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Blockchain Networks as Knowledge Commons

RESEARCH ARTICLE

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ABSTRACT

Researchers interested in blockchains are increasingly attuned to questions of governance, including how blockchains relate to government, the ways blockchains are governed, and ways blockchains can improve prospects for successful self-governance. Our paper joins this research by exploring the implications of the Governing Knowledge Commons (GKC) framework to analyze governance of blockchains. Our novel contributions are making the case that blockchain networks represent knowledge commons governance, in the sense that they rely on collectively-managed technologies to pool and manage distributed information, illustrating the usefulness and novelty of the GCK methodology with an empirical case study of the evolution of Bitcoin, and laying the foundation for a research program using the GKC approach.

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1. INTRODUCTION

Blockchains are distributed, append-only ledgers that uniquely combine features of governments, firms, and commons (Davidson et al., 2018). Recent research on blockchain governance, informed by Ostrom's (2005) studies of commons, share the view that blockchain networks require governance and that a diversity of governing arrangements characterizes blockchain networks (Alston et al., 2022). Despite this burgeoning recent research on blockchain governance, there remain questions as to how to analyze the diversity of blockchain networks from the perspective of commons governance. In this paper, we suggest that blockchain networks are examples of knowledge commons similar to, but analytically distinct from, conventional examples of knowledge commons, including Internet infrastructures, open source intellectual property regimes, and peer production communities. We then describe how the Governing the Knowledge Commons (GKC) framework can be used to analyze the diversity of blockchains and their relationship to regulation and law. We illustrate the GKC methodology with a brief empirical study of Bitcoin, the world's first and still largest (by market capitalization), cryptocurrency.

As articulated by Madison, Frischmann, and Strandburg (2010), the GKC framework is a method of researching "constructed cultural commons," a shorthand for shared resources composed primarily of products of the human mind, namely knowledge and information in scientific domains, domains related to arts and culture, and resource domains defined largely by their human-generated character and their intangibility. "Knowledge commons" is a shorthand for governance of resources with these characteristics (Frischmann et al., 2014). Governance refers to groups or communities of people who share access to and/or use of the resource and who manage their behavior via an established set of formal and informal rules and norms. Commons are distinguished from non-commons by the institutionalization of sharing of resources among community members (Madison et al., 2010).

The GKC perspective makes precise Hess' and Ostrom's (2007) observation that information and the sharing economy have many features of a classic commons, including congestion, the need to adjudicate disputes and to coordinate among information producers and users, inequitable access and distribution, and resource sharing. Knowledge commons research highlights additional critical perspectives, including the fact that knowledge and information resources are constructed by a variety of social, technological, and legal systems; that development, distribution, and use of those resources are subject to numerous possible social dilemmas other than classic "tragic commons" overconsumption dilemmas; that commons governance strategies may be anchored in novel community or collective settings; and that both the character of those communities and the actors within them may be subject to historical contingency, power dynamics, and hierarchies of different sorts. Legal scholars took up this mantle in developing further the GKC framework and applying it to a diversity of circumstances (Frischmann et al., 2014; Madison et al., 2010). Within the domain of new commons analysis, knowledge commons has been applied to education, intellectual property rights, Internet, peer production, libraries, science, and markets (Feinberg et al., 2021).

Our core knowledge commons insight is that blockchain networks rely on collectively-managed technologies to pool distributed information. Blockchain networks are knowledge commons in the sense that they institutionalize community governance to produce resources that both support and reflect collective action and self-governing communities with respect to business objectives and other purposes. While cryptocurrencies and NFTs are "owned," their existence is due in part to the shared knowledge and resources generated by blockchain networks.

We chose a well-known case, Bitcoin, to illustrate the novelty and utility of the GKC framework for blockchains. The future steps in the proposed research agenda include comparisons of public cryptocurrencies (such as Litecoin, Ethereum, Solana, and Monero), comparisons of public cryptocurrencies with private stablecoins (cryptocurrencies whose values is linked to government-issued currencies, such as the US$, including Tether), and comparisons of public and private blockchains.

The balance of the paper is organized as follows. Section 2 reviews the GKC framework. Section 3 explains blockchains as a knowledge commons. Section 4 is our case study of Bitcoin. The conclusion discusses policy relevance of case studies of blockchain networks.

2. THE GOVERNING KNOWLEDGE COMMONS FRAMEWORK

Community or collective self-governance of knowledge, information, and data resources, by individuals who collaborate or coordinate among themselves, is a key feature of knowledge commons. Significantly, unlike research anchored in studies of natural resources, the GKC approach does not presume that resources are rival and depletable. Shared knowledge, information, culture, and data resources, such as Internet and radio spectrum, do not get depleted (Werbach, 2004), but they may be closely linked to material resources, such as human labor and expertise, that do.

