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Joseph Abadi
Federal Reserve Bank of Philadelphia

Markus Brunnermeier
Princeton University

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Token-Based Platform Governance*

Joseph Abadi†   Markus Brunnermeier‡

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Abstract

We develop a model to compare the governance of traditional shareholder-owned platforms to that of platforms that issue tokens. The owners of a traditional platform have incentives to implement policies that extract rents from users. If the platform's owners can commit to future policies, they can implement a more efficient outcome by issuing a token that offers claims on the platform's services. Such a token alleviates conflicts of interest between the platform's owners and its users, mitigating inefficiencies: a policy that benefits users increases the value of tokens and therefore the platform's seignorage revenue. If the platform's owners cannot commit to policies ex ante, however, they can achieve the same outcome by issuing a token that bundles claims on the platform's services with an ownership share (i.e., cash flow claims and voting rights).

Keywords: Utility Tokens, Platforms, Decentralized Finance, Corporate Governance
JEL Codes: D4, D18, E40, G30

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†Federal Reserve Bank of Philadelphia (joseph.abadi@phil.frb.org)
‡Princeton University (markus@princeton.edu)

1 Introduction

In recent years, advances in digital payments technology and decentralized finance (DeFi) have offered an alternative to traditional platforms' model of financing and governance. Traditional platforms typically finance themselves by issuing cash flow claims, and they are owned and governed by shareholders (i.e., residual cash flow claimants). The platform's users do not necessarily play a role in financing or decision-making. Hence, the platform may not undertake some efficient investments that benefit users (Magill, Quinzii, and Rochet 2015), and shareholders may exercise the firm's market power to extract rents from users. Two key innovations have altered these basic relationships between users and platforms.

The first innovation is *financing with tokens*. Many platforms have begun to issue their own currencies or digital credits (called "tokens") to users while retaining the traditional shareholder governance model. For example, the (centralized) Binance cryptocurrency exchange issues a token (BinanceCoin) that users can redeem to receive a discount on trading fees. Blockchain-based platforms often issue "utility tokens" that can be used to purchase a digital service: e.g., the Golem platform's tokens (GLM) can be used to rent out computational resources and Chainlink's token (LINK) is used to pay network operators to retrieve data for smart contracts. Tokens effectively function as claims on the platform's *transaction services*, whereas these platforms continue to issue shares that bundle cash flow claims with the right to vote in governance decisions.

The second innovation is what cryptocurrency and DeFi practitioners often call *decentralized ownership*. Some platforms do away with shareholders entirely: instead, they issue tokens that bundle claims on transaction services with cash flow claims and voting rights. Proof-of-stake cryptocurrency blockchains with "on-chain" governance, like Tezos, are the archetypal example of this type of platform. On these blockchains, tokens play a dual role: they can either be held by users to transact with others, or they can set them aside as collateral (called "staking") to validate blockchain transactions, earn transaction fees, and vote on changes to the protocol. Proponents of this model of governance argue that it will decentralize authority by empowering users to participate in governance, thereby mitigating their vulnerability to rent extraction.

The advent of tokens and decentralized governance raises key economic questions. What is the role of each of these innovations? Do they promote more efficient platform governance?

To answer these questions, we develop a model of a platform economy that is general enough to encompass traditional platforms, platforms that issue tokens, and platforms with decentralized ownership. The model is set in continuous time and has two groups of agents: users (who enjoy the platform's transaction services) and investors (who hold cash flow claims on the platform but do not engage in transactions). The platform's governance determines its policies along two dimensions. First, at each moment in time, the platform may make an investment to improve the quality of its transaction technology, increasing the amount of utility that users derive from transactions. Hence, the platform's investment policy determines the *total surplus* that the platform can create. Second, the platform's governance determines the transaction fee charged to users, which dictates the *split of surplus* between users and investors.

The key outcome in the model is users' transaction demand. Each user must pay a participation cost to transact on the platform (which can be thought of as attention costs, costs of accessing the technology, or the opportunity cost of not transacting elsewhere). Participation costs are heterogeneous across users. In each of the settings we consider, users who pay the participation cost and enter must hold *transaction assets* in order to transact on the platform. In the case of a traditional platform that does not issue tokens, the transaction asset can be thought of as cash or another liquid asset supplied outside the platform. In the other settings, the transaction asset will be tokens issued by the platform. Users' flow payoffs are proportional to their real balances of transaction asset holdings, as in models with money in the utility function. All else equal, more users will choose to enter the platform and transact when the transaction technology is higher-quality (i.e., productivity is higher) or when fees are lower. This extensive margin of participation is the key determinant of efficiency in the model.

The platform's (limited) *market power* generates scope for inefficiencies. The platform faces no competition, so it will retain some of its user base even if fees are set higher than the marginal cost of processing transactions. Importantly, fees are *distortionary*: the platform cannot price-discriminate, so an increase in fees will cause some users with high participation costs to opt out of transacting, leading to deadweight losses.

We consider three different settings in this general environment.

- **Traditional platform**: Users transact with assets that originate outside the platform. The platform issues *shares* to investors that confer cash flow and governance rights. Investors choose the platform's policies to maximize the value of shares.

- **Tokenization**: Users transact with *tokens* that are issued by the platform. Tokens have no voting rights. The platform maintains the shareholder governance model in which investors have claims on the platform's profits and choose policies to maximize their value.

- **Decentralization**: The platform does not issue shares – it issues a *token* that is held by both users and investors. Users hold tokens in order to transact on the platform, whereas investors "stake" tokens to receive a share of the platform's profits. All token holders can vote on governance decisions.

We consider the efficiency of each platform design in terms of the level of user participation and long-run investment in the platform's productivity vis-à-vis the first-best allocation.

A traditional platform simply maximizes the present value of profits, since that is equivalent to shareholder value maximization in this setting. Consequently, as is typical of models with imperfect competition, the platform's fees are set inefficiently high: user *participation is too low* from a social perspective. When investors choose the level of fees, they do not internalize two sources of social surplus. First, all inframarginal users earn some rents because their individual participation costs are below those of the marginal user, who is indifferent between using the platform and opting out. Second, all users earn a *convenience yield* on their transaction assets, reflecting the value that those assets provide in transactions. Lower user participation implies both smaller inframarginal rents and lower aggregate convenience yields. Moreover, low transaction volumes reduce the surplus that investors can extract by (1) investing in the platform's productivity, and then (2) raising fees to offset the increase in users' utility. Therefore, there is *under-investment* in equilibrium.

Why does the Coase theorem fail in this setting? We implicitly assume *limited contracting* between users and investors. The Coase theorem would suggest that users should collectively agree to pay investors to implement a policy with lower fees and higher investment rates. We show that tokenization has the potential to enhance efficiency by providing a partial substitute for these missing contracts.

When we introduce tokenization, we assume that investors (i.e., the platform's owners) are initially endowed with the entire stock of tokens that will be sold to users. Therefore, investors care not only about maximizing the price of shares, but also about maximizing the initial price at which tokens can be sold to users (since the proceeds are paid out as dividends). In addition to choosing fees and the investment rate, the investors who govern the platform must choose whether to finance further investments by issuing shares or by issuing additional tokens. The equilibrium price of tokens, in turn, reflects the present value of *convenience yields* net of future investments financed through token issuance.

We begin by studying governance under *commitment*: investors commit to a full sequence of policies at $t = 0$, then sell tokens to users, after which point no further governance decisions are made. Investors' objective in this case is to maximize the initial value of their shares plus the value of the tokens that they sell to users. Hence, they internalize how policies affect future convenience yields, unlike in the case of a traditional platform. As a result, tokenization with commitment yields an unambiguously more efficient outcome – there is higher platform participation and investment. That is, tokenization partially aligns investors' preferences with users', since users are willing to pay a higher price for tokens when investors pass more favorable policies. However, investors still fail to internalize inframarginal users' rents, so participation and investment remain below their first-best levels.

Under commitment, investors choose to finance all investments after $t = 0$ by issuing equity rather than tokens. Intuitively, in this model there are no financial frictions, so issuing equity is costless. On the other hand, token issuance does have a cost: it creates inflation (i.e., reduces the price of tokens). Inflation raises the opportunity cost of holding tokens and reduces users' incentives to transact, resulting in lower platform participation. Nevertheless, investors' ability to finance the platform by issuing tokens is clearly non-neutral, since tokenization results in more efficient outcomes. Token issuance is not a re-tranching of the platform's cash flows, so the Modigliani-Miller theorem does not apply. Instead, tokens are a claim on future convenience yields. Investors are encouraged to make future investments that increase convenience yields by the prospect of selling tokens at a higher price initially. Without tokens, there would be no reason for investors to make investments that benefit users while reducing the present value of cash flows.

We then turn to the case in which investors *lack commitment*. After selling the initial stock of tokens at $t = 0$, they choose policies sequentially. In this setting, there is no reason for investors to choose policies that benefit users: by the time they make policy decisions, they have already sold tokens to users and no longer internalize changes in future convenience yields. Hence, investors choose fees to maximize profits, just as in the case of a traditional platform. The introduction of tokens also provides a new way to finance investments: in fact, investors choose to finance *all* investments by issuing tokens, since the costs fall on users. Tokenization without commitment thus leads to *over-investment* and inflation (as is typically present in models of private money issuance).

This analysis reveals that commitment is crucial for tokenization to enhance efficiency on its own. Of course, there are several mechanisms that could enhance platform owners' ability to commit to policies that benefit users, such as token retention or smart contracts that pre-program a specified sequence of policies. We show, however, that so long as investors have limited commitment power, *decentralization* can serve as an effective substitute for commitment.

In the setting with decentralization, the platform issues only tokens. Users receive transaction utility from holding tokens, whereas investors stake tokens to receive dividends. In particular, platform profits are paid out pro-rata to staked tokens, so an increase in the quantity of tokens staked by investors reduces the per-token dividend (all else equal). All token holders have the right to vote, so investors get their most preferred policy (i.e., the policy that maximizes the current token value) if they hold the majority of tokens. Users get their most preferred policy (which takes into account both token prices and future inframarginal rents) otherwise.

Equilibrium token prices reflect both their *transaction value* (the present value of convenience yields, which is users' valuation) and their *cash flow value* (the present value of dividends, which is investors' valuation). Both constituencies therefore internalize changes in future cash flows and convenience yields, since both care about keeping token prices high. In fact, when investors control the platform, equilibrium governance decisions are precisely the same as in the case of tokenization with commitment. Why does decentralization overcome the commitment problem? The key intuition is that each constituency holds an asset whose value reflects the future welfare of the other constituency. In the case of tokenization without commitment, by contrast, investors sell off tokens immediately and then may seek to pass policies that increase share prices while reducing token prices.

Organization. In the remainder of this section, we give a review of the related literature. Section 2 gives a brief overview of the types of tokens issued by platforms in practice. Section 3 introduces the economic environment and other preliminary elements of the benchmark model. Section 4 studies the governance of a traditional platform as a benchmark. Section 5 introduces token issuance and outlines how the presence of tokens affects equilibrium governance decisions. The decentralized governance scheme is analyzed in Section 6. Section 7 concludes. All proofs are in the Appendix.

