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WIRTSCHAFTS UNIVERSITÄT WIEN VIENNA UNIVERSITY OF ECONOMICS AND BUSINESS

Foundations of Cryptoeconomic Systems

Working Paper Series
1 / 2020

WU VIENNA
INTERDISCIPLINARY RESEARCH INSTITUTE FOR CRYPTOECONOMICS

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Blockchain networks and similar cryptoeconomic networks are systems, specifically complex systems. They are adaptive networks with multi-scale spatio-temporal dynamics. Individual actions may be incentivized towards a collective goal with "purpose-driven" tokens. Blockchain networks, for example, are equipped cryptoeconomic mechanisms that allow the decentralized network to simultaneously maintain a universal state layer, support peer-to-peer settlement, and incentivize collective action. These networks represent an institutional infrastructure upon which socioeconomic collaboration is facilitated – in the absence of intermediaries or traditional organizations. They provide a mission-critical and safety-critical regulatory infrastructure for autonomous agents in untrusted economic networks. Their tokens provide a rich, real-time data set reflecting all economic activities in their systems. Advances in network science and data science can thus be leveraged to design and analyze these economic systems in a manner consistent with the best practices of modern systems engineering. Research that reflects all aspects of these socioeconomic networks needs (i) a complex systems approach, (ii) interdisciplinary research, and (iii) a combination of economic and engineering methods, here referred to as "economic systems engineering," for the regulation and control of these socioeconomic systems. This manuscript provides a conceptual framework synthesizing the research space and proceeds to outline specific research questions and methodologies for future research in this field, applying an inductive approach based on interdisciplinary literature review and relative contextualization of the works cited.

1. INTRODUCTION

Cryptoeconomics is an emerging field of economic coordination games in cryptographically secured peer-to-peer networks. The term cryptoeconomics was casually coined in the Ethereum developer community, and is generally attributed to Vitalik Buterin. The earliest recorded citation is from a talk by Vlad Zamfir [Zamfir 2015], which was later loosely formalized in blog posts and talks by Buterin [Buterin 2017a], [Buterin 2017b]. The term has gained traction in the broader developer community [Tomaino 2017a] and in the academic community [Catalini and Gans 2016], but it still remains under-defined, possibly because it is often used in so many different contexts. Using the same term in different contexts leads to communication breakdowns and challenges when trying to come up with a rigorous definition of that term.

Zamfir and Buterin are both protocol researchers at the Ethereum foundation. Buterin's work focuses on programmatic resource allocation strategies, e.g. [Buterin, Hitzig and Weyl 2019], whereas Zamfir has crossed into political economics with a focus on governance and law [Zamfir 2017], [Zamfir 2019]. The microeconomic study of cryptoeconomic networks, as pursued by Buterin and many others, is the most commonly used perspective, as it lies neatly within the overlap of mechanism design in economics and computer science; see [Nisan et al. 2007]. One weakness of such a computer science perspective is the tendency to view the technology as neutral and to downplay the creators' responsibility for outcomes [Walch 2019]. This is in stark opposition to the systems engineering literature which places a large responsibility on engineers responsible for design and maintenance of critical infrastructure [Leveson 2016]. A more comprehensive view of cryptoeconomic networks is that they have enabled new types of institutional infrastructure to emerge and will likely continue to foster slow but lasting changes to our social and economic systems which will require legal innovations [De Filippi 2018], [Werbach 2018]. In light of these changes, there is a renewed urgency in the study of economics at the institutional scale [Berg, Davidson and Potts 2019]. However, while many researchers and developers seem to agree that cryptoeconomic networks greatly expand the economic design space, comparatively few acknowledge that the economic models used to date are performative and their design is subjective, [Virtanen et al. 2018].

This paper explores why the term "cryptoeconomics" is context dependent and builds up to providing complementary micro, meso, and macro definitions (Section 9). These context dependent definitions are the synthesis of examinations of cryptoeconomic systems in terms of complexity (Section 2), interdisciplinarity (Section 3), institutional (Section 4), coordination (Section 5), emergence (Section 6), network structure (Section 7), and tokenization (Section 8). The final section (10) focuses on potential research directions and serves as an outlook rather than a conclusion. It identifies potential future research areas that build on the assumptions and definitions provided in this paper.

2. A COMPLEX SYSTEMS PERSPECTIVE

Systems theory [Von Bertalanffy 1969] [Meadows 2008] provides a means to describe any system by its structure, purpose, functioning, as well as spatial and temporal boundaries, including its interdependencies with its environments [Moffatt and Kohler 2008][Parrott and Lange 2013]. Complex systems theory investigates the relationships between system parts with the system's collective behaviors and the system's environment [Nagel 2012].

Complex systems differ from other systems in that the system level behaviour cannot be inferred from the local state changes induced by individual network actors [Parrott and Lange 2013]. Modeling approaches that ignore such difficulties will produce models that are not useful for modeling and steering those system.

Properties such as emergence, nonlinearity, adaptation, spontaneous order, and feedback loops are typical to complex systems [Bar-Yam 2002]. Complex systems research draws contributions from various scientific domains such as mathematics, biology, physics, psychology, meteorology, sociology, economics, and engineering [Parrott and Lange 2013], which all contribute to complexity science, leveraging both analysis and synthesis; analytic

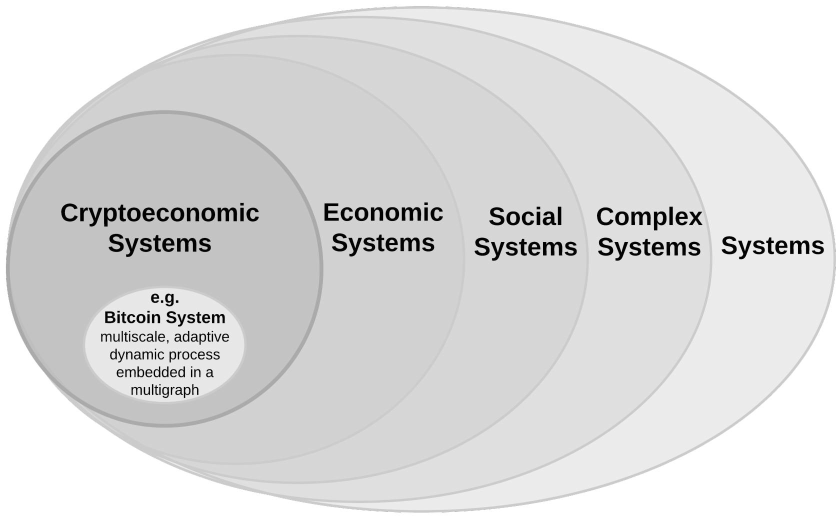

Fig. 1 Cryptoeconomic systems are complex socioeconomic systems.

processes reduce systems to better understand their parts, whereas synthesis is required to understand the whole as greater than the sum of its parts [Quine 1951].

Systems theory can contribute tools for the analysis of how the relationships and dependencies between a cryptoeconomic systems' parts can determine system-wide properties. It allows for the discovery of system's dynamics, constraints, conditions, and principles of cryptoeconomic networks with the aim to understand, model ,and steer them.

A cryptoeconomic system such as the Bitcoin network can be described as a special class of complex socioeconomic system that is dynamic, adaptive, and multi-scale. Cryptoeconomic networks are dynamic due to the flow of information and assets through the network. Cryptoeconomic networks are adaptive because their behaviour adjusts in response to their environment, either directly in the case of the Bitcoin difficulty controller or more broadly through decisions on the part of node operators. Cryptoeconomic networks are multi-scale because they are specified by local protocols but are defined by their macro-scale properties, as is the case with the local "no double spend" rule guaranteeing a globally conserved token supply [Zargham, Zhang and Preciado 2018]. Their design requires a strong interdisciplinary approach to develop resilient protocols that account for the spatial and temporal dynamics of those networks [Liaskos, Wang and Alimohammadi 2019].

3. AN INTERDISCIPLINARY PERSPECTIVE

Interdisciplinary research has been identified as an appropriate research method when (i) the research subject involves complex systems and when (ii) the research question is not confined to a single discipline [Repko 2008]. The necessity of an interdisciplinary approach to the research of complex systems has been addressed by General Systems Theory [Von Bertalanffy 1969], in particular Cybernetics [Wiener 1965], [Barkley Rosser 2010]. Economists like Friedrich Hayek for example were influenced by the interdisciplinary field of Cybernetics, which leveraged systems theory methods available in his time [Oliva 2016], [Lange 2014].

The interdisciplinary research process is often heuristic, iterative and reflexive, and borrows methods from specific disciplines, where appropriate. It is deeply rooted in the disciplines, but offers a correction to the disciplinary way of knowledge creation [Dezure 1999], transcending disciplinary knowledge via the process called integration [Repko 2008]. While disciplines are regarded as foundational, they are also regarded as inadequate to address complex problems, sacrificing comprehensiveness and neglecting important research questions that fall outside disciplinary boundaries. Given the fact that blockchain networks and similar crptoeconomic systems provide a governance infrastructure [Voshmgir 2017] for socioeconomic activities, a symbiosis of both disciplinary and interdisciplinary research is needed to achieve the necessary breath and depth related to complex systems [Repko 2008].

The interdisciplinary research process includes: (i) identification of relevant disciplines, (ii) mapping research questions to identify the disciplinary parts, (iii) reducing the number of potentially relevant disciplines, (iv) literature review in relevant disciplines and for relevant research questions, (v) developing adequacy in relevant disciplines, (vi) analyzing problems and evaluating insights, and (vii) integrating insights and creating common ground for insights [Repko 2008].

