Measuring Complexity in Cryptoeconomic Systems

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1 Cryptoeconomic Systems

Cryptoeconomic systems are a novel form of complex system that are poised to play a significant role in the global political economy. They are unique forms of digitally native economic systems composed of individual autonomous actors, economic policies enforced by software, and emergent properties which arise as a result of the actors interacting according to the software-defined rules [1]. In public blockchain networks like Bitcoin and Ethereum, actors can include anyone on the planet and the software is open-source. In private distributed ledger technology (DLT) systems, such as central bank digital currencies (CBDCs), only a restricted set of participants can contribute to the network's operation, and the software may or may not be open-source. In both cases, the systems are designed to regulate the distribution of efforts, goods, and services in digital economies [2]. Some of the emergent properties that can arise from the interactions of agents in these systems include trustworthiness, adoption rates, value, price, and decentralization.

A steady increase in institutional adoption suggests that blockchains are more than a bubble or a passing fad. Many of the world's largest private banks and payment processing companies are launching products on both public blockchains and private DLT systems [3], [4], [5], [6], [7], [8]. Nearly every central bank in the world is developing some form of Central Bank Digital Currency (CBDC), many of which depend on blockchain technology [9].SWIFT, the global banking message network responsible for handling the majority of international payments, is facilitating the "tokenization" of assets across public and private blockchains and interoperability among the world's CBDCs [10] [11]. The so-called BRICs nations (Brazil, Russia, India, China, South Africa) are creating a "payment system based on digital currencies and blockchain" [12]. The Bank for International Settlements which serves as the bank for central banks is exploring the development of a "unified ledger" that could "enhance the functioning of the monetary system and provide new solutions using smart contracts and programability" [13].

Simultaneously, grassroots efforts focused on using public blockchain networks is aimed at decentralizing finance, corporations, academic research, artificial intelligence, and social media in ways that reduce the power of gatekeepers, provide more freedom to individuals, address coordination failures, increase transparency, and decrease society's reliance on corporate oligopolies [14][15][16][17]. Optimists hope that blockchain-based systems might bring about a human-machine ecosystem that provides "abundance without excess and complexity without chaos" by virtue of their unique capacity to facilitate complex coordination between strangers on a global scale [18]. Critics view the complexity of decentralized cryptocurrencies as proof that they are an inherently destabilizing force which threaten the stability of the financial system [19][20]." Regardless of personal opinions on their virtues, they are increasingly viewed as worthy of study – and complexity is broadly recognized as one of their most important characteristics.

2 Public Blockchains & Complexity Science

2.1 Complexity Science

Complexity scientists study systems that are composed of individual components interacting with each other according to simple rules in ways that lead to the creation of cohesive and complex larger structures. They are especially interested in systems where the creation of complex structures occurs without any central agent directing the system's behavior. Complex systems are challenging to study because their behavior can't be understood or predicted based on an understanding of their individual parts studied in isolation. The key to their behavior lies in the interactions between components which means that traditional reductionist methods which depend on isolating variables and controlled experiments aren't well suited to understanding complex systems. Complexity scientists use computational tools and interdisciplinary methods such as agent-based modeling and network science to develop principles and frameworks that can help explain dynamics of all types of complex systems – from cells and epidemics, to governments and economies.

2.2 Blockchains as Complex Systems

Public blockchain networks are quintessential complex systems whose behavior can only be understood through an interdisciplinary lens. Individual nodes interact with each other, leading to the emergence of peer-to-peer cash systems (Bitcoin) and distributed global computing platforms (Ethereum) with inherently unpredictable behavior. Bitcoin's role as a form of "digital gold"

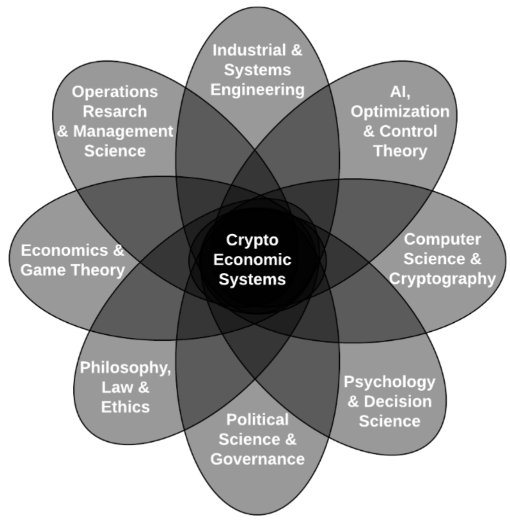

Fig. 2 Venn diagram of disciplines related to cryptoeconomic systems engineering.