Related literature. Our paper is most closely related to the emerging literature that studies the role of tokens in DeFi platforms' governance. In the context of a platform with network externalities, Sockin and Xiong (2023) study the introduction of a token that grants platform membership and permits users to vote on platform policies, preventing the platform from exploiting their data. However, users are not able to share the costs of investments in the platform and therefore cannot subsidize the admission of new users to the platform. Bakos and Halaburda (2023) study a platform that issues tokens that offer cash flow claims and voting rights. They highlight conditions under which token holdings become concentrated among non-users, leading to rent extraction. Similarly, Han, Lee, and Li (2023) develop and empirically test a model in which concentrated token holdings by a large investor can undermine efficient governance. Relatedly, Gan, Tsoukalas and Netessine (2023) compare the inefficiencies in governance of a platform that issues transaction tokens with those of a traditional platform. While our analysis shares some of these themes, it is complementary: we characterize the separate roles of tokens' transaction service claims, cash flow claims, and voting rights, providing novel insights into the optimal *design* of tokens.

The broader literature on financing through token sales and ICOs is also related to our work. Closest to our paper, Goldstein, Gupta, and Sverchkov (2022) show that by issuing utility tokens, a platform can commit to charge lower prices to users, as in our model. Their mechanism, however, is related to the Coase (1972) conjecture and is quite distinct from ours. Cong, Li, and Wang (2022) and Gryglewicz, Mayer, and Morellec (2021) study the optimal issuance of tokens by a financially constrained platform, demonstrating how seignorage policies can be used to reward platform owners for investments. Li and Mann (2018); Chod and Lyandres (2021); and Lee and Parlour (2021) study other reasons why firms might finance themselves through the issuance of utility tokens. Li and Mayer (2022) and d'Avernas, Maurin, and Vandeweyer (2022) present models to study the optimal issuance of stablecoins. Similarly, You and Rogoff (2023) study how the tradability of a platform's utility tokens affects the revenue raised by a token offering. Relative to this literature, our paper differs in that it considers the role of tokens *exclusively* for governance – there are no financial frictions that motivate token issuance.

Of course, our paper connects to the corporate governance literature. There is an extensive body of work on control rights, ownership structure, and the theory of the firm stemming from the work of Coase (1937), Williamson (1979), and Grossman and Hart (1986). Our paper contributes to this literature by characterizing the specific governance consequences brought about by different token designs – we show that despite the fact that users can potentially be exploited by the platform, it is not always most efficient to give them control rights (Hansmann, 1988). User control tends to be more efficient when investors cannot commit to policies up front. Our work is complementary to the literature that studies how different control structures aggregate information in governance decisions (see Aghion and Tirole, 1997, among many others). Recent work has extended this literature to the study of DeFi platforms (Tsoukalas and Falk, 2020; Benhaim, Falk, and Tsoukalas, 2023).

2 An Overview of Tokens

Before introducing the model, we briefly introduce the different claims or rights that tokens may confer and examples of tokens that are issued in practice. Tokens typically grant at least one of (1) claims on a platform's transaction services, (2) claims on cash flows, or (3) voting rights.

Tokens that grant only claims on transaction services are typically referred to as *utility tokens*. The Golem token (GLM) permits users on the Golem network to rent out computational resources from others, for instance. Another example is Binance's token (BNB), which users can redeem for a discount on transaction fees or other perks. Outside of DeFi, some platforms have begun to issue (or have considered issuing) such tokens (e.g., Alibaba's

"Alipay" or Facebook's now-defunct Libra/Diem project).[1] In the context of our model, a token that offers claims on transaction services could also be a pure cryptocurrency that has no intrinsic value but is used for transactions among the platform's users, which applies to many cryptocurrency platforms without explicit governance mechanisms.

Other tokens grant claims on the platform's cash flows (e.g., transaction fees) or seignorage revenues.[2] Usually, such tokens have voting rights in governance decisions as well. The native tokens of the DeFi lending platforms Curve (CRV) and Kyber (KNC) are leading examples. Token holders can "stake" their tokens in order to receive a share of trading fees on the platform. They may also participate in *on-chain governance*: the community regularly votes on referenda that determine the platform's policies, including fees and software upgrades, and voting power is allocated proportionally to token holdings. Most of the assets that users transact on those platforms are cryptocurrencies that originate elsewhere. In the context of our model, a token that offers *only* cash flow claims and voting rights is equivalent to a share of a traditional platform.

Pure governance tokens offer only voting rights. Several platforms that provide automated cryptocurrency market-making services, called decentralized exchanges or DEXs, issue this type of token. For example, the Uniswap DEX issues the UNI token, which entitles holders to vote on changes to the market-making protocol. UNI does not currently pay its holders any dividends, but in principle, token holders could vote to pay themselves a dividend at some point in the future.[3] Tokens that have only voting rights only are beyond the scope of our model.

We also study platforms with tokens that combine claims on transaction services with an ownership share in the platform (consisting of cash flow claims and voting rights). These platforms have two distinguishing features. First, they issue a *native token* that is held by users of the platform's services and is "staked" by investors who contribute to the platform's operation and receive fees or seignorage in return. Second, the native token is used for on-chain governance.

Many proof-of-stake cryptocurrency blockchains, such as Algorand, Tezos, and Decred, are archetypal examples of platforms with native tokens that permit on-chain governance. Tokens are held by users who wish to engage in transactions. They are staked by "validators" (the analogue of investors in the model) who run the computational hardware needed to verify

[1] A key difference, however, is that tokens issued by traditional platform are typically backed at least partially by existing fiat currencies.

[2] These are distinct from *security tokens*, which usually represent a claim on another firm's profits or a claim on a financial asset that exists outside of the blockchain.

[3] In fact, whether UNI will eventually pay dividends has been a topic of intense speculation in the community – see `https://protos.com/to-fee-or-not-to-fee-that-is-the-question-does-uniswap-have-an-answer/`.

transactions and collect monetary rewards, which could take the form of transaction fees or newly minted tokens. Some blockchain platforms permit any token holder to stake and vote on newly proposed policies (e.g., Algorand), whereas others allow users to delegate their votes to validators whom they trust to vote appropriately on their behalf (e.g., Tezos). Typical policies adjust the fees paid for the provision of various transaction processing services on the blockchain or upgrade transaction verification protocols.

This setup is not restricted to stand-alone cryptocurrency blockchains, however. For example, some platforms that enable interoperability across DeFi applications, such as the Cosmos and Polkadot networks, issue tokens with voting rights that users hold to pay network fees and validators stake to provide transaction security. Other DeFi platforms issue tokens that bundle voting rights, cash flow claims, and direct claims on the platform's services. The Filecoin platform, which provides file storage services, issues a token that users exchange for storage and service providers stake to receive payments.

3 Model

We consider a continuous-time, infinite-horizon economy in which agents interact on a *platform*. There are two commodities: a numeraire good (referred to as a "dollar") and transaction services (henceforth "transactions") produced by the platform. The economy is populated by a unit mass of two types of agents: *users* $i \in [0,1]$ and *investors* $j \in [0,1]$. Users enjoy the platform's transaction services, whereas investors do not. All agents are risk-neutral over consumption of dollars and share a common discount rate $r > 0$.

The quality of the platform's transaction technology is summarized by a productivity parameter $A_t \in [\underline{A}, \overline{A}]$, with a higher value of A_t corresponding to a superior technology (e.g., lower transaction latency, a better transaction-matching algorithm, or greater transaction functionality). The platform's *policy* at time t consists of two components: a transaction *fee* $f_t \in [\underline{f}, \overline{f}]$ that the platform charges to users and a level of *investment* $I_t \in [0, \overline{I}]$ in upgrading the platform's technology. Specifically, investment determines the evolution of the platform's productivity – an investment of $I_t dt$ goods at time t increases productivity by $h(I_t)dt$, so that $\dot{A}_t = h(I_t)$. The function $h(\cdot)$ is assumed to be concave and differentiable with $h'(0) = 1$ and $h'(\overline{I}) = 0$.

The platform's policy is determined at each instant by a *governance decision*, in which agents vote on the policy (f_t, I_t) to be implemented at t. A new policy is determined by a majority vote.[4] In subsequent sections, we will consider several different ways of allocating

[4]Specifically, if there exists a Condorcet winner (f_t, I_t) among possible policies $(f, I) \in [\underline{f}, \overline{f}] \times [0, \overline{I}]$, then that policy is implemented. Otherwise, the previous policy is maintained.

voting power. Since each agent is infinitesimal, no individual agent's vote is ever pivotal, so all agents take the sequences $\{A_t, f_t, I_t\}$ as given.

In this economy, assets can play two roles: there is a *transaction asset* that can be held by users to receive the platform's transaction services, and there is a *cash flow asset* that is held by investors and provides a claim on the platform's profits (fees charged to users net of the platform's costs of operation). When the platform makes a governance decision to invest, it must cover the investment costs I_t by issuing additional assets.

We will consider several schemes for the design of assets and governance in this economy.

1. First, we consider a *traditional platform*. The platform issues *shares* to investors, which provide both claims on the platform's cash flows and voting rights during governance decisions. The platform does not issue its own transaction asset – the transaction assets held by users originate outside of the platform and are supplied elastically (e.g., cash or another cryptocurrency). Investors choose the platform's policy so as to maximize the value of their shares.

2. Next, we introduce *tokenization*. We consider the case of a platform that issues its own transaction asset to users (called a *token*). Tokens are distinct from the cash flow assets (shares) held by investors. We maintain the assumption that voting power is allocated to shareholders (hence the platform remains "centralized").

3. Finally, we introduce *decentralization*. In this setting, the platform issues a single asset (called a token) that can *both* be held by users for transaction services or "staked" by investors to receive cash flow claims. That is, the transaction asset and the cash flow asset are no longer distinct. The platform is "decentralized" in the sense that all agents who hold tokens may vote in governance events.

In the remainder of this section, we describe the elements of our model that are held constant across these three environments. In subsequent sections, we describe each platform design individually in greater detail and compare the outcomes they achieve.

3.1 The platform

We begin by describing how the platform's productivity A_t and fees f_t determine users' transaction utility and the platform's profits. A user i who engages in x_{it} transactions at time t receives payoff

$$U_i(x_{it}|A_t, f_t) = \underbrace{u(A_t)\min\{x_{it}, 1\}}_{\text{transaction payoff}} - \underbrace{f_t x_{it}}_{\text{fees}} - \underbrace{\phi_i \mathbf{1}\{x_{it} > 0\}}_{\text{participation cost}},$$

where **1** denotes the indicator function. The first term represents the utility that user i receives from transactions. Productivity affects users' utility through the demand shifter $u(A_t)$, where $u(\cdot)$ is assumed to be increasing, differentiable, and concave with $u'(\overline{A}) = 0$. A user i can consume at most one unit of transaction services at t, hence the term $\min\{x_{it}, 1\}$. The second term represents the fee paid by user i to the platform, which is equal to the per-transaction fee f_t times user i's transaction quantity x_{it}. The third term represents a *participation cost* that user i incurs if she chooses to transact on the platform at t. We assume that participation costs are I.I.D. across users according to a CDF G with support on $[0, \overline{\phi}]$. These participation costs are meant to represent, for example, costs of learning about the technology, maintaining an account on the platform, or opportunity costs of transacting on the platform rather than elsewhere.

