Being an Arthurian: Complexity Economics, Law, and Science

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Abstract

W. Brian Arthur is the father of complexity economics. He is also known for his work on the nature of technology, his experiments with agent-based modeling, and his entrepreneurial approach to science. This article seeks to explore the reasons why a scholar might identify as an "Arthurian," with the aspiration of encouraging others to embrace Arthur's research interests and emulate his approach to science.

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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 behavior. Ecosystems depend on time and history; complexity science looks at the messy vitality of ecosystems. Economists and lawyers, among others, 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 program 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 background, I would argue that being an Arthurian – I am Arthurian myself[2] – implies a number of substantive and methodological interests.[3] I note three of them. This article explores them in turn with the hope of contributing to the diffusion of W. Brian Arthur's ideas, and of inspiring others to embrace his research interest and scientific approach.

[1] About his experience at the Santa Fe, *see* W. Brian Arthur, "Complexity, the Santa Fe Approach, and Non-Equilibrium Economics," *History of Economic Ideas* 18, no. 2 (2010): 149–166 ("The Santa Fe Institute had no students, and therefore no teaching. So we had the luxury of time to think. It had no departments, and no set of colleagues with locked-in ways of thinking. Hence we had no colleagues objecting to our lack of convention, or censoring"). 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.

[2] This article is not about the author. This article is about Arthur's contribution to science, and the author will only appear between the lines to emphasise the importance of Arthur's work.

[3] As far as I know, there has not been an article to date that defines what it means to be an Arthurian. Importantly, please bear in mind that I am a lawyer. I will try to explain why it is not odd for a lawyer to define himself as being closer to an approach created by an economist/engineer/mathematician than by another lawyer. With that in mind, my view of what it means to be an Arthurian is necessarily informed and limited by my legal background. Other economists and scientists will hopefully complete the picture in the coming years.

1. Complexity science and economics

Arthur's work exemplifies the potential of complexity science when applied to existing fields of research (**1.1.**). In economics, Arthur has developed some of the key concepts for understanding today's fast-moving economy where increasing returns are the rule rather than the exception (**1.2.**).

1.1. A pioneering approach

Arthur pushed the boundaries of complexity science to uncharted territory. Arthur not only coined the term "complexity economics,"[4] but he also greatly advanced research in the field.[5]

Arthur defines complexity "not [as] a science, [but] rather [as] movement within science"[6] 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."[7] 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

[4] The term first appeared in Arthur, "Complexity and the Economy," *Science* 284, no. 5411 (1999): 107–109. As W. Brian Arthur recalls, "At 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.' It was one of these things dropped from heaven. I was standing with a landline in my apartment in Paolo Alto and that label locked in." (DCI Lecture, 2023).

[5] Although this article focuses on Arthur scholarship, other scholars have made important contribution to complexity economics, *see* Alan Kirman: Kirman, Kirman, "The Intrinsic Limits of Modern Economic Theory: The Emperor Has No Clothes," *The Economic Journal* 99, no. 395 (1989): 126- 139; Farmer, "Economics Needs to Treat the Economy as a Complex System," 2012 (INET Conference Paper); Farmer and Foley, "The Economy Needs Agent-Based Modelling," *Nature* 460, no. 7256 (August 2009): 685–686; Robert L. Axtell, "What Economic Agents Do: How Cognition and Interaction Lead to Emergence and Complexity," *The Review of Austrian Economics* 20, no. 2–3 (May 2007): 105–122; Axtell, *Dynamics of Firms: Data, Theories and Models: Emergent Scale and Complexity in Modern Economies* (MIT Press, 2020); Epstein, Remarks on the Foundations of Agent-Based Generative Social Science, in *Handbook of Computational Economics 2. Agent-Based Computational Economics* (eds Tesfatsion, L. & Judd, K. L.) (Elsevier, 2006); Waldrop, *Complexity: The Emerging Science at the Edge of Order and Chaos* (New York: Simon & Schuster, 1993); Arthur, Durlauf, and Lane, eds., *The Economy as an Evolving Complex System II* (Addison-Wesley, 1997).

[6] Arthur, "Foundations of Complexity Economics," *Nature Reviews Physics* 3, no. 2 (2021): 136–145.

[7] *Ibid*. Also, Arthur, Beinhocker, and Stanger, eds., *Complexity Economics*, (Santa Fe Institute Press, 2019), 124 ("Complexity, in a phrase, is about systems responding to the context they create").

optimal behavior that is consistent with, or in equilibrium with, the overall outcome caused by that behavior.[8] Neoclassical economists usually agree that these assumptions do not represent the 'real world,' but they maintain them to make economic theory workable.[9] Complexity economists instead turns "to the question of how actions, strategies, or expectations might react in general to (might endogenously change with) the aggregate patterns these create."[10] Economic agents "experiment, explore, adjust, readjust"[11] Their behaviors are unrestricted, they evolve over time and self-reinforce.[12]

Arthur's book "Complexity and the Economy" (2014)[13] and his article "Foundations of Complexity Economics" (2021)[14] are the most comprehensive explorations of complexity economics I have found to date. 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.[15] They connect complexity economics to earlier studies by Adam Smith, Joseph Schumpeter,[16] Thorstein Veblen, Friedrich Hayek, John Maynard Keynes, and Ken Arrow. Perhaps more fundamentally, they identify the main breakthrough of complexity economics: economic problems are ill-defined.[17]

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[8] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018) (underlining that Alfred Marshall already relaxed this assumption in 1891); Arthur, "Foundations of Complexity Economics," *Nature Reviews Physics* 3, no. 2 (2021): 136–145.

[9] Arthur, private conversation, April 2023 (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).

[10] Arthur, "Complexity and the Economy," *Science* 284, no. 5411 (1999): 107–109 at 108.

[11] Arthur, Beinhocker, and Stanger, eds., *Complexity Economics* (Santa Fe Institute Press, 2019), 130-131.

[12] Arthur, Beinhocker, and Stanger, eds., *Complexity Economics* (Santa Fe Institute Press, 2019), 131-132 ("these very actions of agents' exploring, changing, adapting, and experimenting further change the outcome, and they'd have to then re-adapt and re-adjust. So, they are always re-adapting and re-adjusting to the situation they create.").

[13] Arthur, *Complexity and the Economy* (Oxford University Press, 2015).