Figure 1: Voshmgir, S., & Zargham, M. (2020). Foundations of Cryptoeconomic Systems.

was an emergent unplanned outcome, and one of the most popular use cases on Ethereum, non-fungible tokens (NFTs) were "probably the one thing" that its creator did not predict. Because these networks generate such large amounts of openly accessible data, the blossoming cryptoeconomy is well-suited to serve as a laboratory to help advance economic complex systems research.

2.3 Measuring Complexity

One specific way that cryptoeconomic researchers can make meaningful contributions to complex systems research is in developing and comparing formal measures of complexity that can be easily applied to a wide variety of systems. Several different complexity measures have been developed from researchers in fields from architecture and engineering to biology and finance [21]. To be truly interdisciplinary, complexity science needs a set of measures that both capture the various important aspects of complexity, and can be used to compare complexities across systems from different domains [22][23].

While complexity scientists have started measuring the price complexity of the cryptocurrencies associated with public blockchains, their narrow focus on token prices and market dynamics doesn't reveal much about the dynamics of public blockchains viewed holistically as complex systems [24][25]. By exploring formal complexity measures for public blockchain networks I aim to inspire cryptoeconomic scientists and engineers to start measuring systemic complexity, and support increased collaboration and communication between the cryptoeconomics and complex systems research communities.

3 Cryptoeconomic Titans

Bitcoin and Ethereum are two of the oldest, largest, and most widely recognized public blockchain networks. This makes them ideal initial candidates for exploring complexity metrics within cryptoeconomic systems. Because the goal of this paper is to evaluate the complex properties and dynamics of blockchain infrastructure not market-driven price fluctuations of the tokens, it is important to clearly distinguish between the blockchain networks and their cryptocurrencies digital tokens, cryptocurrencies which serve as their internal units of account [26][27]. A brief summary of the purpose, structure, and defining features of Bitcoin and Ethereum will help place the complexity measurements in the following sections in proper context.

3.1 Bitcoin

The Bitcoin network launched in early 2009 in the wake of the 2008 Global Financial Crisis. It was designed to serve as a decentralized system for peer-to-peer transactions of electronic cash. [28] Unlike traditional electronic payment systems, Bitcoin doesn't require a centralized intermediary like a bank to confirm transactions between two parties. Early adopters of the Bitcoin network were technology enthusiasts who chose to embrace the bitcoin token primarily as a form of digital cash, not something to be hoarded and traded for US dollars in the future. Bitcoin's blockchain, a ledger of all historical transactions distributed on computers across the globe, is the first example of "blockchain technology" being adopted in any meaningful way.

The Bitcoin blockchain is secured and maintained through the use of an energy-intensive consensus mechanism known as "proof-of-work" (PoW) which involves "miners" competing to solve cryptographic puzzles. They do so in order to win the right to add new transactions to the blockchain and receive a "block reward" in the form of newly minted Bitcoin released by the software at a pre-determined rate.

3.2 Ethereum

The Ethereum network was created in 2015 by early Bitcoin adopter Vitalik Buterin because he wanted to use blockchains to facilitate more than just digital cash transactions.[29] Buterin was frustrated by the Bitcoin protocol scripting language's lack of support for complex programming. He imagined a future filled with decentralized applications and organizations powered by blockchains that used arbitrarily complex computer programs, “smart contracts” to directly control digital assets [21]. Early adopters of the Ethereum network were developers and users who chose to use “ether”, the cryptoasset, to pay for computations on the Ethereum network.