The platform receives the transaction fees paid by users and incurs a marginal cost c per transaction. Hence, if the aggregate quantity of transactions at t is $X_t \equiv \int_0^1 x_{it} di$, then the platform's profits are

$$\Pi(X_t|f_t) = (f_t - c)X_t.$$

3.2 Asset markets and agents' optimization problems

In each of the settings we consider, there are two types of assets that agents may hold: *transaction assets* that enable users to trade on the platform and *cash flow assets* (held by investors) that grant claims on the platform's profits. The price and supply of transaction assets (resp. cash flow assets) are denoted Q_t^T, A_t^T (resp. Q_t^C, A_t^C). We focus on equilibria in which asset prices follow deterministic processes, so $dQ_t^z = \dot{Q}_t^z dt$ for $z \in \{T, C\}$. A user i enjoys transaction services equal to her real balance of transaction assets (as in most models with money in the utility function). So, if user i holds a_{it} transaction assets at t, she receives transaction services

$$x_{it} = \min\{Q_t^T a_{it}, 1\}. \tag{1}$$

Platform profits are distributed as dividends pro rata to the holders of cash flow assets. Thus, the holder of a cash flow asset receives a dividend $\frac{\Pi(X_t|f_t)}{A_t^C}$. The platform must issue assets to finance investments.

All agents take the sequences of states, asset prices, and asset quantities as given. Users choose their transaction asset holdings to maximize their expected lifetime utility

$$\int_0^\infty e^{-rt}(U_i(x_{it}|A_t, f_t)dt + dc_{it}),$$

(where c_{it} denotes user i's cumulative consumption of dollars through t) subject to a standard budget constraint, $Q_t^T da_{it} = \dot{Q}_t^T a_{it} dt - c_{it}$. In the Appendix, we show that this problem reduces to a static one:

$$\max_{x_{it}, a_{it}} \; U_i(x_{it}|A_t, f_t) + (\dot{Q}_t^T - rQ_t^T)a_{it} \;\; \text{s.t.} \;\; (1).$$

Users' problem yields the optimality condition

$$x_{it} = \mathbf{1}\{\phi_i \leq \phi_t^*\} \;\; \text{where} \;\; \phi_t^* \equiv \underbrace{u(A_t) - f_t}_{\text{payoff}} - \underbrace{\left(r - \frac{\dot{Q}_t^T}{Q_t^T}\right)}_{\text{opp. cost}}. \tag{2}$$

This condition demonstrates that user participation on the platform follows a threshold rule. All users i whose participation cost is below ϕ_t^* choose to transact the maximum possible amount ($x_{it} = 1$) on the platform. The threshold ϕ_t^* can be decomposed into two terms: the net payoff $u(A_t) - f_t$ that users receive from transactions at time t, and the opportunity cost of holding transaction assets, which is equal to users' discount rate r minus the rate of return on transaction assets $\frac{\dot{Q}_t^T}{Q_t^T}$. All else equal, more users will transact on the platform when the transaction technology is better (higher A_t), when fees f_t are lower, or when transaction assets deliver a higher return ($\frac{\dot{Q}_t^T}{Q_t^T}$ higher).

Given this threshold participation rule, the aggregate quantity of transactions satisfies

$$X_t = G(\phi_t^*). \tag{3}$$

The total demand for transaction assets is

$$Q_t^T A_t^T \geq X_t \;\; \text{with} \;\; \frac{\dot{Q}_t^T}{Q_t^T} = r \;\; \text{if} \;\; Q_t^T A_t^T > X_t. \tag{4}$$

As long as the rate of return on transaction assets is below the discount rate r, users will hold transaction assets only to engage in transactions (so $Q_t^T A_t^T = X_t$). For users to be willing to hold transaction assets even when their transaction utility is satiated, the opportunity cost of holding those assets must be zero, $\frac{\dot{Q}_t^T}{Q_t} = r$.

Similarly, investors choose their holdings of cash flow assets to maximize lifetime utility $\int_0^\infty e^{-rt} dc_{jt}$ subject to a standard budget constraint. Investors' problem is formally stated in the Appendix. Their first-order condition implies that cash flow assets are priced according to the present value of dividends:

$$rQ_t^C = \frac{(f_t - c)G(\phi_t^*)}{A_t^C} + \dot{Q}_t^C, \tag{5}$$

where we use (3) to rewrite the platform's total profits in terms of the participation threshold ϕ_t^*, $\Pi(X_t|f_t) = (f_t - c)G(\phi_t^*)$.

Equations (4) and (5) summarize the *demand* for transaction assets and cash flow assets, respectively. The *supply* of each asset is determined in a different way for each of the three platform designs we consider.

3.3 The first-best

Before moving on to the analysis of specific platform designs, we derive the properties of optimal allocations in this environment. This analysis will facilitate a comparison of the inefficiencies that arise under each platform design.

An *allocation* in this environment consists of (1) a sequence of transaction quantities and cumulative consumption $\{x_{it}, c_{it}\}$ for each user as well as consumption $\{c_{jt}\}$ for each investor, (2) a sequence of investment rates $\{I_t\}$, and (3) a sequence of productivity levels $\{A_t\}$. A *feasible* allocation must respect two conditions:

$$\{x_{it}, c_{it}, c_{jt}, I_t, A_t\} \text{ is feasible if } \dot{A}_t = h(I_t) \text{ and } \int_0^1 dc_{it}di + \int_0^1 dc_{jt}dj + I_t dt = 0 \ \ \forall\, t.$$

That is, the process followed by productivity must be consistent with investment, and total consumption of dollars (i.e., transfers across agents) plus investment must be equal to zero.

We will consider the efficiency of allocations implemented by each of the platform governance schemes we consider. There is transferable utility in this environment, so an allocation is *first-best* if it maximizes utilitarian social welfare across all feasible allocations. Note that fees will be irrelevant for total welfare, since they are just a transfer from users to investors.

A first-best allocation can be characterized in terms of the path of two decision variables: an investment rate I_t and a participation threshold ϕ_t^* (so that agent i transacts one unit at t if $\phi_i < \phi_t^*$ and does not transact otherwise).

Proposition 1. *A first-best allocation solves*

$$\max_{\phi_t^*, I_t, A_t} \int_0^\infty e^{-rt}\left(\int_0^{\phi_t^*}(u(A_t) - c - \phi)g(\phi)d\phi - I_t\right)dt \quad s.t. \ \ \dot{A}_t = I_t, \ \ A_0 \ given. \tag{6}$$

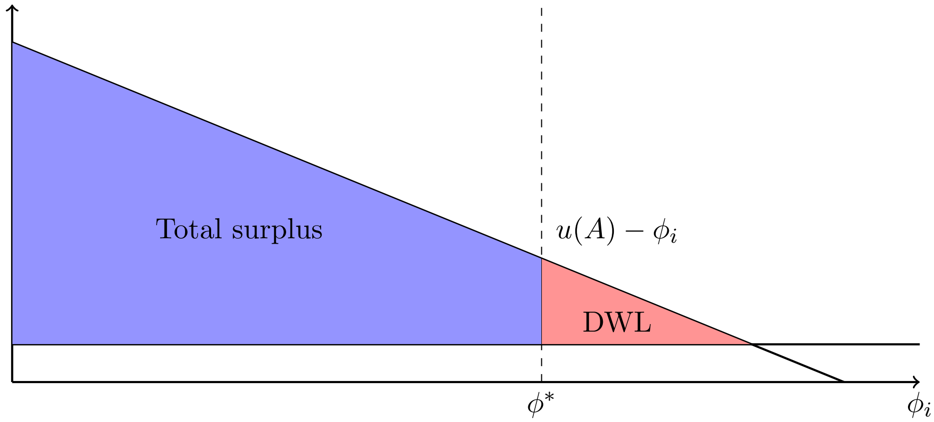

Figure 1: An illustration of deadweight loss relative to the first-best. Users' participation costs ϕ_i, which are assumed to be uniformly distributed, are on the x-axis. The downwards-sloping line is the net utility $u(A) - \phi_i$ generated by user i's transaction. The horizontal line corresponds to the marginal cost c of processing a transaction.

If the optimal participation threshold ϕ_t^* is interior, it satisfies

$$\phi_t^* = \phi_t^{FB} \equiv u(A_t) - c. \tag{7}$$

Productivity and the participation threshold converge to long-run levels A^{FB}, ϕ^{FB} satisfying

$$1 = \frac{u'(A^{FB})}{r} \times G(\phi^{FB}),\ \phi^{FB} = u(A^{FB}) - c. \tag{8}$$

The first-best participation threshold on the platform, ϕ_t^{FB}, is set so that the utility of an additional transaction, $u(A_t)$, is equal to the total cost of the marginal user's transaction, which is the platform's cost c of processing that transaction plus the marginal user's participation cost ϕ_t^{FB}. Figure 1 illustrates why there is deadweight loss if the participation threshold is set any lower.

The optimal long-run level of productivity A^{FB} can be understood by considering the welfare effect of investing an additional unit dI. An additional investment increases productivity by $dA = h'(0)dI = dI$. In turn, this increase in productivity permanently increases each user's utility by $u'(A^{FB})dA = u'(A^{FB})dI$ per unit of time. The discounted value of this increase in utility is $\frac{u'(A^{FB})}{r}dI \times G(\phi^{FB})$, since there are $G(\phi^{FB})$ users. Then, equating the marginal benefit with the cost dI, we obtain (8).

The conditions characterizing the efficient outcome, (7) and (8), will enable us to characterize exactly how outcomes deviate from the first-best in each case we consider. We begin with the analysis of a traditional platform and then introduce tokenization and decentralization.

4 Traditional platforms

In this section, we study the case of a *traditional platform* as a simple benchmark. We demonstrate that the traditional setup leads to inefficiently high fees, under-participation in the platform, and under-investment in the long run.

4.1 Setup

In this setting, there are two distinct assets: *shares* that are issued by the platform and *transaction assets* that originate outside the platform (such as cash, stablecoins, or another cryptocurrency). Shares serve as the economy's cash flow asset and grant investors the right to vote on the platform's policies. Users hold transaction assets for their transaction services but cannot vote in governance decisions. At each time t, investors collectively choose policies (f_t, I_t) to maximize the value of their shares, since doing so is equivalent to maximizing their lifetime utility.[5] Investors are always unanimous in their decision because they have identical objectives.

We assume transaction assets are supplied elastically at a price

$$Q_t^T = 1. \tag{9}$$

The initial supply of shares is normalized to $A_0^C = 1$, and the platform must issue additional shares to finance any investments made during governance events (since it cannot issue transaction assets to cover investment costs). Hence,

$$Q_t^C \dot{A}_t^C = I_t. \tag{10}$$

In equilibrium, of course, the quantity of shares outstanding does not matter: the platform's total value

$$V_t^C \equiv Q_t^C A_t^C \tag{11}$$

is invariant to the share quantity A_t^C, as can be seen from (5).

Thus, the platform's productivity parameter A_t is the only relevant state variable in this economy. We look for Markov equilibria. An equilibrium consists of asset prices and quantities $\{V^C(A), Q^T(A), A^T(A)\}$, a participation threshold $\phi^*(A, f)$,[6] platform policies

[5] In the Appendix, we show that an investor's lifetime utility is linear in the value of her asset holdings.

[6] Users' transaction demand depends on both the current state and the fee chosen by investors. An equi-

$(f(A), I(A))$, and a law of motion of the state $\dot{A}(A)$[7] such that (1) all agents optimize, (2) markets clear, (3) platform policies are consistent with share value maximization, and (4) the law of motion of the state is consistent with the chosen policies. We derive equilibrium outcomes below.

4.2 Governance decisions and equilibrium

We proceed by backwards induction to solve for investors' governance decisions, platform value, and transaction quantities in equilibrium. First, we show that in the case of a traditional platform, transaction quantities depend only on current productivity A and fees f. This result is immediate from users' optimization condition (2), given that transaction asset prices are constant at $Q^T = 1$:

$$\phi^*(A, f) = u(A) - f - r. \tag{12}$$

All else equal, users transact more when fees f are lower or when their utility from transactions is higher (represented by higher $u(A)$).