[14] Arthur, "Foundations of Complexity Economics," *Nature Reviews Physics* 3, no. 2 (2021): 136–145.

[15] Arthur, DCI Lecture, 2023 ("I would say that the standard neoclassical approach is very much an engineering one, where you regard yourself as being very large power stations or at the controls, and you are turning this dial for policy. Once you start to think of the outcome as being an ecology of competing, or sometimes cooperating, behaviors, then you can think of yourself not so much as tweaking the system with large dials, but more as a park ranger").

[16] Arthur, "Is the Information Revolution Dead? If history is a guide, it is not," *In Business* (2002) Volume 2, at 65 ("I believe that Schumpeter will turn out to be the most important economist of the 20th century").

[17] Arthur, "Foundations of Complexity Economics," *Nature Reviews Physics* 3, no. 2 (2021): 136–145, at 137.

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 behavior 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."[18] More generally, his overall contribution to economics stands in contrast to the vast majority of publications in the field that is "very much based on mathematics."[19] Arthur rejects the "highly mechanical"[20] perspective of the economy that often leads to "prim dreams of pure order."[21] Instead, he leans on the side of "messy vitality."[22]

Applied to legal scholarship, Arthur's work on complexity science and economics informs three trends. 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, legal scholars can document how small events trigger chains of legal responses, resulting in a complex network of laws.

Second, the legal system is part of a larger ecosystem — including market, norms and architecture — that constrains everyone's behavior. Legal scholars may be interested in studying the dynamics between these constraints, how agents respond to them,

[18] Arthur, "Foundations of Complexity Economics," *Nature Reviews Physics* 3, no. 2 (2021): 136–145, at 137.

[19] Arthur, DCI podcast, YouTube (Feb. 2023), https://perma.cc/GBT4-FHHB (Gérard Debreu and Samuelson were "trying to reduce economics to a form of mathematics"). Sharing the same view, *see* George A. Akerlof, "Sins of Omission and the Practice of Economics," *Journal of Economic Literature*, no. 58(2) (2020): 405–418.

[20] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018) ("The economy is not machine-like, it is organic, and somehow I find comfort in that.").

[21] Venturi, *Complexity and Contradiction in Architecture* (The Museum of Modern Art, 1966): 104 ("Some of the vivid lessons of Pop Art, involving contradictions of scale and context, should have awakened architects from prim dreams of pure order").

[22] Arthur, "Foundations of Complexity Economics," *Nature Reviews Physics* 3, no. 2 (2021): 136–145. Also, Arthur, Beinhocker, and Stanger, eds., *Complexity Economics*, (Santa Fe Institute Press, 2019), 143 ("complexity shows us what that world looks like. It's not optimal, but it's pretty damn good. And it's alive."). Arthur borrowed the concept of "messy vitality" from Robert Venturi, *see* Venturi, *Complexity and Contradiction in Architecture* (The Museum of Modern Art, 1966).

and how agents' responses in turn affect these constraints.[23] Legal studies that mostly focus on equilibrium, i.e., static, non-adaptive agents. Arthur's work in complexity science informs the need to combine constraints when addressing robust issues (i.e., persistent issues due to agent adaptation).

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.[24] Policymakers and regulators typically ignore the strategies and resources of the agents they regulate.[25] But the ability to adapt to how agents respond to new regulation make them more effective. It makes the law inductive rather than treating rules and standards as perfectly informed solutions to well-defined problems. For example, regulations can document their effects, and adapt (e.g., become stricter) on that basis. Regulating the speed of cars on the highway in order to reduce accidents, the regulation could automatically adapt to the number of cars on the road, the type of cars, the weather, the type of road, the time of the day, etc.[26] Such adaptive regulations allow for real-time laws and standards rather than lagging behind or creating laws ahead of technology. Building on the literature dedicated to 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.[27]

1.2. Increasing returns

There are two fundamental questions in the field of economics. The first concerns the "allocation within the economy: how quantities of goods and services and their prices are determined within and across markets. (...) The other is formation within

[23] *See* Schrepel, "The Not-So-Pathetic Dot Theory," Network Law Review, (2022), https://perma.cc/93XU-RYLK.

[24] Schrepel, "A 'Proof of Vigilance' for Antitrust Constitutional Moment," Network Law Review, (2023), https://perma.cc/88GA-SCLA.

[25] Policymakers often have a linear relation between rules and markets, *see* Lourenço and Turner, "The Role of Regulation in Constituting Markets: A Co-Evolutionary Perspective on The UK Television Production Sector." *Journal of Institutional Economics* 15, no. 4 (2019): 618 (rules are perceived as "incentive mechanisms to which opportunistic and boundedly rational economic agents respond").

[26] Exploring this idea, see Sandy Pentland and Robert Mahari, "Legal Dynamism," Network Law Review (Fall 2022), https://perma.cc/KW47-LE2W.

[27] The idea of adaptive regulations builds on the literature dedicated to epistemic game theory and social systems theory, see Lourenço and Turner, "The Role of Regulation in Constituting Markets: A Co-Evolutionary Perspective on The UK Television Production Sector." *Journal of Institutional Economics* 15, no. 4 (2019): 617.

the economy: how an economy comes into being in the first place, and develops and changes structurally over time." Although the "allocation problem is by now well understood and highly mathematicized, the formation question is less well understood."[28] Arthur's work in complexity economics helps with the second question.[29] 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?"[30]

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.[31] His approach contrasts with that of neoclassical economics. In "Complexity and the Economy" (1999), Arthur observed that "[c]onventional economic theory chooses not to study the unfolding of the patterns its agents create but rather to simplify its questions in order to seek analytical solutions. Thus it asks what behavioral elements (actions, strategies, and expectations) are consistent with the aggregate patterns these behavioral elements co-create?"[32] In short, neoclassical economic theory assumes that "individual behavior produces an outcome that doesn't give that behavior any incentive to change."[33] 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 strong implications because "if everything is the same over time, time disappears and there's no history."[34] By contrast, complexity asks how heterogenous agents react to the outcome they created. Complexity economics looks at changing behaviors.

Arthur's focus on the formation question led him to uncover several of the key mechanisms of today's fast-moving economy. He theorized them in publications that were initially rejected by the profession but are now widely celebrated across

[28] Arthur, *Complexity and the Beginnings of the Santa Fe Institute*, private lecture, Singapore (Mar. 29, 2018).