Ethereum launched using PoW but switched to a less energy-intensive method, proof-of-stake (PoS) in 2022 after which energy consumption dropped by 99.99% [30]. In PoS, validators “stake” or temporarily lock up their tokens in a smart contract in exchange for a chance to validate new transactions and receive rewards.

4 Information-Theoretic Complexity

I propose an information-theoretic approach to measuring complexity in public blockchains as a natural starting point for developing a broader research agenda. Information theory has been frequently cited as a potential foundation for complex systems research and a “lingua franca” for complexity scientists [31][32]. It has also been successfully used to measure the complexity of adaptive peer-to-peer systems, a category that public blockchains clearly fall into[33].

In this paper I demonstrate the utility of an approach grounded in Claude Shannon’s information measures, originally developed for usage in the context of telecommunications. This approach was originally developed for research in Artificial Life and defines complexity as a balance between emergence and self-organization, each of which is quantified in information-theoretic terms.[34] The equations used to measure complexity with this approach are briefly summarized below.

Emergence is equated with “new” information and measured using Shannon’s equation for information which measures uncertainty or surprise:

$$E = -K \sum_{i=i}^{n} p_i \log p_i \tag{1}$$

Self-organization is considered to be anti-correlated with emergence because when a system is highly organized it contains less randomness and therefore requires less information to describe.

$$S = 1 - E \tag{2}$$

Complex systems require a balance between emergence and self-organization to maintain themselves and adapt. Domination of emergence leads to chaos and domination of self-organization leads to immutability. Therefore we can measure complexity, C, with:

$$C = 4 \cdot E \cdot S, \tag{3}$$

The 4 is added to normalize C to [0, 1]. The value of C increases as the two become more balanced and decreases if either one dominates.

5 Data & Methods

5.1 Data Collection

I focused on measuring two important variables to calculate complexity levels for the Bitcoin and Ethereum blockchains. Data from the Cambridge University Centre for Alternative Finance's blockchain sustainability indices is used to acquire estimates for each blockchain's daily electricity consumption because energy is an essential input required for the operation of blockchains. Data from blockchain.com and etherscan.io is used to acquire daily transaction counts for each blockchain because transactions are the core product and key output of blockchain systems. Finally, data from Coingecko.com is used to collect data on the market capitalization for each chain's native cryptoasset, bitcoin and ether. Market capitalization, calculated by multiplying the number of existing units of a cryptoasset by the market price of a single unit captures important information about both market sentiment and demand expressed in prices and systemic structure and activity in terms of supply of the native token.

5.2 Calculating Transactions Per-Watt

I use a Python script to merge the energy and transaction datasets into a single dataset measuring "daily transactions per watt" (TPW). This provides a unified metric that effectively captures fluctuations in key inputs and outputs that can be used to assess the operational dynamics of the networks. It is important to note that I am not measuring "energy efficiency" since energy usage is tied to block production, not transaction count. I use the resulting merged datasets to calculate cumulative, weekly, and monthly complexity for Bitcoin and Ethereum based on TPW and compare changes in complexity with changes in market cap over time. Raw and merged datasets along with scripts are available on Github [35].

6 Results

Applying the complexity measurements to the datasets yields interesting results. There are statistically significant correlations and high levels of mutual information between complexity and market capitalization for both Bitcoin and Ethereum. The direction of correlation is positive for Bitcoin and negative for Ethereum. Bitcoin has higher mutual information between complexity and market capitalization, while Ethereum displays greater variance in its complexity than Bitcoin.

