STANFORD
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ARTICLE

Antitrust Policy and Blockchain Technology: An Exploration from the Complex Systems Perspective

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Abstract. In the past decade, blockchain technology has become ubiquitous in our society to distribute, encrypt, and secure digital transactions in a highly decentralized network. This technology has been used in several applications such as digital currencies, health care, energy markets, and a range of other governance issues. To contribute to the greater theoretical discussion, this paper explores the potential of using complexity science to design a good antitrust policy for blockchain. Particularly, this work provides an intellectual framework (i.e., complex adaptive systems perspective and path dependence) and methodological tools (i.e., agent-based modeling) to explore the dynamics of the antitrust regulatory environment.

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I. Introduction

We know that the world is a complex system comprised of many interconnected and interdependent systems. Global markets and the means of regulating these markets are also complex systems. The churning of variables in complex systems and the intractable mathematics of their dynamic relationships result in an essential uncertainty in the socio-economic-technological realms. Such complex systems can produce novelty that becomes dominant, the novelty that dies, and unintended consequences that elude the prognostications of the wisest among us.

While complex systems are capable of great surprises, their numerous and heterogeneous interconnections can also harden network relationships and limit change. Complex systems can be resilient and adapt yet still create quite path-dependent circumstances in which change is thwarted, even when it is desirable. Changing established complex systems is generally a herculean task or contingent upon crises. Imagine deconstructing the fossil-fuel economy or the U.S healthcare system while attempting to anticipate the scope of potential results. How might emergent technologies such as blockchain become dominant and push out and prevent other technologies from being adopted?

Prior studies have leveraged agent-based simulations to examine a decentralized network of industry agents, mining agents, and government agents. Bookstaber has argued for "the end of theory" in the neoclassical economics realm.[1] The failure of such a theory to anticipate crises or deal with the computational irreducibility of the human realm reduces the relevance of such theory in our world. Instead, Bookstaber argues for a focus on modeling tools such as agent-based modeling to investigate economic reality. Such modeling does not rely on the need for theoretical frameworks or top-down forcing mechanisms such as the assumptions of markets. Agent-based modeling allows simulated worlds to unfold within the probabilistic set of outcomes that describe our fuzzy world. In such a simulated world, we are left with heuristics as our guide. There are no hard and fast rules that might constitute a basis for traditional theory building when examining complex systems. As Gleick noted decades ago, with regard to complex systems, "the act of playing the game has a way of changing the rules."[2] Using blockchain technology to implement smart contracts will help manage supply responsibly and sustainably.

The digital revolution, made possible by vast increases in computational capabilities, has transformed the economy and society.[3] Social media giants such as Facebook, Google (recognizing that Google is basically a search engine but with enormous implications for the dissemination of information in the social media space), Twitter, and others have a pervasive influence on our lives and have come to dominate leading growth sectors of the economy. Moreover, as early players in this digital space, massive market advantages may be conferred, handicapping potential rivals.

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[1] RICHARD BOOKSTABER, THE END OF THEORY (2017).
[2] JAMES GLEICK, CHAOS: MAKING A NEW SCIENCE 24 (2008).
[3] Oliver Budzinski & Victoriia Noskova, *Prospects and Limits of Merger Simulations as a Computational Antitrust Tool*, STANF. COMPUTATIONAL ANTITRUST 57 (2022).

This article uses the lens of the complexity sciences to explore the potential for blockchain technology to re-shape antitrust policy. At first blush, it may be difficult to appreciate how a platform that serves as the platform for the crypto-currency bitcoin to operate could have this alleged impact. At one level, blockchain is a technology that enables distributed, encrypted, and secure logging of digital transactions in an add-only ledger record. It is increasingly viewed as a technology that can be incorporated into any number of applications, ranging from health care and record maintenance to secure digital currencies.

This article is organized into three sections. First, the relevant concepts from the complexity sciences are detailed while introducing regulatory environments as complex adaptive systems. Next, the implications for blockchain and antitrust policy are explored from this perspective. Finally, we propose a generalized approach for developing an agent-based model for examining the evolution of blockchain.

II. Complex Adaptive Systems

We explore issues related to contemporary antitrust policy by utilizing the lenses of complex adaptive systems and related perspectives. Those perspectives include the concept of path dependence and the theoretical-methodological framework of agent-based modeling (ABM). Advancing technologies such as blockchain create the potential for the deployment of technologies derived from blockchain, such as Bitcoin. Understanding how the confluence of these theories and technologies provides insights into crucial public policy questions may provide new understanding into what has to be considered otherwise highly complex and opaque processes.

Understanding the nature of complex adaptive systems (CAS) is relevant for developing better models of a vast array of phenomena in behavioral, life, and social sciences. CAS are typically characterized by multiple entities (actors or agents) that interact in dynamic ways, with their behavior adapting and evolving over time. Such systems are prone to non-linear types of processes that make them extremely difficult to model using traditional linear statistical techniques and methodologies. For example, Forrester discussed the dynamical nature of social systems such as the urban environment;[4] Epstein and Axtell noted the need for a new kind of generative social science that recognized the complex interactions of complex systems,[5] and Epstein examined the nonlinear nature of therapeutic strategies.[6] Farmer and Foley discussed the importance of appreciating the nonlinear dynamic nature of economic processes and the difficulty in developing successful interventions.[7]

Complex systems also exhibit "emergence" by which relatively simple rules governing the actions of individual agents can produce complex and often