[29] Please note the second problem is rarely addressed in antitrust. A complexity-minded antitrust could thus complement the distribution view currently adopted. *See* Petit and Schrepel, "Complexity-Minded Antitrust," *Journal of Evolutionary Economics* (2023).

[30] Arthur, Beinhocker, and Stanger, eds., *Complexity Economics*, (Santa Fe Institute Press, 2019), 137.

[31] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018).

[32] Arthur, "Complexity and the Economy," *Science* 284, no. 5411 (1999): 107–109 at 107 & 108.

[33] Arthur, Beinhocker, and Stanger, eds., *Complexity Economics*, (Santa Fe Institute Press, 2019), 124. He adds that "this particular way of looking at the economy—it may be mechanistic; (…) was borrowed in the late 1800s from physics," 126.

[34] Arthur, Beinhocker, and Stanger, eds., *Complexity Economics*, (Santa Fe Institute Press, 2019), 126.

ideological lines. These mechanisms converge to a nuanced understanding of increasing returns.

Inspired by him because of his background as an electrical engineer and his readings of Ilya Prigogine,[35] 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" (1989) and "Positive Feedbacks in the Economy" (1990), Arthur popularizes the fact that economies with increasing returns (i.e., "the whole high-tech sector")[36] "magnif[y] the effect of small economic shifts.[37] It follows that market outcomes can be decided by random events. These events can be rationalized *ad hoc*, but the multiplicity of small economic events make prediction illusory.

Arthur approach of increasing returns as random (stochastic) processes where there are multiple possible outcomes led several editors to contest his work scientific grounding.[38] It took Arthur six years to publish his increasing returns paper.[39] As he recalls, "I sent the (...) working paper to the American Economic Review, where I thought it had a good chance. Increasing returns, after all, was an important problem in economics. They came back to me. 'We're sorry. We can't find any technical faults in your reasoning, but this is not economics.' I sent it to the Quarterly Journal of Economics. Same thing. 'This looks to be rigorously done and proper, but we don't recognize this as economic theory.' I sent it to the Economic Journal in England. Same thing. I sent it back to the American Economic Review because the editor had

[35] Arthur was motivated to focus on increasing returns after reading the Nobel laureate Ilya Prigogine's work on non-equilibrium thermodynamics, re Arthur, private conversation, April 2023. Arthur also mentions the 1940s literature on economic development and cumulative causation, which explains how countries or regions that are already ahead tend to continue to progress faster than other countries or regions. Previously, Arthur got inspired by "The Eighth Day of Creation: Makers of the Revolution in Biology" by Horace Freeland Judson, "The Making of the Atomic Bomb" by Richard Rhodes".

[36] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018).

[37] Arthur, "Competing Technologies, Increasing Returns, and Lock-in by Historical Events," *The Economic Journal* 99, no. 394 (1989): 116; Arthur, "Positive Feedbacks in the Economy," *Scientific American* 262, no. 2 (1990): 92–99.

[38] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018) ("I that if I could learn enough nonlinear probability theory (stochastic process theory), I could analyse increasing returns.")

[39] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018).

changed. Same outcome."[40] The paper was eventually published in the United Kingdom.

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 explained by Arthur, "[i]ncreasing returns generate not equilibrium but instability: If a product or a company or a technology—one of many competing in a market—gets ahead by chance or clever strategy, increasing returns can magnify this advantage, and the product or company or technology can go on to lock in the market."[41] The lock-in is then typically intensified by path dependency, i.e., the 'autocatalytic' or self-reinforcing outcomes or structures under increasing returns.[42] "[H]istorical 'small events' are not averaged away and 'forgotten' by the dynamics – they may decide the outcome."[43] Arthur calls that phenomenon 'non-ergodicity.'

Arthur's findings cannot be easily used to feed ideological preferences. As a New Yorker journalist recalls, the publication of the article "drew a strong, and largely hostile, response. One Harvard economist, Richard Zeckhauser, stood up afterwards and said, 'If you are right, capitalism can't work.' A few months later, when Arthur read the same paper to a gathering in Moscow, an equally eminent Russian economist declaimed, 'Your argument cannot be true!'."[44] Should the argument be true, the lack of predictability makes the top-down control of the economy illusory while capitalism cannot take care of itself.[45] Applied in practice, Arthur's theory

[40] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018).
[41] Arthur, "Increasing returns and the new world of business", *Harvard Bussiness Review* (1996) 74(4): 100-109, at 100.
[42] Arthur, Ermoliev, and Kaniovski, "Path-Dependent Processes and the Emergence of Macro-Structure," *European Journal of Operational Research* 30, no. 3 (June 1987): 294–303.
[43] Arthur, "Competing Technologies, Increasing Returns, and Lock-in by Historical Events," *The Economic Journal* 99, no. 394 (1989): 116.
[44] Cassidy, "The Force of an Idea," The New Yorker, January 1998, https://perma.cc/HX7R-56C7, (last visited 2 May 2023). Also, Arthur, private conversation, April 2023 ("the neoclassical economists have tried to put me in a corner"). Arthur seems to have no bad feelings toward neoclassical economists. As he explains, researchers had to go on top of the neoclassical mountain first to observe the complexity mountain, *see* Arthur, *Complexity and the Beginnings of the Santa Fe Institute*, private lecture, Singapore (Mar. 29, 2018).
[45] Arthur, "Increasing returns and the new world of business", *Harvard Bussiness Review* (1996) 74(4): 100-109 ("Positive loops in an economy with increasing returns create (...) the ability to lock in a market, the possible predominance of an inferior product, and fat profits for the winner."

were unsurprisingly used by both defendants and plaintiffs in the U.S. Microsoft antitrust case.[46]

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.[47] It gives legal institutions an important role to play, unlike the Chicagoans and even Schumpeter's work, which does not.

In fact, his work informs what policymakers can do. Under constant and diminishing returns, "the evolution of the market reflects only a-priori endowments, preferences, and transformation possibilities; small events cannot sway the outcome. But while this is comforting, it reduces history to the status of mere carrier – the deliverer of the inevitable."[48] If they intervene to avoid the inevitable, policymakers must first choose "which technologies to bet on,"[49] 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."[50] The best policymakers can do is to provide access to business opportunities for several of the competing technologies, e.g., by reducing legal barriers to entry or development.

