Corporate Capture of Blockchain Governance*

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Abstract

We develop a theory of blockchain governance. In our model, the *proof-of-work system*, which is the most common set of rules for validating transactions in blockchains, creates an industrial ecosystem with specialized suppliers of goods and services. We analyze the interactions between blockchain governance and the market structure of the industries in the blockchain ecosystem. Our main result is that the proof-of-work system leads to a situation where a large firm captures the governance of the blockchain.

Keywords: Governance, Blockchain, Industrial Ecosystem, Proof-of-Work

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1. Introduction

"*The greatest challenge that new blockchains must solve isn't speed or scaling – it's governance.*"[1]

Bitcoin's founder Satoshi Nakamoto (2009) describes the need to trust intermediaries (such as banks) and central authorities (such as the central bank) as "*the root problem with conventional currency.*" To solve this problem, Nakamoto created Bitcoin, which is a blockchain that functions as a "*system for electronic transactions without relying on trust*" (Nakamoto, 2008). A blockchain that does not rely on trust requires rules that can be enforced in a decentralized manner. As blockchain stakeholders' views about the adequacy of the existing rules evolve, these rules may change over time. Therefore, blockchains also need a governance system for deciding how to change their rules.

Similar to most political and corporate governance systems, blockchain governance typically relies on a combination of "voice" (i.e., voting) and "exit" (i.e., ceasing to use the blockchain). The largest blockchains (such as Bitcoin and Ethereum) adopt a voice mechanism that assigns more "votes" to those stakeholders with more computational power. Such a system is called *proof-of-work*: "*[proof-of-work] solves the problem of determining representation in majority decision making. (...) Proof-of-work is essentially one-CPU-one-vote*" (Nakamoto, 2008).[2]

In this paper, we develop a theory of governance in proof-of-work blockchains.[3] We use the model to investigate the feasibility of governance without trust, as originally envisioned by Nakamoto. Our main result is that the proof-of-work system may lead to a situation where a large corporate stakeholder captures the governance of the blockchain.

In the proof-of-work system, players, called *miners*, enter a competition in which a single winner is allowed to add a *block* (a set of transactions) to the chain. To win, a miner must solve a mathematical puzzle that requires significant computational power. The probability of a miner being the first to find a solution is proportional to the amount of computational

[1] Kai Sedgwick, "Why Governance is the Greatest Problem for Blockchains to Solve," July 15, 2018, https://news.bitcoin.com/why-governance-is-the-greatest-problem-that-blockchains-must-solve/

[2] Hinzen, Irresberger, John, and Saleh (2019) show that proof-of-work is the leading consensus protocol among public blockchains.

[3] Our focus is on permissionless blockchains (i.e., anyone can join the blockchain in any role). For a discussion of permissioned blockchains or public blockchains with permissioned record-keepers, see, e.g., Chod and Lyandres (2018) and Cong, Li, and Wang (2019).

power they allocate to the process of mining a block. This process – called *mining* – sometimes (intentionally or unintentionally) generates multiple copies of the blockchain. If there are two conflicting versions of the same blockchain, miners collectively "vote" for their preferred version by allocating their computational power to one of the chains. Typically, the chain with more computational power is the one more likely to win; the losing chain is either abandoned or rebranded as a separate blockchain. Thus, the proof-of-work protocol is both a block creation system and a "governance through voice" mechanism.

If stakeholders such as users, merchants, or exchanges disagree with the majority of miners, these stakeholders may stop using the blockchain. Thus, exiting is also a governance mechanism. This mechanism has limitations. First, blockchain usage has network externalities: a blockchain is more valuable when there are more adopters.[4] Second, there are significant coordination issues, leading to multiple equilibria (Biais, Bisière, Bouvard, and Casamatta, 2019; Arruñada and Garicano, 2018). Stakeholders who consider exiting face a trade-off: they can either stay in an inefficient network or exit and risk coordination failures. Because exit is not a perfect governance mechanism, miners (who are the only ones with "votes") typically have a significant influence on the governance of blockchains.

Nakamoto's vision of governance by proof-of-work did not anticipate that block mining would become a specialized activity. The emergence of mining as an economic activity has led to the development of an ecosystem of industries that supply goods and services to miners. These goods and services providers are also stakeholders of the blockchain community, and they can affect the governance of blockchains. They have an economic interest in pushing for rules and protocols that increase demand for their products, raising their profitability.

In our model, we analyze the interactions between blockchain governance and the market structure of the industries in the mining ecosystem. Most mining is performed not by CPU but by specialized equipment that uses *application-specific integrated circuits* (ASIC), which are chips designed to perform a single function: block mining. In addition to specialized equipment, miners also buy mining services from *mining pools*, which are companies that sell insurance to miners.

The model is as follows. Mining requires computational power to generate tentative solutions to the mining puzzle. Each tentative solution is called a *hash.* By making ex ante investments, firms can develop the ability to produce specialized equipment that delivers

[4] For an analysis of the limited adoption problem, see Hinzen, John, and Saleh (2019).

more hashes per unit of time (the *hash rate*) than the existing available technology (e.g., CPU or GPU). Hash rate (which is a measure of computational power) is a homogeneous good. The combination of ex ante sunk costs and a homogeneous good creates a first-mover advantage: a firm that enters early in this market is likely to remain as a profitable incumbent. Even a small entry cost may be sufficient to deter further entry (Stiglitz, McFadden, and Peltzman, 1987). The model thus implies that a single firm dominates the market for specialized mining equipment.

Mining pools offer differentiated services (see Table 1). Miners are heterogeneous in their preferences over mining pool attributes, and differentiated mining pools compete for miners by choosing fees. All else being constant, lower pool fees leave more surplus to miners, making mining a more attractive activity, thus increasing the demand for specialized mining equipment. That is, the equipment producer and the mining pools are "complementors," in the sense used by Brandenburger and Nalebuff (1996). The equipment producer benefits from lower pool fees by selling more equipment. Thus, the equipment producer has incentives to "squeeze" the mining pools, that is, to take actions that are likely to reduce profits in the pool services market (Farrell and Katz, 2000; Chen and Nalebuff, 2006).

We consider two types of profit squeezes. First, when an equipment producer already owns and operates a mining pool, it competes more aggressively with the other mining pools, resulting in a lower average fee in that market. Second, an equipment producer that does not own a mining pool has strong incentives to enter that market. In either case, the conclusion is that the equipment producer ends up controlling a large share of the mining pool services market. Mining pool managers typically decide how to allocate their pools' hash rate when two competing versions of the blockchain coexist. Thus, by acquiring a large share of the pool services market, the equipment producer has a disproportionate influence on the governance of the blockchain.

We show that the equipment producer has economic incentives to control a large share of the total hash rate even if there is no stakeholder disagreement about how the rules of the blockchain should change. That is, blockchain governance capture is a by-product of the equipment producer's incentives to squeeze the profits of the mining pools. If other stakeholders disagree with the equipment producer, the latter has an additional motive for acquiring control over votes: the equipment producer now wants to steer decisions towards its preferred direction. We show that in this case, the equipment producer may also choose to *self-mine* (i.e., proprietary mining of blocks) in order to acquire a larger share of the votes. Interestingly, self-mining occurs in equilibrium even if the equipment producer has no comparative advantage at mining.

Our model fits the description of the Bitcoin mining ecosystem, where a dominant specialized equipment producer is also the largest player in the pool services market. Bitmain Technologies, a private Chinese (PRC) company, is the leader in the ASIC-based cryptocurrency mining hardware industry, with approximately 74.5% of the global market share (Bitmain Prospectus, 2018). Bitmain is also a large player in other segments of the crypto-mining ecosystem. Bitmain fully owns and operates two of the largest mining pools, AntPool and BTC.com, and is also the main investor in another large mining pool, ViaBTC. Many of the other large mining pools are also business partners of Bitmain (see Table 1).[5]

Large stakeholders face a trade-off between the value of their stake in the blockchain and the private benefits they extract from it. For example, an equipment producer is likely to oppose proposals that make the use of specialized mining equipment costlier. ASIC mining is less efficient in the Ethereum network precisely because stakeholders have supported upgrades that make ASIC mining more difficult. Consequently, for the purpose of maximizing the social value of the blockchain, one cannot rely on a large stakeholder's private incentives.

There have been some instances when Bitmain has used its control over a substantial proportion of the hash rate to leave its mark on the governance of blockchains. Control over the hash rate can be used to enforce a blockchain split (sometimes called a *hard fork*). The most famous hard fork of the Bitcoin blockchain was the one that created Bitcoin Cash on August 1, 2017, which resulted from unresolved disagreements among members of the Bitcoin community concerning changes to the size of blocks. A few large players in the Bitcoin ecosystem, including the Bitmain-affiliated pool ViaBTC, sponsored the creation of the new currency, which shared the same history as Bitcoin but had a larger block size. On November 15, 2018, Bitcoin Cash itself split into two competing blockchains. Bitmain rallied behind Bitcoin Cash ABC against Bitcoin Cash SV, in what became known as the "hash wars." The prices of both currencies fell steeply right after the split, as did the prices of Bitcoin and other cryptocurrencies. Blockchain splits are costly. Because of network externalities, splits may reduce the long-term value of a blockchain. In the short term, splits

[5] For detailed evidence of the evolution of mining pool market shares, see Romiti, Judmayer, Zamyatin, and Haslhofer (2019).

may negatively affect the liquidity of a cryptocurrency, increasing volatility and hindering adoption.[6]

Not all blockchains use the proof-of-work protocol. For example, some blockchains rely instead on *proof-of-stake* protocols, in which the probability of becoming a block producer is proportional to one's "stake" in the network. As our model is about proof-of-work, we do not consider these alternative protocols. However, our analysis has broader implications, which could also be relevant for understanding blockchain governance under alternative protocols. Our key message is that to understand the workings of the governance of a blockchain, we need to consider the structure of the ecosystem of industries that serve the block producers.

There is a growing theoretical literature on the economics of cryptomining. Starting with Dimitri (2017), a literature has developed on competition among miners that also produce their own equipment (see Arnosti and Weinberg, 2018; Ma, Gans, and Tourky, 2018; and Alsabah and Capponi, 2019). In such models, miners are Cournot oligopolists who compete by choosing computing power capacity. Our model instead allows block mining and the production of equipment to be separate economic activities. Consistent with the empirical evidence, in our model, an equipment producer sells most of its equipment to individual miners. Our model then implies that a single equipment producer serves the whole market. The producer then captures the governance of the blockchain through its control of the mining pool market.

Budish (2018) shows that proof-of-work is a very costly system for sustaining trust; for honest behavior to be incentive-compatible, the cost of an attack (which is a flow) has to be higher than the benefit derived from attacking the blockchain (which is a stock). Huberman, Leshno, and Moallemi (2017) and Easley, O'Hara, and Basu (2019) develop models of mining that can be used to determine the equilibrium value of Bitcoin transaction fees. Cong, He, and Li (2018) model how competition among pools affects equilibrium fees and pool sizes. Prat and Walter (2018) model miners' decision to invest in specialized equipment. We differ from this literature by modeling a mining ecosystem that includes miners, mining pools, and equipment producers. We also differ from the previous literature by focusing on the governance of blockchains.

Some previous theoretical work also focuses on the economic limitations of blockchain

[6] For an analysis of the importance of liquidity in bitcoin trading, see Makarov and Schoar (2020), who show that bitcoin prices react strongly and persistently to order flows.

technology. Biais, Bisière, Bouvard, and Casamatta (2019a) study competition among miners in proof-of-work blockchains as a coordination game and show that hard forks may occur in equilibrium. Arruñada and Garicano (2018) study the trade-off between coordination and the protection from expropriation in blockchain platforms. Abadi and Brunnermeier (2018) show that ledgers cannot simultaneously attain three desirable properties: correctness, decentralization, and cost-efficiency. Cong and He (2018) study the effect of blockchain technologies on how firms compete with one another. Pagnotta (2020) shows that Bitcoin's monetary rules can be welfare decreasing. For surveys of the economic literature on blockchains, see Biais, Bisière, Bouvard, and Casamatta (2019b), Chen, Cong, and Xiao (2019), and Halaburda and Haeringer (2019). For a broad set of facts on multiple cryptocurrencies, see Hu, Parlour, and Rajan (2019).

Our paper incorporates some of the insights found in the industrial organization literature. Farrell and Katz (2000) and Chen and Nalebuff (2006) show that a monopolist has incentives to enter the market for a complementary good in order to squeeze the profits in that market, thus leaving more surplus to consumers. This surplus then increases the demand for the monopolist's good. Similar to our model, the literature on strategic motives for bundling also considers how firms can leverage their market power in one market to reinforce their market power in another market (Whinston, 1990; Carbajo, De Meza, and Seidmann, 1990; Nalebuff, 2004).

Our paper is also related to the theoretical literature on the impact of large shareholders on corporate governance, mainly through intervention and voting. Examples include Shleifer and Vishny (1986), Winton (1993), Zwiebel (1995), Burkart, Gromb, and Panunzi (1997, 2000), Bolton and von Thadden (1998), Maug (1998), Pagano and Roell (1998), Bennedsen and Wolfenzon (2000), Noe (2002), Brav and Mathews (2011), Edmans and Manso (2011), Levit and Malenko (2011), Malenko and Malenko (2019), Bar-Isaac and Shapiro (2019), and Edmans, Levit and Reilly (2019). See also Edmans (2014) for a review of this literature.

2. Institutional Details

The Bitcoin blockchain is a public ledger showing the history of all transactions involving transfers of bitcoins since the creation of the currency. This history is used to determine and verify the owners of each bitcoin (or fraction of it). When someone "spends" bitcoin, they send a message to some Bitcoin nodes (i.e., computers running Bitcoin software) to notify them of the occurrence of a particular transaction involving changes in the ownership of bitcoins. When a node receives information about a transaction, it verifies whether the transaction is valid by checking it against Bitcoin rules. The node then broadcasts the transactions to other connected nodes, which then repeat the process until all network nodes receive the relevant information about the transaction.

All *full nodes* keep a local copy of the whole ledger. The ledger takes the form of a uniquely ordered chain of blocks; blocks are sets of transactions. The ledger is updated by the addition of new blocks to the chain. Blocks have a maximum size and, once created, cannot be changed by deleting, adding, or modifying transactions. Nodes of a particular type, called *miners*, create the blocks. Miners compete for the right to produce a new block by using their computational power to try to solve a particular mathematical problem. When a miner succeeds at solving the problem, the miner creates a block containing a set of recent transactions and information that allows others to verify that the miner has indeed found the correct solution to the mathematical problem. The miner then shares the block with other full nodes (only some full nodes are miners); all full nodes can easily verify whether the solution is correct. When nodes receive a new valid block with the right solution, they add that block to their local copy of the blockchain. Because nodes are connected to other nodes, information about the updated blockchain quickly propagates through the network, and nodes sequentially update their copies of the blockchain until every node (presumably) has the same copy. Miners that had been working on solving the same problem are then supposed to stop working on that problem and start the process of solving a new problem associated with the next block.