[4] JAY FORRESTER, URBAN DYNAMICS (1969).
[5] JOSHUA EPSTEIN & ROBERT AXTELL, GROWING ARTIFICIAL SOCIETIES: SOCIAL SCIENCES FROM THE BOTTOM UP (1996).
[6] JOSHUA EPSTEIN, NONLINEAR DYNAMICS, MATHEMATICAL BIOLOGY AND SOCIAL SCIENCE: WISE USE OF ALTERNATIVE THERAPIES (1997).
[7] J. Farmer & D. Foley, *The Economy Needs Agent-Based Modeling* 460 NATURE 685-686 (2009).

unexpected effects. This interaction based on the simple rules can lead to novel or unexpected outcomes. So, while the rules themselves are simple, the effects of those rules, by way of the interactions of the individual agents, leads to emergent behavior in the system. It is often said such systems exhibit self-organizing kinds of behavior. Examples of CAS in the literature include the dynamics of the biosphere,[8] various group-based behaviors including competition and cooperation,[9] cultures,[10] global economic dynamics,[11] international politics,[12] segregation dynamics,[13] and numerous other areas.[14] A complex systems perspective is well-suited to examine the intersection between blockchain technology and antitrust law.

Since 2018, there has been a growing number of scholarly articles that leverage a complex adaptive system perspective to examine blockchain technology. Blockchain technology has applications beyond conventional cryptocurrencies, particularly in regulating complex markets. This technology has the potential to address other key issues, such as (1) regulating sand extraction and trade,[15] (2) enabling a peer-to-peer energy market,[16] and (3) reducing drug counterfeiting.[17]

Blockchain illustrates how a mastery of computational complexity can provide potential solutions to our understanding and regulation of complex markets. Previous research has indicated that models of decision making using the game of "Go",[18] have been used to model bounded rationality and decision making in complex environments.[19] The emergence of innovation and novelty within complex environments may offer solutions to problems previously thought to be potentially intractable.[20]

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[8] Franziska Hinkelmann, David Murrugarra, Abdul Salam Jarrah & Reinhard Laubenbacher, *A mathematical Framework for Agent-Based Models of Complex Biological Networks*, 73 BULL. MATH. BIOL. 1583 (2011).
[9] Robert Axelrod, *The Emergence of Cooperation Among Egoists,* 75 AM. POLIT. SCI REV. 306 (1981); ROBERT AXELROD, THE COMPLEXITY OF COOPERATION: AGENT-BASED MODELS OF COMPETITION AND COOPERATION (1997).
[10] Federico Cecconi, Marco Campenni, Giulia Andrighetto & Rosaria Conte, *What do agent-based and equation-based modeling tell us about social conventions: the clash between ABM and EBM in a congestion game framework.* 13(1) J. ARTIF. SOC. SIMUL. 6-8 (2010).
[11] Herbert Dawid & Michael Neugart, *Agent-based Models for Economic Policy Design*, 37 EAST. ECON. J. 44 (2011).
[12] LARS-ERIK CEDERMAN, EMERGENT ACTORS IN WORLD POLITICS: HOW STATES AND NATIONS DEVELOP AND DISSOLVE (1997).
[13] Thomas Schelling, *Dynamic Models of Segregation,* 1 J. MATH. SOCIOL. 143 (1971).
[14] *See* Eric Bonabeau, *Agent-based Modeling: Methods and techniques for Simulating Human Systems*, 99 PROC. NATL. ACAD. SCI. 7280 (2002).
[15] Farinaz Sabz Ali Pour, Unal Tatar & Adrian Gheorghe, *Agent-based model of sand supply governance employing blockchain technology*, PROC. ANN. SIM. SYMP. 1 (2018, April).
[16] Jacob G. Monroe, Paula Hansen, Matthew Sorell & Emily Zechman Berglund, *Agent-based model of a blockchain enabled peer-to-peer energy market: Application for a neighborhood trial in Perth, Australia*, 3 SMART CITIES 1072 (2020).
[17] Monalisa Sahoo, Sunil Samanta Singhar & Sony Snigdha Sahoo, *A blockchain based model to eliminate drug counterfeiting*, MACH. LEARN. INF. PROCESS. 213 (2020).
[18] Cassey Lee, *The Game of Go: Bounded Rationality and Artificial Intelligence*, *in* COMPLEX SYSTEMS IN THE SOCIAL AND BEHAVIORAL SCIENCES: THEORY, METHOD AND APPLICATION 157 (Euel Elliott & Douglas Kiel eds., 2021).
[19] K. Vela Velupillai & Ying-Fang Kao, *Computable and Computational Complexity: Theoretic Bases for Herbert Simon's Cognitive Behavioral Economics*, 29 COGN. SYST. RES. 40 (2014).
[20] Sheri M. Markose, *Novelty in Complex Adaptive Systems (CAS): A Computational Theory of Actor Innovation*, 344 PHYSICS A: STATISTICAL MECHANICS AND ITS APPLICATIONS 41 (2004); Sheri M. Markose, *Complex Type 4 Structure Changing Dynamics of Digital Agents: Nash Equilibria of a Game with Arms Race in Innovations*, 4 J. OF DYNAMICS AND GAMES 255 (2017); Sheri M. Markose, *Novelty Production and Evolvability in Digital Genomic Agents: Logical Foundations and policy Design Implications of Complex Adaptive Systems*, COMPLEX SYSTEMS IN THE SOCIAL AND BEHAVIORAL SCIENCES: THEORY, METHOD AND APPLICATION, 111, 156 (E. Elliott & L.D. Kiel eds., 2021).

III. Agent-based Modeling

Given the complex and non-linear dynamics that may be present in complex systems, new theoretical and methodological tools are required. One approach that has generated substantial interest and provided new insights into a variety of complex phenomena is ABM. ABM is one of several tools, including cellular automata,[21] genetic algorithms,[22] and neural networks,[23] that seek to examine complex phenomena that may not always be amenable to traditional methodological approaches. Many of these methodologies require a degree of computing power that has only become available in the last few decades.