Under increasing returns, "[p]olicies that are appropriate to success in high-tech production and international trade would encourage industries to be aggressive in seeking out product and process improvements. They would strengthen the national research base on which high-tech advantages are built. They would encourage firms in a single industry to pool their resources in joint ventures that share upfront costs, marketing networks, technical knowledge and compatibility conventions. And they might even extend to strategic alliances among companies in several countries to enter a complex industry that none could tackle alone."[51] Policymakers need not choose which technologies to bet on, but they must be prepared for unpredictable

[46] Cassidy, "The Force of an Idea," The New Yorker, January 1998, https://perma.cc/HJ27-UYA2, (last visited 2 May 2023) (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).
[47] Cassidy, "The Force of an Idea", *The New Yorker* (1998) in The World of Business 32-37.
[48] Arthur, "Competing Technologies, Increasing Returns, and Lock-in by Historical Events," *The Economic Journal* 99, no. 394 (1989): 116 at 127. In Arthur, "Positive Feedbacks in the Economy," *Scientific American* 262, no. 2 (1990): 92–99, he higlighted that economies that are resource-based are "still for the most part subject to diminishing returns."
[49] Arthur, "Competing Technologies, Increasing Returns, and Lock-in by Historical Events," *The Economic Journal* 99, no. 394 (1989): 116 at 127.
[50] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018).
[51] Arthur, "Positive Feedbacks in the Economy," *Scientific American* 262, no. 2 (1990): 92–99.

outcomes (*see* 1.1 on how to prepare by using complex adaptive regulation).[52] Their interventions will require little interference if they act early, or stronger remedies that unlock positive feedback loops if they intervene late.

Applied to competition law, Arthur's findings trigger a minimum of two observations. First, Arthur's work on market dynamics has pointed implications for all related rules and standards, including antitrust. In the short run, a complexity-minded antitrust regime sees positive feedback loops as generating economic uncertainty (i.e., competition) because they change the business environment and thus force agents to "cognize"[53] – rather than rationally devise – new strategies.[54] In the medium to long term, a complexity-minded antitrust sees that positive feedback loops have the potential to lead to lock-ins and path dependency. Positive feedback loops can then turn into negative feedback loops, i.e., the state of the ecosystem is frozen. The role of antitrust agencies becomes to ensure (or even encourage) the emergence of positive feedback loops in the short and long term.

Second, Arthur's observations support one of the main tenets of legal institutionalism: regulation can help create dynamic markets.[55] But 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 the type and timing of the intervention required (*see* above). The second condition derives from Arthur's views on complexity: policymakers should be concerned with how firms respond to these rules.[56] As he points out, economic agents respond to the context (legal, economic, etc.) in which

[52] Arthur, *Complexity and the Beginnings of the Santa Fe Institute*, private lecture, Singapore (Mar. 29, 2018) ("policies that foster healthy market conditions, nudge towards favored outcomes, and look toward unexpected ramifications").

[53] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014) ("the challenge of management is not to rationally solve problems but to make sense of an undefined situation—to 'cognize' it, or frame it into a situation that can be dealt with—and to position its offerings accordingly").

[54] *See* Petit and Schrepel, "Complexity-Minded Antitrust," *Journal of Evolutionary Economics* (2023).

[55] Deakin, Gindis, Hodgson, Huang, and Pistor, "Legal Institutionalism: Capitalism and The Constitutive Role of Law," *Journal of Comparative Economics* 45, no. 1 (2017): 188-200; Deakin, Gindis, and Hodgson, "What Is a Firm? A Reply to Jean-Philippe Robé," *Journal of Institutional Economics* 17, no. 5 (2021): 869 ("[n]o institutional theory of the firm, and no institutional theory of capitalism more generally, is worthy of the name if it overlooks the role of law).

[56] Lourenço and Turner, "The Role of Regulation in Constituting Markets: A Co-Evolutionary Perspective on The UK Television Production Sector." *Journal of Institutional Economics* 15, no. 4 (2019): 617 (underlining that economic entities interpret and recodify new rules through internal systems of meaning); also, *see* Schrepel, "The Not-So-Pathetic Dot Theory," Network Law Review, (Fall 2022), https://perma.cc/93XU-RYLK (explaining that one cannot regulate as if the regulated entity was "pathetic" (i.e., unable to react) because entities *adapts* to new constraints).

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.

2. 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 (**2.1.**). Describing technology as "what separates us from the Middle Ages,"[57] the force that "creates our wealth, our economy, our very way of being,"[58] Arthur's appreciation for technology naturally tempted him to use it in his own work (**2.2.**).

2.1. The nature of technology

Arthur's work on the nature of technology is foundational. Although Arthur describes his work on the nature of technology and complexity as separate topics,[59] I would argue that they are, at the very least, 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."[60] 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."[61] Technologies play the role of "Lego pieces to build new

[57] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014).
[58] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014).
[59] In Arthur, *Complexity and the Economy* (Oxford University Press, 2015) (he says: "I got caught up with other questions in the 1990s.").
[60] Arthur, "Chapter 32: Out-of-Equilibrium Economics and Agent-Based Modeling," in *Handbook of Computational Economics*, (ed. Leigh Tesfatsion, Kenneth Judd, 2006) 1551–1564 at 1554.
[61] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014); Arthur, *Technology and Combinatorial Evolution*, private lecture, Singapore (Apr. 3, 2018) ("the economy is not a container for its technologies—not quite anyway. The economy is an expression of its technologies."). Today, Arthur argues that technology is taking economies in a distributive era, *see* Arthur, "Where Is Technology Taking the Economy?" (McKinsey Quarterly, October 2017), https://perma.cc/X2NX-UPRY ("I will argue this is causing the economy to enter a new and different era. The economy has arrived at a point where it produces enough in principle for everyone, but where the means of access to these services and products, jobs, is steadily tightening. So this new period we are entering is not so much about production anymore—how much is produced; it is about distribution— how people get a share in what is produced. Everything from trade policies to government projects to commercial regulations will in the future be evaluated by distribution. Politics will change, free-market beliefs will change, social structures will change.")

organizational models."[62] 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 on a different form of evolution. He published his findings a book entitled "The Nature of Technology: What It Is and How It Evolves" (2011) in which he derives some organizing principles for the emergence of new technologies. This book, which he began researching in 1997, builds on earlier lectures[63] and articles such as "The Evolution of Technology Within a Simple Computer Model" (2006) and "The Structure of Invention" (2007).