	Blockchain	Pearson Correlation	Pearson p-value	Spearman Correlation	Spearman p-value	Mutual Information
0	Bitcoin	0.386105	5.39e-143	0.522647	1.42e-280	0.568668
1	Ethereum	-0.147819	4.90e-17	-0.154251	1.98e-18	0.375642

Figure 2: Correlations and Mutual Information Between Complexity and Market Capitalization

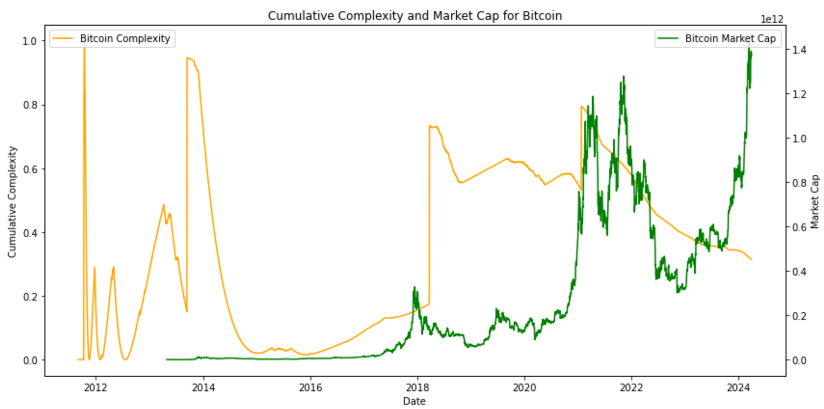

Figure 3: Bitcoin Cumulative Complexity

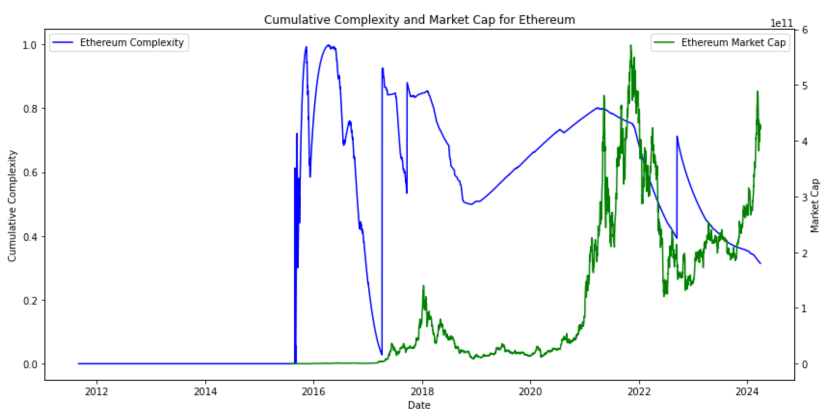

Figure 4: Ethereum Cumulative Complexity

One plausible explanation for the differing directions in correlations is that Bitcoin, being simple and restricted by design, tends to benefit from complexity associated with novel use cases and increased activity. Ethereum, which is complex and flexible by design, might experience overwhelm and strain that negatively impacts the price when there is too much complexity. The fact that Bitcoin has higher mutual information might be a result of its simpler design which is focused on narrower uses cases and contains less computational complexity. This leads to a more direct relationship between transactions, energy usage, and market demand.

It is interesting to note the cumulative complexity spikes and drops associated with major events in the cryptoeconomy. The Mt. Gox Exchange collapsed in 2013 and there are wild fluctuations in Bitcoin's complexity during its first major bull run. In 2016, when the Ethereum community dealt with the infamous DAO hack and resulting hard fork, Ethereum's complexity plummets and then sharply recovered. A gradual decline in complexity in both systems coincided with the collapses of Terra Luna, 3AC and FTX in 2021 which led to a multi-year bear market.

Further investigation and additional datasets are required to make any firm conclusions, but these initial results seem to indicate there may be value in tracking the information-theoretic complexity of these systems. The results for weekly and monthly complexity presented in Appendix A would be a good starting place for a more detailed analysis.

7 Discussion

7.1 Complexity Measurements for Cryptoeconomists

In this paper I have sought to demonstrate that it is possible to measure systemic complexity in blockchain networks, and that doing so might yield useful results. Refining this work and developing complementary approaches in a way that delivers concrete utility for complexity scientists and cryptoeconomic researchers will require a substantial interdisciplinary effort. In light of the fact that complexity has been specifically cited as a significant issue by engineers and scientists focused on public blockchains, I argue it is a worthwhile pursuit.