The ability to run agent-based simulations of various complex phenomena has opened up new avenues of research and has been employed in the study of conflict and cooperation,[24] the emergence of actors in the international system,[25] patterns of residential segregation building upon Schelling's path-breaking work.[26] Hinkelmann et al. have employed agent-based models in order to explain complex biological networks.[27] One of the most famous examples of ABM being deployed to explore important historical events can be found in research by Axtell et al.[28] involving explanations for the demise of the Anasazi Indian culture of the U.S. Southwest and recent contributions involving complex epidemiological modeling.[29] Borill and Tesfatsion[30] cogently argue that agent-based models represent a new and productive mathematical framework for exploring a range of complex phenomena, and Vellupillai[31] argues that the mathematical formalism of economics must give way to new methodologies grounded in algorithmic behavior, a view thoroughly consistent with the belief that agent-based models offer a fruitful alternative to the mainstream economic approach of the last several decades.[32]

In the blockchain context, Pour, Tatar, and Gheorghe leveraged an agent-based model to examine the regulation of sand supply.[33] While sand supply seems niche, it's an essential industrial material for the construction of concrete, glass products, and electronic components. In areas where economies are rapidly expanding, there is high demand for sand, which is creating a serious environmental impact in countries like China and India. This has dramatically affected rivers and has led to lower water tables. Given a highly decentralized and complex supply chain, this is a challenging regulatory issue to address for many countries. As Pour, Tatar, and

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[21] STEPHEN WOLFRAM, A NEW SCIENCE (2012); KENDALL PRESTON & MICHAEL DUFF, MODERN CELLULAR AUTOMATA: THEORY AND APPLICATIONS (2013).
[22] ZBIGNIEW MICHALEWICZ, GENETIC ALGORITHMS + DATA STRUCTURES = EVOLUTION PROGRAMS (1996).
[23] NICOLAOS KARAYIANNIS & ANASTASIOS VENETSANOPAULOS, ARTIFICIAL NEURAL NETWORKS: LEARNING ALGORITHMS, PERFORMANCE EVALUATION, AND APPLICATIONS (1993).
[24] *See* Axelrod, *supra* note 9; ROBERT AXELROD, THE EMERGENCE OF COOPERATION (1984).
[25] See Cederman, *supra* note 12; Bonabeau, *supra* note 14.
[26] See Schelling, *supra* note 13; Erez Hatna & Itzhak Berenson, *The Schelling Model of Ethnic Residential Dynamics: Beyond the Segregated-Integrated Dichotomy of Patterns*, 15 J. OR ARTIFICIAL SOC. AND SOC. SIMULATION 6 (2012).
[27] See Hinkelmann et al., *supra* note 8.
[28] Robert Axtell, *The Complexity of Exchange*, 115 THE ECON. J. 193 (2005).
[29] JOSHUA EPSTEIN, AGENT_ZERO: TOWARD NEUROCOGNITIVE FOUNDATIONS FOR GENERATIVE SOCIAL SCIENCE (2013).
[30] Paul L. Borill & LeighTesfatsion, *Agent-based Modeling: The Right Mathematics for the Social Sciences, in* THE ELGAR COMPANION TO RECENT ECONOMIC METHODOLOGY 228-258 (John B. Davis & D. Wade Hands eds., 2011).
[31] K. VELA VELUPILLAI, FOUNDATIONS OF COMPUTABLE ECONOMICS (2010).
[32] *Id.*, at 358-370.
[33] Pour et al., *supra* note 15.

Gheorghe argue, "Blockchain technology enables the development of a new sand governance system with participatory decision-making and decentralized relevant organizations that can operate over a network of computers without any human intervention."[34] Using blockchain technology to implement smart contracts will help manage supply responsibly and sustainably. To demonstrate the feasibility of this, the authors leveraged agent-based simulations to examine a decentralized network of industry agents, mining agents, and government agents.

ABM basically begins with "agents" interacting in a defined space. The agents are essentially lines of computer code that provide basic instructions on how to "behave" when interacting with other agents or with different aspects of their environment. Agents typically are provided with simple rules governing their behavior. What is notable about ABM is that, consistent with the concepts of emergence and self-organization, relatively simple rules may produce complex and often unanticipated behaviors. Importantly, it is assumed agents are subject to the constraints of bounded rationality. Agent-based models provide a means of evaluating various hypotheses using simple rule-based systems. These models are designed to evolve in a generative "bottom-up" process that may be impossible for the traditional, formal "top-down" models of complex phenomena. The agents thus emulate boundedly rational economic agents responding to complex and uncertain market conditions.

Another potential use of agent-based modeling is to use it in conjunction with blockchain to share electronic health records. A data knowledge integration framework for the implementation of sharing Electronic Health Records (EHR) via autonomous agents and blockchain has been proposed by Yao, Kshirsagar, Vaidya, Ducrée, and Ryan.[35] Blockchain-based EHR Systems already exist, but there are questions as to how to address major concerns such as trust, security, and scalability in the healthcare system. They argue that these issues:

> "[C]an be addressed by transitioning from existing models to convergence of the three technologies – blockchain, agent-based modeling, and knowledge graph in a decentralized ecosystem. Each autonomous agent is responsible for instantiating key processes, such as user authentication and authorization, smart contracts, and knowledge graph generation through data integration among the participating stakeholders in the network."[36]

These processes include integrating knowledge from different databases, establishing consensus-oriented communication and regulation, and generating semantic knowledge graphs at the data security layer. "A knowledge graph, also known as a semantic network, represents a network of real-world entities—i.e. objects, events, situations, or concepts—and illustrates the relationship between them."[37]

[34] *See* Pour et al., *supra* note 15, at 3.
[35] Yao Yao et al. *Convergence of Blockchain, Autonomous Agents, and Knowledge Graph to Share Electronic Health Records*, 4 FRONTIERS IN BLOCKCHAIN 13 (2021).
[36] *Id.*, at 1.
[37] IBM Cloud Education, *Knowledge Grap*h (Apr. 12, 2021), https://www.ibm.com/cloud/learn/knowledge-graph.