Anyone who installs a software application that "implements" the Bitcoin protocol can use their computational power to "mine" blocks. Although entry into the mining business is unrestricted, the process of mining is costly. First, the miner must buy or rent hardware. While most miners used generic CPU or GPU equipment in the early years, currently, most mining is done by specialized hardware (called an *application-specific integrated circuit* [ASIC]), which is many times more efficient than GPUs or CPUs.[7] Second, miners must pay for variable costs, among which electricity is the most important one. The mathemat-

[7] Eghbali and Wattenhofer (2019) estimate that the market share of ASIC mining of bitcoins has been essentially 100% since 2015.

ical problem is solved by brute force and cannot be made easier by coordinating miners, implying that the probability of a miner being the first to find a solution is proportional to the amount of computational power they allocate to the process of mining a block. The Bitcoin algorithm is constantly adjusted (every 2016 blocks) so that the average time for successfully mining a block (the *block interval*) is approximately ten minutes. The miner who wins the competition receives all fees associated with the transactions in the block plus a fixed number of newly created bitcoins (the *block reward*); in early 2020, the block reward was 12.5 bitcoins.[8] Because winning miners have to demonstrate that they have found the correct solution, finding the solution is "proof" that they have "worked" on the problem by directing their hash rate to it. This system is thus called *proof-of-work*.

As cryptomining evolved into a specialized economic activity, many other goods and services were created to support miners. One example is the provision of insurance to miners. Mining is a risky activity: miners pay up-front for electricity, equipment, and maintenance costs but are only rewarded (in cryptocurrencies) if they win the competition by finding the "lucky hash," i.e., the solution to the mathematical problem associated with the current block. An individual miner who owns a single Bitcoin mining machine can expect to wait for decades before mining a single block. Mining pools help diversify the risks faced by small miners. Although the term "pool" suggests some form of cooperative arrangement, mining pools are actually private firms that sell services – such as insurance – to cryptominers. A miner who joins a mining pool directs his/her hash rate to the pool. Pool managers then make the decisions concerning which blocks to mine. Pool owners make profits by charging fees.

In Table 1, we show how some of the (historically) large Bitcoin mining pools differ in some dimensions. As of January 2020, the pools in Table 1 collectively accounted for 82% of the total hash rate employed.[9] All but one pool (SlushPool) have links to Bitmain Technologies, the largest mining ASIC producer.[10] The AntPool-BTC.com combination has

[8] For studies focusing on Bitcoin transaction fees, see Huberman, Leshno, and Moallemi (2017), Easley, O'Hara, and Basu (2019), and Lehar and Parlour (2019).

[9] Newcomers 1THash and BytePool, both owned by Chinese company Valerhash, collectively account for 8.9% of the hash rate. BytePool offers FPPS contracts. We could not find much additional information on Valerhash and their pools.

[10] AntPool and BTC.com are fully-owned subsidiaries of Bitmain. Bitmain is the largest investor in Via-BTC. Both F2Pool and BTC.TOP are partners of BitDeer, which is a Bitmain-sponsored cloud-mining service. The parent companies of Huobi.pool and OkExPool are strategic partners of Bitmain. Jihan Wu, Bitmain's founder and chairman, is also an adviser of Huobi (one of the largest cryptocurrency exchanges in the world and the owner of Huobi.pool).

22.6% of the market, which makes Bitmain the largest mining pool operator, even without taking into account its influence over partner pools.

Pools differ in the types of contracts (usually referred to as "payment methods") they offer. The most popular contract is called *pay-per-share* (PPS), which has three different versions: "plain" PPS, *full pay-per-share* (FPPS), and *pay-per-share plus* (PPS+). In all of these contracts, miners split the expected block reward proportionally to their supplied hash rate, independently of whether the pool succeeds at winning the tournament. That is, PPS contracts offer full insurance.[11] In another standard contract (*pay-per-last-N-shares*), miners share rewards in proportion to their contributed hash rate in the last N rounds, but only when the pool is successful.

Of the largest mining pools, only two (AntPool and ViaBTC) offer a choice between different contracts. Only AntPool, ViaBTC, and SlushPool offer contracts in which block reward payments depend on the pool's success. In contrast, all but one pool (SlushPool) offer some version of PPS (full insurance). PPS fees vary; the lowest fee in January 2020 was provided by BTC.com: 1.5% for its full PPS contract.

At any given point in time, there are multiple copies of the Bitcoin blockchain, and by design, conflicting versions will coexist. For example, suppose that two miners find the solution for the same block at about the same time and forward their blocks to their respective nearest nodes. Because it takes time for information to percolate through the network, not all nodes will receive the two competing blocks in the same order. Thus, members of the Bitcoin community will regularly encounter situations in which they need to decide between two or more different versions of the blockchain. How are such conflicts resolved? The typical answer is to postulate that the longest chain will eventually win; once it becomes clear that one chain is longer than all others, miners will abandon other chains and focus their efforts on the longest one. Blocks recently mined in abandoned chains – "orphan blocks" – are deemed invalid.

The longest chain solution is not a hard feature of Bitcoin. When choosing which chain to support, participants play a standard coordination game: if everyone is expected to support

[11] Under a plain PPS contract, only the block reward is paid to miners; the pool retains the transaction fees. Variations of PPS (PPS+ or FPPS) include the sharing of transaction fees. FPPS distributes expected transaction fees proportionally to the hash rate supplied and, thus, offers full insurance to miners. PPS+ contracts distribute realized transaction fees. Because transaction fees vary from block to block, PPS+ contracts entail some risk. Still, because the average transaction fees per block are much lower than the fixed block reward (typically about 1% of the block reward), the risk in such contracts is negligible.

version A over B, it is individually optimal to support A. The longest-chain selection criterion is intuitive and may serve as a focal point, but in principle, other equilibria are possible. Biais, Bisière, Bouvard, and Casamatta (2019a) aptly name the longest-chain hypothesis *the blockchain folk theorem*. They show that there exist equilibria where a chain might bifurcate at some date, with two different versions of the blockchain coexisting forever. Recent evidence indicates that blockchain splits can be successful and command significant support among miners, such as in the case of Bitcoin Cash, a new blockchain created in 2017 as a bifurcation of the original Bitcoin blockchain. Biais, Bisière, Bouvard, and Casamatta (2019b) document 16 additional hard forks since then.

The longest-chain rule may also fail because of explicit collusion among mining pools. For example, according to Balakrishnan (2020), Bitmain's pools, in an agreement with two of its partner pools, BTC.TOP and Bitcoin.com, have proposed that from May 2020, all miners of Bitcoin Cash must contribute 12.5% of their block rewards to BCH infrastructure development. A newly-created Hong Kong-based corporation will collect the contribution. To enforce this "tax" on mining profits, Bitmain and its partners have threatened to "orphan" the blocks of those miners who choose not to contribute. The Bitmain-led coalition controls 64.9%[12] of BCH hash power and, thus, can credibly punish those who do not pay the tax.

A high degree of coordination is necessary to change the core rules of Bitcoin – what is called the Bitcoin protocol. Anyone can propose a change in rules through a Bitcoin Improvement Proposal (BIP). Such proposals usually have to be vetted by some Bitcoin developers and then face a "vote" among miners. The proposal itself typically sets the requirements for agreement and adoption. For example, the proposal may stipulate that a particular change requires approval from a supermajority of miners (a typical number is 95%) during a given period (measured in blocks). Miners signal their support for a proposal in the blocks they solve. Once the threshold is achieved, the proposal is said to be "locked in," and it is activated at a predetermined later date. It is essential to keep in mind that this is again not a hard feature; proposals can secure support from a large number of miners and still be dropped. An example was the 2017 proposal called SegWit2x, which secured support from 100% of miners but was later dropped due to a lack of consensus among different Bitcoin stakeholders.

[12] One-month average hash rate, as of March 9th, 2020. The Bitmain-led coalition includes AntPool, BTC.com, ViaBTC, BTC.Top, and Bitcoin.com.

The relevant voice mechanism for choosing between alternative versions of the blockchain is by directing hash power to them. When different groups of miners cannot coordinate on a single set of rules, they can direct their hash power to competing versions of the blockchain, creating hard forks.

3. Setup

We first describe the workings of the governance of the blockchain and then introduce three types of stakeholders in the blockchain ecosystem: miners, equipment producers, and mining pools.

3.1. Blockchain Governance

A blockchain may have many stakeholders. Stakeholders can be users, miners, or companies in the blockchain ecosystem, such as equipment producers or mining pools. Let l denote a generic blockchain stakeholder. At the end of each period, the blockchain network collectively chooses between two proposals (i.e., two chains), A and B, which represent two different sets of rules governing the blockchain. For example, A may be a proposal to increase the maximum block size, while B is the status quo. Each stakeholder has a preference for one of the two proposals; let $z_l \in \{A, B\}$ denote stakeholder l's preference. If stakeholder l's preferred proposal is chosen, they receive utility $b_l > 0$; otherwise, they receive zero. Although we assume that the private benefit b_l is exogenous, in reality, such benefit could arise endogenously, for example, if the proposal refers to the adoption of a particular technology that benefits some types of stakeholders more than others.[13]

Stakeholders "vote" for a proposal by allocating their *hash rate* (i.e., computational power) to one of the two chains. Let ε_l be the hash rate controlled by stakeholder l. The interpretation is that ε_l is the hash rate over which l has "voting rights." For example, an individual miner may not be able to support a proposal if the miner directs some of their hash rate to a mining pool. For simplicity, we assume that hash power is a continuous variable so that $\varepsilon_l \in \Re^+$ represents a mass of hash power.

We initially model the governance of the blockchain in reduced form: we assume that

[13] For example, there have been proposals to make blockchains such as Ethereum "ASIC-proof." It is in the interest of ASIC producers to vote against such proposals.

stakeholders' influence over the governance of the blockchain is proportional to the hash rate they control. Let $\varphi_l = \frac{\varepsilon_l}{n}$ denote the share of the overall hash rate controlled by stakeholder l, where n is the total mass of hash rate in the blockchain. The probability that stakeholder l's preferred proposal is implemented is $I\left(\varphi_l, \varphi_{-l}\right)$, where φ_{-l} is the vector of the hash rate shares controlled by all other stakeholders. We assume that this *influence function* is nondecreasing in φ_l; that is, a stakeholder who controls a larger share of the hash rate has (weakly) larger influence on the governance of the blockchain. Given $I\left(\varphi_l, \varphi_{-l}\right)$, l's expected payoff from the choice of proposals is $b_l I\left(\varphi_l, \varphi_{-l}\right)$. We choose to model the decentralized governance system in reduced form for expositional simplicity only. In Section 5, we provide a full microfoundation for the influence function $I\left(\varphi_l, \varphi_{-l}\right)$.[14]

3.2. Miners

To model the behavior of miners, we use an off-the-shelf model of bitcoin mining (here, we follow Budish (2018)). Let r denote the reward to the miner who wins a mining competition. At any period, if miner i supplies n_i units of hash rate, their instantaneous probability of winning the reward is $\frac{n_i}{n}$, where n is the total hash rate in the blockchain.

We model the decision of miners to buy mining equipment as follows. At some time t_0, each miner i simultaneously buys equipment that can produce (at most) n_i of hash rate per unit of time. We assume that mining equipment becomes obsolete (i.e., it fully depreciates) after T periods; miners only repurchase capacity after the existing stock fully depreciates.[15] A miner who buys equipment that can produce n_i for T periods pays an up-front cost of pn_iT (for simplicity, we assume no time discounting). That is, p denotes the up-front price of one unit of computational power (i.e., one hash).

Let θ_i denote miner i's net cost per (unit mass of) hash rate (excluding the cost of the equipment). Mining has many sources of variable costs, such as electricity, storage, maintenance, mining pool fees, management, and effort. In θ_i, we also include nonpecuniary benefits and costs, such as fun, speculative beliefs, preferences for gambling, risk aversion, and the insurance services provided by mining pools. Thus, when needed, we rewrite θ_i as

[14] Our approach here resembles that of Becker (1985), who models political influence by means of a reduced-form influence function.

[15] In reality, new mining rig models are introduced at regular intervals, which tends to make the existing equipment less competitive.

the sum of its N individual components:

$$\theta_i = \theta_{i1} + \theta_{i2} + ... + \theta_{iN}. \tag{1}$$

Let δ denote the amount of time it takes to mine a block (also called the *block interval*); δ is a random variable. The Bitcoin protocol adjusts its difficulty level to keep the expected block interval constant at some level $\overline{\delta}$. Without loss of generality, we normalize $\overline{\delta}$ to 1. That is, over the lifetime of the equipment, miners collectively expect to produce T blocks. For simplicity, we assume that the difficulty is adjusted instantaneously at each period; see the Appendix for an explicit model of difficulty adjustment.[16] We also assume that miners use their equipment at full capacity for T periods. In the Appendix, we show that the case in which miners do not always operate at capacity is similar to our baseline model.

We represent the expected payoff, as of time t_0, of an individual miner who acquires hash rate n_i and uses their full capacity until $t_0 + T$ by

$$V_i = \left(\frac{r}{n} - p - \theta_i\right) n_i T + b_i I\left(\varphi_i, \varphi_{-i}\right) T. \tag{2}$$

We define the per-period utility of a miner as $U_i \equiv \frac{V_i}{T}$.

3.3. Equipment Producers

General-purpose mining equipment (i.e., a CPU/GPU chip) that generates hash rate exists, and its price per hash unit, c, is determined in a larger market; the size of the mining industry does not affect c. There are also producers of specialized equipment; these producers own a technology that produces mining equipment at a constant unit cost $\underline{c} < c$ per hash. This equipment – also called an application-specific integrated circuit (ASIC) – is specific to mining some particular cryptocurrencies and cannot be used for any other purpose.

There are K potential equipment producers, indexed by $k \in \{1, ..., K\}$. Let n'_k denote the amount of computational power per period sold by Firm k to individual miners and let n_k denote the amount of computational power used by Firm k for self-mining. When a firm

[16] A similar assumption can be found in Pagnotta (2020). In reality, in the case of Bitcoin, the difficulty is adjusted every 2016 blocks, or about two weeks, to keep the average block interval at ten minutes. We can modify our model (at the cost of unnecessary complexity) to allow for delayed adjustment. Our results continue to hold as long as the frequency of adjustment (every two weeks) is higher than the typical useful life of the equipment (in practice, about twelve months or more).

self-mines, its payoff is the same as that of an individual miner (see (2)). Firm k's per-period payoff from self-mining is thus

$$U_k = \left(\frac{r}{n} - \underline{c} - \sigma_k\right) n_k + b_k I\left(\varphi_k, \varphi_{-k}\right), \tag{3}$$

where σ_k is Firm k's net cost of mining (excluding equipment costs).

The total per-period utility of an equipment producer that both self-mines and sells n'_k of equipment at price p is thus

$$\pi_k = (p - \underline{c})n'_k + U_k. \tag{4}$$

Let $\tau \in \{t_0, t_0 + T, t_0 + 2T, ..., \infty\}$ denote the periods in which miners buy equipment (i.e., these are the times when the existing stock of equipment fully depreciates). To model first-mover advantages, we follow the literature on sequential entry initiated by Prescott and Visscher (1977) and assume that at each time t, at most one firm has the option to enter. Specifically, at $t = t_0$, there are no incumbents in the market for specialized mining equipment. At $t \in (t_0, t_0 + T]$, exactly one firm – Firm 1 – has the option to enter this market by paying a once-and-for-all sunk cost ι. Similarly, at $t \in (t_0 + (k-1)T, t_0 + kT]$, only Firm k has the option to enter; that is, Firm k has the first-mover advantage over all firms such that $k' > k$.