In the context of cryptoeconomic systems, we have identified the following disciplines as relevant: Industrial and Systems Engineering, AI, Optimization and Control Theory, Computer Science and Cryptography, Economics and Game Theory, Psychology and Decisions Science, Political Science, Institutional Economics and Governance, Philosophy, Law and Ethics, as well as Operations Research and Management Science. The wide range of disciplines may seem arbitrary but they are in fact bound by a central concept: allocation of resources. In particular,

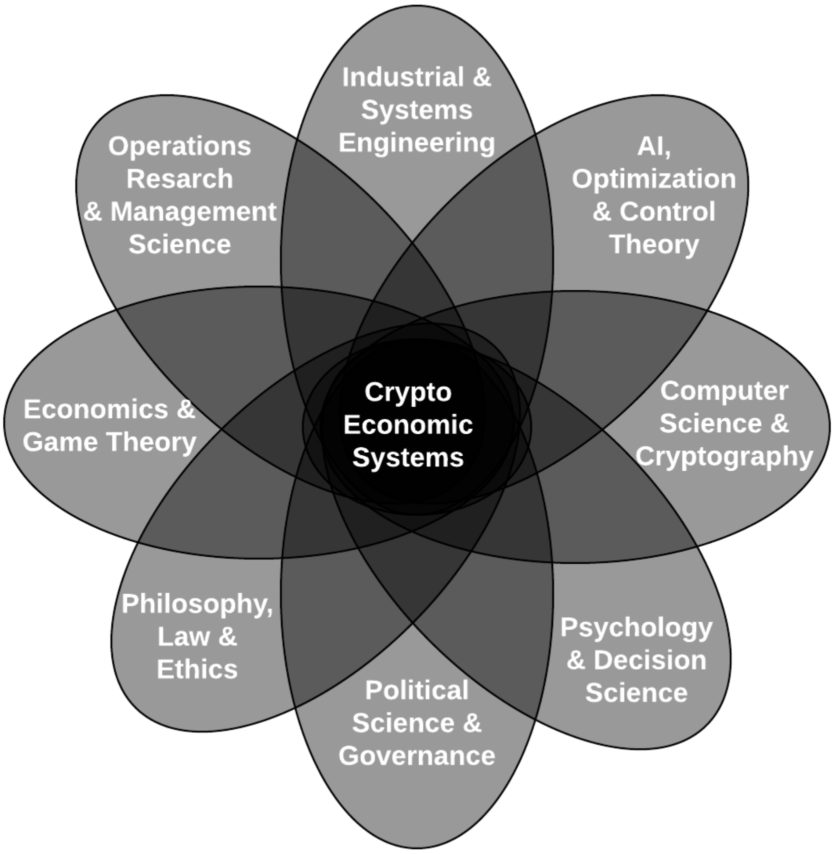

Fig. 2 Venn diagram of disciplines related to cryptoeconomic systems engineering.

cryptoeconomic networks provide coordination and scaling for resource allocation decisions of stakeholders with unique preferences, information, and capabilities. Allocation decisions being made include resources which are: (i) physical, such as hardware and electricity; (ii) financial, such as tokens or fiat money; and (iii) social such as attention, e.g. governance participation, code contributions or evangelism. Envisioning, designing and governing cryptoeconomic systems requires the following questions to be considered:

— Who gets to make which decisions, under which circumstances, and to whom are they accountable for those decisions? Furthermore, how does this change over time?
— How do individuals make decisions given knowledge of the rules of the system, and subject to uncertainty about the decisions of others?
— How can a system be engineered to processes individual decision making into collective decision making such that system may be interpreted as coordinating toward a shared purpose?

Unsurprisingly, disciplinary bias and disciplinary jargon [Repko 2008] are challenges that need to be overcome in the interdisciplinary research process. Addressing this class of challenges adequately in cryptoeconomics research will be crucial to advancing research in this field. The existence of disciplinary jargon will require the development of a common language, or a Rosetta Stone [Gilbert 1998], to facilitate cross disciplinary communication. Auto-ethnographic experience of the authors has furthermore shown that multidisciplinary teams' members require methods to facilitate the transfer of the state of knowledge between researchers of different disciplines. These "knowledge state updates" require time and effort and make the research process slower than in disciplinary research setups.

4. AN INSTITUTIONAL ECONOMICS PERSPECTIVE

The interdisciplinary approach narrowed to the scope of economics brings the institutional perspective to the forefront. Institutional economics is a subset of economics that intersects with political science, sociology, history, management science and cybernetics. It studies the role of formal or informal – and public or private institutions – that are represented by a set of rules, norms, procedure, convention, arrangement, traditions or customs to steer socioeconomic interactions [Chavance and Wells 2008] [Veblen 1973], [Fararo and Skvoretz 1986], [Williamson 2000], [Coase 1937]. Governments, markets, firms, physical infrastructure, and even social patterns such as marriage are institutions.

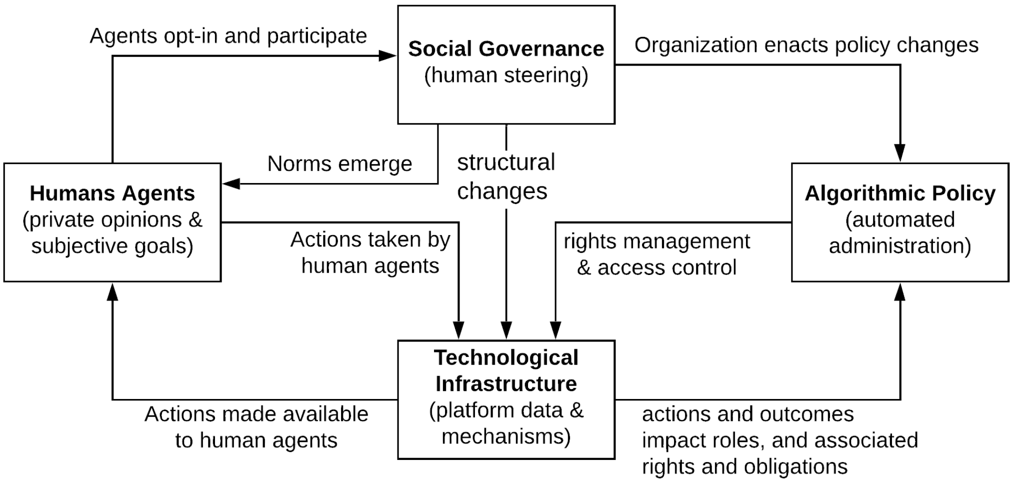

Fig. 3 Cryptoeconomic systems as institutions with social and algorithmic governance feedback loops

The Internet is an institution, and a piece of cultural infrastructure from which many distributed Internet tribes have formed over time [Phillips 2000], first around the infrastructural layer of the Internet [Mueller 2010], and then on the application layer such as e-commerce platforms [Re 1997], [Zhu and Thatcher 2010], [Schmitz et al. 2002], knowledge platforms [Adams and Gordon 1989], or social media platforms. The institutional nature of the internet is underscored by the emergence of recognizable forms in self-organising communities as social activities migrate into digital spaces [Frey and Sumner 2019]. Though platform economies and associated network effects have driven the internet toward more centralized power structures, platform cooperativism demonstrates that digitalization, when wielded by communities, can be a force for democracy [Scholz and Schneider 2017].

Cryptoeconomic networks enable more fluid organizations to formalize over the Internet - around a specific economic, political, or social purpose - commonly referred to as a “Decentralized Autonomous Organizations” or “DAOs” by the crypto-community [Buterin 2014], [Wright and De Filippi 2015]. They reinvent the institutional composition of the Internet, allowing distributed Internet tribes to self-organize and coordinate in a more autonomous way - steered by purpose-driven tokens (read more on purpose-driven tokens in section 10.1). The network protocol and/or the smart contract code formalize the governance rules of the network, regulating and enforcing the behavior of all network participants.

As institutional infrastructure, cryptoeconomic networks resemble nation states much more than they resemble companies. Their protocols are comparable to the constitution and the governing laws of a nation state [Lessig 2009], in a combination of formal (on-chain) and informal (off-chain) rule sets. The network protocols and smart contract represent the computational constitution, while the adaptive social decision processes represent a body of values and rules which govern the collective decision-making process [Zargham et al. 2020], [Voshmgir 2020].

Cryptoeconomic networks provide an infrastructure that can change the composition and dynamics of existing institutions, since the use of such infrastructure can (i) reduce the principal-agent dilemma of organizations providing more transparency, (ii) disintermediate by reducing bureaucracy, and (iii) replace the reactive procedural security of the current legal system, with proactive and automated mechanisms that make a potential breach of contract expensive and therefore infeasible [Davidson, De Filippi and Potts 2016], [Voshmgir 2017], [Allen et al. 2020]. Contract theory and the notion of incomplete contracts are an important institutional aspect in this context and will be discussed in section 10.3 of this paper.

The institutional economist Thorstein Veblem described socioeconomic institutions as complex adaptive systems, stating that they ”are products of the past process, are adapted to past circumstances, and are therefore never in full accord with the requirements of the present” [Veblen 1973] and pointed out the need for a feedback mechanism to maintain an institutional integrity in the light of their complex adaptive nature.

Walter [Hamilton 1919] also pointed out the complex nature of economic systems and ”claimed that institutional economics alone could unify economic science by showing how parts of the economic system related to the whole” [Hodgson 2000] and that ”economic theory must be based on an acceptable theory of human behaviour.”

5. THE EVOLUTION OF COOPERATION PERSPECTIVE

It is up for debate whether the economic theories applied in the conceptualization of these cryptoeconomic networks are - in fact - ”based on an acceptable theory of human behaviour” as expressed by [Hamilton 1919]. Common mathematical and game theoretic arguments about cryptoeconomic networks are based on the canonical results on the evolution of cooperation in an iterative prisoners dilemma [Axelrod and Hamilton 1981], [Rapoport, Chammah and Orwant 1965]. These results demonstrate that coordination is possible (sufficient condition) in the presence of selfish actors, not that it is ‘only possible’ (necessary conditions) in the presence of selfish actors.