IV. Path Dependence

The final major conceptual link to our analysis is path dependence. The concept has taken on increased importance in recent years in the fields of economics, public policy, and other scholarly areas and is used to explain different policy outcomes. Much of this literature seeks to explain why moving from one evolutionary path to another may be difficult once a commitment has been made to a particular course of action.[38] Moreover, over time the commitment to that course of action becomes more difficult to change. It is easier, for example, for a college student to change one's major in their first year of college rather than waiting until their second or third year. It would have been easier to reform the U.S. Social Security retirement system by making modest changes in the early years of its existence instead of waiting until the system approached a financial crisis. In short, path dependence reinforces the notion that "history matters".

At its most basic, path dependence is a concept that recognizes that the options available to some agent at a particular point in time are limited by the choices made at some earlier point. As Djelic and Quack have noted, a "soft" version of path dependence refers to the notion that events occurring at an earlier point in time will influence events at a later point in time.[39] One would say that "history matters." The "hard" or stronger version states that sequences of contingent events establish deterministic institutional patterns. In other words, particular sequences of events produce specific outcomes. Page has noted that there are basically four related but distinct causes of path dependence.[40] Increasing returns is the notion that the more an action is taken, the greater the benefits. Self-reinforcement is characterized by a dynamic whereby actions or choices are incentivized to be repeated. Positive feedback provides alternatives when others make that same choice, and historical "lock-in" means that a particular choice has become entrenched.

As a practical matter, any given phenomenon may exhibit multiple causes, although theoretically, distinguishing them may be useful. There is substantial literature seeking to apply path dependent processes to a range of phenomena. Pierson applies path dependence to an examination of the evolution of major American entitlement programs.[41] Hathaway has explored the evolution of language and laws from a path dependence perspective,[42] and North argued that path dependence is crucial for understanding the evolution of rational political and economic institutions.[43]

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[38] Scott E. Page, *Path Dependence*, 1 Q .J. POL. SCI. 87 (2006).
[39] Marie-Laure Djelic and Sigrid Quack, *Overcoming Path Dependence.: Path Generation in Open Systems*, 36 THEORY AND SOCIETY 161 (2007).
[40] Scott E. Page, *supra* note 38.
[41] PAUL PIERSON, DISMANTLING THE WELFARE STATE? REAGAN, THATCHER AND THE POLITICS OF RETRENCHMENT (1994); but see also a broader discussion of path dependence in Paul Pierson, *Increasing Returns, Path Dependence, and the Study of Politics*, 94 AM. POL. SCI. REV. 251 (2000); and PAUL PIERSON, POLITICS IN TIME: HISTORY, INSTITUTIONS AND SOCIAL ANALYSIS (2004).
[42] Oona Hathaway, *Path Dependence in the Law: The Course and Patterns of Legal Change in a Common Law System*, 86 IOWA L. REV. 601 (2001).
[43] DOUGLAS C. NORTH, INSTITUTIONS, INSTITUTIONAL CHANGE, AND ECONOMIC PERFORMANCE (1990).

An essential element of the literature addresses path dependence and the question of market efficiency. Just to provide a few examples, Veblen as cited in David discusses Great Britain's undersized railway carriages and the penalties associated with "taking the lead."[44] Cowan contends that the evolution of nuclear power technology was profoundly influenced by the development of the Nautilus light water technology, even though heavy water reactors ran at greater efficiency and with greater capacity.[45] Arthur has theorized that path dependence was an important factor in the adoption of the gasoline engine over steam technologies, and more generally, Arthur has contended that path dependence allows products to gain market dominance even though they may be inferior to alternatives.[46] For example, it has been argued that VHS cassette technology was inferior to Betamax, although the former gained market dominance due to early adoption and network effects. Importantly, Arthur stresses that path dependent processes are non-ergodic, promoting multiple equilibria with increasing returns and many possible future trajectories.[47] Ergodic processes promote diminishing returns and demonstrate non-path dependent processes.

Of course, many readers will be intimately familiar with the QWERTY versus Dvorak debate. David has contended that the adoption of the QWERTY keyboard can be explained in large part by path dependence. The QWERTY got a slight initial advantage in terms of adoption of its technology and was able to prevail over time due to network effects even though Dvorak may have been a superior technology. As more adopted the technology others were compelled to adopt as well.[48] This is a highly controversial argument and has resulted in a fierce debate over whether path dependence is a culprit that led to inferior products and technologies gaining market dominance. Liebowitz and Margolis have argued persuasively that QWERTY was indeed the superior technology and did not gain critical market advantages due to path dependence (while recognizing that network effects may promote a particular technology).[49] Kay's research reinforces Liebowitz and Margolis.[50] His simulation analysis suggests that no matter how many times the tape of history is re-run, QWERTY always wins.