Madison, Frischmann, and Strandburg (2010) built on Benkler's (2004) demonstration of the sustainability of Commons-Based Peer Production (CBPP) in open source software production and Wikipedia. They generalize the point that knowledge commons may be sustained as a mode of intellectual production with or without the presence of clearly defined private property rights, given an appropriate blend of social structure and related ideational and material resources, such as a shared collective purpose and relevant time, expertise, and/or leadership. They explained that knowledge commons are typically characterized by three features: (1) the production of knowledge resources via one or more modes of action, (2) institutions and other formal and informal structures for sharing information and knowledge resources, and (3) governance processes that depend significantly on openness (open access to resources and/or open participation by producers). The GKC framework unifies these cases under the heading "commons" to enable research to proceed in a systematic way across different specific cases and hence provides a conceptually appropriate perspective to describe governance of products of the human mind (Madison et al., 2010).

The GKC framework marries that insight to one of the key lessons of Ostrom's work: the fact that commons research is and should be empirical, rather than simply conceptual (Frischmann, 2013). The GKC framework proposes to undertake comparative institutional analysis by evaluating cases of commons resources via a series of questions, or clusters of questions, to be applied in each instance. The clusters include: (1) What are the relevant resources, considering both intangible and tangible or material resources and their individual or social character? (2) What are the boundaries and constitution (membership) of relevant governance communities, including conditions of participation, conflict resolution, and exit from an organization? (3) What are the social dilemmas confronting the specific case? (4) What are the formal and informal (norm-based) rules and practices regarding distribution and coordination of commons resources among participants, including rules for appropriation and replenishment of commons resources? (4) What is the institutional setting(s), including the character of the regime's possibly being "nested" in larger scale institutions and being dependent on other, adjacent institutions? (5) What is the structure of interactions between commons participants and institutions adjacent to and outside the regime? and (6) What are the dispute resolution and other disciplinary mechanisms by which commons rules, norms, and participants are policed?

In the GKC world, "knowledge commons" does not mean "open to the public." "Knowledge commons" means governance (i.e., rules and norms) of a shared information or knowledge resource by some collective or community. Emphasis on shared; emphasis on community or collective; emphasis on structure (governance). The result of those three dimensions (shared; community or collective; governance) may be "accessible to the public" (e.g., Wikipedia) or may not be (e.g., a patent pool). Knowledge commons governing is thus compatible with "private" ownership or control of the resource. Even Wikipedia is built on copyright in individual contributions as are open source computer programs. Corporations spend plenty of time and money managing certain of their private resources as knowledge commons, as shown in research on open innovation in the management literature (Chesbrough, 2003). Publicly-available resources, such as the contents of the public domain in intellectual property law, may be governed as knowledge commons. Privately-produced resources, such as contributions to Wikipedia or to open source software projects, likewise may be governed as knowledge commons.

Questions must be asked concerning explicit and implicit goals and objectives of governance of the knowledge commons, if any such goals and objectives exist. It is possible that commons governance regimes emerge from historical contingency rather than via planning. Likewise, a knowledge commons institution may lack an explicit account of its goals. Goals and objectives may change over time.

How "open" are the knowledge and information resources and the community of participants that create, use, and manage them? The details of the relevant aspects of "openness" should be specified, along with their contributions to the effectiveness of commons. Some commons and commons resources have precise and fixed definitions of both resources and community membership. Either resources or membership or both may be fluid, with boundaries defined by flexible standards rather than by rules.

In knowledge commons, outcomes take different forms. Patterns of participant interaction may constitute both relevant outcomes and relevant inputs. Sustaining the community itself, via its relationship to particular resources, may be the point of knowledge commons governance. Once these outcomes are identified, it is important to look back at the social dilemma(s) that defined knowledge commons governance in the first place. Has the regime solved those problems, and if not, then what gaps remain? How do the outcomes produced by commons governance differ from outcomes that might have been available if alternative governance had been employed? Costs of administration might be needlessly high; costs of participation might be high. Governance of knowledge commons may facilitate

innovation; it may also facilitate stagnation, exploitation, and/or damaging concentrations of power.

3. A CASE FOR BLOCKCHAIN NETWORKS AS KNOWLEDGE COMMONS

3.1 A BRIEF REVIEW OF BLOCKCHAIN GOVERNANCE RESEARCH

The first strand of research on blockchain governance involves a dialogue between techno-determinists who see blockchains as alternatives to government and those who see a productive and even necessary role for law and regulation in the deployment of blockchains (Rozas et al., 2021). As Atzori (2015) explains, techno-determinists see human agents as replaceable by blockchain networks and envision citizen- or participant-level administration, with people choosing their own codes of law and coordination and dispute resolution methods. In effect, this would be rule by code.

