a simple computer model. *Complexity* **11**(5), 23–31. https://doi.org/10.1002/cplx.20130
Arthur W.B., Beinhocker E.D. and Stanger A. (2020). *Complexity Economics: Proceedings of the Santa Fe Institute's 2019 Fall Symposium (Dialogues of the Applied Complexity Network)*. Santa Fe: SFI Press.
Arthur W.B., Andreessen M. and Chokshi S. (2018). *Tech Trends: Network Effects and Increasing Returns | Future, Future*. Available at https://future.com/podcasts/network-effects-increasing-returns-trends/ (accessed 8 February 2024).
Arthur W.B., Ermoliev Y.M. and Kaniovski Y.M. (1987). Path-dependent processes and the emergence of macro-structure. *European Journal of Operational Research* **30**(3), 294–303. https://doi.org/10.1016/0377-2217(87)90074-9
Axtell R.L. (2007). What economic agents do: How cognition and interaction lead to emergence and complexity. *Review of Austrian Economics* **20**(2–3), 105–122. https://doi.org/10.1007/s11138-007-0021-5
Beinhocker E.D. (2007). *The Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics*. New York: Random House.
Beinhocker E.D. (2011). Evolution as computation: Integrating self-organization with generalized Darwinism. *Journal of Institutional Economics* **7**(3), 393–423. https://doi.org/10.1017/S1744137411000257
Bertani F., Ponta L., Raberto M., Teglio A. and Cincotti S. (2021). The complexity of the intangible digital economy: An agent-based model. *Journal of Business Research* **129**, 527–540. https://doi.org/10.1016/j.jbusres.2020.03.041
Brette O. and Chassagnon V. (2021). The business model as a generative replicator. *Journal of Institutional Economics* **17**(5), 746–763. https://doi.org/10.1017/S1744137421000242
Cassidy J. (1998). The Force of an Idea What's really behind the case against Bill Gates?. *New Yorker*, pp. 32–37.
Choi G.S. and Storr V.H. (2022). The market as a process for the discovery of whom not to trust. *Journal of Institutional Economics* **18**, 467–482. https://doi.org/10.1017/S1744137421000370
Deakin S., Gindis D., Hodgson G.M., Huang H., Geoffrey M. and Pistor K. (2021). What is a firm? A reply to Jean-Philippe Robé. *Journal of Institutional Economics* **17**(5), 861–871. https://doi.org/10.1017/S1744137421000369
Deakin S., Gindis D., Hodgson G.M., Kainan H. and Pistor K. (2017). Legal institutionalism: Capitalism and the constitutive role of law. *Journal of Comparative Economics* **45**(1), 188–200. https://doi.org/10.1016/j.jce.2016.04.005
Department of Justice (2023). *Agency Information Collection Activities; Proposed ECollection EComments Requested; Request for a New Collection; Lawful Access Data Collection, Washington DC, 88 FR 24836*. Department of Justice.
Farmer D.J. (2012). Economics needs to treat the economy as a complex system. *Working paper* [Preprint].
Foster J. (2015). Next steps toward an economics for a creative world: A comment. *Journal of Institutional Economics* **11**, 39–45. https://doi.org/10.1017/S174413741400040X
Haldane A.G. and Turrell A.E. (2019). Drawing on different disciplines: Macroeconomic agent-based models. *Journal of Evolutionary Economics* **29**(1), 39–66. https://doi.org/10.1007/s00191-018-0557-5
Harper D.A. (2018). Innovation and institutions from the bottom up: An introduction. *Journal of Institutional Economics* **14**, 975–1001. https://doi.org/10.1017/S174413741800019X
Hodgson G.M. and Stoelhorst J.W. (2014). Introduction to the special issue on the future of institutional and evolutionary economics. *Journal of Institutional Economics* **10**(4), 513–540. https://doi.org/10.1017/S1744137414000393
Holland J.H. (1992). *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. Cambridge, MA: MIT Press.
Kalthaus M. (2020). Knowledge recombination along the technology life cycle. *Journal of Evolutionary Economics* **30**(3), 643–704. https://doi.org/10.1007/s00191-020-00661-z

Kingston C. and Caballero G. (2009). Comparing theories of institutional change. *Journal of Institutional Economics* **5**(2), 151–180.

Kirman A. (1989). The intrinsic limits of modern economic theory: The emperor has no clothes. *The Economic Journal* **99** (395), 126–139. https://doi.org/10.2307/2234075

Koppl R., Gatti R.C., Devereaux A., Fath B.D., Herriot J., Hordijk W., Kauffman S., Ulanowicz R.U. and Valverde S. (2023). *Explaining Technology*. Elements in Evolutionary Economics, Cambridge, UK: Cambridge University Press.