[44] Paul A. David, *Clio and the Economics of QWERTY*, 75 AM. ECON. REV 332 (1985).
[45] Robin Cowan, *Nuclear Power Reactors: A Study in Technological Lock-in*, 50 J. ECON. HIST. 541 (1990).
[46] W. Brian Arthur, *Competing Technologies, Increasing Returns and Lock-in by Historical Events*, 99 ECON. J. 116 (1989); W. BRIAN ARTHUR, INCREASING RETURNS AND PATH DEPENDENCE IN THE ECONOMY [hereinafter INCREASING RETURNS AND PATH DEPENDENCE IN THE ECONOMY] (1994).
[47] ARTHUR, INCREASING RETURNS AND PATH DEPENDENCE IN THE ECONOMY, *supra* note 46, at 13-32.
[48] *See* David, *supra* note 44.
[49] S. J. Liebowitz & Stephen E. Margolis, *The Fable of the Keys*, 33 J. L. & ECON. 1 (1990); S. J. Liebowitz & Stephen E. Margolis, *Path Dependence, Lock-In, and History*, 11 J. L., ECON. & ORG. 205 (1995).
[50] Neil M. Kay, *Re-Run the Tape of History and QWERTY Always Wins*, 42 RSCH POL'Y 1175 (2013).

V. Antitrust and Blockchain

Liebowitz and Margolis also take on the famous Microsoft antitrust case.[51] It is well-known that the federal government's case against Microsoft was based upon the bundling of the Microsoft browser with the basic Microsoft package. Given the pervasive network effects associated with the technological ecosystem in which Microsoft and potential competitors operated, any initial advantage by Microsoft in deploying its product was sure to produce insurmountable advantages representing profound anticompetitive practices. Liebowitz and Margolis reject this argument, relying essentially on arguments similar to the QWERTY case. In other words, Microsoft had a superior product, and any network effects that might be evident would not be sufficient to reach a determination that Microsoft engaged in anticompetitive practices.

At the end of the day, the federal courts rejected the government's arguments against Microsoft. The question of whether and how modern technologies enable or inhibit healthy competition that increases the probability that superior technologies carry the day while simultaneously promoting competition can be usefully examined using a paradigm based upon an understanding of the complex systems-path dependence interface. We do so by using the tools of agent-based modeling that exploit important features of complex systems, including their ability to explore the role of path dependence as a crucial aspect of these systems.

While complex adaptive systems may engender transformational change via the production of bifurcations resulting in instabilities, most complex systems are quite resilient to changes that impact their existing structures. The belief that blockchain may undermine existing antitrust law[52] suggests it represents a phenomenon that alters the very nature of long-held elements of the law.

As noted above, this paper seeks to bring the concepts of CAS, agent-based models and path dependence together in order to better explore the legal and economic realities of antitrust policy. This research builds upon prior models that examine competition law in the era of digital economies[53] and corporate competition from the standpoint of self-organizing networks,[54] and that recognizes the potential importance of agent-based modeling in helping us gain a better understanding of antitrust regulation.[55] Importantly, Kaligotla and Macal propose a generalized agent-based model for modeling a blockchain system.[56]

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[51] Liebowitz and Margolis, *supra* note 49.
[52] Thibault Schrepel, *Is Blockchain the Death of Antitrust Law? The Blockchain Antitrust Paradox,* 3 GEO. L. TECH. REV. 281 (2019).
[53] Ioannis Lianos, *Competition Law for a Complex Economy*, 50 IIC-INT'L REV. INTELL. PROP. & COMPETITION L. 643 (2019).
[54] Dan Braha, Blake Stacey, & Yaneer Bar-Yam, *Corporate Competition: A Self-Organized Network*, 33 SOC. NETWORKS 219 (2011); Réka Albert & Albert-László Barabási, *Statistical Mechanics of Complex Networks*, 74 REVS. MOD. PHYSICS 47 (2002); Albert-László Barabási & Réka Albert, *Emergence of Scaling in Random Networks*, 286 SCI. 509 (1999).
[55] Sebastian Benthall & Katherine J. Strandburg, *Agent-Based Modeling as a Legal Theory Tool*, 9 FRONTIERS PHYSICS 337 (2021).
[56] Chaitanya Kaligotla & Charles M. Macal, *A Generalized Agent-Based Framework for Modeling a Blockchain System*, PROCEEDINGS 2018 WINTER SIMULATION CONF. (2018).

Our specific contribution is to expand upon Kaligotla and Macal's research involving blockchain technology. In doing so, we are informed by Schrepel's work on the impact of blockchain technology on the competition.[57] What are the implications of blockchain technology? At one level, blockchain is "merely" a technology that "enables distributed, encrypted and secure logging of digital transactions in an add-only ledger record".[58] They note that such systems are considered secure by design using cryptographic hashing and exemplify a distributed approach that is insensitive to component failure making it relatively risk-free. It is viewed as an increasingly ubiquitous aspect of modern life and of the internet and is beginning to be seen as a solution to problems ranging from alternative currency systems (Bitcoin is based upon blockchain technology), distributed public ledgers such as Ethereum, and offering solutions for modern healthcare and governance issues.[59]

In a March 2021 article, Lehmann contends that "one of the prime advantages of distributed ledger technology (DLT), more commonly known as 'the blockchain', is the potential to overcome problems that result from the division of the world into different legal systems."[60] This has made capital market integration challenging. The rapid growth in blockchain has caused governments around the world to take an interest in regulating their application.