3.4. Mining Pools

We now introduce a third type of stakeholder: mining pools. Pools are profit-maximizing firms that offer services to miners and charge fees. Let f_j denote the fee charged by pool j. Individual miners can choose to direct some or all of their hash rate to mining pools. Pool managers then choose which blocks to mine using all the hash rate directed to their pool.

When choosing between proposals at the end of each period, each mining pool has the right to vote on behalf of all members of their pool. However, pool managers may have limited influence on the voting behavior of their pool members, either because some pools allow miners to express their voting preferences (e.g., as is the case with SlushPool) or because miners may withdraw their hash rate if they disagree with the direction proposed by their mining pool manager. We assume that pool managers have control over a fraction $\alpha \in \left(0, \frac{1}{2}\right)$ of the votes in their pools; individual miners control the remaining $1 - \alpha$. One interpretation is that α measures the proportion of stakeholders who are indifferent towards voting, possibly because they are indifferent between the two proposals (i.e., if $b_i \to 0$) or because they understand they cannot affect the outcome of the vote (i.e., they know they are not pivotal). We assume that α is less than $\frac{1}{2}$ to make sure that no mining pool can control more than 50% of the votes. This assumption eliminates some potential corner solutions but is otherwise immaterial for the qualitative results we derive.

Let m_j denote the amount of hash power directed to pool j. Pool j's (per-period) utility is thus

$$\Pi_j = f_j m_j + b_j I\left(\varphi_j, \varphi_{-j}\right), \tag{5}$$

where $\varphi_j = \frac{\alpha m_j}{n}$.

4. Economic Incentives for Governance Capture

In this section, we solve for the equilibrium of the game played by all blockchain ecosystem stakeholders. We are interested in understanding how their pure economic motives may lead to the concentration of voting power. Thus, in this section, we assume that the private benefits of control are zero for everyone.

4.1. Equipment Market Equilibrium

Here, we consider the decisions of equipment producers concerning entry, quantities, and prices. For now, we assume that the equipment producers are single-business companies. Later, in Subsection 4.2, we allow the equipment producers to diversify and become mining pool operators.

4.1.1. Single Equipment Producer

To study the equilibrium in this market, we work backward: we first solve for the equilibrium, taking as given a particular market structure (single versus multiple producers), and then we analyze the decision to enter the market.

Suppose there is a single incumbent equipment producer – Firm k – at time $\tau \geq t_0 + kT$. For simplicity, we assume (for now) that $\theta_i = \theta$ for all miners i. The overall hash rate is $n_k + n_k'$, where n_k is the mass of hash rate used by Firm k for self-mining and n_k' is the hash rate of all other miners.[17] The equipment producer chooses a price p per hash produced by its machines. Individual miners buy the specialized equipment only if $p \leq c$; otherwise, they prefer to buy the cheaper generic equipment. From (2), miner i's per-period expected payoff is (recall that $b_i = 0$ in this section)

$$U_i = \left(\frac{r}{n_k + n'_k} - \min\{p, c\} - \theta \right) n_i. \tag{6}$$

Assuming free entry of miners, miners will continue to buy more hash rate unless $U_i \leq 0$. Thus, in equilibrium, either $U_i = 0$, in which case individual miners buy a positive amount of hash rate, or $U_i < 0$, in which case Firm k is the only miner.

Note that if $p > c$, then p does not affect the entry condition for individual miners because they would not buy equipment from Firm k. Thus, without loss of generality, we assume that the equipment producer will not choose $p > c$. With this simplification, we can write the equipment producer's problem as

$$\max_{p, n_k, n'_k} (p - \underline{c}) n'_k + \left(\frac{r}{n_k + n'_k} - \underline{c} - \sigma_k \right) n_k, \tag{7}$$

subject to

$$\begin{aligned} \frac{r}{n_k + n'_k} - \min\{p, c\} - \theta &\leq 0 & (8) \\ p &\leq c & (9) \\ n_k, n'_k &\geq 0. & (10) \end{aligned}$$

The producer's profit contains two terms: the profit from selling equipment (if any) and the profit from self-mining (if any). The next proposition characterizes the equilibrium when there is a single equipment producer.

Proposition 1 *The optimal price is $p^* = c$. There are three cases:*

1. *If $\sigma_k > \theta$, then $n'^*_k = \frac{r}{c+\theta}$ and $n^*_k = 0$.*

2. *If $\sigma_k < \theta$, then $n'^*_k = 0$ and $n^*_k = \frac{r}{c+\theta}$.*

[17] This already anticipates the result that all miners will use specialized equipment in equilibrium and will thus buy equipment from the single producer. This result follows immediately from the assumption that $c > \underline{c}$.

3. *If $\sigma_k = \theta$, then any $n_k^{'*}$ and n_k^* such that $n_k^* + n_k^{\prime *} = \frac{r}{c+\theta}$ is a solution.*

This proposition illustrates three key results. First, the optimal price is c. The equipment producer would like to sell few units of computational power at a very high price because miners impose an externality on one another and, thus, the total surplus decreases with the amount of hash rate supplied. However, the producer cannot charge a price that is higher than the next-best alternative, whose price is c. Second, the equipment producer self-mines only if $\sigma_k < \theta$ because whoever has a (nontransferable) comparative advantage at mining (i.e., the party with the lowest net cost) does all the mining. Third, the entry condition for individual miners determines the total hash rate, even when the equipment producer is the sole miner.

Proposition 1 implies that to focus on the case in which producers sell most of their equipment (as in the case of Bitmain), we need to assume $\sigma_k > \theta$. In the next subsection, we show that when $\sigma_k > \theta$, only one firm will enter the market for specialized equipment. This firm will then behave as in Part 1 of Proposition 1. In Subsection 4.2, we present our main results assuming a single equipment producer. Readers may skip to that subsection without any loss in continuity.

4.1.2. Competition among Equipment Producers

We now consider the case of multiple incumbent equipment producers. For simplicity, we assume that there are only two incumbent firms (call them k and z); the extension to more than two firms is straightforward. If the equipment producers sell to individual miners, they compete with one another by setting prices. If they self-mine, their net cost from mining is $\sigma_k = \sigma_z = \sigma$.

Proposition 2 *There are three cases:*

1. *If $\sigma > \theta$, then $n_k^{\prime *} + n_z^{\prime *} > 0$ and $n_k^* = n_z^* = 0$; both firms have zero profit.*

2. *If $\sigma < \theta$, then $n_k^{\prime *} = n_z^{\prime *} = 0$ and $n_k^* = n_z^* > 0$; both firms enjoy positive profits.*

3. *If $\sigma = \theta$, then there are multiple equilibria such that if $n_k^{\prime *} + n_z^{\prime *} > 0$, profits are zero, and if $n_k^{\prime *} + n_z^{\prime *} = 0$, profits are strictly positive.*

In Case 1, the equipment firms have no special advantage at mining; thus, in equilibrium, both of them sell all of their equipment. Because they compete by setting prices, in equilibrium, prices must equal marginal cost, and thus, profits are zero. In Case 2, the equipment firms have lower mining costs than individual miners; thus, in equilibrium, both firms self-mine and do not sell equipment to individual miners. The equipment firms compete with one another by setting quantities, and thus, they enjoy positive profits in equilibrium.[18] Note also that in any equilibrium in which the amount of computational power sold is strictly positive, we have $\sigma \geq \theta$ and both firms have zero profit.

We now consider the decision to enter the mining equipment market. We have the following result:

Proposition 3 *In any equilibrium with a positive number of individual miners, at most one specialized equipment producer enters the market.*

The intuition is as follows. Because specialized equipment is a homogeneous good, price competition drives profits to zero. Unless a firm expects to have positive profits in this market, it will not pay a positive sunk cost to enter. Thus, the firm with a first-mover advantage is the only one that could enter the market in equilibrium (as in Stiglitz, McFadden, and Peltzman, 1987).

For the remainder of the paper, we assume that the equipment producer does not have a comparative advantage in mining; that is, we set $\sigma > \theta$. From Proposition 2, if there are two incumbent producers, there is a positive number of individual miners, and profits are zero. Proposition 3 thus implies that there is only one incumbent equipment producer in equilibrium. From Proposition 1, we then conclude that the equipment producer does not self-mine.

4.1.3. Mining with Specialized Equipment: Summary

The model in this section illustrates several interesting features of the game played between equipment producers and individual miners. It is useful to summarize its main lessons:

(i) Because ASIC chips are essentially a homogeneous good, even a small sunk cost could prevent entry when there is already an incumbent, thus naturally leading to a structure with

[18] Dimitri (2017) models competition among nonatomistic miners as Cournot competition and shows that miners have positive profits in equilibrium. See also Alsabah and Capponi (2019) for a model where equipment producers compete by choosing their hash rates for self-mining.

a single first-mover incumbent that earns a positive profit.[19] This possibility is in line with the market structure in the Bitcoin ecosystem: the leading cryptocurrency mining ASIC producer – Bitmain Technologies – has approximately 74.5% of the market for specialized equipment. Bitmain entered this market early in 2013; all of its current competitors entered the market more recently than Bitmain and are all very small.

(ii) The producer of specialized equipment will charge as much as the next best alternative (e.g., GPU) for each unit of computational power, thus extracting from miners all the surplus created by its more efficient equipment. The equipment producer is a constrained monopolist. If it were unconstrained, it would always like to sell fewer machines at higher prices.

(iii) The equilibrium amount of computational power (i.e., the hash rate used for mining) is the same with or without specialized equipment. Thus, the deadweight cost from mining is lower in an equilibrium with specialized equipment.

(iv) A specialized equipment producer has a comparative advantage at mining in the sense that it incurs lower equipment costs than individual miners. However, this comparative advantage is transferable: miners can buy equipment from the producer. Thus, this type of comparative advantage does not affect the identity of the miners. Comparative advantages that are nontransferable (i.e., reflected in θ and σ, such as local electricity costs) determine who becomes a miner.[20]

4.2. Equilibrium with Mining Pools

The most obvious service that mining pools offer is insurance. However, miners assign value to pool services beyond insurance. For example, some pools offer a *solo* option (see Table 1), in which a miner uses the mining resources and software from the mining pool without buying insurance; the typical fee for this service is 1%.

As shown in Table 1, mining pools are not all alike and differ in many dimensions. First, pools offer different types of contracts, and there is a limited amount of choice within each pool. Second, the level of transparency varies greatly across pools: for example, some pools do not post information on fees and contracts on their websites, and some pools' websites are in Chinese only. Third, pools differ in many technical aspects, such as server location,

[19] In practice, the most important source of fixed costs for an ASIC producer is its investment in R&D. For example, in 2018, approximately 32% of Bitmain's employees were full-time engineers in research and development.

[20] With cloud mining, even comparative advantages in electricity costs are transferable.

user interface, technical assistance, and the availability of merged mining.[21] Finally, the reputation of a pool is also an important consideration for miners; miners need to trust pools to honor the terms of the contract.[22]

We do not model the reasons for mining pools to offer differentiated services. Instead, we consider a model in which miners are heterogeneous in their preferences over mining pool attributes, and differentiated mining pools compete for miners by choosing fees. At each mining period t, let v_{ij} denote i's valuation of the unique combination of attributes offered by pool j.[23] Let f_j denote the fee charged by pool j. For each miner i, their surplus from joining pool j is thus

$$s_{ij} = v_{ij} - f_j. \tag{11}$$

If miner i chooses pool j, we set $\theta_{i1} = -s_{ij}$ in (1). For simplicity, and without loss of generality, we normalize all other costs (and benefits) to zero; $\theta_{i2} = ... = \theta_{iN} = 0$. Thus, we can replace θ_i with $-s_{ij}$.

For simplicity, we assume that miners do not know their exact valuation v_{ij} before deciding whether to enter the mining market. Although this assumption is not necessary for our results (in the Appendix, we discuss our main result under more general conditions), we note that this assumption is realistic in our application. When deciding whether to become a miner, potential miners may not know all the relevant characteristics of a mining pool. Mining pools' websites differ in the amount and quality of information they provide (see Table 1). In addition, other sources (such as comparison sites) often offer incomplete and conflicting information.[24] Finally, miners can only acquire a sense of the quality of the service through their experience with a particular pool.

To consider the simplest possible scenario, we assume that valuations are independent and identically distributed across both miners and pools, with density function $g(v)$ over the support $[\underline{v}, \overline{v}]$, with $\underline{v} > 0$, $\overline{v}$ finite, cdf $G(\cdot)$ and mean μ. For any pair of pools (j, j'), define

[21] For example, Poolin offers the option of automatically switching between Bitcoin and Bitcoin Cash mining depending on the expected profitability. Huobi.pool gives "Huobi.pool tokens" for free to their miners.

[22] Complaints about lack of transparency in payments and accusations of fraud abound in Internet forums.

[23] Valuation v_{ij} includes, among other things, i's preferences for different contracts, perhaps because of heterogeneity in liquidity and risk preferences.

[24] For example, according to Bitcoin Wiki, AntPool does not offer merged mining. However, cryptocompare.com states that AntPool offers merged mining for five different coins. We could not find any information on AntPool's website about the availability of merged mining.

$$\widehat{\upsilon} \equiv E\left[\max\left\{\upsilon_j, \upsilon_{j'}\right\}\right] = \int_{\underline{\upsilon}}^{\overline{\upsilon}} \left(\int_{\upsilon_{j'}}^{\overline{\upsilon}} \upsilon_j g\left(\upsilon_j\right) d\upsilon_j + G\left(\upsilon_{j'}\right) \upsilon_{j'} \right) g\left(\upsilon_{j'}\right) d\upsilon_{j'}. \tag{12}$$

To avoid infinite entry by miners if fees are zero, we assume $\widehat{\upsilon} < c$.

4.2.1. Competition among Mining Pools

For simplicity, we consider only the case in which there are at most two mining pools; the case with multiple mining pools is conceptually similar. We first assume that there are two incumbent mining pools and that one of the mining pools is wholly owned by a single equipment producer, which we call Pool 1. Later, in Subsection 4.2.2, we analyze players' decisions to enter the mining pool business, including the equipment producer's decision to enter this market.

For each period τ, the timeline of actions is as follows.

Date 1: Pools choose their fees, f_1 and f_2, simultaneously. Everyone observes these fees.

Date 2: Miners enter the mining market and buy equipment from the producer at price c (see Proposition 1).

Date 3: Miners learn their υ_{ij} and then choose which pool to join.

At Date 3, after miner i discovers υ_{ij} for each pool $j \in \{1, 2\}$, the miner chooses which pool to join. We assume that $\underline{\upsilon}$ is sufficiently high so that, in equilibrium, a miner always prefers to join one of the two pools instead of mining solo. That is, the two pools serve the whole market.[25] Thus, miner i's net direct surplus from mining at Date 3 is given by

$$s_i^* = \max_{j \in \{1,2\}} \upsilon_{ij} - f_j. \tag{13}$$

Thus, our modeling of the mining pool market is analogous to traditional random-utility discrete-choice differentiated goods models that are common in the industrial organization literature (e.g., Salop and Perloff, 1986).

At Date 2, miners do not yet know their types; thus, they also do not know which pool they would join after entry. The probability that miner i will choose Pool 1 over Pool 2 is $\Pr(\upsilon_{i1} - \upsilon_{i2} \geq f_1^* - f_2^*)$. Because all valuations are identically and independently distributed, the distribution of $\upsilon_{i1} - \upsilon_{i2}$ is symmetric with zero mean, with support $\left[-\left(\overline{\upsilon} - \underline{\upsilon}\right), \left(\overline{\upsilon} - \underline{\upsilon}\right)\right]$.