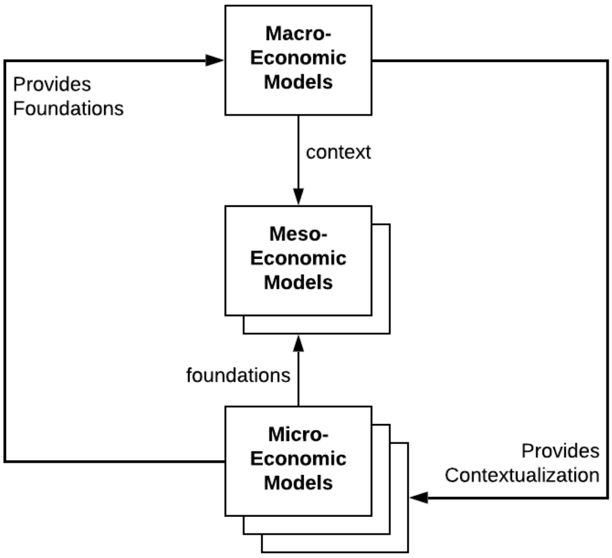

Fig. 4 Micro-Economic foundations and Macro-Economic context together form the basis of a multi-scale model required to capture interscale effects common in complex systems.

This framing is powerful, but the economic framing and behavioral assumptions made are rather limited compared with the existing body of relevant literature. While cryptoeconomics is interdisciplinary by nature, it has so far predominantly been developed in the computer science community. It seems that there is still much room to incorporate methods from various economic disciplines, that are very often interdisciplinary in themselves, like for example political economy (political science) or behavioural economics (cognitive psychology) and business law (legal studies) [Voshmgir 2020]. The idea, for example, that the coordination of a cryptoeconomic system is derived from pure self-interest of individual actors is a conjecture, which while useful as a narrative is unlikely to be factual. For example, the Miner's Dilemma [Eyal 2015] implies that the observed mining pools would break down under pure selfishness.

Therefore, it is entirely possible and actually more likely that cryptoeconomic systems exist as a result of a mixture of strategies, also referred to as norms as in more recent work on the evolution of cooperation [Yamamoto et al. 2017], [Peters and Adamou 2019]. The iterated prisoner's dilemma is an approximation of a complex social phenomena, [Axelrod 1997], and continued study has provided additional insights around concepts such as indirect reciprocity [Nowak 2006] and meta-incentives [Okada et al. 2015], which are directly relevant to the study of cryptoeconomics, in so far as it is viewed as means to engineer incentives that make cooperative norms resistant to invasion by selfish ones in cryptoeconomic networks. In the evolution of cooperation literature theoretical, computational and empirical methods are applied to the study of populations of agents making individual decisions according to certain strategies, with an emphasis on the non-obvious system level properties that arise, and how these properties induce changes in future behavior.

6. A MULTISCALE PERSPECTIVE

Economic systems are often observed to have properties that are not directly attributable to the agents, processes, and policies that make up the economic system. Understanding the emergent properties as arising from relationships between the agents, processes, and policies requires a multiscale perspective. Through a synthesis of these perspectives on multi-scale systems, a basic formula for framing practical economic models is shown in Figure 4. Any model requires assumptions about the properties of its constituent parts and assumptions about the environment or larger system in which the model is embedded. Couched in economic terms the model of the larger system provides macro-economic context and the models of the constituent parts provide micro-economic foundations.

Applying a multiscale perspective to economic systems is not a new idea. It has been addressed implicitly by representatives of the Austrian School of Economics, and also other heterodox economic schools including Complexity Economics [Foster 2005], [Montuori 2005], [Bateson et al. 1989] and Ecological Economics [Common and Stagl 2005], [Schumacher 2011]. While Ecological Economics was originally motivated by ecology rather than systems theory, it also criticized the failings of the orthodox economic canon in addressing the complex dynamics that arise when there are interaction effects between parts and wholes with special attention to human activity as being a part of the natural world. The Lucas Critique [Lucas 1976] is a relatively recently yet widely accepted idea in macroeconomics that explicitly addresses feedback effects between micro and macro scale behavior. The need for multiscale representations is further borne out in Evolutionary Economics [Dopfer, Foster and Potts 2004] and in the standard practice of systems engineering [Hamelin, Walden and Krueger 2010].

Through the multiscale perspective, it is possible to study interscale phenomena such as *emergence* as shown in Figure 5. "Emergence (...) refers to the arising of novel and coherent structures, patterns and properties during

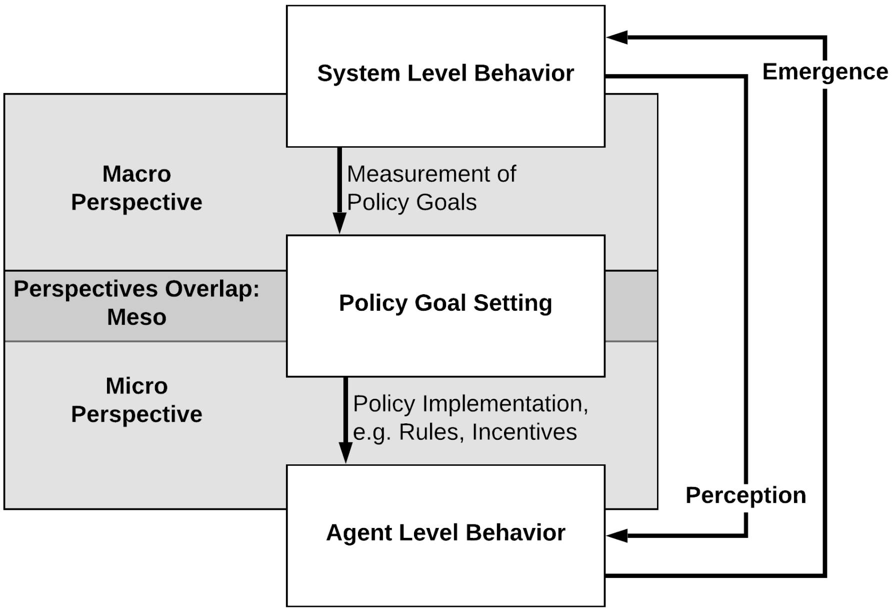

Fig. 5 Multi-Scale Feedback: In cryptoeconomic networks the system level behavior emerges from the agent level behavior responding to rules and incentives implemented as part of cryptoeconomic policy design.

the process of self organization in complex systems. Emergent phenomena are conceptualized as occurring on the macro level in contrast to the micro level components and processes out of which they arise." [Goldstein 1999].

Emergence closes the feedback loop of the macro, meso and micro level activities where policy makers measure phenomena on a macro level, decide over new policies on a meso level, and implement these policies impacting agent behavior a micro level, which in turn result in systemic effects that can only be measured on a macro level. An example of *Multi-scale feedback* in the Bitcoin Network is the interaction between the proof-of-work game being played between the agents (miners), and the Bitcoin Network itself. By introducing a feedback loop to correct the difficulty[1] and maintain the ten minute block time, the system itself becomes part of the game. One way of viewing this macro-scale game is as a two player game between the miners as a population and the network itself. The miners as a collective have their action space defined by the total hashpower provided and the network's action space is to set the difficulty. Even though all of the miners know what strategy the network is playing, the fact that they are still playing a micro-scale game with each other leads to increases in hashpower despite the fact that this is objectively more expensive than providing less hashpower for the same predetermined block rewards.

Another example of multiscale dynamics in cryptoeconomic systems are bonding curves [De La Rouviere 2017], including liquidity pools such as Bancor [Hertzog, Benartzi and Benartzi 2017] and Uniswap [Angeris et al. 2019]. A detailed analysis of bonding curves shows that they encode nontrivial configurations spaces [Zargham, Shorish and Paruch 2019], wherein simple behaviors on the part of individual agents can collectively induce emergent changes to the global state. The interplay between local agent and global system state are explored further in [Zargham, Paruch and Shorish 2020]. This line of mathematical and computational research is consistent with multi-scale systems in robotics, [Kia et al. 2019], [Tsitsiklis 1984]. The Bitcoin network and bonding curve examples show the relevance of multiscale models for cryptoeconomic systems because neither the micro-scale game played between the entities in these systems, nor observations of the macro-scale properties, are sufficient to characterize the system dynamics.

7. A NETWORK SCIENCE PERSPECTIVE

A cryptoeconomic system is a kind of complex system that can be represented by interacting components that collectively form a network. Informally, a network is a group or system of interconnected people or things. A formal mathematical definition of a network is a graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ made up of a set of vertices $\mathcal{V}$ and set of edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$. The edges are simply pairs of vertices and when the order of the vertices matters, the edge (i, j) is said to be directed from i to j. Applying graph theory and networked dynamical systems to study social and economic networks is called network science [Barabási et al. 2016] and therefore relevant in the context of analyzing and modeling cryptoeconomic systems.

As networks grow the number of relationships between entities grows exponentially compared to the number of entities in the network [Dorogovtsev and Mendes 2004]. Furthermore, the topology of the network itself can

[1]To compensate for increasing hardware speed and varying interest in running nodes over time, the proof-of-work difficulty is determined by a moving average targeting an average number of blocks per hour. If they're generated too fast, the difficulty increases.[Nakamoto 2008]

Vertex Type	Definition
Entity	Off-chain unique identity of a person or organization
Account	On-chain address controllable via a private key
Node	Software and hardware participating in a peer-to-peer network

Table I Vertex Types & Definitions in the Bitcoin System

	Entity	Account	Node
Entity	has relationship with	controls keys of	operates
Account		transfers funds to	
Node		sends rewards to	is peer of

Table II Edge types and definitions to be read as directed edges from column to row.

have significant influence on processes playing out within the network [Newman 2010] [Boccaletti et al. 2006]. The interactions between the parts of the system, including agent behaviors, and between the system and its environment often result in unexpected emergent properties, which in practice necessitates some form of human governance for cryptoeconomic networks [Voshmgir 2017].

A cryptoeconomic system like a blockchain network is a multigraph because it has different types of vertices and edges which include labeling maps for the vertices and edges. Depending on the type of network the vertices can be: (i) *nodes* representing computer software in the peer to peer *computation and communication network*, (ii) *accounts* are addresses in the *financial network*, (iii) *entities* are identities of people and organizations in an off-chain *socioeconomic network*. Vertices are depicted in Table I.