A second strand of blockchain research complements the first by focusing on the details of blockchain governance on a case by case basis rather than trying to analyze blockchain networks as a single phenomenon. Rozas et al (2021, pp. 3–4) divide inquiry into questions of governance by blockchains (the organizational processes of communities which rely at least partially on blockchain infrastructure) from governance of blockchains (the organizational processes of developers to build and evolve blockchains and their rules) (3–4).

One theme in Ostromian research on blockchains is their diversity, including differences among public (or permissionless) blockchains, such as cryptocurrencies like Bitcoin and Ethereum (Alston et al., 2022), the tremendous diversity of alternative ways of organizing blockchain networks (Allen, Berg, et al., 2021), and the significance of Ostromian analysis for empirically analyzing the extent to which blockchain networks are self-governing (Bodon et al., 2022). It also recognizes that broad typologies of blockchains, such as public versus private, cannot capture the diversity of blockchain governance within each category, as well as similarities common to public and private blockchains.

Another Ostromian theme is polycentricity of blockchain networks, including the ways in which "external" rules (laws and regulations) influence any given network's performance (Alston et al., 2021), how quality and feature competition enable users to shop across blockchains to find the one(s) that have characteristics most suitable for their preferred transaction(s) (Alston, Forthcoming), the dynamics of entry and exit from blockchains (Berg and Berg 2020), and the ways that disputes are resolved (Howell & Potgieter, 2021). Additional research highlights resolution of disputes on blockchains (Allen, Lane, and Poblet 2019), including conflict arising from reliance on oracles to interface between the real world of data based on human behavior and the algorithmic world of blockchains (Poblet et al., 2020), and the internal dynamics governing choice of protocols to govern blockchain networks (Cowen, 2019).

3.2 INSTITUTIONALIZED COMMUNITY GOVERNANCE

Our application of a GKC approach sees blockchains as a form of community governance. The relevant community in any blockchain network includes different sorts of people with different roles, including code developers, miners (and not just individuals, of course, but organizations), and "ordinary" users (people who simply hold cryptocurrencies in wallets, or own NFTs, etc.) (De Filippi & Loveluck, 2016). Allen and Potts (2016) similarly locate the origin of new technologies in knowledge commons consisting of self-organizing groups of technology enthusiasts. Patterns of cooperation and coordination are multi-dimensional, depending on what kinds of activities are involved, even if everything is resolved "on" the chain (or "on" a different chain). It is therefore too simplistic always to refer to "the community" engaged in blockchain governance without exploring the composition and dynamics of relevant groups. As other research on blockchain networks has argued (Allen & Berg, 2020), identifying additional participants and delineating their community status and governance contributions is critical and may be challenging. Founders and investors may play key roles in addition to developers, miners, and holders. Stakeholders such as government regulators and participants in social media may affect and be affected in multiple ways by practices on and in blockchain networks. Much like research on Wikipedia and open source software has found, blockchain is not purely "democratic" and harmoniously horizontal as Benkler (2002) contended in early work on open source communities.

The resources are, principally, information and data that is produced and maintained by the users of that blockchain and is, by definition, accessible to all of them who have access rights. Some are material resources (in the blockchain space: electricity, computing power, etc.); some are immaterial resources (in the blockchain space: time, labor of human beings – some expert labor, some non-expert labor, and information encoded in blocks). The knowledge or information shared on a blockchain is itself an important resource to differentiate. Shareable attributes – each potentially subject to different governance strategies – may include both the technical attributes of each block and its semantic attributes (what, or whom, the block refers to, if anything) as well as both the technical and semantic attributes of the blockchain network as a whole. In

addition to the technical protocols and computer programs that constitute the blockchain network, the Internet is a shared resource with consequences for blockchains. The Internet is not itself a resource shared in or by blockchain networks; instead, the Internet is a resource on which blockchain networks rely, so that disruptions to the former are connected in complex ways to changes in the latter. It is useful to keep the "pool" metaphor at the center. What is pooled? Who is doing the pooling, and how? These attributes of a blockchain network are typically not the products of top-down decisions by founders or developers; instead, they are characteristically "bottom-up" results of collective activity.

The fact that this information is collaboratively produced and necessarily shared responds to social dilemmas associated with producing and maintaining the identity and integrity of objects in broadly distributed, often anonymous social systems and with resolving conflicts as to priority of interest. Systems for producing and distributing objects of all sorts cannot thrive without participants having appropriate assurances regarding the identity of objects that they are acquiring and using. Equivalent information can be assured by governments, which may issue deeds and other documents of title and operate recording systems for real and personal property, or by regulated markets, via contracts, insurance, and financial instruments. Knowledge commons, in the form of blockchain networks, can and do supply accurate object-specific information. In practice, blockchain networks may fail to do so; they can supply reliable information about blockchain tokens themselves but not necessarily reliable information about objects or resources to which tokens refer.