Buterin highlights the importance of defining systemic complexity in a way that it allows for it to be reduced in a principled manner, and has identified complexity in the Ethereum protocol as a cause of attacks and a factor which increases the likelihood of subtle bugs [36][37]. Another researcher identified the compounding complexity of Ethereum interoperability protocols as the source of poor developer and user experiences that could lead to the“downfall of the network's application dominance” [38]. Jameson Lopp, CTO of Bitcoin security firm Casa, argues that complexity is “crypto's downfall” – it is the enemy of security, a source of fragility, and a source of risk for users [39]. Clearly, the community could benefit from standardized metrics for measuring and quantifying specific forms of complexity.

7.2 Blockchains as Artificial Life

Another research angle worth exploring is the study of Blockchains as a form of virtual Artificial Life (ALife). Virtual ALife is interested in "artificial entities that exist in a virtual environment as software running on a computer or over a network of computers" and aims for these entities to actually live[40]. In 2016, cryptography pioneer Ralph Merkle described Bitcoin as a "new form of life [that] lives and breathes on the internet[41].

In 2021, planetary and earth scientists focused on origins of life research observed several "analogous" properties in the Ethereum distributed virtual machine including replication, reproduction and inheritance, and evolution. They argue that a combination of advanced technologies including autonomous vehicles, mining, and manufacturing along with artificial neural networks could allow blockchains to eliminate their current dependency on humans and evolve into fully living blockchain based-organisms. These are bold claims which seem worth exploring [42].

7.3 Lessons from Quantifying Decentralization

Decentralization, like complexity, is an important attribute of blockchains systems that is hard to define and quantify. In 2017, Balaji Srinivasan, an electrical and chemical engineer, biotech entrepreneur, and venture capitalist argued that decentralization could not be effectively addressed until it was measured[43]. Today, there is a robust body of academic literature focused on quantifying decentralization using a variety of approaches[44][45][46]. Notably information theory is embraced by Wu et al[47]. Replicating this success for complexity is important because, to paraphrase Srinivasan, we must be able to measure blockchain complexity before we can categorize its forms and address it.

A few specific approaches that go beyond information-theoretical methods and focus more concretely on the structural aspects of blockchains include graph analysis to assess smart contract complexity on the blockchain, and cyclomatic complexity to measure complexity in smart contracts[48][49]. A complexity dashboard, similar to those that have been created for decentralization would be useful for various stakeholders.[44].

8 Conclusion

To my knowledge this is the first comprehensive attempt at quantifying systemic complexity in blockchain systems. I have proposed transactions-per-watt

(TPW) as a potentially useful metric for capturing the dynamics of the key inputs and outputs of blockchain systems. It is meant to inspire further research that might support the work of cryptoeconomists who employ engineering and economic methods to create institutional infrastructure for social coordination. [50]. By embracing the types of information-theoretic measures that are widely embraced in complexity science, I hope that this work might facilitate increased collaboration between the community of complexity scientists and the community of researchers focused on public blockchains. This sort of collaboration is essential to ensure that blockchain technology is integrated into society in a way that benefits humanity.

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	Blockchain	Pearson Correlation	Pearson p-value	Spearman Correlation	Spearman p-value	Mutual Information
0	Bitcoin	0.280905	8.50e-12	0.354312	2.66e-18	0.090072
1	Ethereum	-0.106354	2.39e-02	-0.094410	4.51e-02	0.031631

Figure 5: Weekly correlations and Mutual Information Between Complexity and Market Capitalization

	Blockchain	Pearson Correlation	Pearson p-value	Spearman Correlation	Spearman p-value	Mutual Information
0	Bitcoin	0.404825	1.78e-06	0.386017	5.74e-06	0.385541
1	Ethereum	-0.030619	7.59e-01	-0.072310	4.68e-01	0.266898

Figure 6: Monthly correlations and Mutual Information Between Complexity and Market Capitalization