[25] For example, in the Appendix we show that if entry by a second pool leads to a reduction in mining pool fees, a sufficient condition for the miners never to mine alone is $\underline{\upsilon} g\left(\underline{\upsilon}\right)\left(c - \mu + \underline{\upsilon}\right) \geq c - \mu$.

Let $H(.)$ denote the cumulative distribution function for $v_{i1} - v_{i2}$ (note that $H(0) = 0.5$). Note that in equilibrium, Pool 1's market share is $1 - H(f_1^* - f_2^*)$.

At Date 2, let $E[s^* \mid f_1, f_2]$ denote the expectation (conditional on fees f_1 and f_2) of s_i^* as defined in (13). Because all miners are identical at this date,

$$E[s^* \mid f_1, f_2] = \int_{\underline{v}}^{\overline{v}} \int_{\underline{v}}^{\overline{v}} \max\{v_1 - f_1, v_2 - f_2\} g(v_1) g(v_2) dv_1 dv_2. \tag{14}$$

As mentioned before, because we want to focus on the case in which the equipment producer does not have a comparative advantage at mining, we assume that $\sigma > 0$; Proposition 1 then implies that there is no self-mining in equilibrium ($n_1 = 0$) and $p = c$. As in (8), the free entry condition determines the equilibrium hash rate $n_1' = n^*$:

$$n^* = \frac{r}{c - E[s^* \mid f_1, f_2]}. \tag{15}$$

At Date 1, the mining pools anticipate the behavior of the miners, as given in (15), and choose fees simultaneously to maximize their profits. The mining pools' problem is to[26]

$$\max_{f_1} \Pi_1(f_1, f_2) + \pi(f_1, f_2) = \frac{r f_1 (1 - H(f_1 - f_2))}{c - E[s^* \mid f_1, f_2]} + \frac{r(c - \underline{c})}{c - E[s^* \mid f_1, f_2]}, \tag{16}$$

$$\max_{f_2} \Pi_2(f_1, f_2) = \frac{r f_2 H(f_1 - f_2)}{c - E[s^* \mid f_1, f_2]}. \tag{17}$$

Let (f_1^*, f_2^*) denote an equilibrium. At the end of each period t, the miners vote on a proposal. Let $\varphi_j(f_1^*, f_2^*)$, $j = 1, 2$, denote the equilibrium proportion of hash rate controlled by Pool j. That is, $\varphi_1(f_1^*, f_2^*) = \alpha[1 - H(f_1^* - f_2^*)]$ and $\varphi_2(f_1^*, f_2^*) = \alpha H(f_1^* - f_2^*)$. Pool 1's influence on the voting outcome is measured by $I(f_1^*, f_2^*) \equiv I(\varphi_1(f_1^*, f_2^*), \varphi_2(f_1^*, f_2^*))$.

The next proposition presents our main result:

Proposition 4 *In any equilibrium, the equipment producer is the stakeholder with the greatest influence on the governance of the blockchain.*

This proposition shows that when the equipment producer owns a mining pool, it offers a lower fee, and its pool is larger than the pool of its competitor. Because the equipment producer has the largest market share, it is the player with the greatest influence on the governance of the blockchain.

[26] Recall that we assume that $b_1 = b_2 = 0$.

Intuitively, this result arises because the equipment producer benefits more from offering low fees than does an independent pool. Lowering fees has three positive effects: (i) it allows the firm to acquire a larger share of the pool market, (ii) it increases the overall demand for pool services, and (iii) it increases the demand for equipment. Only the equipment producer internalizes (iii); thus, it will choose lower fees than its competitor. Because we assume that mining pool managers derive no private benefits from the adoption of specific proposals, this proposition implies that blockchain governance capture is a by-product of the equipment producer's economic incentives to squeeze the profits of the mining pools.

Proposition 4 implies that market power in the market for mining equipment spills over to the market for mining services. Conditional on being an incumbent in the pool market, the equipment producer always operates the largest mining pool. If the equipment producer is not an incumbent in the pool market, it will have strong incentives to enter this market, as we show in the next subsection.

The theoretical intuition for Proposition 4 is as follows. The equipment producer faces a trade-off between surplus creation and surplus extraction. When the equipment producer lowers its pool fee, more miners enter the market. Because of network externalities, the entry of additional miners reduces the total surplus. Thus, for the equipment producer to benefit from lowering its pool fee, it must extract a larger fraction of this reduced surplus. This form of surplus capture can happen, for example, if Pool 2 (the independent pool) also lowers its fee in response to the fee set by the equipment producer. Thus, the equipment producer "squeezes" Pool 2's profit. Proposition 4 holds because this profit-squeeze effect is sufficiently strong.

The existence of a profit-squeeze effect is robust to modifications to the model setup and assumptions. In particular, it is robust to different assumptions about functional forms, mode of competition, and learning about pool preferences, as we show in the Appendix.

4.2.2. Entry into the Mining Pool Market

We now consider the decision to enter the mining pool market. We start at some time τ when there is only one incumbent firm in the mining pool market. This firm is an independent mining pool.

At period τ, we slightly modify the timeline to allow for entry:

Date 0: There is one incumbent mining pool. A second pool can enter this market by paying a once-and-for-all sunk cost κ.

Date 1: Pools choose their fees, f_1 and f_2, simultaneously. Everyone observes these fees.

Date 2: Miners enter the mining market and buy equipment from the producer at price c.

Date 3: Miners learn their υ_{ij} and then choose which pool to join.

To simplify the analysis, here, we assume that only one firm may enter at time τ and, if it does, no other firm may enter in subsequent periods. The potential entrant is either the equipment producer or an independent pool.

We assume that there are two potential ownership structures upon entry. The choice between the two ownership structures is only relevant for the equipment producer. The first ownership structure is such that the equipment producer has full control rights and cash flow rights over the pool. In the second ownership structure, the equipment producer has full cash flow rights but no control rights over the pool. If it enters with full control rights, the equipment producer will set fees as in (16); that is, it internalizes the effect of the fees on the mining equipment profit. If it enters without control rights, the pool manager maximizes profits in the pool market only, without taking into account any side effects on the equipment market, in which case both pools will have the same size.[27]

The option to choose between the two different modes of entry matters. In the previous section, we have considered only the more natural case in which the equipment producer has full control rights over the choices made by its pool. In some cases, however, the producer may prefer not to have control over fees, as we show in the next proposition.

Proposition 5 *The equipment producer may be better off entering the pool market without control over fees than entering with control over fees.*

To understand the intuition, suppose that the equipment producer can set the prices of its pool. Because the producer has incentives to squeeze the profits of the other pool, the producer will choose a price that is lower than the price that would be chosen by an independently managed pool. However, this lower price leads to losses for the equipment producer in the pool market; that is, the producer "self-squeezes" its profit. If the loss in

[27] Entering without control is a realistic possibility. For example, Bitmain Technologies is the largest financial investor in ViaBTC, but control rights are concentrated in the hands of a few owners not related to Bitmain. As shown in Table 1, ViaBTC charges higher fees than those set by the pools controlled by Bitmain.

the pool business is too large, the equipment producer may prefer to commit to choosing a higher pool fee. Entering without control is a way of making such a commitment.[28]

The possibility demonstrated by Proposition 5 is, however, unlikely to be of practical importance if private benefits are significant. By entering the pool market without controlling a mining pool, the equipment producer would also surrender its right to vote on proposals. If such rights are sufficiently valuable, the equipment producer would always prefer to enter with control rights.

We now make the following assumption:

Assumption 1 *Competition increases the expected surplus of the miners:*

$$\widehat{v} - f^* > \mu - \underline{v}, \tag{18}$$

where $\widehat{v}$ is given by (12) and

$$f^* = \frac{-\left(h^*\left(0\right)\left(c-\widehat{v}\right)-0.25\right)+\sqrt{\left(h^*\left(0\right)\left(c-\widehat{v}\right)+0.25\right)^2+1}}{2h^*\left(0\right)}. \tag{19}$$

Condition (18) is sufficient for miners' expected surplus to increase after the entry of a new pool. The entry of a new pool benefits the miners in two ways: (i) miners can now choose between two pools with different attributes, and (ii) pool fees typically fall upon entry. Thus, condition (18) is violated only if pool fees increase by a substantial amount after entry.

Proposition 6 *If condition (18) holds, the equipment producer has stronger incentives to enter the mining pool market than does an independently owned pool.*

This proposition shows that as long as more mining pool competition benefits miners, for any constellation of parameters for which an independent firm finds it profitable to enter the pool market, the equipment producer also profits from entering this market. There are parameter values for which only the equipment producer profits from entering.[29]

[28] Gawer and Henderson (2007) study Intel's use of organizational structure and processes as a means to commit not to squeeze the profits of independent suppliers and thereby induce efficient R&D investment in the complementary goods.

[29] The analysis so far assumes that there is an incumbent equipment producer that can also enter the mining pool market. This option to enter does not affect the equilibrium in the equipment market, as described

The intuition behind Proposition 6 is as follows. If Assumption 1 holds, entry by any type of firm reduces the average fee, thus increasing the demand for mining equipment. Only the equipment producer internalizes this effect; thus, the producer is willing to absorb lower profits in the pool market.

In the proof of Proposition 6, we show that the equipment producer's incentive to enter relative to that of an independent entrant is

$$RI \equiv r(c-\underline{c})\frac{\widehat{v}-f^{*}-\int_{f^{0}}^{\overline{v}}\left(v-f^{0}\right)g\left(v\right)dv}{\left(c-\widehat{v}+f^{*}\right)\left(c-\int_{f^{0}}^{\overline{v}}\left(v-f^{0}\right)g\left(v\right)dv\right)}>0,$$

where f^0 is the equilibrium fee without entry, and f^* is the equilibrium fee after entry by an independent firm. We also show that f^0 and f^* are independent of r and $\underline{c}$.

We thus have the following comparative statics:

Result 1 *The equipment producer has stronger incentives to enter when it is more efficient (i.e., lower $\underline{c}$):*

$$\frac{\partial RI}{\partial \underline{c}}=-r\frac{\widehat{v}-f^{*}-\int_{f^{0}}^{\overline{v}}\left(v-f^{0}\right)g\left(v\right)dv}{\left(c-\widehat{v}+f^{*}\right)\left(c-\int_{f^{0}}^{\overline{v}}\left(v-f^{0}\right)g\left(v\right)dv\right)}<0.$$

Result 2 *The equipment producer has stronger incentives to enter when mining rewards are higher (i.e., higher r):*

$$\frac{\partial RI}{\partial r}=(c-\underline{c})\frac{\widehat{v}-f^{*}-\int_{f^{0}}^{\overline{v}}\left(v-f^{0}\right)g\left(v\right)dv}{\left(c-\widehat{v}+f^{*}\right)\left(c-\int_{f^{0}}^{\overline{v}}\left(v-f^{0}\right)g\left(v\right)dv\right)}>0.$$

These two results show that the equipment producer's incentives to enter the pool market become stronger as the equipment producer becomes more efficient (lower $\underline{c}$) and as the blockchain becomes more successful, that is, as crypto prices increase (higher r). Our model thus predicts that corporate capture of governance is more likely in more valuable blockchains.

in Subsection 4.1. In particular, there will be at most one equipment producer entering the market. This producer's entry condition is slightly modified to take into account the option value of entering the pool market at some future date.

5. Governance Capture with Private Benefits

We now consider the case in which private benefits are non-zero. Our goal is to derive the conditions under which Proposition 4 holds with positive private benefits.

5.1. Voting on Proposals

In this subsection, we provide an explicit model of voting on proposals. This model is meant as a microfoundation for the influence function $I\left(\varphi_l, \varphi_{-l}\right)$, introduced in Subsection 3.1.

We assume that proposals are chosen by a majority rule, in which only active miners can vote. In practice, "voting" occurs by miners directing their hash rate to one of the two competing chains; here, we assume that the minority chain is abandoned.[30] The aggregate distribution of miners' preferences over proposals is unknown until the end of the block interval, which is when voting happens. Let ρ denote the proportion of stakeholders such that $z_l = A$. For simplicity only, we assume that ρ is uniformly distributed over $[0, 1]$. That is, at each period t, a new ρ is independently drawn from a uniform distribution. The realized value of ρ is never directly revealed, but it might be inferred ex post from the voting outcome.

We first consider a fully decentralized benchmark; that is, there are only individual miners and no mining pools. Let n be the total mass of hash rate. For simplicity, we assume that the number of miners is sufficiently large so that we may think of each miner as having measure zero (alternatively, we could assume that there is a continuum of mass n of miners). A consequence of this assumption is that individual miners understand that they cannot affect the outcome of the vote and, thus, their decision to enter the mining market is independent of their private benefits. Therefore, active miners are drawn randomly from the population of stakeholders. By the Law of Large Numbers, the mass of miners is such that $z_i = A$ is also ρ. Because of majority voting, and assuming that all active miners vote according to their preferences, proposal A wins if and only if $\rho \geq \frac{1}{2}$.

To consider the case in which mining pools also vote, we proceed in three steps. First, we take market shares as given and solve for the voting game. Second, we endogenize market shares as in Section 4.2. Finally, we also consider the case in which the equipment producer may find it optimal to self-mine.

[30] In reality, if no chain is abandoned, then a blockchain splits into two new chains.

5.2. Exogenous Market Shares

As in Section 4.2, there are two incumbent mining pools: Pool 1, which is owned by the equipment producer, and Pool 2, which is an independent pool. In this subsection, we take market shares as exogenously given.

Let $1 - H$ denote Pool 1's market share and H denote Pool 2's market share. Thus, the votes controlled by Pool 1 and Pool 2 are $\varphi_1 = \alpha(1 - H)$ and $\varphi_2 = \alpha H$, respectively.

Suppose that the fully decentralized voting outcome is different from what Pool 1 would choose. What is the probability that Pool 1's preferred proposal is adopted in such a case? We need to consider two cases:

Case 1. Suppose that the majority of stakeholders prefer proposal A, that is, $\rho \geq \frac{1}{2}$. Suppose that Pool 1 and Pool 2 prefer proposal B. Then, the probability that Pool 1's preferred proposal wins the vote is

$$\Pr\left((1-\alpha)\rho \leq \frac{1}{2} \mid \rho \geq \frac{1}{2}\right) = \frac{\frac{1}{2(1-\alpha)} - \frac{1}{2}}{\frac{1}{2}} = \frac{\alpha}{1-\alpha}. \tag{20}$$

Similarly, if the majority prefers proposal B ($\rho \leq \frac{1}{2}$), and both pools prefer A, then the probability that Pool 1's preferred proposal wins the vote is

$$\Pr\left(\alpha + (1-\alpha)\rho \geq \frac{1}{2} \mid \rho \leq \frac{1}{2}\right) = \frac{\alpha}{1-\alpha}. \tag{21}$$

Case 2. Suppose that the majority of stakeholders and Pool 2 prefer proposal A. If Pool 1 prefers B, then the probability that Pool 1's preferred proposal wins the vote is

$$\Pr\left(\alpha H + (1-\alpha)\rho \leq \frac{1}{2} \mid \rho \geq \frac{1}{2}\right) = \max\left\{\frac{\alpha(1-2H)}{1-\alpha}, 0\right\}. \tag{22}$$

Similarly, if the majority and Pool 2 prefer proposal B and if Pool 1 prefers A, then the probability that Pool 1's preferred proposal wins the vote is

$$\Pr\left(\alpha(1-H) + (1-\alpha)\rho \geq \frac{1}{2} \mid \rho \leq \frac{1}{2}\right) = \max\left\{\frac{\alpha(1-2H)}{1-\alpha}, 0\right\}. \tag{23}$$

There are two reasons for decisions to differ from those obtained in the fully decentralized benchmark. The first one is *proxy voting*: because some miners delegate their rights to vote to the mining pools, pools become nonatomistic and, thus, can sometimes impose their preferences. Parameter α measures the importance of proxy voting. The second reason is the *concentration of voting rights.* In our model, since there are only two pools, concentration is minimized when market shares are equal (i.e., $H = \frac{1}{2}$) and is maximized when a single pool controls all the market ($H = 1$ or $H = 0$).