3.3 SOCIAL DILEMMAS

We argue that knowledge commons governance acts as an institutionalized response to social dilemmas regarding shared knowledge and information resources. By "social dilemma" we mean a context-specific conflict between individual welfare and social welfare. A social dilemma is often described as a conflict between rational choosing at the individual level and the product of rational choice at the collective level. The metaphorical tragedy of the commons fits that model, as one prototypical collective action and coordination dilemma. Our use of the phrase "social dilemma" is not constrained to rational choice expectations or to the premise that we are exploring only choice-directed activity. Individual and collective action in the real world is subject to behavioral and cognitive constraints. Welfare at many levels is subject to various historical contingencies.

For blockchain networks, the key, intuitive starting point for describing social dilemmas is the proposition that various social and economic systems depend on mechanisms for describing objects and assets in stable, secure, reliable, and timely ways, often as inexpensively as possible. Information standards often provide those mechanisms; third-party registries and insurers may do so; formalized legal categories enforced by governments can stabilize information systems; affordances of objects embedded in systems of social norms and practice offer another approach. Madison (2005) offers a taxonomy of techniques that the legal system has used to identify and define objects, borrowing partly from systems of social norms, partly from market transactions, and partly from practical reasoning. Larger social systems, with more actors and possibly diverse objectives, threaten that relative economy of information with information complexity. Both individual actors and collections of actors may prefer more detailed specification of attributes to a less detailed one, or the reverse, or may prefer to disrupt an established mechanism for selfish or nefarious reasons by adding or removing types of attributes or attributes associated with specific objects.

For blockchain networks, the following inventory of relevant social dilemmas is a starting point. For research purposes, these are hypotheses, and as such, not each hypothesis will be relevant in each context, and sometimes, hypotheses will be interconnected. They vary in terms of the level of governance generality that each one addresses.

- What conflicts exist between the affordances offered by the structure or system in which information is shared, on the one hand, and the agency of actors operating in that system, on the other hand?
- What conflicts regarding object identity and integrity stem from divergence in governance as to the intangible attributes of an information object relative to governance as to physical or other material attributes in which that information object is embedded?
- What conflicts arise based on spillovers from a system in which information is shared in adjacent systems, markets, or communities, whether those spillovers are positive or negative, or intended or unintended?
- Is information sharing in context a source of cultural or economic stagnation, or waste?
- Is information sharing in context a source of overload in terms of individual cognition or in terms of a system's ability to generate, store, and/or process information in a timely and reliable way?

This list is provisional and illustrative of the dilemmas and types of dilemmas to which a pool of shared knowledge or information might be subject. In different combinations, they may call for governance. The GKC framework offers a way to systematize research into the precise character of the dilemmas and the governance arrangements that exist to address them.

3.4 RESOURCE SHARING

Given that summary of social dilemmas, it is apparent that blockchain networks may be the source of social dilemmas as well as solutions to social dilemmas. While we emphasize the latter, we understand that a full account of a blockchain as knowledge commons governance should look to interdependencies and feedback loops among solutions and problems. Understanding the dynamics of sharing is key.

One of the purposes of blockchains is to share resources, where these resources include knowledge, data, and opportunities to use outputs created by networks (we highlight opportunities since the outputs, such as tokens, can be privately owned). Knowledge commons involve institutional solutions to innovation problems in which knowledge, information, and resources are pooled under defined governance rules that enable communities to access those inputs into innovation (Potts, 2019). The information produced by blockchain networks can be accessed by community members, including information that is transparent and accessible to participants (Allen, Davidson, et al., 2021). Transparent protocols constitute shared knowledge resources as well (Potts 2018).

Blockchain networks rely on sharing of resources in nested, or layered, patterns; each layer should be considered both part of a macro system of knowledge commons governance and potentially a micro knowledge commons layer in itself. Blockchain networks rely on open source code (a shared resource) to develop smart contracts (which may circulate in private blockchain networks). The Ethereum cryptocurrency relies on shared code stored in a GitHub repository, a code sharing resource that is currently owned and operated by a private firm, Microsoft. Each of those layers depends not only on sharing information and code within that layer but also on shared expertise of coders and users that may cut across layers.

Private blockchains have boundaries and very in the degree they are centralized (Alston, 2020). Public blockchains also vary in boundaries and centralization; some, such as Cosmos (an ecosystem of blockchains interacting with each other), promise greater decentralization of governance as a key feature, as decisions about the evolution of the blockchain are not made by key programmers and investors of any single blockchain network. Private blockchains define boundaries of users and establish protocols that define how governance is structured. These features are more akin to a traditional firm but differ in the ways that blockchain technologies unlock potential for decentralized innovation, opportunities for participation in governance, and in the reliance of the network on shared resources.