Next, we derive the platform's value and governance decisions. First, we re-write the asset pricing equation (5) in terms of the platform's value:

$$\begin{aligned} rQ_t^C A_t^C &= (f_t - c)G(\phi_t^*) + \dot{Q}_t^C A_t^C \\ &= (f_t - c)G(\phi_t^*) + (\dot{Q_t^C A_t^C}) - Q_t^C \dot{A}_t^C \\ \Rightarrow rV_t &= (f_t - c)G(\phi_t^*) - I_t + \dot{V}_t, \end{aligned}$$

where the third equality uses (10). Thus, the platform's value is simply the discounted value of net payouts $(f_t - c)G(\phi_t^*) - I_t$. Note that in a Markov equilibrium with $V_t = V(A_t)$, the rate of change of the platform's value can be written as $\dot{V}_t = \dot{A}_t V'(A_t) = h(I_t)V'(A_t)$.

How do investors choose the platform's policies? They maximize the platform's value, which is equivalent to maximizing the current share price. When current productivity is A, investors choose a fee f and an investment rate I to maximize

$$rV(A) = \max_{f,I} \, (f - c)G(\phi^*(A, f)) - I + h(I)V'(A), \tag{13}$$

where $\phi^*(A, f)$ is given by (12).

An equilibrium is summarized by (12)-(13).

librium must specify transaction demand even for off-equilibrium fees f, since investors must be able to contemplate what transaction demand *would have been* had they chosen a different fee.

[7]Productivity must always evolve continuously, since $dA_t = h(I_t)dt$.

4.3 Welfare and efficiency under the traditional scheme

Under the traditional governance scheme, the platform is just a value-maximizing firm. Investors care only about maximizing the value of their shares. Since the platform is monopolistic, changes in the platform's policies affect user surplus, but investors do not internalize these effects. As a result, investors choose the sequence of policies that is most beneficial to them, but these policies need not maximize total welfare. That is, investors maximize their own rents at the expense of total surplus.

Proposition 2. *Under the traditional scheme, the sequence of policies* $\{f_t, I_t\}$ *maximizes expected investor surplus (but not necessarily total surplus) over all feasible sequences of policies.*

What are the sources of inefficiency in this model? There are two necessary ingredients. First, the platform has market power, so shareholder value maximization is not equivalent to maximization of social surplus. Put differently, the platform's market power creates a *conflict of interest* between the two constituencies. Second, the platform's owners can extract rents from users only by charging *distortionary* fees: it is not possible to perfectly price-discriminate based on users' participation costs, so any increase in fees necessarily results in some users with high participation costs opting out of platform use.

The nature of the distortions in this model can be seen explicitly in the first-order conditions characterizing the optimal policy from investors' perspective. Investors set fees so that the participation threshold ϕ_t^* satisfies

$$\phi_t^* = \underbrace{u(A_t) - c}_{\text{first-best}} - \underbrace{\left(r + \frac{G(\phi_t^*)}{g(\phi_t^*)}\right)}_{\text{distortion}} . \tag{14}$$

That is, the participation level is equal to the first-best level minus a distortion that can arises because investors fail to internalize two sources of user surplus: the *convenience yields* they receive from holding transaction assets and *inframarginal rents.* The convenience yield z_t is the marginal utility that the *marginal* user gets from holding an additional unit of transaction assets:

$$z_t = u(A_t) - f_t - \phi_t^*, \tag{15}$$

which is equal to r by (2). All users i with participation costs below the threshold earn an additional inframarginal $\phi_t^* - \phi_i$. The aggregate user surplus neglected by investors then

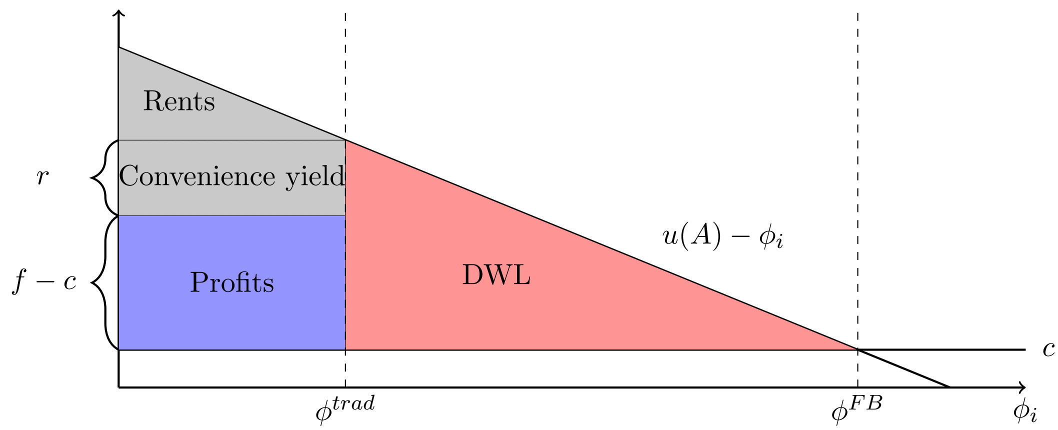

Figure 2: An illustration of the sources of neglected surplus in the case of a traditional platform. Users' participation costs ϕ_i, which are assumed to be uniformly distributed, are on the x-axis. The downwards-sloping line is the net utility $u(A) - \phi_i$ generated by user i's transaction. The horizontal line corresponds to the marginal cost c of processing a transaction.

satisfies

$$\frac{d}{d\phi_t^*} \underbrace{\int_0^{\phi_t^*} (r + \phi_t^* - \phi) g(\phi) d\phi}_{\text{neglected user surplus}} = rg(\phi_t^*) + G(\phi_t^*),$$

hence the distortion in (14). Figure 2 illustrates how these distortions cause investors to set fees too high and destroy surplus.

Under-participation on the platform due to high fees leads to under-investment in the long run. Investors' first-order condition for investment I_t implies that in the long run, productivity converges to a level A^{trad} such that[8]

$$1 = \frac{u'(A^{trad})}{r} \times G(\phi^{trad}), \tag{16}$$

where ϕ^{trad} denotes the long-run equilibrium participation threshold. Just as in the analysis of the first-best, the marginal value of investing an additional unit is equal to $\frac{u'(A^{trad})}{r}$,[9] the additional discounted surplus that each user receives, times $G(\phi_t^*)$, the measure of users. Investors fully internalize this surplus: they can invest an additional unit to increase users'

[8]This claim is proven in the Appendix. Formally, this claim holds only if the long-run level of productivity is interior (otherwise, productivity in the long run is simply $\overline{A}$).

[9]Here we use the assumption that $h'(0) = 1$, so that in the long run, the marginal investment increases A_t by one unit.

marginal utility of transactions by $u'(A)$ and then raise fees by precisely the same amount to offset that gain in utility, keeping the user base exactly the same. Relative to the first-best, then, investment is too low, $A^{trad} < A^{FB}$, simply because there is under-participation, $\phi^{trad} < \phi^{FB}$. The following proposition summarizes the analysis of the inefficiencies that arise with a traditional platform.

Proposition 3. *With a traditional platform, equilibrium participation is inefficiently low, $\phi_t^* < \phi_t^{FB}$ for all t. There is also under-investment: the long-run level of productivity is below its first-best level, $A^{trad} < A^{FB}$ (where A^{trad} is defined in (16)).*

While we have examined the distortions that lead to inefficiencies in this model, we have not been explicit about why users and investors cannot write contracts that circumvent those distortions. The Coase theorem implies that absent restrictions on contracting, investors and users would nevertheless arrive at an efficient outcome. The second necessary ingredient for inefficiency, therefore, is *limited contracting*: users cannot sign a contract in which they commit to compensate investors for choosing a more socially beneficial policy. These limits to contracting could be micro-founded, for instance, by assuming that users are unable to commit to a sequence of payments in response to the policies chosen by investors.

How can agents overcome the problem of limited contracting? In the next section, we outline conditions under which *token issuance* can partially substitute for the missing contracts between users and investors.

5 Tokenization

In this section we consider a platform that issues tokens. The platform remains "centralized" in the sense that shareholders are the only agents who can participate in governance. We differentiate between two cases: the case in which investors can commit to a sequence of policies ex ante, and the case in which they have no ability to commit whatsoever. We show that token issuance can substitute for missing contracts between users and investors (and therefore increase welfare) only if investors can commit to future policies.

5.1 Setup

Consider an environment in which the two assets are *shares* held by investors, which serve as the cash flow asset, and *tokens* that the platform issues to users, which serve as the transaction asset. Since the transaction asset is issued by the platform rather than supplied elastically, in this case, its price Q_t^T evolves endogenously. We maintain the assumption that all voting rights are allocated to shareholders unless noted otherwise. The platform in this setting can be thought of as the issuer of a "utility token" or as a tech platform that issues its own currency. The initial supply of each asset is normalized to one.

Unlike the case of a traditional platform, investments can be financed by issuing either new shares or tokens. Thus,

$$Q_t^C \dot{A}_t^C + Q_t^T \dot{A}_t^T = I_t \quad \text{with} \quad \dot{A}_t^C, \dot{A}_t^T \geq 0. \tag{17}$$

Investors optimally choose what fraction $\theta_t = \frac{Q_t^T \dot{A}_t^T}{I_t}$ of the investment to finance with tokens and what fraction $1 - \theta_t$ to finance with share issuance. As before, choices are made to maximize the value of shares. The assumption that the platform cannot buy back assets (e.g., $\dot{A}_t^C \geq 0$) ensures that the platform cannot issue a large quantity of tokens and pay the proceeds out as a dividend to investors. The model remains tractable if we allow for this possibility but raises additional commitment issues that are separate from our main focus, which is on investors' ability to commit to a sequence of *policies* (rather than on commitment to an inflation rate).

Again, the quantity of each asset outstanding will be irrelevant to real outcomes in equilibrium. Nevertheless, the *growth rate* of the token supply in governance events $\mu_t^T \equiv \frac{\dot{A}_t^T}{A_t^T}$ will matter, since it determines the rate of inflation on tokens and hence the quantity of real balances that users wish to hold. Therefore, the endogenous variables to be solved for are the platform's value V_t, the aggregate value of tokens $M_t \equiv Q_t^T A_t^T$, the participation threshold ϕ_t^*, the growth rate of tokens μ_t^T, and policies $\{f_t, I_t, \theta_t\}$. Below, we consider equilibria in which investors can commit to a sequence of decisions ex ante and equilibria without commitment, at which point we impose a Markov restriction as before.

5.2 Equilibrium with commitment

Suppose that investors can commit to a sequence of policies ex ante. That is, at $t = 0$, they choose a feasible sequence of fees and investment rates $\{f_t, I_t\}$ as well as the fraction of investment $\{\theta_t\}$ to finance by issuing tokens. To solve this problem, we first derive the evolution of the platform's value and transaction quantities for a given sequence of policies and then find the optimal sequence from investors' perspective.

First, we determine the rate of token "inflation" $\pi_t = -\frac{\dot{Q}_t^T}{Q_t^T}$, the market capitalization of tokens M_t, and the participation threshold ϕ_t^* at each moment in time.