A cryptoeconomic network consists of three interconnected networks: (i) the *computation and communication network* comprised of *nodes* that leverage a peer-to-peer protocol to validate transactions by mining new blocks, (ii) the *financial network* comprised of Bitcoin *addresses*, which may sign transactions and transfer funds, and the (iii) the off-chain *socioeconomic network* representing people and organizations that control the tokens in the financial network and operate those nodes in the computation and communication network. A summary of the types of edges is provided in table II. Incidentally, this hierarchical layering of networks is consistent with strategies for optimization decomposition [Chiang et al. 2007], providing a formal basis vertically disintegrated network economies [Aymanns, Dewatripont and Roukny 2019]. In blockchain networks, the base layer data structure comes with cryptographic guaranties, but does not represent a human readable ledger, rather a formal mapping to the statespace representation is required to lift the data from its hash space to the record of accounts, which is recognizable as a ledger [Shorish 2018].

8. TOKENS AS SYSTEM STATE

Tokens represent a part of the state of any cryptoeconomic system and can be seen as their atomic unit [Voshmgir 2020]. The term *state* refers to a unique set of data (the ledger) that is collectively managed by all nodes in the network. Tokens are a representation of an individualized state of an economic system, including a specific right to change the system state. The existence of a universal state makes tokens provable and durable, and is a solution to the double spending [Nakamoto 2008] of digital values over the public networks.

While the existence of tokens in general and digital tokens in particular is not new, cryptoeconomic systems provide a public infrastructure that allow the issuance and management of tokens with lower friction [Voshmgir 2019]. The speed with which cryptoeconomic systems and their tokenized applications are being deployed, is an indicator for the pervasiveness of the technology and its applications [Filippova 2019],[Voshmgir 2019]. Tokens can make all socioeconomic activities publicly verifiable, thus visible to all network actors, and could provide the basis for data driven economic modeling with more feedback loops of tokenized socioeconomic activities. However, it is unclear if and when the tokenization of all economic activities will become feasible.

Asset tokens and *access-right tokens* [Voshmgir 2019] represent business models and governance systems that are mostly well understood, and can be categorized as *simple token systems*. They can be modeled and steered with existing reductionist tools [Lipset 1980][Ruse 2005]. Such simple token systems require mostly *legal engineering*, which we define as the intersections of information systems and legal studies and deals with the question of how to make these tokenized use cases regulatory compliant [Voshmgir 2020].

Purpose-driven tokens are tokens that are programmed to steer automated collective action of autonomous network actors in a public network towards a collective goal in the absence of intermediaries [Voshmgir 2020]. They represent *complex token systems* and require complex system approach [Foster and Metcalfe 2012][Kurtz and Snowden 2003] to be modelled. Purpose-driven tokens that enable complex token systems differ from simple token systems in that they close the loop in so far as the system becomes autonomous and is not being steered by single institutions. Complex token systems requires mostly *economic systems engineering*, which we define on the intersection of information systems and economics including political economy and other related social science domains. Economic systems engineering can build on systems engineering [Sage 1992], [Blanchard and Fabrycky 1990],[Novikov 2016], but deals with research questions that model and steer aggregate agent behaviour, which brings us into the emerging field of complex systems engineering [Bar-Yam 2003] [Rhodes and Hastings 2003] that requires a multi-scale perspective on how to steer these systems.

Table III. Cryptoeconomics*

Level of Analysis	Economic Perspective	Governance Perspective	Design Perspective	Bitcoin Reference
Macro[a]	Global Outcomes	Policy Goals Measurement	Performance Metrics	Stability, Security, etc.
Meso[b]	Institutional Dynamics	Policy Goal Setting	Performance Targets	Informal Governance†
Micro[c]	Protocol Foundations	Implementation of Incentives	Asserted Properties	Nakamoto Consensus

*Cryptoeconomics relates three interactions layers or *levels of analysis* that define characteristics at the micro-foundational, meso-institutional, and macro-observerable domains of scope.

[a]**Macro-observables** are system global properties that inform decision-making at the meso-institutional level and provide stakeholder feedback, performance indicators and measures that can impact micro-foundational properties.

[b]**Meso-institutional** characteristics encompass decision-making and goal determination, based upon and requiring micro-foundations. Mechanism design as used in Economics informs institutions, organisations and teams.

[c]**Micro-foundational** characteristics are assumption specifications with a natural expression within mechanism design as used within Computer Science.

†**Informal Governance** is a form of decentralized governance whereby changes to the protocol are made locally by individual participants operating nodes in the peer-to-peer network and changes only take effect if the majority of participants adopt the change. In the case of Nakamoto Consensus such a majority is measured in hashpower.

9. A UNIFYING PERSPECTIVE ON CRYPTOECONOMICS

Cryptoeconomic systems are complex socioeconomic networks defined by (i) individual autonomous actors, (ii) economic policies embedded in software (the protocol or smart contract code), and (iii) emergent properties arising from the interactions of those actors with the whole network, according to the rules defined by that software. A comprehensive definition of cryptoeconomics therefore includes three levels of analysis: (i) micro-foundational, relating to agent level behaviors (ii) meso-institutional, relating to policy setting and governance and (iii) macro-observerable, relating to the measurement and analysis the system level metrics. Critically, the dynamics at each level of analysis are interdependent in a manner which cannot be simply reduced into a single layer–governance is precisely managing the relationship between the micro and macro scales.

Micro-foundational characteristics of cryptoeconomic systems are commonly expressed in terms of algorithmic game theory in the computer science literature [Nisan et al. 2007] and mechanism design in the economics literature [Hurwicz and Reiter 2006]. Mechanism design is sometimes referred to as reverse game theory as it pertains to the construction of games to produce specific behaviors from agents. Nakamoto Consensus, for example, is a cryptoeconomic mechanism based on proof-of-work that is designed to provide convergence to a dynamic equilibrium–a synchronous shared global state, which furthermore remains resistant to a range of attacks constituting of self-interested misinformation despite being a permissionless network. An attack would be any violation of the state transition rules encoded in the protocol, such as a "double spend'. Nakamoto consensus uses a combination of cryptographic tools with economic incentives that make economic cost of wrongdoing disproportionate to the benefit of doing so [Nakamoto 2008], [Antonopoulos 2014]. Proof-of-stake mechanisms provide similar game theoretic arguments for network security. Interestingly, proof-of-authority networks [De Angelis et al. 2018] offer a more traditional approach where the validator role is permissioned and stems from social and institutional reputational processes which exist outside the computational environment. Most current definitions of cryptoeconomics focus on this level of analysis and modeling [Buterin 2017a], [Buterin 2017b] [Tomaino 2017a]. However, the level of security very much depends on how people react to economic incentives, which in turn has been a field of study in economics [Voshmgir 2020]; the security of the network is an emergent macro level property.

Macro-observables are system-wide metrics or properties which may inform decision-making of stakeholders within the system. Macro-observables often include performance indicators that impact governance decisions at the meso-institutional level as well as measures that can impact perception and thus behavior at the micro-foundational level. In addition to security, market capitalization, price [Shorish 2019], [Cong, Li and Wang 2019] and price stability are the most commonly studied macro-observables. Other important macro-observables include wealth distributions, governance participation, monthly active users, and any other measure or estimate which serves as a proxy for system level goal that matters to a cryptoeconomic network's human stakeholders. Critically, macro-observables are not directly controllable; efforts to impact these metrics are determined at the meso scale and the consequences of those interventions are borne out at the micro scale.

Meso-institutional characteristics encompass decision-making and goal determination, based upon macro-observables and requiring micro-foundations. This level builds on political science, law, governance and economics to design the steering processes of communities, by some referred to as institutional cryptoeconomics [Berg, Davidson and Potts 2019]. Ethical design and informed governance of cryptoeconomic systems resides in the meso-institutional level and requires an understanding of both the micro-foundations and macro-observables, as well as the relations between them. This manuscript, as a whole, addresses the meso-instutional perspective as a keystone in the coherent synthesis of macro and micro perspectives on cryptoeconomics through the observation that automation in socioeconomic systems is tantamount to algorithmic policy making.

10. RESEARCH DIRECTIONS

Cryptoeconomic systems provide an institutional infrastructure that facilitates a wide range of socioeconomic interactions. The design space for this institutional infrastructure includes novel socioeconomic interaction patterns thanks to the peer-to-peer protocols' support for state dependence via tokens. Research regarding the analysis and design of cryptoeconomic systems is necessarily interdisciplinary. Building on other interdisciplinary research future work includes - but is not limited to - the following topics: (i) purpose-driven tokens, (ii) data driven economies, (iii) incomplete contracts, (iv) ethics of decision algorithms as social infrastructure, (v) applying computational social science to cryptoeconomic systems, and (vi) applying cyberphysical systems engineering to cryptoeconomic design and analysis.

10.1. Purpose-Driven Tokens

Bitcoin's *proof-of-work* [Nakamoto 2008] introduced an incentive mechanism to get network actors to collectively manage a distributed ledger in a truthful manner, by rewarding them with network tokens which are minted upon *proof-of* a certain behaviour. The idea of aligning incentives among a tribe of anonymous actors with a network token, introduced a new type of public infrastructure that is autonomous, self-sustaining, and attack resistant [Voshmgir 2020]. Such networks, therefore, represent a collectively produced and collectively consumed economic infrastructure. This common economic infrastructure can be viewed as a commons whose design and governance should be held to Ostrom's principles [Ostrom 1990]. If there is an underlying optimal choice to be uncovered through a social process there is some hope that this optimal could be learned via a consensus process [Jadbabaie et al. 2012]. However, it is more realistic to take a *polycentric* viewpoint where there is no one social optimum and thus it is important to take a wider view of social choice [Arrow 2012] [Ostrom 2000] before embarking on the design of a purpose-driven token. After all, any choice of coordination objective is a subjective choice. Assuming one can define a common objective, the token designer would encode this objective as a cost function and strive for dynamic stability around a minimum cost outcome over time as is done with dynamic potential games [Candogan, Ozdaglar and Parrilo 2013], swarm robotics [Gazi and Passino 2003] and vehicle formations[Olfati-Saber and Murray 2002]. In all cases the design goal is strong emergence around some objective [Klein et al. 2001]. It is also possible to envisage the objective selection process as dynamic consensus [Kia et al. 2019]. Broadly speaking purpose-driven token design lives at the boundary of behavioral economics and dynamic decentralized coordination in multi-agent systems which bridges with institutional economics[Coase 1998], and in particular platform economics [Rochet and Tirole 2003].