The openness of blockchains is a feature of knowledge commons more generally. The openness of participation is especially significant with public blockchains, as essentially anyone can become a participant and may opt to participate in that blockchain's governance. Private blockchains are closed in the sense that that boundaries between insiders and outsiders is not porous, but knowledge commons governance concepts – such as the character of participation, the manner in which resources are shared and governance is managed on the blockchain, and the extent to which the private blockchain depends on resources provided by public blockchains – may nevertheless illuminate important features of how those blockchains function. Openness is not, however, always a pure or unmitigated good in knowledge and information systems. The GKC framework is premised in part on the intuition that open and participatory collective governance of knowledge resources can be sustainable and productive (Madison et al., 2010). But as in Hess' and Ostrom's call for research on knowledge sharing, open access, and commons practices (Hess & Ostrom, 2007), the GKC approach suggests that openness and its possible benefits are matters for empirical study rather than only premises to be assumed. Different attributes of knowledge commons may be open or not, and to differing degrees and to different effects.

3.5 ADVANTAGES OF THINKING OF BLOCKCHAIN AS KNOLWEDGE COMMONS

Conceptualizing blockchain networks as knowledge commons is useful for several reasons. Blockchain networks are subject to similar governance issues that arise with any knowledge commons, such as power concentrations. There is no unique ruleset across all blockchains; the character and the content of the rules is one of the key questions raised in knowledge commons research. The multiplicity of blockchain networks means that there are abundant opportunities to distinguish commons governance from non-commons governance even with this blockchain context, and to sort similarities and differences in opportunity, power, and transparency. For example, all blockchain networks rely on power differences that arise from reliance on miners to translate physical resources into outputs that can be used by community members.

Treating blockchain networks as knowledge commons brings this research in line with research on CBPP communities, which Benkler (2002) defined as a non-market, non-government sector of information, knowledge, and cultural production. Its defining features are ethics of open sharing and cooperation, enhanced by the Internet and open source software. Similarly but distinctly, blockchain networks are part of the non-market, non-government sector of information, knowledge, and cultural production defined by an ethic of sharing and cooperation anchored in self-governing communities, enhanced by the Internet and open source software. To be

sure, blockchain networks are linked to and in some respects incorporate features of commercial markets. Miners are are compensated for contributing their computational work to the pool, in block rewards and sometimes, and to a far lesser extent, in transaction fees. Blockchain networks not merely examples of CBPP communities, either; they have certain properties (transparency, immutability, and openness) that not all peer production communities have. For example, Helium – which is hailed by its developers as "the people's Internet" – is a blockchain-based application that enables creation of wireless hotspots because of blockchain's affordances and that operates as an infrastructure for potentially any CBPP community. More generally, the extent to which blockchains can assist in self-governance of CBPP communities depends on the ability of blockchain networks to resolve knowledge commons dilemmas.

3.6 THE ROLE OF PRIVATE PROPERTY IN KNOWLEDGE COMMONS

Blockchain networks involve private uses. Miners receive rewards; they work because they are paid. People who purchase nonfungible tokens (NFTs), an increasingly popular and valuable blockchain application, own them (Vee, 2021). If you buy a token, it's yours. Property rights to digital assets can be stronger that property rights enforced by law because they are enforced by cryptography. To an extent, digital assets are also scarce by design, including cryptocurrencies and NFTs. And while public blockchains may be decentralized in that the verification of information does not require a trusted party, it is possible to gate them with token ownership to enforce boundaries.

The GKC approach sees the private property approach as missing important aspects of knowledge commons governance of blockchain. First, knowledge commons perform an important infrastructural function that is often neglected in considering the private aspects of new commons (Frischmann, 2012). Just as market supporting institutions are knowledge commons (Dekker & Kuchar, 2021), blockchain networks support a wide range of market transactions, such as allowing people to purchase and hold tokens, to write smart contracts for their business, and nonprofits to use distributed ledgers to set up crowdfunding. In addition, any given private blockchain owes its existence to the knowledge and resources generated by blockchain communities such as Ethereum, which provides the architecture for smart contracts.

Second, a GKC perspective provides a potentially richer analysis of boundaries of the community or collective: who is a member or participant (and in what respects), and who is not? How do people get included? How do people get excluded? What kinds of access do participants have relative to the commons (shared) resource(s)? Who has access to use resources? To take? To contribute? Who can modify the pool?