Seeking to document and analyze *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. (...) What we should really be looking for is not how Darwin's mechanism should work to produce radical novelty in technology, but how 'heredity' might work in technology."[64]

His interest in the emergence of new technologies led him to question the process of invention - as truly innovative technologies result from invention.[65] Arthur first read historians of technology, but desired to know more on the "act of insight" they only mentioned when describing the appearance of new inventions.[66] He went on to study "about 20 technologies" with the goal of knowing "about a dozen extremely well."[67] A pattern emerged: invention is problem solving, and the problem is solved thanks to what he calls "combinatorial evolution." As he summarizes it: "[n]ovel

[62] Arthur, "Where Is Technology Taking the Economy?" (McKinsey Quarterly, October 2017), https://perma.cc/X2NX-UPRY, at 6.

[63] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014) ("It grew out of two sets of lectures I gave: the 1998 Stanislaw Ulam Memorial Lectures at the Santa Fe Institute on 'Digitization and the Economy'; and the Cairnes Lectures in 2000 at the National University of Ireland, Galway, on 'High Technology and the Economy.'")

[64] Although Arthur often describes his approach as different from Darwin's theory, I see them as complementary, *see* Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014) ("Darwin's solution, as I have said, does not work for technology"). But Arthur also mentions complementarities between his theory and Darwin's work, *see* Arthur, Technology and Combinatorial Evolution, private lecture, Singapore (Apr. 3, 2018) ("Darwin's variation and selection are not absent, but they come in once a novel technology is in place").

[65] Arthur, *Technology and Combinatorial Evolution*, private lecture, Singapore (Apr. 3, 2018).

[66] Arthur, "The Structure of Invention," *Research Policy* 36, no. 2 (2007): 274–287.

[67] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014).

technologies must somehow arise by combination of existing technologies."[68] Contrary to Darwinian evolution that proceeds by variation and selection, *radical* innovation proceeds by combination and selection. W. Brian Arthur just developed a comprehensive theory of the emergence of new technology,[69] calling it "a vast system that creates itself out of itself constantly."[70]

Arthur's inductive approach to the nature of technology is inspiring.[71] Instead of starting with a pen (or computer), Arthur started in the field. 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.[72] He did this for 12 years before finally putting his first word on paper.[73] By getting very close to his subject, Arthur learned to appreciate its force. 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."[74]

Applied to legal scholarship, Arthur's work on the nature of technology provides 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

[68] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014).
[69] Pioneer work on the subject includes Thurston, *A History of the Growth of the Steam-Engine* (N.Y.: D. Appleton, 1878); William F Ogburn, *Social Change with Respect to Culture and Original Nature* (DELL, 1922); Kaempffert, *Invention and Society*, Reading with a Purpose Series, 56 (American Library Association, 1930). Arthur remains 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," *see* Arthur, "The Structure of Invention," *Research Policy* 36, no. 2 (2007): 274–287 at 275.
[70] Arthur, *Technology and Combinatorial Evolution*, private lecture, Singapore (Apr. 3, 2018) ("no matter how radical novel technologies are, they're put together from existing technologies or at least from existing technologies that can be put together from existing technologies." He added: "The collective of technology isn't an ancestral tree, it's a huge network of things that gave birth to things over time, a long space of time.")
[71] Palmer et al., "Artificial Economic Life: A Simple Model of a Stockmarket," *Physica D: Nonlinear Phenomena* 75, no. 1–3 (1994): 264–274 (describing his approach adopted in one article as "generally inductive, not deductive; the agents typically generalize patterns observed in the past to guide their behavior in the future. This inductive approach is much closer to normal human behavior than the deductive one of deriving particular choices from general principles").
[72] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014).
[73] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014): ("only around 2000 did I begin to think systematically again about technology and how it gets generated").
[74] Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014).

(positively or negatively) all the others.[75] For example, regulating blockchain immutability affects all Web3 applications.[76] The same is true for encryption.[77] This co-evolving ecosystem view leads to a preference for regulating use cases or individuals (e.g., users, developers, companies) rather than technical features.[78] 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 we take seriously Arthur's reminder of the overall positive impact of technology on our modern world, we need to enact pro-innovation policies and regulations.[79] In balancing different objectives, regulation should first and foremost seek to ensure the survival of each technology and a global environment conducive to the emergence of new technologies. To this end, regulation should not freeze the development of a technology, favor 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,[80] etc. Regular studies can and should be conducted to list and remove such regulations.

[75] Schrepel, "Law + Technology," *The Journal of Law and Technology at Texas*, (2022). Also, Schrepel, "Blockchain: from Ideology to Implementation," in *Blockchain + Antitrust: The Decentralization Formula* (Elgar Law, 2021), 2-17 at 6.

[76] Schickler, "EU Parliament Passes Bill Requiring Smart Contracts to Include Kill Switch," CoinDesk, (2023), https://perma.cc/FT49-8LLV.

[77] Department of Justice, "Agency Information Collection Activities; Proposed eCollection eComments Requested; Request for a New Collection; Lawful Access Data Collection," *Federal Bureau of Investigation Notice*, Washington DC (2023), 88 FR 24836.

[78] Schrepel, "Blockchain and Darwin," in *Blockchain + Antitrust: The Decentralization Formula* (Elgar Law, 2021), 38–50.

[79] As Arthur notes, pro-innovation policies do not come naturally, *see* Arthur, *The Nature of Technology: What It Is and How It Evolves* (Free Press, 2014) (""We are attuned in the deepest parts of our being to nature, to our original surroundings and our original condition as humankind. We have a familiarity with nature, a reliance on it that comes from three million years of at-homeness with it. We trust nature. When we happen upon a technology such as stemcell regenerative therapy, we experience hope. But we also immediately ask how natural this technology is").

[80] Schickler, "Google's $4B Fine May Threaten Web3 Protocols, Legal Expert Says," CoinDesk (2022), https://perma.cc/LE3J-4788.