10.2. Data-Driven Economic Systems

Cryptoeconomic systems provide near real-time data of on-chain economic activities, and may govern access rights or provide proofs related to data stored off-chain. The advancement in machine learning and system identification methods over the past decade has increased our capacity for creating novel, useful models in across a wide range of applications [Jordan and Mitchell 2015], and in the context of economics [Mullainathan and Spiess 2017] in particular. This, for the first time, allows for almost real time steering of these economies and a level of applied cybernetics that was not possible before. Furthermore, it increases the precision of modeling and measurement required for steering these economies. This results in a data driven regulatory process, as shown in Figure 3.

However, the advances of machine learned models [Jordan and Mitchell 2015] is a consequence of the growth of the digital economy that captures a large amount of economic data. This data is largely controlled by large tech firms operating platform based services, which are often subject to algorithmic bias [Garcia 2016], [Lewis and Westlund 2015],[Sætra 2019], [Von Foerster 2003]. The stateful nature of cryptoeconomic systems has the potential to cede control of data back to the users of these platforms, if *privacy by design* is considered in the modeling of the cryptoeconomic systems and their applications [Voshmgir 2020].

10.3. Incomplete Contracts

A specific question relevant to cryptoeconomic systems is contract theory [Bolton, Dewatripont et al. 2005], in particular how to consider incomplete contracts [Hart and Moore 1988] in a computational environment. Contract theory is the study of contractual arrangements at the intersection of economics and law, and is further divided into representations where contracts are complete (i.e. all possible outcomes are enumerated in the contract) and where they are incomplete (i.e. one or more possible contingencies cannot be expressed in the contract), cf. e.g.[Grossman and Hart 1981],[Grossman and Hart 1983], [Hart and Holmström 1987], [Hart and Moore 1990]. Contract theory further addresses the goals of cryptoeconomic system design through its attention to the efficiency of resource allocation problems [Hurwicz 1960] in cases where information required to solve the associated optimization problems is distributed amongst agents [Hurwicz 1972].

The theory of complete contracts is based on concepts such as mechanism design [Hurwicz and Reiter 2006] and principal agent theory [Holmstrom and Milgrom 1991], including concepts such as incentive compatibility, asymmetric information, adverse selection, and moral hazard [Laffont and Martimort 2009], which are relevant for algorithmic policy administration, including design of cryptoeconomic systems. While machine level behavior may be well represented by complete contracts, human behavior rarely is. Incomplete contract theory assumes that most contracts cannot enumerate contracting outcomes for every possible state of the world as the complexity of socioeconomic interactions makes it infeasible to formalize any eventuality of a contractual outcome ex-ante [Tirole 1999]. One can resort to formal dispute resolution (judiciary) or informal dispute resolution (bargaining) to resolve such contractual gaps [Salanié 2005]. The impossibility of codifying every eventuality into a computational constitution or smart contract code and the necessity for dispute resolution and off-chain governance mechanisms has also been the subject of ample debate within the context of cryptoeconomic systems [Voshmgir 2017], [Voshmgir 2020] and will be a necessary line of research to pursue.

10.4. Ethics and Governance of Decision Algorithms in Social Systems

Assumptions that are programmed into the cryptoeconomic protocols might be biased and will be subject to a line of ethical studies covering how the associated cryptoeconomic systems behave over time. When automated systems are envisaged as closed systems they are tantamount to complete contracts–supposing that a prespecified algorithm suffices to judge all possible eventualities. All algorithms presuppose some representation or model of reality; models are always reductions of reality based on some assumptions, and therefore must be judged by their usefulness to some ends[Box 1976][Green and Viljoen 2020]. This places the focus on the assumptions embedded in the models and the effects those assumptions have on people. By acknowledging the subjective and performative aspects of models, and more broadly the synergies between human and machine decision makers, the domain mirrors that of incomplete contracts more closely. The policy-making, machine learning and cryptoeconomic systems design communities share a common need to address ethical questions about the social-systemic effects of algorithm design and implementation [Orlikowski and Scott 2015] [Loukides, Mason and Patil 2018]. To design or govern algorithms which make decisions requires a theory of fairness such as Rawl's Veil of Ignorance [Rawls 1958] [Heidari et al. 2018]. Fairness cannot be expected to emerge from purely self-interested agents because fairness provides a constraint on profit seeking behavior [Kahneman, Knetsch and Thaler 1986]. As a result, a code of ethics for algorithm designers, as found in other engineering disciplines [Pugh 2009], is required.

Furthermore, it is important to note that data governance [Soares 2015] is not equivalent to protocol governance. Data governance relates to the management of rights to read, write or manipulate data. Emerging data economies must respect regulations such as General Data Protection Regulation [Voigt and Von dem Bussche 2017] and therefore one cannot simply store private or sensitive information in a public ledger where it cannot be deleted. However, data governance can be addressed through business process automation [Ter Hofstede et al. 2009] using smart contracts [Christidis and Devetsikiotis 2016], which encode the aforementioned rights to read, write or manipulate data which is stored using other cryptographic technologies such as a content addressable distributed hash tables [Benet 2014]. Federated machine learning [Bonawitz et al. 2017][Geyer, Klein and Nabi 2017] is a growing area of research, but practical implementation is hindered by the ethical and regulatory requirement that there are guarantees of privacy preservation [Ahmad, Stoyanov and Lovat 2019].

10.5. Computational Social Science

Computational social science [Johnson and Lux 2011], is a particularly relevant branch of interdisciplinary research for cryptoeconomic systems. This is the primary field of social science that uses computational approaches in studying the social phenomena [Cioffi-Revilla 2016]. Modern computational social science is much more deeply coupled with behavioral economics and data science where advanced computational statistics are combined with social networks, market dynamics, and more [Easley and Kleinberg 2010], [Jackson 2008]. The advancing power of computation has lead some to refer to computational science as a "new kind of science" [Wolfram 2002]. This paradigm is backed up by an emerging computational epistemology [Kelly 2000] [Blum and Blum 1975] [Chaitin 2011]. It is precisely in the context of complex systems that counterintuitive outcomes are common, and computational methods expose unforeseen pitfalls before they can cause irrecoverable harm [Forrester 1971] [Merton 1936]. Computational methods in cryptoeconomic systems combine data science tools with system dynamics and agent based models to explore the relation between agent behavior and protocol design [Zhang, Zargham and Preciado 2020]. The approach of combining data with theory and computation is consistent with methods in econophysics [Lux 2009] and ergodicity economics [Peters and Adamou 2018], though in the case of cryptoeconomics the volume and precision of data available for backtesting models is higher.

10.6. Cyberphysical Systems Engineering

In the field of engineering, especially for large scale cyberphysical systems, computer aided design is standard practice[Baheti and Gill 2011] [Rajkumar et al. 2010]. The United States National Science Foundation defines a cyberphysical system (CPS) as "a mechanism that is controlled or monitored by computer-based algorithms, tightly integrated with the Internet and its users. In cyberphysical systems, physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioral modalities, and interacting with each other in a lot of ways that change with context" [National Science Foundation Directorate for Computer and Engineering 2010], [Lee 2006], [Lee 2008].

Examples of existing cyberphysical systems include power grids and large scale transportation systems [Greer et al. 2019], which both share the property that behavior of uncontrolled human actors can create undesirable or even unsafe conditions in entirely counterintuitive ways. A common criticism for using this analogy is the presence of attackers, but this a common concern in the CPS literature [Cardenas et al. 2009],[Barreto et al. 2014]. In practice, the design, operation, and governance of such large scale systems is accomplished through computational models called digital twins, [Grieves and Vickers 2017] [Uhlemann, Lehmann and Steinhilper 2017] which are also closely related to the practice of model based systems engineering [Estefan et al. 2007]. Model based systems engineering has previously been applied for multi-agent systems [DeLoach, Wood and Sparkman 2001] [Fallah et al. 2010], and the relation from cryptoeconomic networks to cyberphysical systems has already been observed in the literature, [Bahga and Madisetti 2016].

The systems engineering methodology [Hamelin, Walden and Krueger 2010] as applied to cyberphysical systems relies on a composite of theoretical, computational, and empirical methods [Banerjee et al. 2011]; thus building on the experimental economic tradition [Roth 2002] [Kagel and Roth 2016]. A natural path forward is to treat cryptoeconomic systems as cyberphysical systems and to approach them with the diligence an engineer must afford to any public infrastructure [Hou et al. 2015]. As with other complex engineered systems, informed governance requires both specialized tools and expertise, so even when governance systems are polycentric the parties responsible for governance are accountable to the public they serve [Walch 2015][Ostrom 2010]. To do so, it is necessary to develop a holistic perspective for cryptoeconomic systems which relates the locally implemented protocols, behavioral response to those mechanisms, and the systemic properties that emerge therefrom.

The crossover between cyberphysical systems as an engineering concept and a commons as an institutional economics construct is fertile ground for research in cryptoeconomic systems. The Commons Stack project has introduced the notion of a cyberphysical commons [Emmett 2019]. Several initiatives are exploring the relationships between governance of commons and cryptonetworks through the lens of Ostrom's Principles [Rozas et al. 2018], [Schadeck 2019]. Organizations pursuing commons related research include the P2P Foundation [Bauwens, Kostakis and Pazaitis 2019] and the Commons Engine which is associated with the Holochain technology [Harris-Braun, Luck and Brock 2018].

REFERENCES

Adams, John, and Wendell C Gordon. 1989. *Economics as Social Science: An Evolutionary Approach.* Riverdale Company.