Third, GKC distinguishes between bounded-ness of the shared resource, that is, the pool, and the definability of any resource units that are identifiable within the pool. Sometimes, as in, say, water systems, "resource units" are entirely fictitious, because they are created by legal rules. Sometimes, as in blockchains, the resource units are cryptographically distinct. Hence, "boundaries" do not define blockchains, because "boundaries" in a unit-specific setting tends to point people toward "property rights," and "boundaries" of property are almost always porous – in legal terms, if not necessarily in physical terms.

This can be further illustrated by considering Hendrickson's (2021) cogent argument that a property rights approach can explain NFTs, in particular the value or prestige of ownership. His evidence is two popular forms of NFT art, CryptoPunks and Bored Apes Yacht Club (BAYC). As BAYC includes broader IP rights relative to the NFT asset (rights to reuse the NFT commercially, for example) compared to CryptoPunks, a property rights theory could explain why the price of BAYC is going up, and CryptoPunks is declining. In Hendrickson's account, property rights are valuable in the blockchain context and explain differences between the performance of two, competing blockchain networks.

Knowledge commons thinking suggests that differences in value between different NFT systems are possible in part because each consists of a distinct decentralized application on the Ethereum blockchain. Each application has its own governance relative to transferability and reuse of NFTs and relative to external IP law; NFT prices (among other attributes of NFT systems) bear no standard relationship to the existence or nonexistence of IP rights in objects to which NFTs refer. This example illustrates the nested, polycentric character of blockchains. The fact that both are valuable illustrates that private property is not necessary for NFTs to have economic or cultural value. Value may derive from the character of the community and its governance. From a knowledge commons perspective, the fact that people buy CryptoPunks is not as surprising as it may be from a more strictly private property perspective.

4. AN EMPIRICAL STUDY OF BITCOIN

4.1 A DESCRIPTION OF THE BITCOIN NETWORK AND ITS RELATED SOCIAL DILEMMA

The first step in in applying the GKC framework to Bitcoin is to consider the social dilemmas it addresses. As a peer to peer cryptocurrency, Bitcoin is a blockchain application that enables users to transact using cryptocurrency. Transactions are initiated when senders broadcast proposed transactions to the network, with (depending

on the network and depending on the transaction speed desired by the sender) an attached network fee. The transactions are then processed by miners who collect proposed transactions into a block and verify if the sender of the proposed transactions has sufficient funds. To do this, miners must solve cryptographic puzzles to be able to attach new blocks to the public chain. Bitcoin's consensus mechanism is Proof of Work, which assigns tasks to miners based on their computing power and which, as we discuss below, contributes to governance dilemmas involving concentrations of power. Assignments based on computing power privileges mining collectives.

The shared information resource – the ledger of verified transactions that is distributed across all nodes of the Bitcoin network, documenting transactions in Bitcoin, which are resource units – addresses a specific social dilemma, namely an alternative currency for those who may not see government currency as reliable (Berg 2021). Bitcoin is more adaptable to different contexts and less amenable to regulatory oversight than government-sponsored or market-supported systems, and hence has the potential to disrupt existing payment and perhaps monetary systems (Böhme et al., 2015).

As a solution to that dilemma, Bitcoin offers several affordances that have been described in analysis of cryptocurrencies (De Filippi & Wright, 2018). Bitcoin is transparent in that no single individual controls information (the full history of the blockchain is publicly available to network users) and distributed in that the governance authority for processing and validating transactions resides with some probability with all network participants (Luther and Stein Smith 2020). Bitcoin's protocols are embedded in open-source programs that also make the code-based process transparent itself to any interested party. Bitcoin's operation rules are transparent in that any party has knowledge of its features, such as the number of tokens (though not exactly how many are still active, as some may be lost), its money supply and growth rates. It is immutable in that attempts by any individual to tamper with the system, such as through double spending, will be rejected by other nodes. It is an open system, at least in principle, in that anyone can participate by acquiring existing Bitcoin (by purchasing it or receiving it in exchange for services) or by "minting" new Bitcoin (Bitcoin are stored in secure digital wallets). Bitcoin is democratic in that anyone can technically participate in change in the rules (Berg, Davidson, and Potts 2018).

4.2 RULES WITHIN THE BITCOIN NETWORK

The second step is to articulate the rules governing Bitcoin. Like other public cryptocurrencies, Bitcoin is governed in its day-to-day interactions by algorithmic protocols running on open-source software. Since blockchain networks are complex organizations and cryptocurrencies are governed autonomously, they require updates and maintenance, which is usually done by software developers who propose alternative software. These choices are subject to negotiation and debate within the Bitcoin community and are adopted only once consensus is reached (De Filippi & Loveluck, 2016).