2.2. Realistic agent-based modeling

In addition to pioneering the use of agent-based modeling in economics ("ABM"),[81] Arthur has developed a unique methodology for complexity economics.[82] This was years in the making. As early as 1988, Arthur discussed with John Holland his desire to simulate a stock market.[83] Holland had published a book entitled "Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence" (1975) in which he deployed the process of adaptation by natural selection across the fields. Holland and Arthur relied on this pioneering approach to move away from rule-based simulations to agent-based simulations.

On the methodological side, W. Brian Arthur has published articles expressing his preference for inductive reasoning. As he puts it, "[i]f you want to crack anything, first comes the idea, then comes the technique."[84] In "On Learning and Adaptation in the Economy" (1992),[85] he emphasized that inductive reasoning allows taking account of "internal models of and hypotheses about the problems they are dealing with; and they constantly monitor, update, and revise these by importing feedback--new data-from their environment." Four years later, in "Inductive Reasoning, Bounded Rationality and the Bar Problem" (1994),[86] Arthur linked his preference for inductive reasoning to ABM. His simulation featured "many rules per agent,"[87] 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

[81] Economists at the Santa Fe Institute used to call ABM "element based modeling," W. Brian Arthur, private conversation, April 2023.

[82] Arthur, Beinhocker, and Stanger, eds., Complexity Economics, (Santa Fe Institute Press, 2019), https://perma.cc/LBV4-G7FQ, 122-123 ("Does this mean the complexity-economics approach will be eclipsed—shut out—by all this enthusiasm for agent-based modeling? I don't think it will. There is a symbiosis between the two.").

[83] Arthur, *Complexity and the Economy* (Oxford University Press, 2015) at Preface [xiii]. DCI Lecture, 2023 ("What we saw, looking more closely at the data, was quite amazing. We had bubbles and crashes, our model showed the emergence of technical trading, we saw periods of high and low volatility, a market psychology emerged, meaning different opinions, trading volume was not zero, it was quite significant. All of these phenomena you might see in real markets in New York, London, or Frankfurt, were emergent phenomena. Our new approach had discovered real phenomena that the standard methods couldn't see.") W. Brian Arthur describes John Holland as "an inspiration," private conversation, April 2023.

[84] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018).

[85] Arthur, "On Learning and Adaptation in the Economy" (1992) Working Paper 854, Economics Department, Queen's University.

[86] Arthur, *Inductive Reasoning, Bounded Rationality and the Bar Problem*, SFI Working Paper (1994).

[87] Arthur, *Complexity and the Beginnings of the Santa Fe Institute*, private lecture, Singapore (Mar. 29, 2018).

put in their place."[88] In other words, the rules that prove accurate are noticed and used by the agents, while the rules that are not accurate "go down the chute."[89]

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" (1998).[90] 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[91] with agents adapting to an "environment created by other agents' hypotheses."[92] He "landed in a world where forecasts, strategies, and actions of agents are being 'tested' for survival within an 'ecology' that these forecasts, strategies and actions together create."[93]

Arthur followed Tom Sargent's suggestion to start with a neoclassical model and make the agents non-identical to increase realism.[94] Him 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 of which represented 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

[88] Arthur, "Inductive Reasoning and Bounded Rationality," *The American Economic Review* 84, no. 2 (1994): 406–411 at 408. Palmer et al., "Artificial Economic Life: A Simple Model of a Stockmarket," *Physica D: Nonlinear Phenomena* 75, no. 1–3 (1994): 264–274 at 264.

[89] Arthur, *Complexity and the Beginnings of the Santa Fe Institute*, private lecture, Singapore (Mar. 29, 2018) ("If you want to model an economics problem realistically, you need to allow that there is a lot of uncertainty: typically agents don't know what other agents are doing or thinking, and they may not have a clear idea of what situation they are in").

[90] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018) ("There was an atmosphere in Berkeley as in the rest of the United States where if you did science, you saw the world as mathematical (…) There was no mention of the human side of such systems.")

[91] Palmer, Arthur, Holland & LeBaron, "An Artificial Stock Market," *Artificial Life and Robotics* 3, no. 1 (March 1999): 27–31, at 27.

[92] Arthur, *Inductive Reasoning, Bounded Rationality and the Bar Problem*, SFI Working Paper (1994), at 4.

[93] Arthur, *Complexity and the Beginnings of the Santa Fe Institute*, private lecture, Singapore (Mar. 29, 2018). As he also puts it: realistic ABM show "how agents' actions, strategies, or expectations might react to—might endogenously change with—the patterns they create," *see* Arthur, "Chapter 32: Out-of-Equilibrium Economics and Agent-Based Modeling," in *Handbook of Computational Economics*, (ed. Leigh Tesfatsion, Kenneth Judd, 2006) 1551–1564 at 1551.

[94] Arthur, *Complexity and the Beginnings of the Santa Fe Institute*, private lecture, Singapore (Mar. 29, 2018).

understand systems that are alive. To quote John Holland, "[i]f it's in equilibrium, it must be dead."[95]

Arthur eventually published the results of his experiment in "Designing Economic Agents That Act like Human Agents" (1991).[96] As he recalls, "we saw little bubbles and crashes, just like in real markets. We saw price correlations in our time series, just like in real markets. We saw technical trading, where investors use past pricing and volume information to direct their buying behavior, just like in real markets. We saw periods of high volatility and periods of nothing much happening, just like in real markets. We started to see all these emergent phenomena in our market."[97] His agents found what worked temporarily. Their adaptive behavior led 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" (2006), he modeled the apparition of new technologies by constructing what he called an "artificial world within the computer."[98] He concluded that "all novel technologies are constructed by combining assemblies and components that already exist; the needs they satisfy are usually clearly signaled economically and technically; and existing technologies form a substrate or library of building blocks for future ones."[99] In "All Systems will be Gamed: Exploitive Behavior in Economic and Social Systems" (2014), he used ABM to simulate the exploitation of social and economic systems.[100] 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'."[101] In the end, Arthur's approach to ABM "is not that different from what

[95] A quote attributed to John Holland, *see* Arthur, Beinhocker, and Stanger, eds., *Complexity Economics*, (Santa Fe Institute Press, 2019), 39.

[96] Arthur, "Designing Economic Agents That Act like Human Agents: A Behavioral Approach to Bounded Rationality," *The American Economic Review* 81, no. 2 (1991): 353–359.

[97] Arthur, *Complexity and the Beginnings of the Santa Fe Institute*, private lecture, Singapore (Mar. 29, 2018).