Proposition 4. *In the case of a centralized platform that issues tokens, the total value of tokens at t is equal to the present value of aggregate convenience yields minus the costs of* *investment financed with tokens,*

$$M_t = \int_0^\infty e^{-rs}\Big(\underbrace{(u(A_{t+s}) - f_{t+s} - \phi^*_{t+s})G(\phi^*_{t+s})}_{\textit{convenience yields}} - \underbrace{\theta_{t+s}I_{t+s}}_{\textit{token financing}}\Big)ds. \tag{18}$$

The rate of token inflation $\pi_t = -\frac{\dot{Q}^T_t}{Q^T_t}$ *satisfies*

$$\pi_t = \max\left\{\frac{\theta_t I_t - g(\phi^*_t)\dot{\phi}^*_t}{G(\phi^*_t)}, -r\right\}. \tag{19}$$

The market capitalization of tokens reflects the users' discounted future transaction benefits (i.e., convenience yields) minus the costs of dilution from additional token issuance to finance investment. Token issuance dilutes current users' holdings because it causes inflation, as indicated by (19): all else equal, inflation is higher when the rate of token issuance is higher (higher $\theta_t I_t$) or when the expansion of the user base is slower (lower $\dot{\phi}^*_t$), since an expansion of the user base increases token demand and therefore slows inflation. Note that the rate of inflation cannot fall below $-r$; at that point, the opportunity cost of holding tokens goes to zero, so users are willing to hold an arbitrary quantity of tokens.

It is similarly possible to show that, as in the case of a traditional platform, the total value of the platform's shares is equal to the present value of profits net of the costs of investment *financed by equity issuance*:

$$V_t = \int_0^\infty e^{-rs}\Big(\underbrace{(f_{t+s} - c)G(\phi^*_{t+s})}_{\text{profits}} - \underbrace{(1 - \theta_{t+s})I_{t+s}}_{\text{equity financing}}\Big)ds. \tag{20}$$

Investors are endowed with the entire initial stock of shares plus the initial stock of tokens. The token stock is immediately sold off to users at $t = 0$ and paid out as a dividend. Hence, they choose a sequence of policies to maximize $V_0 + M_0$. Investors' commitment power incentivizes them to choose a sequence of policies beneficial to users, even if that comes at the expense of future profits: policies that benefit users encourage greater transaction quantities, thereby increasing the ex ante value of tokens. Using (18) and (20), their problem can be written as

$$\max_{f_t, I_t, \theta_t} \int_0^\infty e^{-rt}\Big(\underbrace{(u(A_t) - c - \phi^*_t)G(\phi^*_t)}_{\text{conv. ylds. + profits}} - I_t\Big)dt \quad \text{s.t. } \dot{A}_t = h(I_t), (2), (19). \tag{21}$$

An *equilibrium with commitment* in this environment consists of a sequence of policies

$\{f_t, I_t, \theta_t\}$ that solves (21), a sequence of participation thresholds and inflation rates $\{\phi_t^*, \pi_t\}$ that solve (2) and (19), and market capitalizations for tokens and shares $\{M_t, V_t\}$ satisfying (18) and (20).

Under this arrangement, how do investors choose to finance investments in the platform? Does the ability to issue tokens result in investments that would not otherwise be carried out? As it turns out, after the initial token sale at $t = 0$, all future investments are financed by issuing additional shares.

Proposition 5. *Under the optimal policy with commitment, all interim investments are financed through equity issuance, $\theta_t = 0$ for all t.*

The logic underlying this result is simple: investors face no frictions in equity issuance, but additional token issuance results in inflation (i.e., a drop in the token's price). In turn, inflation acts like a tax on users that disincentivizes transactions, lowering both the platform's profits and users' ex ante token valuation. Despite the fact that inflation induces an ex post transfer from users to investors, the decrease in ex ante token valuations implies that investors are better off committing not to inflate away the value of users' tokens.

Even though the platform does not issue tokens at the interim stage to finance investments, the ability to issue tokens at $t = 0$ leads investors to choose a different sequence of upgrades to invest in. That is, the sequence of policies chosen by a platform that can initially issue equity and tokens is different from the sequence chosen by a platform that can initially issue only equity. In this sense, the mix of assets used to finance the platform initially is non-neutral (as opposed to, for example, a frictionless traditional model of corporate financing in which the Modigliani-Miller theorem holds). When token issuance is possible and investors have commitment power, they are willing to undertake investments that benefit users but decrease platform value ex post because doing so increases their profits from the initial token sale.

Hence, the introduction of tokens may permit the financing of socially beneficial platform upgrades that would not have otherwise been in investors' interest. Conceptually, the reason for the non-neutrality of token issuance is that tokens are effectively a claim on future *user surplus* rather than *cash flows*: the precise manner in which investors tranche claims on cash flows is irrelevant in this model, but the introduction of long-lived claims on user surplus introduces new possibilities for profitable investments. The motive to issue tokens at a high price permits investors to partially internalize how policies change future user surplus as well as profits.

Of course, investors do not fully internalize how policies affect user surplus – token prices reflect only users' convenience yields, so investors remain indifferent as to how their policies affect users' inframarginal rents. Consequently, they optimally set fees at a level lower than

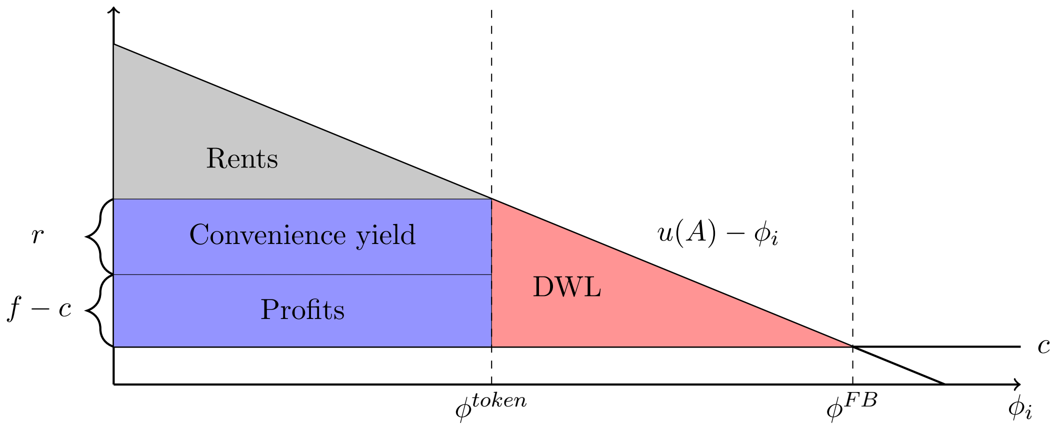

Figure 3: Illustration of the sources of surplus in the case of a centralized platform that issues tokens. Unlike in the case of a traditional platform (Figure 2), investors internalize users' convenience yields. Profits are maximized by setting lower fees than in the traditional case, raising the participation threshold to ϕ^{token} (which remains below the first-best ϕ^{FB}).

in the case of a traditional platform, but still above the first-best level. Investors set fees so that the participation threshold is

$$\phi_t^* = \underbrace{u(A_t) - c}_{\text{first-best}} - \underbrace{\frac{G(\phi_t^*)}{g(\phi_t^*)}}_{\text{distortion}} . \tag{22}$$

A comparison with (14) makes it clear that participation is greater than in the case of a traditional platform precisely because investors internalize convenience yields, eliminating one source of distortions. Figure 3 illustrates this point.

Again, the equilibrium level of investment in the long run is characterized by a productivity level A^{token} and a participation threshold ϕ^{token} such that

$$1 = \frac{u'(A^{token})}{r} \times G(\phi^{token}). \tag{23}$$

The logic is familiar: this first-order condition equates the marginal cost of an additional investment with the benefit, which is equal to the change in (discounted) future convenience yields, $\frac{u'(A^{token})}{r}$, times the measure of users $G(\phi^{token})$. Since the participation threshold ϕ^{token} is above the threshold in the traditional case ϕ^{trad} but below the first-best level ϕ^{FB}, token issuance *partially* alleviates the under-investment problem that arises with a traditional platform.

Proposition 6. *In the case of a centralized token-issuing platform, if investors can fully commit to future policies, then the participation threshold ϕ_t^{token} and long-run productivity A^{token} satisfy*

$$\phi_t^{trad} < \phi_t^{token} < \phi_t^{FB} \quad \text{and} \quad A^{trad} < A^{token} < A^{FB}.$$

Total welfare is higher than in the case of a traditional platform but remains below first-best.

5.3 Equilibrium without commitment

The welfare benefits of token issuance rely critically on the assumption that investors can commit to future policies. When investors choose policies sequentially, then they no longer face a disincentive to enact policies that extract rents from users: by the time they choose a policy, they have already sold off tokens to users and therefore do not benefit from a high token price. In this section, we formally demonstrate this point by characterizing equilibrium when investors cannot commit to policies at all, and we highlight the precise inefficiencies that arise in this setting.

The equilibrium definition and characterization are somewhat more involved when policies are chosen sequentially. It is important to be clear about the timing of decisions in this setting.

1. Investors announce new policies: total investment I_t, the fraction θ_t that will be financed by issuing additional tokens, and the level of fees f_t.

2. Asset markets open, tokens are issued to finance investment, and users choose their aggregate token holdings $M_t = Q_t^T A_t^T$ in the current period.

When investors choose policies, they take *as given* users' conjectures about their policies in the future. Again, we consider Markov equilibria in which the only state variable is productivity A_t. Users form conjectures about the total market capitalization of tokens $M(A)$, policies $\{f(A), I(A), \theta(A)\}$, the participation threshold $\phi^*(A)$, and the rate of inflation $\pi(A)$. Actual policies (and therefore other outcomes) may differ from conjectured policies. For a variable y with conjectured value $y(A)$, we denote the actual realized value simply by $\tilde{y}$, and we denote the deviation from the conjectured value by $\Delta y \equiv \tilde{y} - y(A)$.[10] Of course, in equilibrium, it must be the case that actual outcomes are equal to conjectured outcomes.

The equations characterizing equilibrium are precisely the same as in the case with commitment with the exception of investors' optimal policy decisions. We formally define equilibrium without commitment in the Appendix, but we give the main results here. The key observation is that the deviations of inflation and the participation threshold from their

[10]The actual value of any endogenous outcome is implicitly a function of A and of chosen policies $\tilde{f}, \tilde{I}, \tilde{\theta}$.

conjectured values, $\Delta\pi$ and $\Delta\phi^*$, can be derived solely in terms of the deviation of fees Δf:

$$\Delta\pi = \frac{g(\phi^*(A))}{G(\phi^*(A))}\Delta\phi = -\frac{\frac{g(\phi^*(A))}{G(\phi^*(A))}}{1+\frac{g(\phi^*(A))}{G(\phi^*(A))}}\Delta f. \tag{24}$$

The platform's profits can then be written as

$$(f(A)+\Delta f-c)G(\phi^*(A)+\Delta\phi) = (u(A)-r-\pi(A)-\phi^*(A)-c-(1+\frac{g(\phi^*(A))}{G(\phi^*(A))})\Delta\phi)G(\phi^*(A)+\Delta\phi).$$

Investors maximize the value of their shares, which again is simply the discounted value of profits net of equity-financed investment. In contrast to the case with commitment, when investors choose their policies, they internalize only the effects their policies have on (1) current profits and (2) the evolution of productivity. Their problem is

$$rV(A) = \max_{\Delta f,\Delta I,\Delta\theta} \left(u(A)-r-\pi(A)-\phi^*(A)-c-\big(1+\frac{g(\phi^*(A))}{G(\phi^*(A))})\Delta\phi\right)G(\phi^*(A)+\Delta\phi)$$
$$-(\theta(A)+\Delta\theta)(I(A)+\Delta I)+h(I(A)+\Delta A)V'(A).$$

Note that investors do not have to bear any of the costs of investment: if they choose, they can finance all investment by issuing tokens. Indeed, this is what they choose to do in equilibrium: they invest the maximum amount $\overline{I}$ at each instant and issue as many tokens as necessary to do so. Unlike in the case with commitment, investors do not care that by doing so, they are reducing the initial price of tokens – they have already sold off tokens to users by the time they make the investment decision. In the long run, then, productivity also converges to its maximum possible level $\overline{A}$. There is *over-investment* rather than under-investment.