Alston (2020) contends that public blockchains like Bitcoin create unprecedented participation in governance authority compared to any other monetary system, as members are essentially designing their own constitutions. Change in Bitcoin's internal rules occur through a distributed process. Consensus algorithms or consensus rules are the rules that determine how protocols are updated. With Bitcoin, as with any public blockchain, any knowledgeable person with access to the technology to become a potential decision-maker on the network. Developers have influence through their ability to propose updates to protocols, but that influence may be countered by that of miners.

Still, Bitcoin's decentralized character does not eliminate concentrations of power in developers, investors, programmers, and miners with more computing power. Bitcoin's network has been described as operating like a cooperative managed by a small group of individual leaders (core developers and investors) whose decisions ultimately govern the service provided (Alston et al., 2022).

4.3 BITCOIN AND THE INSTITUTIONAL CONTEXT

The third step, analyzing relevant institutional settings, including legal regimes relevant to Bitcoin, is a key aspect of knowledge commons analysis. Though legal scholars have not generally viewed blockchain and law as incompatible, the GKC framework makes this ongoing relationship explicit by considering how additional layers of legal or regulatory authority address challenges.

Innovation opportunities depend in part on what regulators and the law enable. Alston et al (2021) refer to this aspect of blockchain networks as superior governance, which refers how blockchains relate to the legal and regulatory apparatus in a nested, polycentric enterprise. In this context, "superior" refers to governance institutions external to blockchains, though in polycentric systems, the divide between external and internal rules is often less important than the interaction between rules arising from a given blockchain network and those which are enforced primarily by governments. Initially, the question of Bitcoin regulation asked whether regulators could ban cryptocurrencies and, if so, what the consequences would be (Hendrickson & Luther, 2017). Since then, legal analysis has focused on the question of how law can assist in the evolution of blockchain, including Bitcoin, and on the extent

to which blockchain systems are not truly independent of external legal foundations.

Bitcoin implicates property, contract, tax, and securities law. From a property perspective, a significant question is the scope of the legal rights that come with ownership of a digital wallet, such as how Bitcoin might be used as collateral for a loan. Contract law is evolving to recognize that transactions on blockchains, including those involving Bitcoin, are legally binding, though for that to occur, it is necessary for the law to say so (Werbach & Cornell, 2017). As to tax law, Bitcoin mining is likely a taxable activity, but principles and practices for applying tax law is unsettled (Alston et al., 2021). Securities law, so far, has not posed a regulatory hurdle for Bitcoin, but the character of the intersection between cryptocurrency and securities law depends largely on how the blockchain application is used, such as in connection with investing activity (Mendelson, 2019).

Further legal complexity arises precisely because of the distributed character of the blockchain. International commercial law has evolved a complex set of regulatory and market-based instruments for cross-border currency and commercial transactions. Bitcoin is presently the subject of a pattern of inconsistent jurisdictional rules. In some jurisdictions, Bitcoin cannot be privately held. In others, individuals can hold Bitcoin, but private banks cannot. In the US, Bitcoin is mostly regulated as a commodity, much like gold or silver, but differences persist between federal regulators and state regulators, and between different state regulators.

4.4 INTERACTIONS BETWEEN BITCOIN USERS AND OUTSIDERS

A fourth step is to consider how Bitcoin relates to users outside the Bitcoin network, or to participants and institutions adjacent to and outside the regime, and how it resolves disputes between users and non-users. Since Bitcoin is used by many, and has many uses, interactions with users and non-users are significant. This also invites consideration of competitive governance aspects of blockchain, as who is a user and non-user is fluid: individuals choose Bitcoin or not. Patterns of entry, exit, and voice (described below) create competitive forces that influence the governance of Bitcoin and how competing currencies (altcoins) organize qualities and features for their own provisioning of services. Non-users include both holders of alternative cryptocurrencies and users of traditional fiat currencies.

One important question is how Bitcoin competes with altcoins, as well as how it continues to dominate the cryptocurrency market. For our purposes this involves ensuring that users remain users, rather than becoming non-users, as well as attracting users. One way to think about Bitcoin's relationship to users and non-users is with quality and feature differentiation. Given the availability of altcoins, switching costs offers a distinct, related way to approach the question. One competitive feature is speed of processing and the related environmental (energy) cost of updating the ledger. Bitcoin creates new blocks every ten minutes, and merchants and exchanges usually wait 60 minutes before confirming a transaction. This, for users, is not fast enough for transactions that are often done instantly, and the Proof of Work (PoW) contest that validates each transaction is enormously wasteful in environmental terms. Concentration of governance power in certain developers and large miners may also contribute to reduced security of Bitcoin networks. Since Bitcoin is not as private as some users might like, and it experiences large fluctuations in exchange rates against fiat currencies, there are opportunities for product differentiation. Mining is another area where there can be differentiation. PoW favors larger miners, as they can mine more with specific machines that are costly. Proof of Stake (PoS) blockchain systems, such as the Solana cryptocurrency, reduce the environmental wastefulness of PoW in validating transactions by rewarding computational efficiency rather than simple processing power.