[98] Arthur and Polak, "The Evolution of Technology within a Simple Computer Model," *Complexity* 11, no. 5 (2006): 23–31 at 24. In a private conversation (April 2023), Arthur described complexity as "what happens when Darwin gets a computer."

[99] Arthur and Polak, "The Evolution of Technology within a Simple Computer Model," *Complexity* 11, no. 5 (2006): 23–31 at 30.

[100] Arthur, "All Systems will be Gamed: Exploitive Behavior in Economic and Social Systems", (2014) *Santa Fe Institute* Working Paper: 2014-06-016.

[101] Arthur, "All Systems will be Gamed: Exploitive Behavior in Economic and Social Systems", (2014) *Santa Fe Institute* Working Paper: 2014-06-016.

really good playwrights have done (…) many very good writers don't have an idea how it's going to come out."[102] Plays and ABMs unfold in unexpected ways.[103]

Applied to legal scholarship, Arthur's approach to ABM suggests a new avenue for research. Realistic ABM à la Arthur can be used to (better) anticipate the effects of new rules, standards, policies, and enforcement actions. First, ABM could allow policymakers, regulators, and enforcers to incorporate the time factor into their decision making, rather than trying to calculate how events will unfold. More specifically, ABMs in which agents learn over time which of their hypotheses work in their (new) environment will help anticipate the evolving response of agents to new regulations and how their response, in turn, will change their environment. 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 response of all kinds of different agents and the dynamics that emerge from this vibrant ecosystem. For example, antitrust authorities could simulate how privacy sensible and quality sensible agents respond (differently) to the implementation of GDPR or the emergence of new competitors.[104] Third, realistic ABM could be used to analyze the importance of the order in which the environment (economic, legal, architectural and normative) changes. For example, if privacy regulations are introduced before pro-competitive regulations and the emergence of new competitors, ABM could show a different (dynamic) state of the ecosystem than if new competitors emerge before these regulations.[105] This anticipation of dynamics would inform policymakers, regulators, and enforcers about when and how to intervene.

[102] Arthur, private conversation, April 2023.

[103] For further work the deployment of ABM in economics, *see* the *Handbook of Computational Economics: Agent-Based Computational Economics* (eds Tesfatsion, L. & Judd, K. L.) (Elsevier, 2006)

[104] In the making, Thibault Schrepel and John Schuler (2023).

[105] In the making, Thibault Schrepel and John Schuler (2023).

3. Approach to science

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 (**3.1.**). His research approach led to academic endeavors such as running the Santa Fe Institute's economics program rather than keeping his university chair (**3.2.**).

3.1. 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.[106] As he advised, "it's a good idea at the start of a research project to ignore everything that's been written and simply think for yourself."[107] For example, his famous El Farol article (1994) occurred to him "a bar in Santa Fe, El Farol. There was Irish music on Thursday nights and if the bar was not too full it was enjoyable, if the bar was crowded it was much less so. It occurred to me that if everyone predicted that many would come on a given night, they would not come, negating that forecast; and if every-one predicted few would come they would come, negating that forecast too."[108] This approach to research allowed Arthur to avoid researching problems that others had preconceived. This led him to big questions like "what is technology,"[109] which technology will succeed,[110] how do economic systems evolve,[111] are economic agents rational,[112] is the information

[106] Arthur recently shared with me that his temperament leans towards artistic expression rather than strictly-defined scientific endeavors, *see* Arthur, private conversation, April 2023 ("Until about 10 or 15 years ago, I realized that my temperament all my life has been more like an artist than a scientist." He adds that he likes "creating little worlds and wondering about them." He further said that "if you want to learn about the world, you should be reading an awful lot of really good fiction").

[107] Arthur, "Where Is Technology Taking the Economy?" (McKinsey Quarterly, October 2017), https://perma.cc/X2NX-UPRY (He adds: "The opposite of this is to read everything and everyone on the topic and to simply write down their ideas").

[108] Arthur, *Complexity and the Economy* (Oxford University Press, 2015) at *Preface* [xvi].

[109] Arthur, private conversation, April 2023: ("Occasionally, I would get problems like, what is technology?").

[110] Arthur, "Competing Technologies and Economic Predictions", (1994), 108 and Arthur and Polak, "The Evolution of Technology within a Simple Computer Model," *Complexity* 11, no. 5 (2006): 23–31 at 24.

[111] Arthur, "Positive Feedbacks in the Economy," *Scientific American* 262, no. 2 (1990): 92–99 and Arthur, "Why Do Things Become More Complex?," Scientific American, (1993), https://perma.cc/9VGG-MCSZ.

[112] Arthur and Polak, "The Evolution of Technology within a Simple Computer Model," *Complexity* 11, no. 5 (2006): 23–31 at 30.

revolution dead,[113] how can we simulate markets with computers,[114] and how do inventions come about.[115]

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.[116] As a result, W. Brian Arthur's work is technically deep, and relevant across the political spectrum.[117] 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.[118] These concepts allow Arthur to get even closer to the reality of the markets and escape what he calls "economics using stick figures."[119] 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."[120] 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 key to

[113] Arthur, "Is the Information Revolution Dead? If history is a guide, it is not," *In Business* (2002) Volume 2, at 65.
[114] Palmer et al., "Artificial Economic Life: A Simple Model of a Stockmarket," *Physica D: Nonlinear Phenomena* 75, no. 1-3 (1994): 264–274 at 264.
[115] Arthur, "The Structure of Invention," *Research Policy* 36, no. 2 (2007): 274–287.
[116] Arthur, "Competing Technologies, Increasing Returns, and Lock-in by Historical Events," *The Economic Journal* 99, no. 394 (1989): 116 at 126. *See* also Arthur, "Positive Feedbacks in the Economy," *Scientific American* 262, no. 2 (1990): 92–99.
[117] Arthur also shows a lack of interest in influencing politic, *see* Arthur, private conversation, April 2023 ("I didn't see it was up to me to go on a crusade"). As a result, Arthur does not force policy recommendations when they do not appear to be clear. In "Positive Feedbacks in the Economy," for example, he highlighted that "policies such as subsidizing and protecting new industries such as bioengineering to capture foreign markets are debatable," *see* Arthur, "Positive Feedbacks in the Economy," *Scientific American* 262, no. 2 (1990): 92–99.
[118] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018) ("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").
[119] Arthur, private conversation, April 2023.
[120] Arthur, "Economics in Nouns and Verbs," *Journal of Economic Behavior & Organization* 205 (2023): 638–647, at 638.

understanding how variables and events lead to new ones; in different words, that algorithms help address ill-defined problems.[121] 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.[122] Arthur suggests using computational thinking to approach the 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."[123] Algorithms enable the understanding of processes. In other words, Arthur links what he observes in economics to a new scientific method.[124] This method does not necessarily require the use of computers, [125] but a new approach that integrates processes and actions.[126] 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 scholarship, 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 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

[121] Arthur, Beinhocker, and Stanger, eds., *Complexity Economics*, (Santa Fe Institute Press, 2019), 124 (explaining that algebra is convenient when one can keep the object still while examining it, but is not well suited in other situations).