Ahmad, Omer F., Danail Stoyanov, and Laurence B. Lovat. 2019. "Barriers and Pitfalls for Artificial Intelligence in Gastroenterology: Ethical and Regulatory issues." *Techniques in Gastrointestinal Endoscopy*, 150636.

Allen, Darcy W.E., Chris Berg, Brendan Markey-Towler, Mikayla Novak, and Jason Potts. 2020. "Blockchain and the evolution of institutional technologies: Implications for innovation policy." *Research Policy*, 49(1): 103865.

Angeris, Guillermo, Hsien-Tang Kao, Rei Chiang, Charlie Noyes, and Tarun Chitra. 2019. "An analysis of Uniswap markets." *ArXiv.org:1911.03380*.

Antonopoulos, Andreas M. 2014. *Mastering Bitcoin: unlocking digital cryptocurrencies.* O'Reilly Media, Inc.

Arrow, Kenneth J. 2012. *Social choice and individual values.* Vol. 12, Yale university press.

Axelrod, Robert. 1997. *The complexity of cooperation: Agent-based models of competition and collaboration.* Vol. 3, Princeton University Press.

Axelrod, Robert, and William D Hamilton. 1981. "The evolution of cooperation." *Science*, 211(4489): 1390–1396.

Aymanns, Christoph, Mathias Dewatripont, and Tarik Roukny. 2019. "Vertically Disintegrated Platforms." *SSRN:3507355*.

Baheti, Radhakisan, and Helen Gill. 2011. "Cyber-physical systems." *The impact of control technology*, 12(1): 161–166.

Bahga, Arshdeep, and Vijay K Madisetti. 2016. "Blockchain platform for industrial internet of things." *Journal of Software Engineering and Applications*, 9(10): 533.

Banerjee, Ayan, Krishna K Venkatasubramanian, Tridib Mukherjee, and Sandeep Kumar S Gupta. 2011. "Ensuring safety, security, and sustainability of mission-critical cyber–physical systems." *Proceedings of the IEEE*, 100(1): 283–299.

Barabási, Albert-László, et al. 2016. *Network science.* Cambridge university press.

Barkley Rosser, J. 2010. "How complex are the Austrians?" In *What is so Austrian about Austrian Economics?*. 165–179. Emerald Group Publishing Limited.

Barreto, C., J. Giraldo, Á. A. Cárdenas, E. Mojica-Nava, and N. Quijano. 2014. "Control Systems for the Power Grid and Their Resiliency to Attacks." *IEEE Security Privacy*, 12(6): 15–23.

Bar-Yam, Yaneer. 2002. "General features of complex systems." *UNESCO Encyclopedia of Life Support Systems*.

Bar-Yam, Yaneer. 2003. Proceedings of the IEEE International Conference on Systems, Man and Cybernetics.

Bateson, Gregory, et al. 1989. *The individual, communication, and society: Essays in memory of Gregory Bateson.* Cambridge University Press.

Bauwens, Michel, Vasilis Kostakis, and Alex Pazaitis. 2019. *Peer to peer: the commons manifesto.* London: University of Westminster Press.

Benet, Juan. 2014. "Ipfs-content addressed, versioned, p2p file system." *ArXiv:1407.3561.*

Berg, C., S. Davidson, and J. Potts. 2019. "Understanding the Blockchain Economy: An Introduction to Institutional Cryptoeconomics." In *New Horizons in Institutional and Evolutionary Economics*. Edward Elgar Publishing.

Blanchard, Benjamin S, and Wolter J Fabrycky. 1990. *Systems Engineering and Analysis.* Prentice Hall.

Blum, Lenore, and Manuel Blum. 1975. "Toward a mathematical theory of inductive inference." *Information and Control*, 28(2): 125 – 155.

Boccaletti, S., V. Latora, Y. Moreno, M. Chavez, and D.U. Hwang. 2006. "Complex Networks: Structure and Dynamics." *Physics Reports*, 424(4): 175–308.

Bolton, Patrick, Mathias Dewatripont, et al. 2005. *Contract theory.* MIT press.

Bonawitz, Keith, Vladimir Ivanov, Ben Kreuter, Antonio Marcedone, H Brendan McMahan, Sarvar Patel, Daniel Ramage, Aaron Segal, and Karn Seth. 2017. "Practical secure aggregation for privacy-preserving machine learning." 1175–1191, ACM.

Box, George EP. 1976. "Science and statistics." *Journal of the American Statistical Association*, 71(356): 791–799.

Buterin, Vitalik. 2014. "DAOs, DACs, DAs and More: An Incomplete Terminology Guide." *https://blog.ethereum.org/2014/05/06/daos-dacs-das-and-more-an-incomplete-terminology-guide/.*

Buterin, Vitalik. 2017a. "The Meaning of Decentralization." *https://medium.com/@VitalikButerin/the-meaning-of-decentralization-a0c92b76a274.*

Buterin, Vitalik. 2017b. "Introduction to Cryptoeconomics." *https://www.youtube.com/watch?v=pKqdjaH1dRo.*

Buterin, Vitalik, Zoë Hitzig, and E Glen Weyl. 2019. "A Flexible Design for Funding Public Goods." *Management Science*, 65(11): 5171–5187.

Candogan, Ozan, Asuman Ozdaglar, and Pablo A Parrilo. 2013. "Dynamics in near-potential games." *Games and Economic Behavior*, 82: 66–90.

Cardenas, Alvaro, Saurabh Amin, Bruno Sinopoli, Annarita Giani, Adrian Perrig, Shankar Sastry, et al. 2009. "Challenges for securing cyber physical systems." Vol. 5.

Catalini, Christian, and Joshua S Gans. 2016. "Some simple economics of the blockchain." National Bureau of Economic Research.

Chaitin, Gregory J. 2011. *Metaphysics, metamathematics and metabiology.* World Scientific, Singapore.

Chavance, B., and F. Wells. 2008. *Institutional Economics. Routledge frontiers of political economy*, Routledge.

Chiang, M., S.H. Low, A.R. Calderbank, and J.C. Doyle. 2007. "Layering as optimization decomposition: A mathematical theory of network architectures." *Proceedings of the IEEE*, 95(1): 255–312.

Christidis, Konstantinos, and Michael Devetsikiotis. 2016. "Blockchains and smart contracts for the internet of things." *IEEE Access*, 4: 2292–2303.

Cioffi-Revilla, Claudio. 2016. "Bigger Computational Social Science: Data, Theories, Models, and Simulations–Not Just Big Data." *Theories, Models, and Simulations–Not Just Big Data (May 24, 2016).*

Coase, R. H. 1937. "The Nature of the Firm." *Economica*, 4(16): 386–405.

Coase, Ronald. 1998. "The new institutional economics." *The American Economic Review*, 88(2): 72–74.

Common, Michael, and Sigrid Stagl. 2005. *Ecological Economics: An Introduction.* Cambridge University Press.

Cong, Lin William, Ye Li, and Neng Wang. 2019. "Tokenomics: Dynamic adoption and valuation." *Becker Friedman Institute for Research in Economics Working Paper*, , (2018-49): 2018–15.

Davidson, Sinclair, Primavera De Filippi, and Jason Potts. 2016. "Disrupting governance: The new institutional economics of distributed ledger technology." *Available at SSRN 2811995.*

De Angelis, Stefano, Leonardo Aniello, Roberto Baldoni, Federico Lombardi, Andrea Margheri, and Vladimiro Sassone. 2018. "Pbft vs proof-of-authority: applying the cap theorem to permissioned blockchain." *https://eprints.soton.ac.uk/415083/2/itasec18_main.pdf.*

De Filippi, Primavera. 2018. *Blockchain and the law: The rule of code.* Harvard University Press.

De La Rouviere, Simon. 2017. "Tokens 2.0: Curved Token Bonding in Curation Markets." *https://medium.com/@simondlr/tokens-2-0-curved-token-bonding-in-curation-markets-1764a2e0bee5.*

DeLoach, Scott A, Mark F Wood, and Clint H Sparkman. 2001. "Multiagent systems engineering." *International Journal of Software Engineering and Knowledge Engineering*, 11(03): 231–258.

Dezure, Deborah. 1999. "Interdisciplinary teaching and learning." *Teaching excellence: toward the best in the academy*, 10(3): 1–2.

Dopfer, K., J. Foster, and J Potts. 2004. "Micro-Meso-Macro." *Journal of Evolutionary Economics*, Springer–Verlag.

Dorogovtsev, Sergei N, and José FF Mendes. 2004. "The shortest path to complex networks." *arXiv:0404593.*

Easley, D., and J. Kleinberg. 2010. *Networks, Crowds, and Markets.* Vol. 8, Cambridge University Press.

Emmett, Jeff. 2019. "Automating Ostrom for Effective DAO Management." *https://medium.com/commonsstack/automating-ostrom-for-effective-dao-management-cfe7a7aea138.*

Estefan, Jeff A, et al. 2007. "Survey of model-based systems engineering (MBSE) methodologies." *Incose MBSE Focus Group*, 25(8): 1–12.

Eyal, Ittay. 2015. “The miner’s dilemma.” *IEEE Symposium on Security and Privacy*.

Fallah, Yaser P, ChingLing Huang, Raja Sengupta, and Hariharan Krishnan. 2010. “Design of cooperative vehicle safety systems based on tight coupling of communication, computing and physical vehicle dynamics.” 159–167, ACM.

Fararo, Thomas J, and John Skvoretz. 1986. “Action and institution, network and function: The cybernetic concept of social structure.” Vol. 1, 219–250, Springer.

Filippova, E. 2019. “Empirical Evidence and Economic Implications of Blockchain as a General Purpose Technology.” 1–8.

Forrester, Jay W. 1971. “Counterintuitive behavior of social systems.” *Technological Forecasting and Social Change*, 3: 1–22.

Foster, John. 2005. “From simplistic to complex systems in economics.” *Cambridge Journal of Economics*, 29(6): 873–892.

Foster, John, and J. Stan Metcalfe. 2012. “Economic emergence: An evolutionary economic perspective.” *Journal of Economic Behavior & Organization*, 82(2): 420 – 432. Emergence in Economics.