This provides a way to think about knowledge commons as a function of user engagement; governance of Bitcoin is disciplined by the fact that users can stay and participate or can exit and join one or more alternative communities. Competitors to Bitcoin offer faster processing of transactions, more accessible mining algorithms, more flexible application options, and other protocol choices that democratize the mining process. Consensus mechanisms are equality differentiations. Distinguishing networks based on consensus mechanisms, network transparency, block size, type of cryptographic hash puzzle, and many more network characteristics that provide margins of choice for protocol designers: for example, Tether promises more stability than Bitcoin because it is pegged to a currency; Ethereum can support smart contracts and DAOs; and Monero, which makes transactions almost impossible to trace, offers superior privacy. These alternatives constitute opportunities for choice of relatively autonomous cryptocurrencies. These added exit options in turn create opportunities for voice (A. Berg & Berg, 2020).

4.5 DISPUTE RESOLUTION ON THE BITCOIN NETWORK

Disputes about blockchain attributes are an ever-present feature of cryptocurrency networks, including Bitcoin, with outcomes that, to date, reflect either consensus resolution and continuing operation of the platform, or forking, with

the dissenting group launching a new application. These are more than mere technical debates; power concentrations by developers and miners are a concern (Böhme et al., 2015).

To illustrate, a debate over block size gave rise to a governance crisis and, ultimately, to the creation of Bitcoin Cash (De Filippi & Loveluck, 2016). De Filippi and Loveluck (2016) review governance issues arising over block size with Bitcoin. Block size determines how many transactions can be included in a block; the smaller the block size, the slower the performance of the blockchain. Bitcoin was initially fixed as one megabyte, a low limit that arguably increased security of the blockchain and limited the concentrated governance power of larger miners. Users became concerned that Bitcoin could not handle increasing volume of transactions in a timely fashion. The example of credit cards, which can be hundreds of times faster than Bitcoin in processing transactions, was often invoked. The fear was that users would be driven to competing networks to make transactions. The result of users' objections was a hard fork, resulting in a new blockchain network, Bitcoin Cash (BCH), with a 32 megabyte block size.

An analogous example can be drawn from the experience of the Ethereum blockchain. In 2016, Slock.it, a small blockchain company, launched The DAO on the Ethereum platform that allowed cryptocurrency investors to manage their business in Ethereum's digital currency, Ether. After $150 USD million was raised through a token sale, a hacker figured out how to steal from the pool of funds, but the automated system was unable to immediately stop the outflow of funds because it was autonomous and decentralized. Soon afterward, Vitalik Buterin and several allies proposed to reverse the transactions and return the stolen funds to investors, while others objected because they thought that doing so undermined the immutability of blockchains. The result was a hard fork, which occurs when two independent blockchains with identical histories emerge following a governance dispute. Buterin continued to play a leadership role in Ethereum, which reversed the disputed transactions, while the new chain, Ethereum Classic (ETC), did not and allowed the diverted funds to continue to exist.

5. CONCLUSION

Blockchains are complex organizations that combine aspects of regulatory and algorithmic law, private and public systems, with substantial uncontrollability and arbitration (Frolov, 2021). The GKC approach is a useful framework for empirical studies of blockchains that is attuned specifically to the social dilemmas associated with knowledge resources. Our case study of Bitcoin illustrates its utility in a preliminary way.

In pragmatic, policy terms, an empirical methodology, and an empirical research program, is useful as these law-code hybrids evolve. Analysis along the lines suggested by the GKC framework has the potential to inform regulations to more fully account for both the similarities and differences among blockchains, including public cryptocurrencies.

In conceptual, longer-range terms, conceptualizing blockchain networks as knowledge commons offers the ability to add a considerable amount of case-based research to the growing field of knowledge commons governance. Blockchain networks are both significant research opportunities in themselves and also important opportunities to compare and contrast them as knowledge commons institutions with other well-studied knowledge commons cases, such as CBPP. The GKC framework invites additional case studies as well as comparative research, such as how legal regimes account (or fail to account for) differences in blockchain networks. As the field of GKC-based research is comparatively young (the foundational paper is (Madison et al., 2010), techniques for conducting comparisons will co-evolve with research results. The character and purposes of blockchain networks may evolve as well, calling for adaptability on the part of researchers. Given the tremendous diversity of blockchains, and experience with successful and unsuccessful governance, it is the right time to initiate empirical research programs informed by knowledge commons thinking.

COMPETING INTERESTS

The authors have no competing interests to declare.

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