Interestingly, when investors lack commitment, they have even less of an incentive to charge low fees than in the case of a traditional platform. To see this, note that the first-order condition of investors' problem with respect to the participation threshold $\Delta\phi$ implies that in the long run (with zero inflation), participation converges to a level ϕ^{nc} such that

$$\phi^{nc} = \underbrace{u(\overline{A})-c}_{\text{first-best}} - \underbrace{\big(r+1+\frac{G(\phi^{nc})}{g(\phi^{nc})}\big)}_{\text{distortion}}. \tag{25}$$

The term corresponding to the distortion is $r+1+\frac{G(\phi^{nc})}{g(\phi^{nc})}$ rather than $r+\frac{G(\phi^{nc})}{g(\phi^{nc})}$, as it was in the case of a traditional platform. There is a larger distortion because in this setting, investors do not face as large a cost when they raise fees: an increase in fees *lowers* current token prices, so the expected rate of return on tokens from t to $t+dt$ *increases*. The higher return on tokens offsets the higher fee, mitigating the reduction in participation.

However, it does not follow that the *level* of participation is lower in the case without commitment than it would have been for a traditional platform. There are two competing forces: on the one hand, investors' incentives to set high fees, and on the other, the higher productivity $\overline{A}$ that results from over-investment. Hence, it is ambiguous whether investors' lack of commitment power is detrimental to platform participation in the long run.

In any case, the lack of commitment power must clearly be detrimental to investors' profits, and so investors may therefore seek mechanisms that permit them to commit. Of course, in reality, a platform's founders and investors can use smart contracts to commit to future token issuance, or they could use token retention schemes to incentivize them to pass policies that benefit users. To the extent that such mechanisms are imperfect, though, the next section argues that decentralized governance can provide an effective substitute for missing commitment mechanisms.

6 Decentralized Governance

In this section, we consider a platform with "decentralized" governance. It issues tokens that bundle (1) cash flow claims, (2) transaction services, and (3) governance rights. These types of tokens are common in DeFi applications: for instance, they are commonly issued by cryptocurrency platforms such as Ethereum or Algorand. We characterize conditions under which this scheme achieves the commitment outcome in the long run, despite the fact that governance decisions are made sequentially without commitment.

6.1 Setup

In this economy, there is a single asset called a *token*. Tokens serve as both the economy's transaction asset and as its cash flow asset: users can hold tokens for their transaction services, whereas investors can hold tokens to receive dividends. Our interpretation is that tokens can either be set aside as collateral ("staked") to receive cash flows generated by the platform (as done by investors) or kept available for transactions (as done by users). Given that there is only one asset, we let Q_t denote the price of tokens (dispensing with our previous notation Q_t^C, Q_t^T). Furthermore, we denote the total supply of tokens at t by $A_t = A_t^C + A_t^T$, where A_t^C (resp. A_t^T) denotes the quantity of tokens held by investors (users) at t. Henceforth, we let $\zeta_t = \frac{A_t^C}{A_t^C + A_t^T}$ denote the *fraction* of tokens that are staked at t.

As before, user i's transaction services are equal to her real balance of token holdings, $x_{it} = Q_t a_{it}^T$, where a_{it}^T is the quantity of tokens held by i. Dividends are distributed pro rata to the holders of staked tokens, so the dividend paid to a staked token at t is $\frac{(f_t - c)G(\phi_t^*)}{A_t^C}$. The pricing conditions (2)-(5) then imply that the convenience yield paid by tokens has to equal the dividend yield:[11]

$$\frac{(f_t - c)G(\phi_t^*)}{\zeta_t} = \frac{u(A_t) - f_t - \phi_t^*}{1 - \zeta_t}. \tag{26}$$

In governance decisions, all token holders are permitted to vote on policies (f_t, I_t). Investors vote for the state that maximizes the value of their token holdings (since they do not earn rents). We focus on equilibria in which the participation threshold ϕ_t^* is increasing for all t: in this case, users are unanimous in voting for the state that maximizes the value of their token holdings plus their expected future inframarginal rents.[12] The platform is governed by majority rule, so investors' choice is implemented if $\zeta_t > \frac{1}{2}$, whereas users' chosen state is implemented otherwise.[13] Any investment following a governance decision is financed through token issuance, so

$$Q_t(\dot{A}_t^T + \dot{A}_t^C) = I_t. \tag{27}$$

As before, the total quantity of tokens outstanding is irrelevant: only the growth rate of the token stock matters. We denote by $W_t \equiv Q_t(A_t^T + A_t^C)$ the total market capitalization of tokens. Votes are cast without commitment, so we look for Markov equilibria in the state A_t. The key equilibrium outcomes are the token market capitalization $W(A)$, the participation threshold $\phi^*(A)$, the fraction of tokens staked by investors $\zeta(A)$, and conjectured policies $(f(A), I(A))$.

6.2 Equilibrium

We begin by deriving the equilibrium value of tokens and users' inframarginal rents given a particular policy rule. Then, we turn to the governance decision.

Users' optimality condition (2) can be re-written as

$$rW(A) = \frac{(u(A) - f(A) - \phi^*(A))G(\phi^*(A))}{1 - \zeta(A)} - I(A) + h(I(A))W'(A)$$

by multiplying by $W(A)$ on both sides and noting that users' token holdings are equal to the aggregate quantity of transactions, $(1 - \zeta(A))W(A) = G(\phi^*(A))$. This pricing equation says that the price of tokens must be equal to their *transaction value*, which is the present value of the convenience yields that accrue to users net of the costs of dilution resulting from

[11] For the case in which tokens were separate from cash flow assets, the convenience yield could be equal to zero as long as the opportunity cost of holding tokens was equal to zero ($\frac{\dot{Q}_t^T}{Q_t^T} = r$). By contrast, here dividends are always positive, so the convenience yield must always be positive as well.

[12] We prove this unanimity result in the Appendix.

[13] That is, ties are broken in favor of users.

future token issuance.

Similarly, investors' asset pricing condition (5) can be written as

$$rW(A) = \frac{(f(A) - c)G(\phi^*(A))}{\zeta(A)} - I(A) + h(I(A))W'(A).$$

Investors are willing to hold tokens only if their price does not exceed their *cash flow value*, which is the present value of profits net of future investment costs.

When combined, these two equations yield

$$rW(A) = \underbrace{(u(A) - \phi^*(A) - c)G(\phi^*(A))}_{\text{convenience yield + profits}} - I(A) + h(I(A))W'(A). \tag{28}$$

The price of tokens is equal to the present value of convenience yields plus profits net of future investments.

Next, we turn to users' inframarginal rents. Every user who transacts on the platform at t expects to transact at all future times, so the present value of user i's inframarginal rents $\phi_t^* - \phi_i$ is

$$R_i(A) = R^*(A) - \frac{\phi_i}{r},$$

where $R^*(A)$ satisfies

$$rR^*(A) = \phi^*(A) + h(I(A))R^{*\prime}(A). \tag{29}$$

Note that fees do not appear in the token pricing equation (28) or in inframarginal rents (29). Fees affect only the participation threshold $\phi^*(A)$ through users' optimality condition (2). Therefore, we can re-cast the policy problem in terms of choosing a participation threshold $\tilde{\phi}^*$ and an investment rate $\tilde{I}$ (both of which may differ, off-equilibrium, from the conjectured policies $\phi^*(A)$ and $I(A)$). As before, deviations from conjectured policies are denoted $\Delta\phi^* \equiv \tilde{\phi}^* - \phi^*(A)$ and $\Delta I \equiv \tilde{I} - I(A)$. The fraction of staked tokens $\zeta(A)$ enters only in that it determines which constituency makes the governance decision in each state A (investors whenever $\zeta(A) > \frac{1}{2}$ and users otherwise).

When investors control the platform, they choose $(\Delta\phi^*, \Delta I)$ to maximize token values:

$$rW(A) = \max_{\Delta\phi^*, \Delta I} (u(A) - \phi^*(A) - \Delta\phi^* - c)G(\phi^*(A) + \Delta\phi^*) - I(A) - \Delta I + h(I(A) + \Delta I)W'(A). \tag{30}$$

Similarly, when users control the platform, they choose policies to maximize the value of their tokens (which are worth $(1-\zeta(A))W(A)$) plus their future inframarginal rents:

$$
\begin{aligned}
r\big((1-\zeta(A))W(A)+R^*(A)\big) = \max_{\Delta\phi^*,\Delta I}\ & (1-\zeta(A))\bigg((u(A)-\phi^*(A)-\Delta\phi^*-c) \\
& \times G(\phi^*(A)+\Delta\phi^*)-I(A)-\Delta I\bigg) \\
& +\phi^*(A)+\Delta\phi^*+h(I(A)+\Delta I)((1-\zeta(A))W'(A)+R^{*\prime}(A)).
\end{aligned} \tag{31}
$$

An *equilibrium* consists of policies $(\phi^*(A), I(A))$, token prices $W(A)$, inframarginal rents $R^*(A)$, and a fraction of staked tokens $\zeta(A)$ such that (28)-(31) hold.

6.3 Attaining the commitment outcome

Under decentralized governance, the long-run equilibrium coincides with the commitment outcome if investors control the platform. If users control the platform, then participation and investment are both *higher* than under the commitment outcome. Our main result is summarized below.

Proposition 7. *Consider an equilibrium with decentralized governance in which productivity A converges to some level A^{dc}.*

1. *If investors control the platform in the long run ($\zeta(A^{dc}) > \frac{1}{2}$), then the participation threshold and productivity converge to the commitment outcome of Proposition (6), $\phi^*(A^{dc}) = \phi^{token}, A^{dc} = A^{token}$.*

2. *If users control the platform in the long run ($\zeta(A^{dc}) > \frac{1}{2}$), then the participation threshold and productivity converge to levels greater than those in the commitment outcome, $\phi^*(A^{dc}) > \phi^{token}, A^{dc} > A^{token}$.*

The central intuition, which explains why the decentralized scheme overcomes commitment problems, is given by the token pricing equation (28). In the case of a centralized platform that issued tokens, the initial value of shares plus the value of tokens reflected future profits plus convenience yields. Investors were initially endowed with the entire stock of shares and tokens, so if they had commitment power to choose policies ex ante, they would maximize the present value of convenience yields plus profits. Here, investors would like to maximize that present value at *every* instant, since doing so is equivalent to maximizing the value of tokens.

It is not obvious, at first glance, why investors would not want to maximize fee income at users' expense. Intuitively, in this setting, users and investors hold the same asset. Unlike in the case of a centralized platform, it is not possible for investors that pass policies that extract rents and increase the value of shares while decreasing the value of tokens. Both constituencies hold the same asset and have an interest in maintaining its value. The token pricing condition (28) implies that to do so, investors must maximize the present value of convenience yields plus profits, rather than simply maximizing profits alone.

Why must the value of tokens be equal to the present value of convenience yields plus profits? The key idea is that the fraction of staked tokens ζ adjusts so that the cash flow value of tokens is equal to their transaction value. Suppose that investors pass a policy that increases fee income by sacrificing total surplus. Off-equilibrium, this raises the cash flow value of tokens. As long as the cash flow value of tokens exceeds the transaction value, users will sell tokens to investors. But this increases the fraction of tokens that are staked, diluting investors' claims on profits and reducing the dividend paid to each staked token. In turn, reduced dividends lower tokens' cash flow value. This process continues until the cash flow value is brought back in line with the transaction value, preventing investors from fully reaping the benefits of higher fees.