Frey, Seth, and Robert W Sumner. 2019. “Emergence of integrated institutions in a large population of self-governing communities.” *PloS one*, 14(7): e0216335.

Garcia, Megan. 2016. “Racist in the machine: The disturbing implications of algorithmic bias.” *World Policy Journal*, 33(4): 111–117.

Gazi, Veysel, and Kevin M Passino. 2003. “Stability analysis of swarms.” *IEEE transactions on automatic control*, 48(4): 692–697.

Geyer, Robin C, Tassilo Klein, and Moin Nabi. 2017. “Differentially private federated learning: A client level perspective.” *arXiv preprint arXiv:1712.07557*.

Gilbert, Lewis E. 1998. “Disciplinary breadth and interdisciplinary knowledge production.” *Knowledge, Technology & Policy*, 11(1-2): 4–15.

Goldstein, Jeffrey. 1999. “Emergence as a Construct: History and Issues.” *Emergence*, 1(1): 49–72.

Green, Ben, and Salomé Viljoen. 2020. “Algorithmic Realism: Expanding the Boundaries of Algorithmic Thought.” *FAT* ’20*, 19–31. New York, NY, USA:Association for Computing Machinery.

Greer, Christopher, Martin Burns, David Wollman, and Edward Griffor. 2019. “Cyber-Physical Systems and Internet of Things.” *NIST Special Publication 1900-202*.

Grieves, Michael, and John Vickers. 2017. “Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems.” In *Transdisciplinary perspectives on complex systems*. 85–113. Springer.

Grossman, Sanford J., and Oliver D. Hart. 1981. “Implicit Contracts, Moral Hazard, and Unemployment.” *The American Economic Review*, 71(2): 301–307.

Grossman, Sanford J., and Oliver D. Hart. 1983. “An Analysis of the Principal-Agent Problem.” *Econometrica*, 51(1): 7–45.

Hamelin, R Douglas, David D Walden, and Michael E Krueger. 2010. “4.4. 2 incose systems engineering handbook v3. 2: Improving the process for se practitioners.” Vol. 20, 532–541, Wiley Online Library.

Hamilton, Walter. 1919. “The Institutional Approach to Economic Theory.” *American Economic Review*, , (9): 309–318.

Harris-Braun, Eric, Nicolas Luck, and Arthur Brock. 2018. “Holochain: scalable agent-centric distributed computing.” *GitHub: https://github.com/holochain/holochain-proto/blob/whitepaper/holochain*.

Hart, Oliver, and Bengt Holmström. 1987. “The theory of contracts.” *Advances in Economic Theory: Fifth World Congress*, , ed. Truman FassettEditor Bewley *Econometric Society Monographs*, 71–156. Cambridge University Press.

Hart, Oliver, and John Moore. 1988. “Incomplete contracts and renegotiation.” *Econometrica: Journal of the Econometric Society*, 755–785.

Hart, Oliver, and John Moore. 1990. “Property Rights and the Nature of the Firm.” *JOURNAL OF POLITICAL ECONOMY*, 98(6).

Heidari, Hoda, Claudio Ferrari, Krishna Gummadi, and Andreas Krause. 2018. “Fairness behind a veil of ignorance: A welfare analysis for automated decision making.” 1265–1276.

Hertzog, Eyal, Guy Benartzi, and Galia Benartzi. 2017. “Bancor Protocol.”

Hodgson, Geoffrey M. 2000. “What Is the Essence of Institutional Economics?” *Journal of Economic Issues*, 34(2): 317–329.

Holmstrom, Bengt, and Paul Milgrom. 1991. “Multitask principal-agent analyses: Incentive contracts, asset ownership, and job design.” *JL Econ. & Org.*, 7: 24.

Hou, Yunfei, Yunjie Zhao, Aditya Wagh, Longfei Zhang, Chunming Qiao, Kevin F Hulme, Changxu Wu, Adel W Sadek, and Xuejie Liu. 2015. “Simulation-based testing and evaluation tools for transportation cyber–physical systems.” *IEEE Transactions on Vehicular Technology*, 65(3): 1098–1108.

Hurwicz, L., and S. Reiter. 2006. *Designing Economic Mechanisms.* Cambridge University Press.

Hurwicz, Leonid. 1960. “Optimality and informational efficiency in resource allocation processes.” In *Mathematical Methods in the Social Sciences*. , ed. K.J. Arrow, S. Karlin and P. Suppes. Stanford University Press.

Hurwicz, Leonid. 1972. “On informationally decentralized systems.” *Decision and organization: A volume in Honor of J. Marschak*.

Jackson, M.O. 2008. *Social and Economic Networks.* Princeton University Press.

Jadbabaie, Ali, Pooya Molavi, Alvaro Sandroni, and Alireza Tahbaz-Salehi. 2012. "Non-Bayesian social learning." *Games and Economic Behavior*, 76(1): 210 – 225.

Johnson, Neil, and Thomas Lux. 2011. "Financial systems: Ecology and economics." *Nature*, 469(7330): 302.

Jordan, Michael I, and Tom M Mitchell. 2015. "Machine learning: Trends, perspectives, and prospects." *Science*, 349(6245): 255–260.

Kagel, John H, and Alvin E Roth. 2016. *The handbook of experimental economics.* Vol. 2, Princeton university press.

Kahneman, Daniel, Jack L Knetsch, and Richard H Thaler. 1986. "Fairness and the assumptions of economics." *Journal of business*, S285–S300.

Kelly, Kevin T. 2000. "The logic of success." *Philosophy of science today*, 11–38.

Kia, S. S., B. Van Scoy, J. Cortes, R. A. Freeman, K. M. Lynch, and S. Martinez. 2019. "Tutorial on Dynamic Average Consensus: The Problem, Its Applications, and the Algorithms." *IEEE Control Systems Magazine*, 39(3): 40–72.

Klein, Mark, Hiroki Sayama, Peyman Faratin, and Yaneer Bar-Yam. 2001. "What complex systems research can teach us about collaborative design." In *Proceedings of the Sixth International Conference on Computer Supported Cooperative Work in Design*.

Kurtz, Cynthia F, and David J Snowden. 2003. "The new dynamics of strategy: Sense-making in a complex and complicated world." *IBM systems journal*, 42(3): 462–483.

Laffont, Jean-Jacques, and David Martimort. 2009. *The theory of incentives: the principal-agent model.* Princeton university press.

Lange, Oskar. 2014. *Introduction to economic cybernetics.* Elsevier.

Lee, Edward A. 2006. "Position Paper for NSF Workshop On Cyber-Physical Systems: Research Motivation, Techniques and Roadmap." *National Science Foundation*.

Lee, Edward A. 2008. "Cyber-physical systems: Design challenges." In *Proceedings of the 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing*.

Lessig, Lawrence. 2009. "Code: And other laws of cyberspace." *http://codev2.cc/download+remix/Lessig-Codev2.pdf*.

Leveson, Nancy G. 2016. *Engineering a safer world: Systems thinking applied to safety.* The MIT Press.

Lewis, Seth C, and Oscar Westlund. 2015. "Big data and journalism: Epistemology, expertise, economics, and ethics." *Digital journalism*, 3(3): 447–466.

Liaskos, S., B. Wang, and N. Alimohammadi. 2019. "Blockchain Networks as Adaptive Systems." In *Proceedings of the IEEE/ACM 14th International Symposium on Software Engineering for Adaptive and Self-Managing Systems*. 139–145.

Lipset, D. 1980. *Gregory Bateson: The Legacy of a Scientist.* Prentice-Hall.

Loukides, Mike, Hilary Mason, and DJ Patil. 2018. *Ethics and Data Science.* O'Reilly Media.

Lucas, Robert E. 1976. "Econometric policy evaluation: A critique." *Carnegie-Rochester Conference Series on Public Policy*, 1: 19 – 46.

Lux, Thomas. 2009. "Applications of Statistical Physics in Finance and Economics." In *Handbook of Research on Complexity*. Chapter 9. Edward Elgar Publishing.

Meadows, Donella H. 2008. *Thinking in systems: A primer.* chelsea green publishing.

Merton, Robert K. 1936. "The Unanticipated Consequences of Purposive Social Action." *American Sociological Review*, 1(6): 894–904.

Moffatt, Sebastian, and Niklaus Kohler. 2008. "Conceptualizing the built environment as a social–ecological system." *Building research & information*, 36(3): 248–268.

Montuori, Alfonso. 2005. "Gregory Bateson and the promise of transdisciplinarity." *Cybernetics & Human Knowing*, 12(1-2): 147–158.

Mueller, Milton. 2010. "Critical resource: An institutional economics of the Internet addressing-routing space." *Telecommunications Policy*, 34(8): 405 – 416.

Mullainathan, Sendhil, and Jann Spiess. 2017. "Machine learning: an applied econometric approach." *Journal of Economic Perspectives*, 31(2): 87–106.

Nagel, Thomas. 2012. *Mind and Cosmos: Why the Materialist Neo-Darwinian Conception of Nature Is: Why the Materialist Neo-Darwinian Conception of Nature is Almost Certainly False.* Oxford University Press USA.

Nakamoto, Satoshi. 2008. "Bitcoin: A Peer-to-Peer Electronic Cash System." *https://bitcoin.org/bitcoin.pdf*, Accessed: 2015-07-01.

National Science Foundation Directorate for Computer, Information Science, and Engineering. 2010. "Cyber-Physical Systems Program Solicitation." *https://www.nsf.gov/pubs/2010/nsf10515/nsf10515.html*.

Newman, M. E. 2010. *Networks: An Introduction.* Oxford University Press.

Nisan, Noam, Tim Roughgarden, Eva Tardos, and Vijay V Vazirani. 2007. *Algorithmic game theory.* Cambridge university press.

Novikov, Dmitry. 2016. "Systems Theory and Systems Analysis. Systems Engineering." In *Cybernetics: from past to future*. 39–44.

Nowak, Martin A. 2006. "Five rules for the evolution of cooperation." *science*, 314(5805): 1560–1563.