One of the most active areas for legislation is cryptocurrencies. In one radical move, President Nayib Bukele of El Salvador made bitcoin the official national currency.[61] With a very unreliable launch, the move has been highly unpopular among citizens in the country. In 2021, the New York Times reported that China has banned cryptocurrency mining.[62] Within the U.S., the house has passed a bill to create a working group to study possible frameworks and legislations for cryptocurrencies.[63] Because of this, there is an increase in lobbying within this space. In March 2022, President Biden issued an executive order calling for a study of digital currencies and stated six objectives: (1) consumer protection; (2) financial stability; (3) preventing illicit finance; (4) increasing economic competitiveness; (5) financial inclusion; and (6) responsible innovation.[64]

So how does blockchain represent a threat to competition, and is the threat greater than the economic and social, and even cultural advantages of blockchain? Schrepel goes so far as to suggest the potential for blockchain to upend

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[57] Schrepel, *supra* note 52; THIBAULT SCHREPEL, BLOCKCHAIN + ANTITRUST: THE DECENTRALIZATION FORMULA (2021).
[58] Kaligotla and Macal, *supra* note 56, at 1001.
[59] *Id.*
[60] Matthias Lehmann, *National Blockchain Laws as a Threat to Capital Markets Integration*, 26 UNIFORM L. REV. 148 (2021).
[61] David Gerard, *Bitcoin Failed in El Salvador. The President Says the Answer Is More Bitcoin*, (Dec. 6, 2021), https://foreignpolicy.com/2021/12/06/bitcoin-city-el-salvador-nayib-bukele/
[62] Amy Qin and Ephrat Livni, *China Cracks Down Harder on Cryptocurrency With New Ban* (September 24, 2021), https://www.nytimes.com/2021/09/24/business/china-cryptocurrency-bitcoin.html
[63] Eric Lipton, *As Scrutiny of Cryptocurrency Grows, the Industry Turns to K Street* (May 9, 2021), https://www.nytimes.com/2021/05/09/us/politics/cryptocurrency-regulation-sec-ripple-labs.html
[64] David Lopez-Kurtz & Vincent Mora, President Biden Issues Executive Order on Cryptocurrencies, Taking Steps Toward Regulation (March 21, 2022), https://www.natlawreview.com/article/president-biden-issues-executive-order-cryptocurrencies-taking-steps-toward.

competition law completely.[65] As there is a lot of uncertainty in the blockchain technology space, it is important to begin to leverage agent-based models as a means to better understand these complex systems.

Unilateral practices on blockchain	**Exclusionary Abuses**							**Exploitative Abuses**	**Discriminatory Abuses**
	Refusal to deal	**Tying / bundling**	**Predatory innovation**	**Predatory pricing**	**Margin squeeze**	**Exclusive dealing**	**Rebates / discounts**		
Public blockchain	**Very Unlikely** Public blockchains are accessible to the public by definition	**Very unlikely** Access to public blockchains cannot be cannot be conditionally restricted unless it was implemented from start	**Unlikely** A majority of all users must agree to modifying the blockchain functioning	**Very unlikely** Changes in governance required to manipulate use pricing which is public information	**Unlikely** Platform layer as no financial utility	**Unlikely** Using a blockchain is expensive to use and exclusivity would have to be integrated from the start	**Unlikely** Granting rebates / will be visible by all, making it less attractive	**Unlikely** Access is free, switching costs are low and blockchain do not enjoy real power on the market	**Unlikely** Because it is public, price discrimination will deter use of the blockchain
Private blockchain	**Very likely** Private blockchains exist in order to refuse access	**Very likely** Access could be predicated on multiple conditions	**Very likely** Functioning can be easily modified	**Likely** Predatory pricing is likely since access price can be manipulated	**Likely** Allowance of multiple income-generating applications on the software layer in addition to platform layer being a financial target	**Very likely** Foreclosing competitors: increase the overall blockchain price for users + attractiveness	**Very likely** Incentive rebates for some users to join and use the blockchain	**Likely** Power of private blockchain may be increased via high switching costs and token effects	**Very likely** Incentives to join the blockchain or stay active on it likely to cause discrimination

Figure 1: Schrepel's Typology

There are ways that agent-based models have been used to test for exclusionary abuses. One very successful market example was conducted by researchers with the Argonne National Lab regarding electricity markets. In their market investigations, industry experts in each sector of the market were consulted and engaged in a participatory simulation approach. By running through several iterations of the electricity purchasing cycle, from generation to transmission, to distribution, to consumption, the molders were able to identify agent behaviors in various market conditions. These behaviors were then programmed into the agents within the computer simulation. They discovered that there were behaviors of the agents representing the generation companies that could have a dramatic impact on the spot price of electricity. While electricity is a commodity that is purchased from the lowest bidder, the generators can withhold capacity. If there is not enough electricity provided at the pre-negotiated rate, then the spot rate applies.

The less electricity the generators offer to make up the difference between supply and demand, the higher the prices go. Those generators that held back supply to sell into the ancillary or spot market stand to make significant profits as the bids for electricity accelerate upward (which is a high-risk market play). While this possible strategy was considered and noted during the participatory simulations, it was considered an outlier strategy due to the levels of risk assumed by the generators. However, when programmed into the computer-based simulation, it became the dominant strategy after multiple iterations of the market cycle.[66] With this model in mind, it is possible to design Agent-based Models to test how monopolization practices could be implemented.

To investigate, each of the exclusionary abuses outlined in Schrepel's typology could be simulated (see figure 1).[67] Or, we can begin by looking at the typology in

[65] Schrepel, BLOCKCHAIN + ANTITRUST: THE DECENTRALIZATION FORMULA, *supra* note 57.
[66] MICHAEL J. NORTH AND CHARLES M. MACAL, MANAGING BUSINESS COMPLEXITY: DISCOVERING STRATEGIC SOLUTIONS WITH AGENT-BASED MODELING AND SIMULATION (2007).
[67] Schrepel, *supra* note 52.

aggregate; the relationship between public and private blockchains in the cryptocurrency market. The difference that stands out is transparency. But what if the transparent public blockchain could be manipulated by a much less transparent digital currency referred to as "stablecoins", which are supposed to be pegged to assets such as the Euro or U.S. dollar?[68] If those private blockchain digital currencies are able to manipulate the price of the public blockchain currencies, then the transparency attributes can be subverted. These are the issues that John M. Griffin and Amin Shams found in their research into the digital currency markets.[69]