If users control the platform in the long run, of course, policies will be tilted even more in their favor. In particular, users benefit from lower fees and from greater investment in the platform because such policies increase their future inframarginal rents. The costs of these policies are not fully borne by users – instead, they are distributed equally across all token holders. As such, users fully internalize the benefits but not the costs. Therefore, if they have decision-making power, users choose to set fees too low and the investment rate too high (from a social perspective).

Both users and investors would like to extract rents at the expense of total surplus, so it is not *a priori* clear which constituency will govern the platform more efficiently. The value of the decentralized governance scheme, instead, is the presence of a single asset held by both constituencies, which partially aligns their policy preferences.

7 Conclusion

We develop a general model of platform governance that is flexible enough to capture both traditional platforms as well as two key innovations that have emerged in recent years: *tokenization* and *decentralized governance*.

A traditional platform extracts rents from its users by setting fees above its marginal costs. This discourages user participation and distorts transaction volumes downwards, below the first-best level. Low platform participation, in turn, reduces the benefit that shareholders can derive from investing in upgrades to the platform, leading to under-investment in equilibrium.

Token issuance can partially align shareholders' policy preferences with those of users, as long as shareholders are able to commit to future policies ex ante. If the platform passes policies that benefit users, they will be willing to pay a greater price to purchase tokens. Hence, if investors commit to pass such policies, they can issue tokens to users at a higher price. However, if investors lack the ability to commit, this mechanism no longer aligns preferences: after selling tokens to users, investors will again be tempted to extract rents from them.

Decentralized governance – in the sense that the platform issues a single token with voting rights to both users and investors – can overcome the commitment problem. Both constituencies care about maintaining the token's value, which partially aligns policy preferences even without commitment and thereby limits rent extraction regardless of which group controls the majority of voting power.

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A Model

A.1 Agents' optimization problems

Users: Users' optimization problem can be written as

$$W_{i0} = \max_{x_{it},a_{it},c_{it}} \int_0^\infty e^{-rt}\Big(\big(U_i(x_{it}|A_t, f_t)dt + dc_{it}\Big)$$
$$\text{s.t. } Q_t^T da_{it} = \dot{Q}_t^T a_{it}dt - dc_{it},\ x_{it} = \min\{Q_t^T a_{it}, 1\},\ a_0 \text{ given},$$

where the function $v_i(x_{it}|f_t, A_t)$ is defined as

$$U_i(x_{it}|A_t, f_t) = (u(A_t) - f_t)x_{it} - \mathbf{1}\{x_{it} > 0\}\phi_i.$$

The only individual state variable for user i is her asset holdings a_{it}.

Define

$$w_{it} = Q_t^T a_{it} - x_{it}$$

to be agent i's total wealth in excess of the assets required for transactions x_{it}. The intertemporal budget constraint can be rewritten as

$$dc_t = \frac{\dot{Q}_t^T}{Q_t^T}(w_{it} + x_{it})dt - dw_{it} - dx_{it}. \tag{32}$$

Using integration by parts, it is possible to rearrange an agent's lifetime utility from consumption of dollars:

$$\begin{aligned}\int_0^\infty e^{-rt}dc_t &= -e^{-rt}(w_{it} + x_{it})\Big|_0^\infty - \int_0^\infty (r - \frac{\dot{Q}_t^T}{Q_t^T})e^{-rt}(w_{it} + x_{it})dt \\ &= (w_{i0} + x_{i0}) - \int_0^\infty (r - \frac{\dot{Q}_t^T}{Q_t^T})e^{-rt}(w_{it} + x_{it})dt.\end{aligned}$$

Note that $w_{i0} + x_{i0}$ must be equal to initial wealth $Q_0^T a_{i0}$.

Using this equation, agent i's optimization problem can be reformulated as

$$W_{i0} = \max_{x_{it}, w_{it}} Q_0^T a_{i0} + \int_0^\infty e^{-rt} \left(U_i(x_{it}|A_t, f_t) - (r - \frac{\dot{Q}_t^T}{Q_t^T}) x_{it} \right) dt \tag{33}$$
$$- \int_0^\infty e^{-rt} (r - \frac{\dot{Q}_t^T}{Q_t^T}) w_{it} dt \text{ s.t. } x_{it} \in [0, 1], w_{it} \geq 0.$$

Users' problem then reduces to a sequence of static optimizations over (x_{it}, w_{it}).

The optimal x_{it} solves

$$\max_{x_{it}} U_i(x_{it}|A_t, f_t) - (r - \frac{\dot{Q}_t^T}{Q_t^T}) x_{it},$$

so

$$x_{it} = \mathbf{1}\left\{ \phi_i \leq u(A_t) - f_t - (r - \frac{\dot{Q}_t^T}{Q_t^T}) \right\}, \tag{34}$$

as claimed in (2).

Similarly, the optimal w_{it} is

$$w_{it} = \begin{cases} \infty & r < \frac{\dot{Q}_t^T}{Q_t^T} \\ \in [0, \infty) & r = \frac{\dot{Q}_t^T}{Q_t^T} \\ 0 & r > \frac{\dot{Q}_t^T}{Q_t^T} \end{cases} . \tag{35}$$

Hence, user i does not demand transaction assets in excess of $Q_t^T a_{it}$ if $r > \frac{\dot{Q}_t^T}{Q_t^T}$. An equilibrium with $r < \frac{\dot{Q}_t^T}{Q_t^T}$ is impossible because users would demand an infinite quantity of transaction assets. Therefore, in equilibrium, total transaction demand can exceed aggregate transactions X_t only if $r = \frac{\dot{Q}_t^T}{Q_t^T}$, proving (4).

We also derive users' value functions, since those will be important in determining users' preferences over sequences of policies. We have just shown that in equilibrium, $r \geq \frac{\dot{Q}_t^T}{Q_t^T}$. Users' problem (33) then implies that at time t,

$$W_{it} = Q_t^T a_{it} + R_{it}, \tag{36}$$

where

$$R_{it} = \max_{x_{i,t+s}} \int_0^\infty e^{-rs}\big((u(A_{t+s}) - f_{t+s})x_{i,t+s} - \mathbf{1}\{x_{i,t+s} > 0\}\phi_i - (r - \frac{\dot{Q}^T_{t+s}}{Q^T_{t+s}})\big)ds \text{ s.t. } x_{i,t+s} \in [0,1]. \tag{37}$$

Investors: Investor j's problem is

$$W^I_{j0} = \max_{c_{jt}, a_{jt}} \int_0^\infty e^{-rt} dc_{jt} \text{ s.t. } Q^C_t da_{jt} = \left(\frac{(f_t - c)X_t}{A^C_t} + \dot{Q}^C_t\right) a_{jt} dt - dc_{jt}, \; a_{j0} \text{ given.}$$

Again, defining $w^I_{jt} = Q^C_t a_{jt}$, we can rewrite investors' optimization problem as

$$W^I_{j0} = \max_{w^I_{jt}} Q^C_0 a_{j0} - \int_0^\infty e^{-rt}\left(r - \frac{(f_t - c)X_t}{Q^C_t A^C_t} + \frac{\dot{Q}^C_t}{Q^C_t}\right) w^I_{jt} dt. \tag{38}$$

Investors' problem then also reduces to a sequence of static optimization problems,

$$\max_{w^I_{jt}} -\left(r - \frac{(f_t - c)X_t}{Q^C_t A^C_t} + \frac{\dot{Q}^C_t}{Q^C_t}\right) w^I_{jt}.$$

Investor j's cash flow asset demand is

$$w^I_{jt} = \begin{cases} \infty & \frac{(f_t-c)X_t}{Q^C_t A^C_t} + \frac{\dot{Q}^C_t}{Q^C_t} > r \\ \in [0, \infty] & \frac{(f_t-c)X_t}{Q^C_t A^C_t} + \frac{\dot{Q}^C_t}{Q^C_t} = r \\ 0 & \frac{(f_t-c)X_t}{Q^C_t A^C_t} + \frac{\dot{Q}^C_t}{Q^C_t} < r \end{cases}.$$

In equilibrium, then, if cash flow asset demand is positive and finite, it must be that the returns on those assets are exactly equal to the discount rate r,

$$rQ^C_t = \frac{(f_t - c)X_t}{A^C_t} + \dot{Q}^C_t,$$

as claimed by (5). It follows immediately from this result that investor j's value function is

$$W_{j0} = Q^C_0 a_{j0},$$

i.e., an investor's lifetime utility is equal to total wealth.

A.2 The first-best

Proof of Proposition 1. A first-best allocation solves the constrained optimization problem

$$\max_{c_{it},c_{jt},x_{it},I_t,A_t} \int_0^\infty e^{-rt}\Big(\int_0^1 \big(((u(A_t)-c)x_{it} - \mathbf{1}\{x_{it}>0\}\phi_i)dt + dc_{it}\big)di + \int_0^1 dc_{jt}dj\Big)$$

$$\text{s.t.} \quad \int_0^1 dc_{it}di + \int_0^1 dc_{jt}dj = -I_t dt,\ dA_t = h(I_t)dt,\ x_{it} \le 1 \ \ \forall\ i.$$

Notice that optimization over x_{it} is static: transaction quantities do not enter the evolution of the state A_t or the resource constraint. Optimal transaction quantities satisfy

$$x_{it} = \mathbf{1}\{\phi_i \le \phi_t^{FB}\} \ \text{ where } \phi_t^{FB} \equiv u(A_t) - c.$$

Then at an optimum,

$$\int_0^1 \big((u(A_t)-c)x_{it} - \mathbf{1}\{x_{it}>0\}\big)\phi_i di = \int_0^{\overline{\phi_t^{FB}}} (u(A_t) - c - \phi)g(\phi)d\phi.$$

Then, plugging the resource constraint $\int_0^1 dc_{it}di + \int_0^1 dc_{jt}dj + I_t dt = 0$ into the objective function, we obtain

$$\max_{\phi_t^*,I_t,A_t} \int_0^\infty e^{-rt}\Big(\int_0^{\phi_t^*}(u(A_t)-c-\phi)g(\phi)d\phi - I_t\Big)dt \ \text{ s.t. } \ \dot{A}_t = h(I_t),$$

as claimed.