9 Appendix A

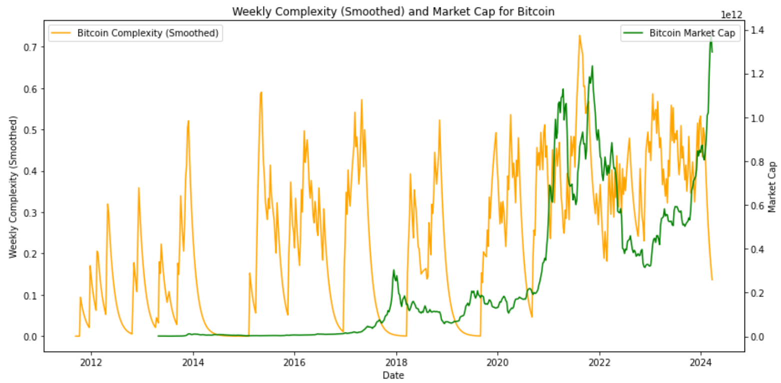

Figure 7: Bitcoin Weekly Complexity

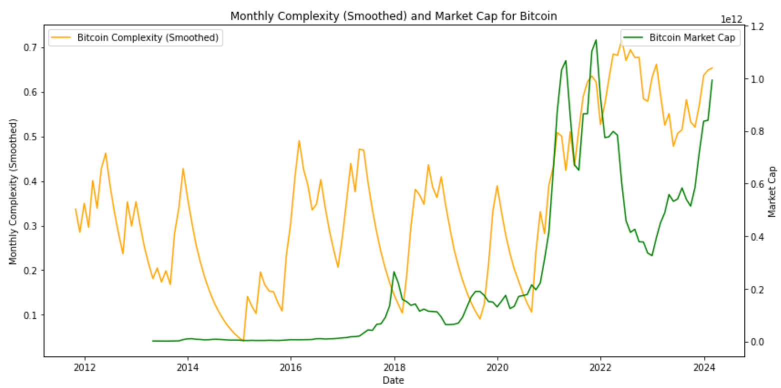

Figure 8: Bitcoin Monthly Complexity

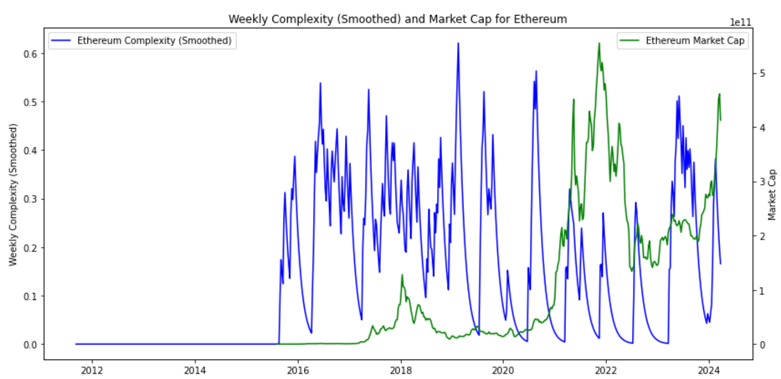

Figure 9: Ethereum Weekly Complexity

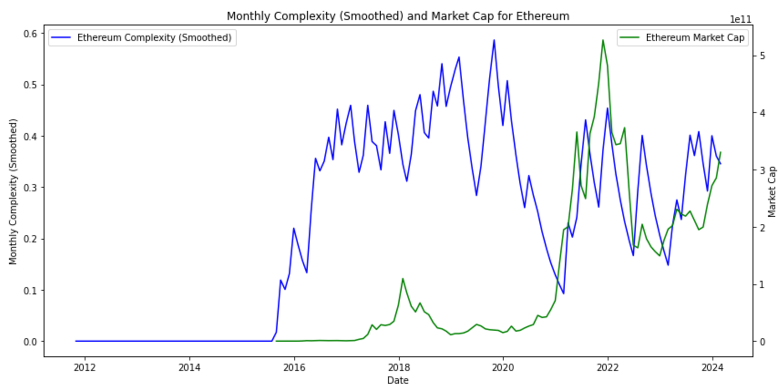

Figure 10: Ethereum Monthly Complexity