Okada, Isamu, Hitoshi Yamamoto, Fujio Toriumi, and Tatsuya Sasaki. 2015. "The Effect of Incentives and Meta-incentives on the Evolution of Cooperation." *PLOS Computational Biology*, 11(5): 1–17.

Olfati-Saber, Reza, and Richard M. Murray. 2002. "Distributed Cooperative Control Of Multiple Vehicle Formations Using Structural Potential Functions." *IFAC Proceedings Volumes*, 35(1): 495 – 500. 15th IFAC World Congress.

Oliva, Gabriel. 2016. "The road to servomechanisms: the influence of Cybernetics on Hayek from the sensory order to the social order." In *Research in the History of Economic Thought and Methodology*. 161–198. Emerald Group Publishing Limited.

Orlikowski, Wanda, and Susan V Scott. 2015. "The algorithm and the crowd: Considering the materiality of service innovation." *https://dspace.mit.edu/handle/1721.1/96870*.

Ostrom, Elinor. 1990. *Governing the commons: The evolution of institutions for collective action.* Cambridge university press.

Ostrom, Elinor. 2000. "Collective action and the evolution of social norms." *Journal of economic perspectives*, 14(3): 137–158.

Ostrom, Elinor. 2010. "Beyond markets and states: polycentric governance of complex economic systems." *American economic review*, 100(3): 641–72.

Parrott, Lael, and Holger Lange. 2013. "An introduction to complexity science." In *Managing Forests as Complex Adaptive Systems*. 31–46. Routledge.

Peters, Ole, and Alexander Adamou. 2018. *Ergodicity Economics.* London Mathematical Laboratory.

Peters, Ole, and Alexander Adamou. 2019. "An evolutionary advantage of cooperation."

Phillips, Ronnie J. 2000. "Digital Technology and Institutional Change from the Gilded Age to Modern Times: The Impact of the Telegraph and the Internet." *Journal of Economic Issues*, 34(2): 267–289.

Pugh, E. W. 2009. "Creating the IEEE Code of Ethics." 1–13.

Quine, Willard V. 1951. "Main trends in recent philosophy: Two dogmas of empiricism." *The philosophical review*, 20–43.

Rajkumar, Ragunathan, Insup Lee, Lui Sha, and John Stankovic. 2010. "Cyber-physical systems: the next computing revolution." 731–736, IEEE.

Rapoport, Anatol, Albert M Chammah, and Carol J Orwant. 1965. *Prisoner's dilemma: A study in conflict and cooperation.* Vol. 165, University of Michigan press.

Rawls, John. 1958. "Justice as fairness." *The philosophical review*, 67(2): 164–194.

Re, ARNOLD PICOT CHRISTINE BORTENLANGER HEINER. 1997. "Organization of Electronic Markets: Contributions from the New Institutional Economics." *The Information Society*, 13(1): 107–123.

Repko, Allen F. 2008. *Interdisciplinary research: Process and theory.* Sage.

Rhodes, Donna, and Daniel Hastings. 2003. "The Case for Evolving Systems Engineering as a Field within Engineering Systems." *http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.86.7496&rep=rep1&type=pdf*.

Rochet, Jean-Charles, and Jean Tirole. 2003. "Platform competition in two-sided markets." *Journal of the european economic association*, 1(4): 990–1029.

Roth, Alvin E. 2002. "The economist as engineer: Game theory, experimentation, and computation as tools for design economics." *Econometrica*, 70(4): 1341–1378.

Rozas, David, Antonio Tenorio-Fornés, Silvia Díaz-Molina, and Samer Hassan. 2018. "When Ostrom Meets Blockchain: Exploring the Potentials of Blockchain for Commons Governance." *Available at SSRN 3272329*.

Ruse, Michael. 2005. "Models in Science." In *The Oxford companion to philosophy.* , ed. Ted Honderich. OUP Oxford.

Sætra, Henrik Skaug. 2019. "The tyranny of perceived opinion: Freedom and information in the era of big data." *Technology in Society*, 59: 101155.

Sage, A. P. 1992. "Environment, rationality perspectives, and coordination structures for decision aiding in complex distributed organizational systems." 874–879 vol.1.

Salanié, Bernard. 2005. *The economics of contracts: a primer.* MIT press.

Schadeck, Wendy Xiao. 2019. "8 Nobel-Prize Winning Rules for Governance Design."

Schmitz, Stefan W, et al. 2002. "The effects of e-commerce on the structure of intermediation." University Library of Munich, Germany.

Scholz, Trebor, and Nathan Schneider. 2017. *Ours to hack and to own: The rise of platform cooperativism, a new vision for the future of work and a fairer internet.* OR books.

Schumacher, Ernst Friedrich. 2011. *Small is beautiful: A study of economics as if people mattered.* Random House.

Shorish, Jamsheed. 2018. "Blockchain State Machine Representation." *SocArXiv*.

Shorish, Jamsheed. 2019. "Hedonic pricing of cryptocurrency tokens." *Digital Finance*.

Soares, Sunil. 2015. *The chief data officer handbook for data governance.* Mc Press.

Ter Hofstede, Arthur HM, Wil MP Van der Aalst, Michael Adams, and Nick Russell. 2009. *Modern Business Process Automation: YAWL and its support environment.* Springer Science & Business Media.

Tirole, Jean. 1999. "Incomplete contracts: Where do we stand?" *Econometrica*, 67(4): 741–781.

Tomaino, Nick. 2017a. "Cryptoeconomics 101." *https://thecontrol.co/cryptoeconomics-101-e5c883e9a8ff*.

Tsitsiklis, John Nikolas. 1984. "Problems in decentralized decision making and computation." Massachusetts Inst of Tech Cambridge Lab for Information and Decision Systems.

Uhlemann, Thomas H-J, Christian Lehmann, and Rolf Steinhilper. 2017. "The digital twin: Realizing the

cyber-physical production system for industry 4.0." *Procedia Cirp*, 61: 335–340.
Veblen, Thorstein. 1973. *The theory of the leisure class.* Houghton Mifflin Boston.
Virtanen, Akseli, Dick Bryan, Benjamin Lee, and Robert Wosnitzer. 2018. "Economics Back in Cryptoeconomics." *https://medium.com/econaut/economics-back-into-cryptoeconomics-20471f5ceeea*.
Voigt, Paul, and Axel Von dem Bussche. 2017. "The eu general data protection regulation (gdpr)." *A Practical Guide, 1st Ed., Cham: Springer International Publishing*.
Von Bertalanffy, Ludwig. 1969. *General System Theory: Foundations, Development, Applications.* George Braziller, Inc.
Von Foerster, Heinz. 2003. "Ethics and second-order cybernetics." In *Understanding understanding*. 287–304. Springer.
Voshmgir, Shermin. 2017. "Disrupting governance with blockchains and smart contracts." *Strategic Change*, 26(5): 499–509.
Voshmgir, Shermin. 2019. *What is Token Economy?* Vol. 1, O'Reilly Media, Inc.
Voshmgir, Shermin. 2020. *Token Economy: How the Web3 reinvents the Internet.* Vol. 2, BlockchainHub.
Walch, Angela. 2015. "The Bitcoin Blockchain as Financial Market Infrastructure: A Consideration of Operational Risk." *New York University Journal of Legislation and Public Policy*, 18: 837.
Walch, Angela. 2019. "In Code (Rs) We Trust: Software Developers as Fiduciaries in Public Blockchains." In *Regulating Blockchain. Techno-Social and Legal Challenges*.
Werbach, Kevin. 2018. "Trust, but verify: Why the blockchain needs the law." *Berkeley Tech. LJ*, 33: 487.
Wiener, Norbert. 1965. *Cybernetics or Control and Communication in the Animal and the Machine.* Vol. 25, MIT press.
Williamson, Oliver E. 2000. "The new institutional economics: taking stock, looking ahead." *Journal of economic literature*, 38(3): 595–613.
Wolfram, Stephen. 2002. *A new kind of science.* Vol. 5, Wolfram media Champaign, IL.
Wright, Aaron, and Primavera De Filippi. 2015. "Decentralized blockchain technology and the rise of lex cryptographia." *Available at SSRN 2580664*.
Yamamoto, Hitoshi, Isamu Okada, Satoshi Uchida, and Tatsuya Sasaki. 2017. "A norm knockout method on indirect reciprocity to reveal indispensable norms." *Scientific reports*, 7: 44146.
Zamfir, Vlad. 2015. "What is Cryptoeconomics." *Presentation at CryptEconomicon 2015. Crypto Technology Conference, Mountain View CA, 26-29 January*.
Zamfir, Vlad. 2017. "Against on-chain governance." *Refuting (and rebuking) Fred Ehrsam's governance*.
Zamfir, Vlad. 2019. "Against Szabo's Law, For A New Crypto Legal System." *Crypto Law Review*.
Zargham, Michael, Jamsheed Shorish, and Krzysztof Paruch. 2019. "From Curved Bonding to Configuration Spaces." Research Institute for Cryptoeconomics Working Paper Series, Vienna.
Zargham, Michael, Krzysztof Paruch, and Jamsheed Shorish. 2020. "Economic Games as Estimators." WU Vienna University of Economics and Business, Vienna.
Zargham, Michael, Primavera de Filippi, Joshua Tan, and Jeff Emmett. 2020. "Exploring DAOs as a New Kind of Institution." *Commons Stack, Medium*, Accessed: 2020-06-10.
Zargham, Michael, Zixuan Zhang, and Victor Preciado. 2018. "A State-Space Modeling Framework for Engineering Blockchain-Enabled Economic Systems." https://arxiv.org/pdf/1807.00955.pdf:ArXiv.org.
Zhang, Z., M. Zargham, and V. Preciado. 2020. "On Modeling Blockchain-Enabled Economic Networks as Stochastic Dynamical Systems." *Applied Network Science: Blockchain and Cryptocurrency*.
Zhu, Ling Yin, and Sherry M. B. Thatcher. 2010. "National Information Ecology: A New Institutional Economics Perspective on Global E-Commerce Adoption."