Note that when $H = \frac{1}{2}$, if there is disagreement among pools, the biases cancel each other out, and the fully decentralized outcome is obtained.

5.3. Endogenous Market Shares

We now incorporate voting rights motives into pools' objective functions. For simplicity, we assume that $\{z_1, z_2\}$ – the mining pools' preferences over proposals – are distributed independently from the z_l's of the other stakeholders, $l \neq 1, 2$. Let ϕ denote the probability of disagreement between the pools, that is, $z_1 \neq z_2$.

The influence functions of the pools are now

$$I\left(f_1, f_2\right) = \frac{1 - 2\alpha H(f_1 - f_2)\phi}{2\left(1 - \alpha\right)} \tag{24}$$

$$I\left(f_2, f_1\right) = \frac{1 - 2\alpha\left(1 - H(f_1 - f_2)\right)\phi}{2\left(1 - \alpha\right)}. \tag{25}$$

The influence functions increase with one's market share in the pool market, consistent with the assumption made in Subsection 3.1. We can now see how the choice of fees affects pools' influence on the governance of the blockchain: lower fees imply more influence.

We now solve for the equilibrium with mining pools as in Subsection 4.2. All steps are unchanged, except for those at Date 1, which is when mining pools choose fees simultaneously to maximize their payoffs:

$$\max_{f_1} \Pi_1\left(f_1, f_2\right) + \pi\left(f_1, f_2\right) + b_1 I\left(f_1, f_2\right) \tag{26}$$

$$\max_{f_2} \Pi_2\left(f_1, f_2\right) + b_2 I\left(f_2, f_1\right), \tag{27}$$

where $\Pi_j\left(f_1, f_2\right)$, $j = 1, 2$, and $\pi\left(f_1, f_2\right)$ are given by (16) and (17).

In Subsection 4.2, we show that the equilibrium market shares are asymmetric and that Pool 1 – the equipment producer – has the larger market share. The next proposition shows that this result continues to hold unless b_2 is sufficiently larger than b_1.

Proposition 7 *If $b_1 \geq b_2$, in any equilibrium, the equipment producer is the stakeholder with the greatest influence on the governance of the blockchain.*

As in Proposition 4, the equipment producer (Pool 1) has a purely economic motive for setting low fees: lower fees attract more miners to the market and, thus, increase the demand for mining equipment. Now, both the equipment producer and the independent pool (Pool 2) have an additional governance motive for setting lower fees: they both want to gain market share to increase the probability of winning the vote. Because the strength of this last motive is proportional to their private benefits, unless b_2 is sufficiently larger than b_1, the equipment producer's economic incentives to lower fees dominate. Such an effect implies that the equipment producer charges lower fees and, thus, has the larger share of the pool market.

Although we have assumed that private benefits are exogenous, it is reasonable to expect $b_1 \geq b_2$ in reality. For example, some proposals may affect the equipment producer directly, such as changes that make the protocol less compatible with the existing specialized equipment. Because the equipment producer controls a large share of the whole mining ecosystem, there are many more ways in which proposals can directly affect its payoff than that of independent pools.

As both b_1 and b_2 converge to zero, the equilibrium market shares converge to those in Proposition 4. If b_1 is small but not exactly zero, the equipment producer will still have a disproportionate impact on the governance of the blockchain.

5.4. Self-Mining

We have assumed that the equipment producer has no comparative advantage at mining; that is, σ is sufficiently large. Proposition 1 then implies that the equipment producer does not self-mine. In the next proposition, we show that this result no longer holds if the equipment producer's private benefits of control are sufficiently large.

Proposition 8 *A sufficient condition for the equipment producer to self-mine is*

$$\frac{b_1}{2\left(1-\alpha\right)} > \frac{r\left(\widehat{v}+\sigma\right)}{c-\widehat{v}}. \tag{28}$$

Intuitively, if b_1 is sufficiently large, the equipment producer is willing to give up some of the profit in the sale of equipment in order to self-mine and increase the probability that it wins the vote. To understand the right-hand side of (28), note that $\widehat{\upsilon}+\sigma$ is a measure of the comparative advantage at mining that individual miners have over the equipment producer. As this advantage increases, it would take a larger private benefit to induce the producer to self-mine. Incentives to self-mine are also curbed when mining rewards are high, i.e., when r is large. A larger r implies that mining is more attractive; thus, there is potentially more demand for equipment. This increase in potential demand increases the shadow cost of self-mining. Similarly, $c-\widehat{\upsilon}$ is a measure of individual miners' net cost of mining. A lower net cost of mining increases the demand for equipment and thus reduces the equipment producer's incentives to self-mine.

6. Countervailing Forces

Our model predicts that a large equipment producer will dominate the ASIC market. This producer will then enter the mining pool market, where it will also become the largest player. Because of its leading position in the pool market, the dominant producer will have a disproportionate influence on the governance of the blockchain. The producer may then use its influence to push for changes that do not necessarily reflect the view of the majority of the stakeholders.

It is natural to ask whether, in practice, other forces moderate such conclusions. In this section, we briefly discuss some of these countervailing forces.

6.1. Can the incumbent equipment producer sustain its dominance?

Our model implies that a single ASIC producer acquires 100% of the market. In reality, the dominant producer is likely to compete with fringe players. Technological change is also likely to foster entry by more efficient producers. As of 2020, the dominant ASIC producer (Bitmain) has faced competition from some smaller players, in particular, Canaan, another Chinese company that went public in 2019. It is also possible that some large chip producers may consider entering this market.

To date, most of Bitmain's problems seem to be caused less by competition than by their working capital management choices. Because Bitmain typically prepays for their inventory up to six months before delivery, it risks being stuck with unwanted machines when crypto prices fall. This risk is compounded by Bitmain's practice of holding large balances of cryptocurrencies on its balance sheet, which are then liquidated when crypto prices are low, precisely when Bitmain has liquidity needs. As a consequence of such choices, Bitmain's free cash flow fell from more than one billion USD in 2017 to minus three hundred million USD in the first semester of 2018 (Ferreira, 2019).

Our model is about governance capture by a dominant equipment producer. The model is silent about the identity of such a producer. If an incumbent producer is ousted by more efficient competitors, or if it fails because of financial choices, our prediction is that some other company will take that role.

6.2. Can mining pool competition reduce the equipment producers' influence?

Our model assumes that all mining pool operators are equally efficient. In reality, some mining pool operators may be more efficient than others in the sense of being able to deliver high-quality service at lower costs. As an example, Poolin was founded in 2018 and quickly became one of the largest mining pools. Poolin has introduced some technical innovations – such as automatically switching between BTC and BCH – and may have benefited from the expertise of its founders, who previously worked for Bitmain's pool BTC.com.

Our model implies that the existence of more efficient mining pools is a mixed blessing for the equipment producer. On the one hand, more competition in the mining pool market implies lower pool fees and, thus, higher demand for equipment. On the other hand, the dominant producer may have less influence on the governance of the blockchain.

Our model predicts that a dominant producer who enjoys significant benefits from control will choose to self-mine. If the dominant producer is unable to compete in the mining pool market, it should then invest more in self-mining. There is some evidence that Bitmain is currently trying to refocus toward more self-mining. Bitmain has recently introduced "joint mining" contracts, in which miners get free equipment but are responsible for storing the equipment and managing the mining operation. Bitmain pays for all electricity costs, as long as expected mining profits are larger than such costs, and pockets 75% of the mining rewards. Bitmain's renewed interest in self-mining might be a response to tougher competition in the mining pool market.

6.3. Can alternative systems deliver "governance without trust"?

To avoid governance capture, blockchain stakeholders could consider alternative governance systems. The most popular alternative to proof-of-work is *proof-of-stake*, a system in which the probability of a node becoming a block producer is proportional to that node's "stake" in the network.[31] It is, however, not clear that such a system would avoid the problem of corporate capture. First, by design, this system gives more voting power to larger players.[32] Second, such a system may also create its own industrial ecosystem where certain corporate stakeholders play an important role. An example is the emergence of *staking pools*, which are conceptually similar to mining pools. Cryptocurrency exchanges own many of the staking pools.

Another governance structure is *delegated proof-of-stake.* In such a system, blockchain stakeholders vote for delegates who then directly monitor the blockchain (an example is EOS). This system essentially replicates the traditional governance structure of corporations, in which shareholders vote for corporate directors, who then monitor management. Such a system is very different from the direct democracy envisioned by Nakamoto; it is essentially a system of representative democracy. In a representative democracy – by definition – voters need to trust their representatives.

Proof-of-stake (and delegated proof-of-stake) systems may have many advantages over proof-of-work, such as lower electricity consumption, faster transaction validation, and improved scalability. There is some evidence that such alternatives to proof-of-work are becoming more popular (Hinzen, Irresberger, John, and Saleh, 2019). Whether such systems can deliver "governance without trust" is an open question, which we leave for future research.

7. Conclusion

In this paper, we develop a model in which the proof-of-work protocol creates an industrial ecosystem where miners, mining equipment producers, and mining services providers have

[31] The definition of *stake* varies across different implementations. For an economic analysis of the proof-of-stake concept, see Saleh (2018).

[32] Roşu and Saleh (2019) show, however, that the proof-of-stake protocol does not lead to increasing accumulation of wealth.

conflicting interests. Our model implies that the emergence of such stakeholders has a substantial effect on the governance of blockchains. We show that some stakeholders have incentives to control a large portion of the whole mining ecosystem. In particular, we show that the dominant equipment producer captures the governance of the blockchain.

What factors explain the influence of specialized equipment producers on blockchain governance? We show that the combination of a homogeneous good (computational power) and sunk entry costs (R&D costs) leads to a situation in which a large firm dominates the market for specialized mining equipment. Such a firm then has incentives to enter the mining pool market to squeeze the profits of other mining pools and, thus, increase the demand for its equipment. Such incentives are stronger as the equipment producer becomes more efficient and as the blockchain becomes more successful, that is, as crypto prices increase.

According to our model, the equipment producer invests in the mining ecosystem to encourage more individuals to become miners. This explanation corresponds to what Bitmain Technologies – the leading specialized cryptomining equipment producer – states in its IPO prospectus:

> "*Catering to our customers' evolving needs, we supplement our core cryptocurrency mining ASIC chips design business with (...) our mining pool business. (...) Our mining pools reduce the risks and volatility of mining and facilitate a steady return for individual cryptocurrency miners, which encourage more participants to engage in mining activities.*"[33]

Our model has clear policy implications. We show that integration in the mining ecosystem is detrimental to the governance of the blockchain. In addition to its governance benefits, policies that forbid equipment producers from operating mining pools may have other social benefits. Because miners compete for a fixed prize, such policies can decrease the social deadweight cost of mining by reducing the amount of computational power allocated to it.

Our model suggests that Nakamoto's vision of blockchain governance is untenable. Because market power propagates through the mining ecosystem, corporate capture is in proof-of-work's DNA. If a large firm captures the governance of the blockchain, blockchain stakeholders have to trust one company to look after their interests. In that case, one may ask how

[33] This quote is from Bitmain's IPO application to the Hong Kong Stock Exchange in September 2018.

a permissionless blockchain differs from a traditional financial intermediary as a provider of trust.

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8. Appendix

A model of mining with difficulty adjustment.

At time t_0, each miner i simultaneously chooses their hash rate capacity n_i; total hash rate in the economy is n. They pay p per unit of hash rate. Capacities remain fixed until date $t_0 + T$. Let δ denote the block interval; δ is a random variable.

For each hash unit (attempted solution), let q denote the probability of finding a solution. Because all trials are independent, the expected number of trials before the first success is $E[n\delta] = \frac{1}{q}$. Let $w = \frac{1}{q}$; w is a measure of the difficulty of the problem. Now, because n is deterministic, we have $E[\delta] = \frac{w}{n}$.

The expected utility of mining a block is

$$\frac{rn_i}{n} - (p + \theta_i)\, n_i E[\delta] = \frac{rn_i}{n} - (p + \theta_i)\, n_i \frac{w}{n} = (r - pw - \theta_i w)\, \frac{n_i}{n}. \tag{29}$$

The Bitcoin protocol adjusts w to keep $E[\delta]$ constant at some level $\overline{\delta}$; without loss of generality we normalize $\overline{\delta}$ to 1. We assume that this adjustment happens immediately after capacity decisions are made. The adjustment is such that $w = n$. Then, the expected utility of mining a block is

$$\left(\frac{r}{n} - p - \theta_i\right) n_i, \tag{30}$$

which implies (2).

A model of mining with capacity utilization decisions.

Suppose that $\theta_{it} = e_{it} + \overline{\theta}$, where $e_{it} > 0$ is a random variable that may change in each period (e.g., electricity costs) and $\overline{\theta}$ is deterministic. We assume that e_{it} is i.i.d, across miners and across time, with support $[0, \infty)$. Suppose that r is constant, for simplicity. For $t \in [t_0, t_0 + T]$, let $h_{it} \leq n_i$ denote the hash rate used by miner i at time t, which may now be less than the miner's capacity n_i.

Miner i's instantaneous incremental utility from mining at time t (ignoring private benefits from control and assuming instantaneous difficulty adjustment) is

$$\left(\frac{r}{h_t} - e_{it} - \overline{\theta}\right) h_{it}, \tag{31}$$

where h_t is total hash rate employed at time t. Miner i will either choose $h_{it} = n_i$ or $h_{it} = 0$. The cutoff for supplying a positive hash rate is $\tilde{e} = \frac{r}{h_t} - \overline{\theta}$. We then have the following equilibrum condition for each t

$$F\left(\frac{r}{h_t} - \overline{\theta}\right) n = h_t, \tag{32}$$

where $F(x) = \Pr(e < x)$, which uniquely defines $h^*\left(r, \overline{\theta}, n\right)$. Note that $\partial h^* / \partial n > 0$. That is, at each period, miners with low variable costs use their full capacity while miners with high variable costs supply zero hash rate. The i.i.d. assumption implies that the aggregate capacity utilization rate is constant.

The expected payoff, as of time t_0, of an individual miner who acquires hash rate capacity n_i and uses it optimally until $t_0 + T$ is

$$\begin{aligned} & F\left(\frac{r}{h^*\left(r, \overline{\theta}, n\right)} - \overline{\theta}\right)\left(\frac{r}{h^*\left(r, \overline{\theta}, n\right)} - \overline{\theta} - E[e \mid e < \frac{r}{h^*\left(r, \overline{\theta}, n\right)} - \overline{\theta}]\right) n_i T - p n_i T + b_i I\left(\varphi_i, \varphi_{-i}\right) T \\ = & \left[F\left(\frac{r}{h^*\left(r, \overline{\theta}, n\right)} - \overline{\theta}\right)\left[\frac{r}{h^*\left(r, \overline{\theta}, n\right)} - \overline{\theta}\right] - \int_0^{\frac{r}{h^*\left(r, \overline{\theta}, n\right)} - \overline{\theta}} e dF(e)\right] n_i T - p n_i T + b_i I\left(\varphi_i, \varphi_{-i}\right) T, \end{aligned}$$

which is the analog of (2).