Using these behaviors, we can design a series of model modules that capture each of the components of Schrepel's typology. These modules can be validated individually and then assembled into a single model to more closely approximate the behaviors of the overall market given various policy options. At this point, it is also helpful to ensure that even perceived irrational behaviors are captured to enable them to be introduced into simulations since what is irrational behavior for an expert may seem perfectly reasonable for a novice. Once these experts are carefully debriefed on their actions for each discrete event, that data is used to program the agents in the computer-based simulation. The Dogecoin Model tests the extreme ends of market behavior, where meme-based agents are willing to collude. With this design shell in mind, the following issues from Schrepel's typology could be addressed:[70]

- Testing the six theories of liability (The Dominant Position)
- Testing the "Abuse of Dominance"
    - Does blockchain further enable anticompetitive practices that are already recognized?
    - Does blockchain give rise to new anticompetitive practices that are related to the technology?
- Testing "Code as Law" concepts
    - Agent responses to imposing fair regulatory mechanisms to blockchain communities through the implementation of code.
    - Developer and user responses to incentives (such as safe harbor) to comply with regulators requests.

[68] Christine Idzelis, *Bitcoin Prices Are Likely Manipulated, Research Affiliates Warns* (January 13, 2021), https://www.institutionalinvestor.com/article/b1q3fpwznhvbox/Bitcoin-Prices-Are-Likely-Manipulated-Research-Affiliates-Warns
[69] John M. Griffin and Amin Shams, *Is Bitcoin Really Un-tethered?*, 75 THE J. OF FIN. 1913 (2020).
[70] Blockchain communities agreeing to introduce such mechanisms would be treated by regulators and courts as being more in line with the law than blockchains refusing to do so. Stricter measures challenging one of the five principles could be imposed on the latter, which could be a powerful tool at the disposal of public authorities. Five Principles :

1. Pseudonymity
2. Distributed architecture
3. Peer-to-peer transmission between users
4. Free to choose the consensus mechanism used
5. Data immutability

VI. Model Construction

Using modeling software such as NetLogo allows investigators to both graphically and quantitatively examine the ecosystem of digital currencies. The following description is from *the NetLogo 6.2.2 User Manual: Programming Guide.*[71]

> “In NetLogo, there are four types of agents: turtles, patches, links, and the observer. Turtles are agents that move around the world. The world is two-dimensional and is divided up into a grid of patches. Each patch is a square piece of “ground” over which turtles can move. Links are agents that connect two turtles.”

The starting point in design is to construct a mental model of the ecosystem under consideration. A model that is currently in the NetLogo library involves the predator-prey relationship. In the zoological instance of the model, predators eat prey, which in turn eat grass to survive. The predators and prey are the agents referred to in NetLogo as “turtles”. The grass is represented as patches. The prey animals move about on the patches gaining sustenance and reproducing. The number of prey animals that can occupy the system is determined by the rate of regrowth of the grass. The number of predators the system can support is dependent upon the number of prey animals available. If the reproductive rates of either predator or prey get out of balance, the numbers can rise dramatically to an unsustainable level and then crash. The same holds for the rate of regrowth of the grass. Figure (1) demonstrates the graphic interface of this model as it runs in NetLogo.[72]

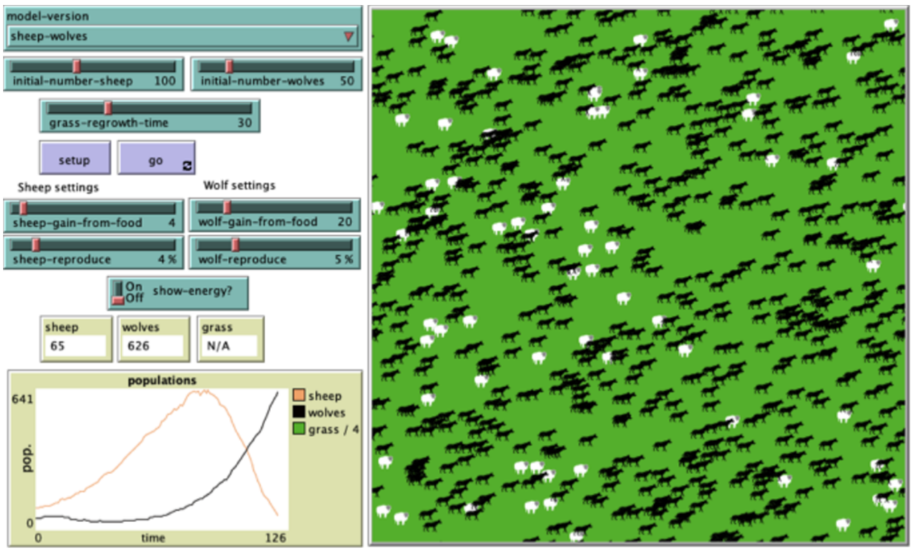

Figure 2: Visualization of NetLogo

[71] Uri Wilensky, *NetLogo* (1999), http://ccl.northwestern.edu/netlogo/
[72] *Id.*

This demonstrates in a straightforward and easily visualized manner what happens in nature when the natural order of elements in the system is upset. The graphic interface of the simulation allows observers to watch the changes take place as the program runs. But what if the predators could change the rate the grass regrows to their advantage? More grass supports more prey, which supports more (or fatter) predators. Would the manipulation of the grass regrowth become a dominant strategy for the predators? What if the control of the grass regrowth of the predators is unstable and could allow the system to crash? Would the predators be able to regulate themselves in a manner congruent with long-term self-interest?