[122] Arthur, private conversation, April 2023 (explaining that one can do nearly all computations if the number of equations one could process was unlimited).

[123] Arthur, Beinhocker, and Stanger, eds., *Complexity Economics*, (Santa Fe Institute Press, 2019), 133.

[124] Arthur, DCI Lecture, 2023 ("new tools in economics always bring new theory").

[125] Out-of-Equilibrium Economics and Agent-Based Modeling ("exploring the economy out of equilibrium does not require computation").

[126] Evidently, this approach can also rely on computer, *see* Arthur, DCI Lecture, 2023 ("It is not surprising that this approach arose in the 1980's and early 1990's, because that is when we all got desktop computers.").

sources.[127] In answering these questions, Arthur suggests that a deep technical understanding of the subject is more than a nice feature to have, it is a necessity. When it comes to digital legal scholarship, this means having a (self-made) background in computational thinking. More specifically, when it comes to AI-related legal scholarship, it means having a technical background in machine learning to, at the very least, be able to communicate and collaborate effectively with computer scientists.[128] Indirectly, Arthur's work also suggests exploring legal subjects with computational tools. These tools, as he shows in economics, allow scientists not only to better understand 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.[129]

3.2. Entrepreneurship

Two of Arthur's character traits have persisted throughout his career. First, Arthur is a risk-taker.[130] 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, and I quote, he was "bored."[131] 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 5 economics journals that were not open to theories other than neoclassical, despite having strong credentials in both mathematics and economics.[132]

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[127] As Nicolas Petit puts it, utilizing Arthur's approach in antitrust research helps one avoid living in the disconnected world of "antitrustia" and stay grounded in reality.

[128] The same point could be made for practitioners, which means that law schools should reform their curriculum.

[129] On the subject of computational law, *see* Schrepel, "Law + Technology," *The Journal of Law and Technology at Texas*, (2022). Applied to a specific legal field, *see* the Computational Antitrust project at Codex, the Stanford Center for Legal Informatics, https://perma.cc/3XPJ-UX58.

[130] When Arthur left Stanford, Ken Arrow told him he was taking a big risk. Arthur answers it was a bigger risk to stay, Arthur, private conversation, April 2023. On his instinct ("most of my [professional] movements are based on instinct, much more than spreadsheet calculation").

[131] Arthur, private conversation, April 2023 ("I didn't leave for any reason except boredom, I suppose. Maybe that sounds awful"). Arthur also confessed: "I got tired of academia… I just felt it was just one battle after another").

[132] Arthur published two articles in the American Economic Review, *see* Arthur, "Inductive Reasoning and Bounded Rationality," *The American Economic Review* 84, no. 2 (1994); Arthur, "Designing Economic Agents That Act like Human Agents: A Behavioral Approach to Bounded Rationality," *The American Economic Review* 81, no. 2 (1991).

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. At the invitation of Ken Arrow, Arthur traveled to New Mexico in 1987 to participate in a meeting Ken had convened with Philip Anderson. As Arthur recalls, "Arrow brought 10 theoretical economists to the meeting and Anderson brought 10 physicists and mathematicians. The physicists and mathematicians included John Farmer and John Holland.[133] The theoretical economists included Tom Sargent, Larry Summers, and other people you'd recognize, including myself."[134] A year later, Arthur became the head of the Santa Fe Institute's economic program. 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."[135] Arthur hired 25 people that first year. He then developed a unique research program. 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."[136] The rest is history. If you are interested in how the Santa Fe Institute came to be, I suggest you read "Complexity Economics: Proceedings of the Santa Fe Institute's 2019 Fall Symposium."[137] Today, the Santa Fe Institute's economics program is one of the most prestigious in the world.

Applied to legal scholarship, 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 drawback, in Arthur's words, is that this approach "ignores other things like how much money is

[133] Arthur regularly cites John Holland's influence on his work. He writes: "it took me a few days to realize I was dealing with one of the smartest people I had ever met." Also: "I sat there thinking, 'If John Holland is the answer, what is the question?'," *see* Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018).
[134] DCI Lecture, 2023.
[135] DCI Lecture, 2023 ("I called Kenneth Arrow at Stanford. This was before emails. 'Ken', I said, 'We are not quite sure what to do or how daring we can be here. What do you think?' Arrow called Anderson at Princeton, and Phil Anderson called John Reed, who was chairman of Citibank at the time, and was putting up the money. The word came back from Reed via Andersen via Arrow to me, 'Do anything you like, providing it is at the foundations of economics, and is not conventional.'").
[136] Arthur, *Berkeley, Increasing Returns, and Silicon Valley*, private lecture, Singapore (Mar. 28, 2018).
[137] Arthur, Beinhocker, and Stanger, eds., *Complexity Economics*, (Santa Fe Institute Press, 2019).

in [your] bank."[138] 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.

4. Conclusive thoughts

Arthur's work on complexity science and economics, his substantive and methodological insights on technology, and his creative thinking can be an inspiration to other economists, lawyers, engineers, and social scientists. His work serves as a powerful inspiration, a driving force of sorts. As I await new publications of his, I want to close with a final quote to ponder about: "Complexity is (...) a marvel."[139]

[138] Arthur, private conversation, April 2023.

[139] Arthur, "Positive Feedbacks in the Economy," *Scientific American* 262, no. 2 (1990): 92–99 and Arthur, "Why Do Things Become More Complex?," Scientific American, (1993), https://perma.cc/9VGG-MCSZ.