Proposition 1.

Proof. Firm k's problem is to

$$\max_{p,n_k,n'_k} \pi_k = (p - \underline{c})n'_k + \left(\frac{r}{n_k + n'_k} - \underline{c} - \sigma_k\right) n_k, \tag{33}$$

subject to

$$\frac{r}{n_k + n'_k} - \min\{p, c\} - \theta \;\leq\; 0 \tag{34}$$

$$p \;\leq\; c \tag{35}$$

$$n_k, n'_k \;\geq\; 0. \tag{36}$$

First, note that (35) implies $\min\{p, c\} = p$. Suppose now (34) is slack in equilibrium, then we must have $n'_k = 0$. The profit function becomes

$$\pi_k = r - (\sigma_k + \underline{c})\, n_k, \tag{37}$$

and the producer's profit decreases with n_k, which implies that (34) must eventually bind. Thus (34) cannot be slack. Because (34) binds, then we can rewrite the profit function as

$$\pi_k = (p - \underline{c})\,(n_k + n'_k) + (\theta - \sigma_k)\, n_k. \tag{38}$$

If $(\theta - \sigma_k) < 0$, then the producer wants the minimum possible n_k, which implies $n_k = 0$, and thus

$$n'_k = \frac{r}{p + \theta}. \tag{39}$$

Replacing (39) in the profit function yields:

$$\pi_k = r\frac{p - \underline{c}}{p + \theta}. \tag{40}$$

Since

$$\frac{\partial \pi_k}{\partial p} = r\frac{\underline{c} + \theta}{(p + \theta)^2} > 0, \tag{41}$$

constraint $p \leq c$ binds. In either case, $p^* = c$.

If $(\theta - \sigma_k) > 0$, then the producer wants the maximum possible n_k, which implies $n'_k = 0$, which requires $p = c$ and

$$n_k = \frac{r}{c+\theta}. \tag{42}$$

Finally, if $(\theta - \sigma_k) = 0$ then any n_k and n'_k such that $n_k + n'_k = \frac{r}{c+\theta}$ is a solution. ■

Proposition 2.

Proof. Firm k's problem is to

$$\max_{p_k, n_k, n'_k} \pi_k = (p_k - \underline{c})n'_k + \left(\frac{r}{n_k + n'_k + n_z + n'_z} - \underline{c} - \sigma\right) n_k, \tag{43}$$

subject to

$$\begin{aligned} \frac{r}{n_k + n'_k + n_z + n'_z} - \min\{p_k, p_z, c\} - \theta &\leq 0 && (44) \\ p_k &\leq \min\{p_z, c\} && (45) \\ n_k, n'_k &\geq 0. && (46) \end{aligned}$$

Firm z's problem is symmetric.

First, note that, in an equilibrium where both firms sell a positive number of machines, it must be that $p_k = p_z = p$. This follows from usual Bertrand competition reasoning: if, say, $p_k < p_z$, all miners would buy only from Firm k. Furthermore, it must be that $p = \underline{c}$. If not, there is a profitable deviation: a firm may reduce its price by small $\varepsilon > 0$ and capture the whole market.

We need to consider three cases.

Case 1: $(\sigma - \theta) > 0$. (i) Suppose first that $n'_k + n'_z > 0$. Then it follows that $p = \underline{c}$ and thus we have

$$\frac{r}{n_k + n'_k + n_z + n'_z} - \underline{c} - \theta = 0. \tag{47}$$

The profit function becomes

$$\pi_k = \left(\frac{r}{n_k + n'_k + n_z + n'_z} - \underline{c} - \sigma\right) n_k, \tag{48}$$

which is strictly negative for any $n_k > 0$, implying that we must have $n^*_k = n^*_z = 0$. This is the only equilibrium with positive sales $n'^*_k + n'^*_z > 0$.

Thus, in any equilibrium with positive sales, there is no self mining and profits are zero

$(p = \underline{c})$.

(ii) Suppose now that $n_k'^* = n_z'^* = 0$. Let $p = \min\{p_k, p_z\}$, and without loss of generality, suppose $p = p_k$. If $n_k'^* = n_z'^* = 0$ in equilibrium, the miners' utility per unit of computational power is

$$\frac{r}{n_k^* + n_z^*} - p_k - \theta < 0. \tag{49}$$

Firm k's profit is

$$\pi_k = \left(\frac{r}{n_k^* + n_z^*} - \underline{c} - \sigma \right) n_{k.} \tag{50}$$

For an equilibrium, we need $\pi_k \geq 0$. Define

$$\widehat{p} = \frac{r}{n_k^* + n_z^*} - \theta. \tag{51}$$

For π_k to be positive while (49) holds, $p_k > \widehat{p} > \underline{c}$.

We now show that this cannot be an equilibrium. Consider a deviation where Firm k sets $p_k = \widehat{p}$ and chooses $n_k = 0$. The firm will then sell an amount n_k' such that

$$\frac{r}{n_z^* + n_k'} - \widehat{p} - \theta = 0, \tag{52}$$

which implies $n_k' = n_k^*$. The profit is then

$$(\widehat{p} - \underline{c})n_k^* = \left(\frac{r}{n_k^* + n_z^*} - \underline{c} - \theta \right) n_k^* > \left(\frac{r}{n_k^* + n_z^*} - \underline{c} - \sigma \right) n_k^*, \tag{53}$$

thus this is a profitable deviation. Thus, there is no equilibrium with zero sales.

We conclude that, if $\sigma - \theta > 0$, all equilibria require $n_k^* = n_z^* = 0$ and both firms make zero profit.

Case 2: $\sigma - \theta < 0$. (i) Suppose first that $n_k'^* = n_z'^* = 0$. The maximization problem becomes

$$\max_{n_k} \pi_k = \left(\frac{r}{n_k + n_z} - \underline{c} - \sigma \right) n_k, \tag{54}$$

and the first-order condition is

$$\frac{r}{n_k + n_z} - \underline{c} - \sigma - \frac{r n_k}{(n_k + n_z)^2} = 0. \tag{55}$$

In a symmetric equilibrium

$$n_k^* = n_z^* = \frac{r}{4\left(\underline{c} + \sigma\right)}, \tag{56}$$

provided that the free entry condition is slack:

$$2\left(\underline{c} + \sigma\right) < c + \theta, \tag{57}$$

and total profit is then

$$\pi = \frac{r}{4\left(\underline{c} + \sigma\right)}\left[2\left(\underline{c} + \sigma\right) - \underline{c} - \sigma\right] = \frac{r}{4}. \tag{58}$$

If (57) does not hold, we have

$$n_k^* = n_z^* = \frac{r}{2\left(c + \theta\right)}, \tag{59}$$

and the profit is

$$\pi = \frac{r\left(c - \underline{c} - \sigma + \theta\right)}{2\left(c + \theta\right)}. \tag{60}$$

We now show that this is an equilibrium. Define

$$\widehat{p} = \frac{r}{n_k^* + n_z^*} - \theta. \tag{61}$$

Consider a deviation where Firm k sets $p_k = \widehat{p}$ and chooses $n_k = 0$. The firm will then sell an amount n_k' such that

$$\frac{r}{n_k' + n_z^*} - \widehat{p} - \theta = 0, \tag{62}$$

which implies $n_k' = n_k^*$. Firm k's profit is then

$$(\widehat{p} - \underline{c})n_k^* = \left(\frac{r}{n_k^* + n_z^*} - \underline{c} - \theta\right) n_k^* < \left(\frac{r}{n_k^* + n_z^*} - \underline{c} - \sigma\right) n_k^*, \tag{63}$$

thus no profitable deviation exists.

(ii) Suppose now that $n_k'^* + n_z'^* > 0$. The entry constraint must be binding:

$$\frac{r}{n_k'^* + n_z'^* + n_k^* + n_z^*} - \underline{c} - \theta = 0. \tag{64}$$

Because $p = \underline{c}$, Firm k's profit is

$$\left(\frac{r}{n_k'^* + n_z'^* + n_k^* + n_z^*} - \underline{c} - \sigma\right) n_k^* = -(\sigma - \theta) n_k^* > 0 \tag{65}$$

so there is a profitable deviation, which is to increase n_k'. Thus, this cannot be an equilibrium.

We conclude that, if $\sigma - \theta < 0$, all equilibria require $n_k'^* = n_z'^* = 0$ and both firms make positive profit.

Case 3: $\sigma - \theta = 0$. Using the same arguments as in Cases 1 and 2, it can be shown that both types of equilibria are possible in this zero measure case. ■

Proposition 3.

Proof. At $t = t_0$, there are no incumbents in the market for specialized mining equipment. At $t \in (t_0, t_0 + T]$, Firm 1 has the option to enter this market by paying an once-and-for-all sunk cost ι. At $t \in (t_0 + T, t_0 + 2T]$, Firm 2 can now enter after paying the same cost ι, and so on for $t > t_0 + 2T$. That is, Firm 1 has a first-mover advantage over all other firms.

Let ξ denote the common discount rate. Proposition 2 implies that in any equilibrium with two firms and $n_1'^* + n_2'^* > 0$, profits are zero for both firms, and $\sigma \geq \theta$. Thus, assume $\sigma \geq \theta$. At $t \in (t_0 + T, t_0 + 2T]$, suppose that Firm 1 is an incumbent. If Firm 2 enters, it enjoys zero profit in perpetuity (we assume that Firm 1 does not exit after Firm 2 enters) and pays entry cost ι, thus it will not enter in this case. At $t \in (t_0 + 2T, t_0 + 3T]$, the same reasoning implies that Firm 3 will also not enter if either Firm 1 or Firm 2 is an incumbent, and so on for $t > t_0 + 3T$. Thus, if Firm 1 enters, no firm at periods $t > t_0 + T$ will enter. Thus Firm 1 chooses to enter if and only if

$$\frac{r\,(c - \underline{c})}{\xi\,(c + \theta)} \geq \iota. \tag{66}$$

If condition (66) does not hold, Firm 1 will not enter. Firm 2 then faces the same problem as Firm 1, and also chooses not to enter, and so on for $t > t_0 + 2T$. Thus, equilibrium is such that only Firm 1 enters if and only if (66) holds, otherwise no firm enters. ■

Fully served mining pools market

We first derive the condition under which the mining pools market is fully served (i.e., no miner chooses to mine alone) when there is a monopolist mining pool. The objective function of a monopolist mining pool is:

$$\max_{f} \Pi(f) = \frac{f(1-G(f))r}{c - \int_{f}^{\overline{\upsilon}} (\upsilon - f)\, g(\upsilon)\, d\upsilon}. \tag{67}$$

For $f < \underline{\upsilon}$, we have

$$\frac{\partial \Pi(f)}{\partial f} = \frac{r}{c-\mu+f} - \frac{rf}{(c-\mu+f)^2} = \frac{r(c-\mu)}{c-\mu+f} > 0. \tag{68}$$

It follows that, with a monopolist pool, $f \geqslant \underline{\upsilon}$. We now derive $\frac{\partial \Pi(f)}{\partial f}$ for $f \geqslant \underline{\upsilon}$:

$$\begin{aligned} \frac{\partial \Pi(f)}{\partial f} &= \frac{r((1-G(f))-fg(f))}{c-\int_{f}^{\overline{\upsilon}}(\upsilon-f)g(\upsilon)d\upsilon} - \frac{rf(1-G(f))^2}{\left(c-\int_{f}^{\overline{\upsilon}}(\upsilon-f)g(\upsilon)d\upsilon\right)^2} \\ &= \frac{r((1-G(f))-fg(f))}{c-\int_{f}^{\overline{\upsilon}}(\upsilon-f)g(\upsilon)d\upsilon}\left((1-G(f)) - fg(f) - \frac{f(1-G(f))^2}{c-\int_{f}^{\overline{\upsilon}}(\upsilon-f)g(\upsilon)d\upsilon}\right). \end{aligned} \tag{69}$$

If $\frac{\partial \Pi(f)}{\partial f} \leq 0$ for $f = \underline{\upsilon}$, then the monopolist chooses $f = \underline{\upsilon}$, and all miners choose to join the mining pool. The condition for $f^* = \underline{\upsilon}$ is:

$$1 - \underline{\upsilon} g(\underline{\upsilon}) - \frac{\underline{\upsilon}}{c-\mu+\underline{\upsilon}} \leq 0 \tag{70}$$

$$\Leftrightarrow \underline{\upsilon} g(\underline{\upsilon})(c-\mu+\underline{\upsilon}) \geq c-\mu. \tag{71}$$

If competition leads to a reduction in mining pool fees, then (71) is a sufficient condition for the market to be fully served by two pools.

Proposition 4

Proof. The two pools choose f_1 and f_2, such that:

$$\max_{f_1} \Pi_1(f_1, f_2) + \pi(f_1, f_2) = \frac{rf_1(1-H(f_1-f_2))}{c - E[s^* \mid f_1, f_2]} + \frac{r(c-\underline{c})}{c - E[s^* \mid f_1, f_2]}, \tag{72}$$

$$\max_{f_2} \Pi_2(f_1, f_2) = \frac{rf_2 H(f_1-f_2)}{c - E[s^* \mid f_1, f_2]}. \tag{73}$$

We have defined $H(f_1 - f_2) = \Pr(\upsilon_1 - \upsilon_2 \leq f_1 - f_2)$. We then have

$$H(f_1 - f_2) = \left\{ \begin{array}{l} 1 - G(\overline{\upsilon} - f_1 + f_2) - \int_{\underline{\upsilon}}^{\overline{\upsilon}-f_1+f_2} G(\upsilon_2 + f_1 - f_2)\, g(\upsilon_2)\, d\upsilon_2 \text{ for } f_1 - f_2 > 0 \\ \int_{\underline{\upsilon}-f_1+f_2}^{\overline{\upsilon}} G(\upsilon_2 + f_1 - f_2)\, g(\upsilon_2)\, d\upsilon_2 \text{ for } f_1 - f_2 \leq 0 \end{array} \right. .$$

We have defined $E\left[s^{*} \mid f_1, f_2\right] = E\left[\max\left\{\upsilon_1 - f_1, \upsilon_2 - f_2\right\}\right]$. For $f_1 - f_2 > 0$

$$\begin{aligned} E\left[s^{*} \mid f_1, f_2\right] = & \textstyle\int_{\overline{\upsilon}-f_1+f_2}^{\overline{\upsilon}} (\upsilon_2 - f_2) g\left(\upsilon_2\right) d\upsilon_2 \\ & + \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}-f_1+f_2} \left[\int_{\upsilon_2+f_1-f_2}^{\overline{\upsilon}} (\upsilon_1 - f_1) g\left(\upsilon_1\right) d\upsilon_1 + G\left(\upsilon_2 + f_1 - f_2\right)\left(\upsilon_2 - f_2\right)\right] g\left(\upsilon_2\right) d\upsilon_2 \end{aligned}$$

which implies

$$E\left[s^{*} \mid f_1, f_2\right] = E\left[\upsilon \mid f_1, f_2\right] - \left(1 - H\left(f_1 - f_2\right)\right) f_1 - H\left(f_1 - f_2\right) f_2,$$

where

$$E\left[\upsilon \mid f_1, f_2\right] = \int_{\underline{\upsilon}}^{\overline{\upsilon}-f_1+f_2} \left[\int_{\upsilon_2+f_1-f_2}^{\overline{\upsilon}} \upsilon_1 g\left(\upsilon_1\right) d\upsilon_1 + G\left(\upsilon_2 + f_1 - f_2\right) \upsilon_2\right] g\left(\upsilon_2\right) d\upsilon_2 + \int_{\overline{\upsilon}-f_1+f_2}^{\overline{\upsilon}} \upsilon_2 g\left(\upsilon_2\right) d\upsilon_2.$$