By changing this scenario slightly, we can set up a simple model of interaction present in the alleged market manipulation found in the Griffin and Shams research.[73] The turtles in this model would be the digital currency traders, but some would have greater market holdings than others. Some of these turtles would have links that connect them in such a way as to provide them with the ability to manipulate the price of the primary digital commodity, either bitcoin or Ethereum, through the use of a stablecoins, such as tender or tornado. This would be done by manipulating and then using the stablecoins to bid up the price of the primary digital commodity. The price of the primary digital commodity would be represented by the patches in the simulation. This would allow the linked turtles to manipulate a public blockchain currency like bitcoin by manipulating the private blockchain currency such as tender. This anticompetitive behavior can be simulated, and the stability of this behavior in the market can be set at different levels to investigate the need for various policy solutions, such as regulating stablecoins as securities or by a market-based introduction of a central bank digital currency (CBDC).

From this basic building block, additional modules of behaviors can be introduced to account for speculative behaviors such as runs into or out of the market. Also, the implications of regulating bitcoin and Ethereum 'mixers' that are currently used to anonymize transactions and digital currency ownership can be explored.[74] Finally, meme-based trading behaviors could be added to account for dogecoin and some of the other less stable assets in the digital currency ecosystem. Each of these small models can be individually validated and then be assembled into a larger model that can demonstrate possible outcomes in real-world markets. This larger model would not be used for prediction but as a tool to explore outcomes that are not apparent when considering each system component individually.

VII. The Limitations of ABM

The limitations of ABM revolve around the fidelity of the simulation and the perceived usefulness of its support in decision making. There is always the issue of models not containing all the elements of the system under study. By definition

[73] Griffin and Shams, *supra* note 69.
[74] Sam Reynolds, *Crypto.com's Stolen Ether Being Mixed Through Tornado Cash* (January 18, 2022), https://www.coindesk.com/business/2022/01/18/cryptocoms-stolen-ether-being-laundered-via-tornado-cash/

models are abstractions of reality which cannot represent all the nuances of the system. The goal of modeling is to select the proper elements of the system and program their interaction in such a way that the model is able to provide a reasonable approximation of the system – albeit a rather simplified one.

Suppose the wrong variables are used, or the rules for the interactions of the variables within the simulation are incorrect. In that case, the model is nothing more than an elaborate video game. This is why verification and validation of the model are critical to its usefulness and adaptation by policymakers. Verification is the process of ensuring the programming of the simulation is running in the way the developers intended. Are the algorithms stable and free of errors?[75]

The next and most critical step is the verification of the model. Is the model addressing the proper issue? Do the outcomes of the model match reality? It is important to have domain-specific experts review the outputs of the model during the verification stage to ensure that it is producing results that are reflected in the real world. Think of an aircraft simulator. The engineers want to ensure the simulated flight behaviors a pilot finds in the simulator match those of the actual aircraft when the same control inputs are used. Once this verification takes place, the more extreme aspects of the flight envelope can be explored in the simulator and then attempted in the aircraft by a test pilot. All of these activities are important to ensure that the decision-makers using the simulator (the pilots) are getting valid training to aid their decision-making processes. This same concept holds true for policymakers and ABMs that are helping inform policy decisions.

The purpose of this type of model design is not to emulate what we think will happen; it is to investigate what may happen. We wish to investigate the possible Black Swan events that could occur in this complex adaptive ecosystem. These Black Swan events are found through running multiple scenarios that vary individual variables. This leads to a better understanding of possible causalities. The fundamental assumption here is that the market behaviors could approximate a fat-tailed distribution, where meme behaviors are more common than expected. Suppose that outcome fails to come to fruition, all the better for the comfort level of stakeholders within the market ecosystem. This will be the first step toward proving the null hypotheses.

VIII. Conclusion

The lens of complexity sciences offers an intellectual framework and methodological tools, such as agent-based modeling, to explore the dynamics of the antitrust regulatory environment. Viewing emerging regulatory challenges such as blockchain from the perspective of the complexity sciences also offers a means to examine the dynamics of such emerging challenges to traditional regulatory regimes. What we know from the study of complex systems is that hard rules do not apply. In the world of economic dynamics, where neoclassical theory is increasingly questioned as an analytic device, we are left with a world where heuristics are our most adaptive means for contending with these dynamics. The

[75] MICHAEL J. NORTH AND CHARLES M. MACAL, MANAGING BUSINESS COMPLEXITY: DISCOVERING STRATEGIC SOLUTIONS WITH AGENT-BASED MODELING AND SIMULATION (2007).

adaptive mechanisms of both change and stability can be reflected in the modeling regimes now available to analysts. But the only certainty we can count on is the unfolding of reality itself.

New technologies will inevitably push the boundaries of regulatory regimes.[76] We will see if emerging technologies such as blockchain resulting in genuine bifurcations and truly novel regulatory regimes or if the larger goal of transparency in economic transactions is simply folded into existing dominant regimes. We have presented an outline for exploring the dynamics of blockchain within market environments using agent-based modeling. We must learn to accept that our desire for certainty must always be tempered with the fundamental realities of uncertainty in our world. If there is wisdom in the notion of free markets, with the usual caveats concerning their limits, then we must begin to understand that the limits of our knowledge are bounded by the parameters of our models. It is the degrees of freedom in our models that may be seen as the space for new and emergent behavior. We must also be constantly aware that emergent novelty often eventuates in new path-dependent formulations that then create their own often determinative and stultifying dynamics.

[76] Cary Coglianese & Alicia Lai, *Antitrust by Algorithm*, 2 STANF. COMPUTATIONAL ANTITRUST 1 (2022).