Kupers R. and Colander D. (2014). *Complexity and the Art of Public Policy: Solving Society's Problems from the Bottom Up*. Princeton, NJ: Princeton University Press.

Lessig L. (2006). *Code: And Other Laws of Cyberspace*. New York: Basic Books.

Lourenço A. and Turner S. (2019). The role of regulation in constituting markets: A co-evolutionary perspective on the UK television production sector. *Journal of Institutional Economics* **15**(4), 615–630. https://doi.org/10.1017/S174413741900002X

Mokyr J. (1992). *The Lever of Riches: Technological Creativity and Economic Progress*. New York: Oxford University Press.

North D.C. (1999). Dealing with a non-ergodic world: Institutional economics, property rights, and the global environment. *Duke Environmental Law & Policy Forum* **10**, 1.

Ostrom E. and Basurto X. (2011). Crafting analytical tools to study institutional change. *Journal of Institutional Economics* **7** (3), 317–343. https://doi.org/10.1017/S1744137410000305

Palmer R.G., Arthur W.B., Holland J.H. and LeBaron B. (1999). An artificial stock market. *Artificial Life and Robotics* **3**, 27–31.

Palmer R.G., Arthur W.B., Holland J.H., LeBaron B. and Tayler P. (1994). Artificial economic life: A simple model of a stock-market. *Physica D: Nonlinear Phenomena* **75**(1–3), 264–274. https://doi.org/10.1016/0167-2789(94)90287-9

Pentland A. and Mahari R. (2022). Legal dynamism. *Network Law Review*.

Petit N. and Schrepel T. (2023). Complexity-minded antitrust. *Journal of Evolutionary Economics* **33**(2), 541–570. https://doi.org/10.1007/s00191-023-00808-8

Schmitt-Grohé S. (2000). Endogenous business cycles and the dynamics of output, hours, and consumption. *American Economic Review* **90**(5), 1136–1159. https://doi.org/10.1257/aer.90.5.1136

Schrepel T. (2021a). Blockchain and Darwin. In *Blockchain + Antitrust*. Cheltenham, UK: Edward Elgar Publishing, pp. 38–50. https://doi.org/10.4337/9781800885530.00009

Schrepel T. (2021b). Blockchain: From ideology to implementation. In *Blockchain + Antitrust*. Cheltenham, UK: Edward Elgar Publishing, pp. 2–17. https://doi.org/10.4337/9781800885530.00007

Schrepel T. (2021c). Computational antitrust: An introduction and research agenda. *Stanford Computational Antitrust* **1**, 1–15. https://doi.org/10.51868/1

Schrepel T. (2022). The not-so-pathetic dot theory. *Network Law Review*.

Schrepel T. (2023a). A 'proof of vigilance' for antitrust constitutional moment. *Network Law Review*.

Schrepel T. (2023b). Law + technology. *The Journal of Law and Technology at Texas* **2023**, 1–19.

Schumpeter J.A. (1911). *Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle*. New York: Routledge. https://doi.org/10.4324/9781315135564

Silverberg G. and Verspagen B. (2005). A percolation model of innovation in complex technology spaces. *Journal of Economic Dynamics and Control* **29**(1–2), 225–244. https://doi.org/10.1016/j.jedc.2003.05.005

Tetzeli R. (2016). *A Short History of the Most Important Economic Theory in Tech*, Fast Company. Available at https://www.fastcompany.com/3064681/most-important-economic-theory-in-technology-brian-arthur (accessed 8 February 2024).

Thurston R.H. (1878). *A History of the Growth of the Steam-Engine*. New York: D. Appleton.

Van Bavel B. (2020). Market dominance and endogenous decline: The contribution of historical analysis. *Journal of Institutional Economics* [Preprint]. https://doi.org/10.1017/S1744137420000405

Venturi R. (1966). Complexity and contradiction in architecture. *Anthologie zum Städtebau. Band III: Vom Wiederaufbau nach dem Zweiten Weltkrieg bis zur zeitgenössischen Stadt*. https://doi.org/10.5771/9783786175247-348

Waldrop M.M. (1992). *Complexity: The Emerging Science at the Edge of Order and Chaos*. New York: Simon and Schuster.

Wang T. (2015). Competition and increasing returns to scale: A model of bank size. *Economic Journal* **125**(585), 989–1014. https://doi.org/10.1111/ecoj.12104

Wright N.L., Nagle F. and Greenstein S. (2023). Open source software and global entrepreneurship. *Research Policy* 52, 104846. https://doi.org/10.1016/j.respol.2023.104846

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