The partial effect of increasing of f_1 on $E\left[s^{*} \mid f_1, f_2\right]$ is

$$\begin{aligned} \frac{\partial E\left[s^{*} \mid f_1, f_2\right]}{\partial f_1} = & - \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}} (\upsilon_1 - f_1) g\left(\overline{\upsilon} - f_1 + f_2\right) g\left(\upsilon_1\right) d\upsilon_1 \\ & - \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}-f_1+f_2} \int_{\upsilon_2+f_1-f_2}^{\overline{\upsilon}} g\left(\upsilon_1\right) g\left(\upsilon_2\right) d\upsilon_1 d\upsilon_2 \\ & - \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}-f_1+f_2} (\upsilon_2 - f_2) g\left(\upsilon_2 + f_1 - f_2\right) g\left(\upsilon_2\right) d\upsilon_2 \\ & + \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}-f_1+f_2} (\upsilon_2 - f_2) g\left(\upsilon_2 + f_1 - f_2\right) g\left(\upsilon_2\right) d\upsilon_2 \\ & - G\left(\overline{\upsilon}\right)\left(\overline{\upsilon} - f_1\right) g\left(\overline{\upsilon} - f_1 + f_2\right) + \left(\overline{\upsilon} - f_1\right) g\left(\overline{\upsilon} - f_1 + f_2\right) \end{aligned}$$

After simplifying:

$$\frac{\partial E\left[s^{*} \mid f_1, f_2\right]}{\partial f_1} = - \int_{\underline{\upsilon}}^{\overline{\upsilon}-f_1+f_2} (1 - G\left(\upsilon_2 + f_1 - f_2\right)) g\left(\upsilon_2\right) d\upsilon_2 = -(1 - H(f_1 - f_2)).$$

By symmetry:

$$\frac{\partial E\left[s^{*} \mid f_1, f_2\right]}{\partial f_2} = -H(f_1 - f_2).$$

For $f_1 - f_2 \leq 0$, we have

$$\begin{aligned} E\left[s^{*} \mid f_1, f_2\right] = & G(\underline{\upsilon} - f_1 + f_2) \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}} (\upsilon_1 - f_1) g\left(\upsilon_1\right) d\upsilon_1 \\ & + \textstyle\int_{\underline{\upsilon}-f_1+f_2}^{\overline{\upsilon}} \left[\int_{\upsilon_2+f_1-f_2}^{\overline{\upsilon}} (\upsilon_1 - f_1) g\left(\upsilon_1\right) d\upsilon_1 + G\left(\upsilon_2 + f_1 - f_2\right)\left(\upsilon_2 - f_2\right)\right] g\left(\upsilon_2\right) d\upsilon_2 \end{aligned}$$

or

$$E\left[s^{*} \mid f_1, f_2\right] = E\left[\upsilon \mid f_1, f_2\right] - \left(1 - H\left(f_1 - f_2\right)\right) f_1 - H\left(f_1 - f_2\right) f_2,$$

where

$$\begin{aligned} E\left[\upsilon \mid f_1, f_2\right] &= \int_{\underline{\upsilon}-f_1+f_2}^{\overline{\upsilon}} \left[\int_{\upsilon_2+f_1-f_2}^{\overline{\upsilon}} \upsilon_1 g\left(\upsilon_1\right) d\upsilon_1 + G\left(\upsilon_2+f_1-f_2\right)\upsilon_2\right] g\left(\upsilon_2\right) d\upsilon_2 \\ &\quad + G(\underline{\upsilon}-f_1+f_2) \int_{\underline{\upsilon}}^{\overline{\upsilon}} \upsilon_1 g\left(\upsilon_1\right) d\upsilon_1. \end{aligned}$$

which gives us

$$\begin{aligned} \frac{\partial E\left[s^* \mid f_1, f_2\right]}{\partial f_1} = \; & -g(\underline{\upsilon}-f_1+f_2) \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}} (\upsilon_1 - f_1) g\left(\upsilon_1\right) d\upsilon_1 \\ & -G(\underline{\upsilon}-f_1+f_2) + g(\underline{\upsilon}-f_1+f_2) \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}} (\upsilon_1 - f_1) g\left(\upsilon_1\right) d\upsilon_1 \\ & - \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}} (\upsilon_2 - f_2) g\left(\upsilon_2+f_1-f_2\right) g\left(\upsilon_2\right) d\upsilon_2 \\ & + \textstyle\int_{\underline{\upsilon}}^{\overline{\upsilon}} (\upsilon_2 - f_2) g\left(\upsilon_2+f_1-f_2\right) g\left(\upsilon_2\right) d\upsilon_2 \\ & - \textstyle\int_{\underline{\upsilon}-f_1+f_2}^{\overline{\upsilon}} \int_{\upsilon_2+f_1-f_2}^{\overline{\upsilon}} g\left(\upsilon_1\right) g(\upsilon_2) d\upsilon_1 d\upsilon_2 \end{aligned}$$

After simplifying:

$$\frac{\partial E\left[s^* \mid f_1, f_2\right]}{\partial f_1} = -1 + \int_{\underline{\upsilon}-f_1+f_2}^{\overline{\upsilon}} G(\upsilon_2+f_1-f_2) g(\upsilon_2) d\upsilon_2 = -(1 - H(f_1 - f_2))$$

Again, by symmetry:

$$\frac{\partial E\left[s^* \mid f_1, f_2\right]}{\partial f_2} = -H(f_1 - f_2)$$

We now derive the first order conditions with respect to f_1 and $f_{2.}$ Let $H^* \equiv H(f_1^* - f_2^*)$ and $h^* \equiv h(f_1^* - f_2^*)$. Assuming that an interior solution exists, the simplified first-order conditions are:

$$\left(c - E\left[s^* \mid f_1, f_2\right]\right)(1-H^*) - f_1^* h^* \left(c - E\left[s^* \mid f_1, f_2\right]\right) - (c - \underline{c} + f_1^*(1-H^*))(1-H^*) = 0 \quad (74)$$

$$\left(c - E\left[s^* \mid f_1, f_2\right]\right) H^* - f_2^* h^* \left(c - E\left[s^* \mid f_1, f_2\right]\right) - H^* f_2^* H^* = 0, \quad (75)$$

Rearrange equations (74) and (75) as follows:

$$f_1^* \left(c - E\left[s^* \mid f_1, f_2\right]\right) h^* = \left(c - E\left[s^* \mid f_1, f_2\right]\right)(1-H^*) - (c - \underline{c} + f_1^*(1-H^*))(1-H^*) \quad (76)$$

$$f_2^* \left(c - E\left[s^* \mid f_1, f_2\right]\right) h^* = \left(c - E\left[s^* \mid f_1, f_2\right]\right) H^* - f_2^* H^{*2} \quad (77)$$

We subtract (77) from (76) and simplify:

$$\begin{aligned}(f_1^* - f_2^*)\left(c - E\left[s^* \mid f_1, f_2\right]\right) h^* &= \left(c - E\left[s^* \mid f_1, f_2\right]\right)(1 - 2H^*) \\ &\quad -(c - \underline{c})(1 - H^*) - f_1^*(1 - H^*)^2 + f_2^* H^{*2},\end{aligned}$$

which can also be rewritten as follows

$$(f_1^* - f_2^*)\left(c - E\left[s^* \mid f_1, f_2\right]\right) h^* = \left(c - E\left[s^* \mid f_1, f_2\right] - f_1^*\right)(1-2H^*) - (c-\underline{c})(1-H^*) - (f_1^* - f_2^*) H^{*2}$$

Rearranging,

$$\begin{aligned}(f_1^* - f_2^*)\left[h^*\left(c - E\left[s^* \mid f_1, f_2\right]\right) + H^{*2}\right] &= \left(c - E\left[\upsilon \mid f_1, f_2\right] + (1 - H^*) f_1^* + H^* f_2^* - f_1^*\right)(1 - 2H^*) \\ &\quad -(c - \underline{c})(1 - H^*),\end{aligned}$$

or

$$(f_1^* - f_2^*)\left[h^*\left(c - E\left[s^* \mid f_1, f_2\right]\right) + (1 - H^*)H^*\right] = \left(c - E\left[\upsilon \mid f_1, f_2\right]\right)(1-2H^*) - (c-\underline{c})(1-H^*).$$

We replace $H^* = 0.5 + \epsilon$, where $\epsilon \in [-0.5, 0.5]$ and simplify:

$$(f_1^* - f_2^*)\left[h^*\left(c - E\left[s^* \mid f_1, f_2\right]\right) + (0.25 - \epsilon^2)\right] = -2\epsilon\left(c - E\left[\upsilon \mid f_1, f_2\right]\right) - (c - \underline{c})(0.5 - \epsilon) \tag{78}$$

Suppose now that $\epsilon \geq 0$, that is $H^* \geq 0.5$. Since

$$h^*\left(c - E\left[s^* \mid f_1, f_2\right]\right) + (0.25 - \epsilon^2) > 0,$$

and since for $\epsilon \geq 0$ the right-hand side of equation (78) is negative, it follows that $f_1^* < f_2^*$, which is in contradiction with $H^* \geq 0.5$.

Since $\varphi_1(f_1^*, f_2^*) = \alpha(1 - H^*)$ and $\varphi_2(f_1^*, f_2^*) = \alpha H^*$ and $H^* < 0.5$, it follows that $\varphi_1(f_1^*, f_2^*) > \varphi_2(f_1^*, f_2^*)$ and $I\left(\varphi_1(f_1^*, f_2^*), \varphi_2(f_1^*, f_2^*)\right) > I\left(\varphi_2(f_1^*, f_2^*), \varphi_1(f_1^*, f_2^*)\right)$. ■

Proposition 4 in a more general setting.

Here we show that the existence of a profit-squeeze effect is robust to modifications to the model setup and assumptions. In particular, it is robust to different assumptions about functional forms, mode of competition, and learning about pool preferences. Let $\pi(f_1, f_2)$ denote the profit in the market for equipment and let $\Pi_1(f_1, f_2)$ and $\Pi_2(f_1, f_2)$ denote the profit functions in the pool market, for firms 1 and 2 respectively. Here we do not make any explicit assumption about how competition among miners and among mining pools works. We also make no assumption about when miners learn their pool preferences.

Here we describe a sufficient set of assumptions to show that the equipment producer is the stakeholder with the greatest influence on the governance of the blockchain.

1. $\Pi_1(f_1, f_2) = \Pi_2(f_2, f_1)$ (pool profit functions are symmetric),
2. $\frac{\partial \pi}{\partial f_1} < 0$ (lower fees in the pool market increase profit in the market for mining equipment),
3. $\frac{\partial^2 \Pi_1(f_1,f_2)}{\partial f_1 \partial f_2}, \frac{\partial^2 \Pi_2(f_1,f_2)}{\partial f_1 \partial f_2} > 0$ (pool fees are strategic complements), and
4. $\frac{\partial^2 \Pi_1(f_1,f_2)}{\partial f_1^2}, \frac{\partial^2 \Pi_2(f_1,f_2)}{\partial f_2^2} < 0$ (the pool profit function is globally concave).

The proof is as follows. The first-order conditions that determine the equilibrium fees are:

$$\frac{\partial \Pi_1(f_1^*, f_2^*)}{\partial f_1} + \frac{\partial \pi(f_1^*, f_2^*)}{\partial f_1} = 0 \quad (79)$$

$$\frac{\partial \Pi_2(f_1^*, f_2^*)}{\partial f_2} = 0. \quad (80)$$

Suppose that the equilibrium is such that $f_1^* > f_2^*$. Then, because of strategic complementarities, we have

$$\frac{\partial \Pi_2(f_2^*, f_2^*)}{\partial f_2} < 0. \quad (81)$$

Symmetry implies

$$\frac{\partial \Pi_2(f_2^*, f_2^*)}{\partial f_2} = \frac{\partial \Pi_1(f_2^*, f_2^*)}{\partial f_1} < 0. \quad (82)$$

Now, concavity implies

$$\frac{\partial \Pi_1(f_2^*, f_2^*)}{\partial f_1} > \frac{\partial \Pi_1(f_1^*, f_2^*)}{\partial f_1}, \quad (83)$$

and therefore

$$\frac{\partial \Pi_1(f_1^*, f_2^*)}{\partial f_1} < 0. \quad (84)$$

But because $\frac{\partial \pi(f_1,f_2)}{\partial f_1} < 0$, (84) contradicts (79). Thus, there cannot be an equilibrium where $f_1^* \geq f_2^*$.[34]

Proposition 5.

Proof. We start by characterizing the equilibrium when 2 independent pools compete in the pool market. As before $b_j = 0 \ \text{ for } j = \{1, 2\}$. Each pool maximizes its expected profit:

$$\max_{f_1} \Pi_1 = \frac{r f_1 \left(1 - H(f_1 - f_2)\right)}{c - E\left[s^* \mid f_1, f_2\right]} \tag{85}$$

$$\max_{f_2} \Pi_2 = \frac{r f_2 H(f_1 - f_2)}{c - E\left[s^* \mid f_1, f_2\right]} \tag{86}$$

Let $H^* \equiv H(f_1^* - f_2^*)$ and $h^* \equiv h(f_1^* - f_2^*)$, the simplified first order conditions are:

$$\left(c - E\left[s^* \mid f_1, f_2\right]\right)(1 - H^*) - f_1^* h^* \left(c - E\left[s^* \mid f_1, f_2\right]\right) - (1 - H^*) f_1^* (1 - H^*) = 0 \tag{87}$$

$$\left(c - E\left[s^* \mid f_1, f_2\right]\right) H^* - f_2^* h^* \left(c - E\left[s^* \mid f_1, f_2\right]\right) - H^* f_2^* H^* = 0, \tag{88}$$

From the first order conditions we can express f_1^* and f_2^* as follows

$$f_1^* \left(c - E\left[s^* \mid f_1, f_2\right]\right) h^* = \left(c - E\left[s^* \mid f_1, f_2\right]\right)(1 - H^*) - (1 - H^*) f_1^* (1 - H^*), \tag{89}$$

$$f_2^* \left(c - E\left[s^* \mid f_1, f_2\right]\right) h^* = \left(c - E\left[s^* \mid f_1, f_2\right]\right) H^* - H^* f_2^* H^*. \tag{90}$$

From (89) and (90),

$$\left(f_1^* - f_2^*\right)\left(c - E\left[s^* \mid f_1, f_2\right]\right) h^* = \left(c - E\left[s^* \mid f_1, f_2\right]\right)(1 - 2H^*) - f_1^* (1 - H^*)^2 + f_2^* H^{*2}$$

which is equivalent to

$$\left(f_1^* - f_2^*\right)\left[\left(c - E\left[s^* \mid f_1, f_2\right]\right) h^* + H^{*2}\right] = \left(c - E\left[v \mid f_1, f_2\right] - \left(f_1^* - f_1^*\right) H^*\right)(1 - 2H^*),$$

or

$$\left(f_1^* - f_2^*\right)\left[\left(c - E\left[s^* \mid f_1, f_2\right]\right) h^* + (1 - H^*) H^*\right] = \left(c - E\left[v \mid f_1, f_2\right]\right)(1 - 2H^*). \tag{91}$$

[34] The case of $f_1^* = f_2^*$ is trivial to rule out by using only symmetry and $\frac{\partial \pi(f_1,f_2)}{\partial f_1} < 0$.

Assume that $H^* > 0.5$. Then, the right hand side of (91) is negative which would imply that $f_1^* < f_2^*$,which contradicts $H^* > 0.5$. Assume now that $H^* < 0.5$, then the right hand side of (91) is positive which would imply $f_1^* > f_2^*$,which contradicts $H^* < 0.5$.Since $H(0) = 0.5$, (91) is only satisfied for $f_1^* = f_2^* = f^*$. We can now simplify (89) as follows

$$(c - \widehat{v} + f^*)\, 0.5 - f^* h^*(0)\,(c - \widehat{v} + f^*) - 0.25 f^* = 0 \tag{92}$$

$$\Leftrightarrow f^{*2} h^*(0) + f^* \left[h^*(0)\,(c - \widehat{v}) - 0.25\right] - 0.5\,(c - \widehat{v}) = 0 \tag{93}$$

$$f^* = \frac{-\left(h^*(0)\,(c - \widehat{v}) - 0.25\right) + \sqrt{\left(h^*(0)\,(c - \widehat{v}) + 0.25\right)^2 + 1}}{2h^*(0)}, \tag{94}$$

where

$$\widehat{v} = \int_{\underline{v}}^{\overline{v}} \left(\int_{v_2}^{\overline{v}} v_1 g(v_1)\, dv_1 + G(v_2)\, v_2 \right) g(v_2)\, dv_2. \tag{95}$$

Note that f^* is independent of r and $\underline{c}$.

The equipment producer is better off entering the market without full control, rather than entering the market with full control if:

$$\frac{r\,(c - \underline{c})}{c - E\left[s^* \mid f_1, f_2\right]} + \frac{r f_1^*\,(1 - H^*)}{c - E\left[s^* \mid f_1, f_2\right]} < \frac{r\,(c - \underline{c})}{c - \widehat{v} + f^*} + \frac{r 0.5 f^*}{c - \widehat{v} + f^*}, \tag{96}$$

where f_1^* and f_2^* are the equilibrium fees and $(1 - H^*)$ (*resp.* H^*) is the equilibrium market share of Pool 1 (*resp.* Pool 2) in the case where Pool 1 is fully controlled by the equipment producer, and f^* is as in equation (94). ■

Proposition 6.

Proof. Suppose that an independent pool enters the market. Let Π^I denote the equilibrium profit of this pool, gross of entry costs. Suppose instead that the equipment producer is the entrant. Let Π^C denote the equilibrium profit in the pool market (gross of entry costs) of the producer if it enters with full control rights. If it instead enters without control rights, its profit is identical to that of an independent entrant, Π^I. Let π_1^I denote the equilibrium profit in the equipment market if an independent pool enters the pool market. Let π_1^C denote the equilibrium profit in the equipment market if the pool that enters the pool market is fully controlled by the equipment producer. Finally, let π_1 denote the equilibrium profit in the equipment market if there is only one pool in the market.

An independently-owned pool enters the mining pool market if:

$$\Pi^I \geq \kappa. \tag{97}$$

The equipment producer enters the mining pool market if:

$$\max\left\{\Pi^I + \pi_1^I, \Pi^C + \pi_1^C\right\} - \pi_1 \geq \kappa \tag{98}$$

A sufficient condition for the equipment producer to have higher incentives to enter the pool market relative to an independent pool is:

$$\pi_1^I > \pi_1 \tag{99}$$

$$\frac{r(c-\underline{c})}{c-\widehat{\upsilon}+f^*} > \frac{r(c-\underline{c})}{c-\int_{f^0}^{\overline{\upsilon}}\left(\upsilon-f^0\right)g\left(\upsilon\right)d\upsilon}, \tag{100}$$

where f^* is the equilibrium fee with two independent pools and f^0 is the equilibrium fee chosen by a monopolist pool. Since the fee chosen by a monopolist pool is always such that $f^0 \geq \underline{\upsilon}$, then a sufficient condition for (100) to hold is:

$$\widehat{\upsilon}-f^* > \mu-\underline{\upsilon} \Leftrightarrow \widehat{\upsilon}-\mu > \frac{-\left(h^*\left(0\right)\left(c-\widehat{\upsilon}\right)-0.25\right)+\sqrt{\left(h^*\left(0\right)\left(c-\widehat{\upsilon}\right)+0.25\right)^2+1}}{2h^*\left(0\right)}-\underline{\upsilon}. \tag{101}$$

which holds because of Assumption 1.

The equipment producer's incentive to enter relative to an independent pool is therefore given by:

$$RI = \frac{r(c-\underline{c})}{c-\widehat{\upsilon}+f^*} - \frac{r(c-\underline{c})}{c-\int_{f^0}^{\overline{\upsilon}}\left(\upsilon-f^0\right)g\left(\upsilon\right)d\upsilon} = r(c-\underline{c})\frac{\widehat{\upsilon}-f^*-\int_{f^0}^{\overline{\upsilon}}\left(\upsilon-f^0\right)g\left(\upsilon\right)d\upsilon}{\left(c-\widehat{\upsilon}+f^*\right)\left(c-\int_{f^0}^{\overline{\upsilon}}\left(\upsilon-f^0\right)g\left(\upsilon\right)d\upsilon\right)} > 0.$$

■

Proposition 7.

Proof. Mining pools choose fees simultaneously to maximize their profits:

$$\max_{f_1} \Pi_1\left(f_1, f_2\right) + \pi\left(f_1, f_2\right) + \frac{b_1}{2\left(1-\alpha\right)}\left[1-2\alpha H(f_1-f_2)\phi\right] \tag{102}$$

$$\max_{f_2} \Pi_2 \left(f_1, f_2\right) + \frac{b_2}{2\left(1-\alpha\right)} \left[1 - 2\alpha \left(1 - H(f_1 - f_2)\right) \phi\right], \tag{103}$$

where ϕ is the probability that Pool 1 and Pool 2 disagree on their preferred proposal. Let $H^* \equiv H(f_1^* - f_2^*)$ and $h^* \equiv h(f_1^* - f_2^*)$, the simplified first order conditions are as follows:

$$\frac{(c-E[s^*|f_1,f_2])(1-H^*)-f_1^* h^*(c-E[s^*|f_1,f_2])-(c-\underline{c}+f_1^*(1-H^*))(1-H^*)}{(c-E[s^*|f_1,f_2])^2} - \frac{b_1\alpha\phi h^*}{(1-\alpha)r} = 0, \tag{104}$$

$$\frac{(c-E[s^*|f_1,f_2])H^*-f_2^* h^*(c-E[s^*|f_1,f_2])-H^* f_2^* H^*}{(c-E[s^*|f_1,f_2])^2} - \frac{b_2\alpha\phi h^*}{(1-\alpha)r} = 0. \tag{105}$$

From equations (104) and (105) we express f_1^* and f_1^* as follows

$$f_1^* \frac{(c-E[s^*|f_1,f_2])h^*}{(c-E[s^*|f_1,f_2])^2} = \frac{(c-E[s^*|f_1,f_2])(1-H^*)}{(c-E[s^*|f_1,f_2])^2} - \frac{(c-\underline{c})(1-H^*)}{(c-E[s^*|f_1,f_2])^2} - \frac{f_1^*(1-H^*)^2}{(c-E[s^*|f_1,f_2])^2} - \frac{b_1\alpha\phi h^*}{(1-\alpha)r}, \tag{106}$$

$$f_2^* \frac{(c-E[s^*|f_1,f_2])h^*}{(c-E[s^*|f_1,f_2])^2} = \frac{(c-E[s^*|f_1,f_2])H^*}{(c-E[s^*|f_1,f_2])^2} - \frac{f_2^*(1-H^*)^2}{(c-E[s^*|f_1,f_2])^2} - \frac{b_2\alpha\phi h^*}{(1-\alpha)r}. \tag{107}$$

We can subtract (107) from (106), which after simplification becomes:

$$\frac{\left(f_1^*-f_2^*\right)[(c-E[s^*|f_1,f_2])h^*+(1-H^*)H^*]}{(c-E[s^*|f_1,f_2])^2} = \frac{(c-E[v|f_1,f_2])(1-2H^*)}{(c-E[s^*|f_1,f_2])^2} - \frac{(c-\underline{c})(1-H^*)}{(c-E[s^*|f_1,f_2])^2} - \frac{(b_1-b_2)\alpha\phi h^*}{(1-\alpha)r}. \tag{108}$$

For $b_1 \geqslant b_2$, the proof follows from the same arguments as in the proof of Proposition 4. ■

Proposition 8.

Proof. Let $\beta \equiv \frac{n}{n+n'}$, where n is the amount of computational power used by the equipment producer for self-mining and n' is the amount of computational power sold by the equipment producer. In this setting the share of hash rate controlled by Pool 1 (the pool owned by the equipment producer) is:

$$\varphi_1 = \beta + (1-\beta)\alpha(1-H)$$

In the voting game we consider four cases, depending on the preferences of Pool 1 and Pool 2.

Case 1: $z_1 = z_2 = A$. The fraction of votes for proposal A is

$$\beta + (1-\beta)\left(\alpha + (1-\alpha)\rho\right). \tag{109}$$

Case 2: $z_1 = A$ and $z_2 = B$. The fraction of votes for proposal A is

$$\beta + (1 - \beta)\left(\alpha\left(1 - H\right) + \left(1 - \alpha\right)\rho\right). \tag{110}$$

Case 3: $z_1 = B$ and $z_2 = A$. The fraction of votes for proposal A is

$$(1 - \beta)\left(\alpha H + \left(1 - \alpha\right)\rho\right). \tag{111}$$

Case 4: $z_1 = z_2 = B$. The fraction of votes for proposal A is

$$(1 - \beta)\left(1 - \alpha\right)\rho. \tag{112}$$

The probability that Pool 1's preferred proposal is adopted is then:

$$I = \begin{cases} \frac{1-2\alpha H(1-\beta)\phi}{2(1-\alpha)(1-\beta)} & \text{if } \beta < \frac{0.5-\alpha}{1-\alpha} \\ 1 - \frac{0.5-\alpha(1-H)-\beta(1-\alpha(1-H))}{2(1-\alpha)(1-\beta)}\phi & \text{if } \frac{0.5-\alpha+\alpha H}{1-\alpha+\alpha H} > \beta \geq \frac{0.5-\alpha}{1-\alpha} \\ 1 & \text{if } \beta \geq \frac{0.5-\alpha+\alpha H}{1-\alpha+\alpha H} \end{cases}, \tag{113}$$

where ϕ is the probability that the two Pools disagree (that is, Case 2 and Case 3). It follows that

$$\frac{\partial I}{\partial \beta} = \begin{cases} \frac{1}{2(1-\alpha)(1-\beta)^2} & \text{if } \beta < \frac{0.5-\alpha}{1-\alpha} \\ \frac{0.5\phi}{2(1-\alpha)(1-\beta)^2} & \text{if } \frac{0.5-\alpha+\alpha H}{1-\alpha+\alpha H} > \beta \geq \frac{0.5-\alpha}{1-\alpha} \\ 0 & \text{if } \beta \geq \frac{0.5-\alpha+\alpha H}{1-\alpha+\alpha H} \end{cases}. \tag{114}$$

The expected profit of the equipment producer is:

$$\Pi_1 + \pi_1 = \frac{r\left[c - \underline{c} + f_1\left(1 - H\right) - \beta\left(E[\upsilon \mid f_1, f_2] - f_2 H + \sigma\right)\right]}{c - E[\upsilon \mid f_1, f_2] + f_1\left(1 - H\right) + f_2 H} + b_1 I \tag{115}$$

and therefore the first order condition with respect to β (the amount of self mining) is

$$\frac{\partial\left(\Pi_1 + \pi_1\right)}{\partial \beta} = -\frac{r\left(E[\upsilon \mid f_1, f_2] - f_2 H + \sigma\right)}{c - E[\upsilon \mid f_1, f_2] + f_1\left(1 - H\right) + f_2 H} + b_1 \frac{\partial I}{\partial \beta} = 0. \tag{116}$$

There will be some level of self mining in equilibrium if, for $\beta = 0$,

$$\frac{\partial \left(\Pi_1 + \pi_1\right)}{\partial \beta} = -\frac{r\left(E[v \mid f_1,f_2] - f_2 H + \sigma\right)}{c - E[v \mid f_1,f_2] + f_1\left(1 - H\right) + f_2 H} + b_1 \frac{\partial I}{\partial \beta} > 0, \tag{117}$$

that is,

$$-\frac{r\left(E[v \mid f_1,f_2] - f_2 H + \sigma\right)}{c - E[v \mid f_{1,},f_2] + f_1\left(1 - H\right) + f_2 H} + \frac{b_1}{2\left(1 - \alpha\right)} > 0. \tag{118}$$

Setting $f_1 = f_2 = 0$, we get that if $\frac{b_1}{2(1-\alpha)} > \frac{r(\widehat{v}+\sigma)}{c-\widehat{v}}$, then condition (118) always holds and $\beta > 0$ in equilibrium. ■

Table 1. Comparison of Mining Pools

Information from various Internet sources, as of January 2020.

	Mining Pools								
	AntPool	**BTC.com**	**F2Pool**	**Poolin**	**ViaBTC**	**Huobi.pool**	**OKExPool**	**BTC.TOP**	**SlushPool**
Relationship with Bitmain	Fully-owned subsidiary	Fully-owned subsidiary	BitDeer partner	Founded by former Bitmain employees	Bitmain's associate company	Bitmain's strategic partner	Bitmain's strategic partner	BitDeer partner	Unrelated
BTC hash rate (Average in January 2020, as of Jan 28)	10.7%	11.9%	17.8%	17.1%	7.1%	4.8%	5.0%	3.0%	4.6%
Contracts offered (for BTC only)	PPS+, PPLNS, Solo	FPPS	PPS+	FPPS	PPS+, PPLNS, Solo	FPPS	FPPS	PPS	Score
Fees for BTC mining	2.5% (PPS+)	1.5%	2.5%	2.5%	4.0% (PPS+)	Unknown	4.0%	unknown	2.0%
Minimum threshold for payment (BTC)	0.001	0.005	0.005	0.005	0.01	Unknown	Unknown	0.01	0.001
Server location	Asia	Asia, USA	Asia, USA	China, US, EU	Asia	Unknown	Unknown	Unknown	Asia, Europe, USA, Canada
Merged Mining coins	NMC, LTC, DOGE	NMC, RSK	NMC, SYS, DOGE	VCASH	NMC, SYS, EMC, ELA, DOGE	ELA	DOGE	Unknown	NMC
Quality of information on website	Medium	Medium	Low	High	High	Low	Medium/High	No information	High
Fees available on website	No	No	No	Yes	Yes	No	Yes	No	Yes