The optimal participation threshold is

$$\phi_t^* = \phi_t^{FB} \equiv u(A_t) - c.$$

We take a Lagrangian approach to solve for optimal investment. The Lagrangian can be written as

$$\mathcal{L} = \max_{\phi_t^*,I_t,A_t} \int_0^\infty e^{-rt}\Big(\int_0^{\phi_t^*} \big(u(A_t)-c-\phi\big)g(\phi)d\phi - I_t - \lambda_t\big(\dot{A}_t - h(I_t)\big)\Big)dt. \tag{39}$$

The first-order condition with respect to I_t is

$$\lambda_t h'(I_t) = 1. \tag{40}$$

The Euler-Lagrange equation for A_t is

$$\begin{aligned} 0 &= \frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{A}_t} - \frac{\partial \mathcal{L}}{\partial A_t} \\ &= e^{-rt}\Big(r\lambda_t - \dot{\lambda}_t - G(\phi_t^*)u'(A_t)\Big), \end{aligned}$$

which yields

$$r\lambda_t = G(\phi_t^*)u'(A_t) + \dot{\lambda}_t.$$

This equation can be solved forward to obtain a closed-form relationship between current investment and future (ϕ_{t+s}^*, A_{t+s}):

$$\lambda_t = \frac{1}{h'(I_t)} = \int_0^\infty e^{-rs}G(\phi_{t+s}^*)u'(A_{t+s})ds. \tag{41}$$

Investment is bounded by $[0, \overline{I}]$, so it must eventually converge to a steady-state limit. Of course, a steady state is reached only if $I_t \to 0$ (since $h'(I_t) > 0$ for all $I < \overline{I}$). Moreover, ϕ_t^* and A_t converge to levels ϕ^{FB} and A^{FB}, respectively. The optimality condition (41) implies that productivity converges to some steady state such that

$$1 = \frac{G(\phi^{FB})u'(A^{FB})}{r} \quad \text{where} \quad \phi^{FB} = u(A^{FB}) - c. \tag{42}$$

□

B Traditional platform

Proof of Proposition 2. Problem (13) is a standard dynamic programming problem with bounded and continuous payoffs. Typical arguments (See Lucas and Stokey, 1986) guarantee that the solution to this HJB equation corresponds to the solution of the sequence problem

$$\max_{f_t, I_t} \int_0^\infty e^{-rt}\big((f_t - c)G(\phi^*(f_t, A_t)) - I_t\big)dt \quad \text{s.t.} \quad \dot{A}_t = h(I_t), (12). \tag{43}$$

Hence, the chosen sequence of policies maximizes investor surplus, since the integral above is just V_0, the initial value of the shares endowed to investors.

To see that this sequence of policies does not necessarily maximize total surplus, note that the surplus-maximizing fee (given current productivity A) satisfies

$$\max_f \int_0^{\phi^*(A,f)} (u(A) - c - \phi) dG(\phi) \quad \Rightarrow \quad f = c - r.$$

By contrast, the fee chosen by investors maximizes

$$\max_f \, (f - c)G(\phi^*(A, f)) \quad \Rightarrow \quad f = c + \frac{G(\phi^*(A, f))}{g(\phi^*(A, f))} > c - r.$$

Therefore, the fee chosen by investors is always greater than the surplus-maximizing fee. □

Proof of Proposition 3. We now solve Problem (43). The Lagrangian for this problem is

$$\mathcal{L} = \max_{f_t, I_t, A_t, \phi_t^*} \int_0^\infty e^{-rt} \Big((f_t - c)G(\phi_t^*) - I_t - \lambda_t(\dot{A}_t - h(I_t)) - \mu_t(\phi_t^* - u(A_t) + f_t + r) \Big) dt. \tag{44}$$

The optimality conditions are

$$\begin{aligned}
(\phi_t^*) &: \mu_t = (f_t - c)g(\phi_t^*); \\
(f_t) &: \mu_t = G(\phi_t^*); \\
(I_t) &: 1 = \lambda_t h'(I_t); \\
(A_t) &: r\lambda_t = \mu_t u'(A_t) + \dot{\lambda}_t.
\end{aligned}$$

The first-order conditions for ϕ_t^* and f_t can be combined with (12) to obtain

$$\phi_t^* = u(A_t) - c - r - \frac{G(\phi_t^*)}{g(\phi_t^*)} < \phi_t^{FB}, \tag{45}$$

where ϕ_t^{FB} is defined in (7). This proves that participation is inefficiently low with a traditional platform.

The first-order condition for A_t implies

$$\frac{1}{h'(I_t)} = \int_0^\infty e^{-rs} u'(A_{t+s}) G(\phi_{t+s}^*) ds. \tag{46}$$

Productivity is bounded and evolves continuously with I_t, so in the long run, it must converge to some limit A^{trad} such that[14]

$$1 = \frac{u'(A^{trad})G(\phi^*(A^{trad}))}{r}. \tag{47}$$

Let $H_{trad}(A) \equiv u'(A)G(\phi^*(A))$, where $\phi^*(A)$ is defined by (45). Define $H_{FB}(A) = u'(A)G(\phi^{FB}(A))$, where $\phi^{FB}(A)$ is defined by (7). Since $\phi^*(A) < \phi^{FB}(A)$ for all A, $H_{trad}(A) < H_{FB}(A)$ for all A. Both H_{trad} and H_{FB} are concave functions whose derivatives go to zero as $A \to \overline{A}$, so this inequality implies that the unique A^{trad} satisfying $1 = \frac{H_{trad}(A^{trad})}{r}$ is smaller than the unique A^{FB} satisfying $1 = \frac{H_{FB}(A)}{r}$. Therefore, long-run productivity with a traditional platform is below the first-best, as desired. □

C Tokenization

Proof of Proposition 4. The relationship $\theta_t = \frac{Q_t^T \dot{A}_t^T}{I_t}$ can be re-written as

$$\dot{M}_t = \theta_t I_t - \pi_t M_t. \tag{48}$$

Combining this relationship with (2) and (4), we obtain[15]

$$rM_t = (u(A_t) - f_t - \phi_t^*)G(\phi_t^*) - \theta_t I_t + \dot{M}_t,$$

which implies that the total market capitalization of tokens at t is equal to

$$M_t = \int_0^\infty e^{-rs}\Big((u(A_{t+s}) - f_{t+s} - \phi_{t+s}^*)G(\phi_{t+s}^*) - \theta_{t+s} I_{t+s}\Big) ds, \tag{49}$$

the present value of aggregate convenience yields minus the costs of investment financed with tokens.

Note that (48) can be re-written as

$$\pi_t = \frac{\theta_t I_t - \dot{M}_t}{M_t}.$$

[14] Here we use the fact that in the long run, investment $I_t \to 0$, and $h'(0) = 1$ by assumption.

[15] This equation uses the fact that whenever $M_t > G(\phi_t^*)$, we also have $u(A_t) - f_t = \phi_t^*$.

For all t, (4) implies that either $M_t = G(\phi_t^*)$, in which case

$$\pi_t = \frac{\theta_t I_t - g(\phi_t^*)\dot{\phi}_t^*}{G(\phi_t^*)},$$

or $\pi_t = -r$. We then have (19). □

Proof of Propositions 5 and 6. Both propositions follow from the solution to investors' problem (21). The Lagrangian of this problem is

$$\mathcal{L} = \max_{f_t, I_t, \theta_t, A_t, \phi_t^*, \pi_t} \int_0^\infty e^{-rt}\Bigg((u(A_t) - \phi_t^* - c)G(\phi_t^*) - I_t - \lambda_t(\dot{A}_t - h(I_t))$$
$$- \mu_t(\phi_t^* - u(A_t) - f_t - r - \pi_t) - \gamma_t\big(\pi_t - \max\big\{\frac{\theta_t I_t - g(\phi_t^*)\dot{\phi}_t^*}{G(\phi_t^*)}, -r\big\}\big)\Bigg)dt.$$

The optimality conditions are

$$(f_t) : \mu_t = 0;$$
$$(I_t) : 1 = \lambda_t h'(I_t) + \gamma_t \theta_t;$$
$$(\theta_t) : \gamma_t = 0 \quad \text{or} \quad \theta_t = 0;$$
$$(\pi_t) : \gamma_t = \mu_t;$$
$$(A_t) : r\lambda_t = u'(A_t)G(\phi_t^*) - \mu_t u'(A_t) + \dot{\lambda}_t;$$
$$(\phi_t^*)\ G(\phi_t^*) = (u(A_t) - \phi_t^* - c)g(\phi_t^*) - \mu_t + \gamma_t \mathbf{1}\{\pi_t > -r\}\frac{\partial}{\partial \phi_t^*}\frac{\theta_t I_t - g(\phi_t^*)\dot{\phi}_t^*}{G(\phi_t^*)} - \frac{d}{dt}e^{-rt}\frac{g(\phi_t^*)}{G(\phi_t^*)}\gamma_t.$$

From these conditions, it is clear that $\mu_t = \gamma_t = 0$ for all t. Hence, the choice of θ_t is irrelevant. It is always possible to choose an optimal plan for investors such that $\theta_t = 0$ for all t, proving Proposition 5.

With $\mu_t = \gamma_t = 0$, we have

$$\phi_t^* = u(A_t) - c - \frac{G(\phi_t^*)}{g(\phi_t^*)}. \tag{50}$$

Comparing this equation to (45), it is clear that ϕ_t^* is higher than in the case of a traditional platform for any given value of A_t. Optimal investment requires that

$$\frac{1}{h'(I_t)} = \int_0^\infty e^{-rs} u(A_{t+s})G(\phi_{t+s}^*)ds. \tag{51}$$

As in the proof of Proposition 3, we conclude that A_t converges to a steady state A^{token} such that

$$1 = \frac{u'(A^{token})G(\phi^{token})}{r}. \tag{52}$$

Again, using the same reasoning as in that proof, we use the fact that ϕ_t^* is higher than in the case of a traditional platform to conclude that $A^{trad} < A^{token} < A^{FB}$ and that $\phi^{trad} < \phi^{token} < \phi^{FB}$, as desired. □

D Decentralized Governance

Proof of Proposition 7. **Case 1: Investors control the platform.** The analysis in Online Appendix E.4 shows that in states A in which investors control the platform ($\zeta(A) > \frac{1}{2}$), they choose policies to solve

$$rW(A) = \max_{\tilde{f},\tilde{I}} (u(A) - \tilde{\phi}^* - c)G(\tilde{\phi}^*) - \tilde{I} + h(\tilde{I})W'(A)$$
$$\text{s.t.} \quad \tilde{\phi}^* = u(A) - f - r - \tilde{\pi}, \; \tilde{\pi} = \max\left\{\frac{\tilde{I} - h(\tilde{I})W'(A)}{W(A)}, -r\right\}.$$

The first-order conditions imply that in such states,

$$\phi^*(A) = u(A) - c - \frac{G(\phi^*(A))}{g(\phi^*(A))}, \tag{53}$$

$$1 = W'(A)h'(I). \tag{54}$$

The envelope condition is

$$rW'(A) = u'(A)G(\phi^*(A)) + h(I(A))W''(A). \tag{55}$$

The envelope condition and the first-order conditions imply that at a steady-state level of productivity A^{dc} in which investors control the platform, it must be that

$$1 = \frac{u'(A^{dc})G(\phi^*(A^{dc}))}{r}. \tag{56}$$

Note that the first-order conditions (53) and (56) are the same as the corresponding first-order condition (50) in the case of commitment. Therefore, if equilibrium converges to a steady state such that investors control the platform, it must be that the steady state is the same as in the commitment case, $A^{dc} = A^{token}$ and $\phi^{dc} = \phi^{token}$.

Case 2: Users control the platform. Online Appendix E.4 shows that when users control the platform, they choose policies to solve

$$\max_{\tilde{f},\tilde{I}} (1-\zeta(A))\Big((u(A)-\tilde{\phi}^*-c)G(\tilde{\phi}^*)-\tilde{I}+h(\tilde{I})W'(A)\Big)+(\tilde{\phi}^*+h(\tilde{I})R^{*\prime}(A))$$
$$\text{s.t.}\ \ \tilde{\phi}^*=u(A)-f-r-\tilde{\pi},\ \tilde{\pi}=\max\left\{\frac{\tilde{I}-h(\tilde{I})W'(A)}{W(A)},-r\right\}.$$

The first-order condition with respect to $\tilde{\phi}$ implies that for any A in which users control the platform,

$$\phi^*(A)=u(A)-c+\frac{\frac{1}{1-\zeta(A)}-G(\phi^*(A))}{g(\phi^*(A))}>u(A)-c. \tag{57}$$

Optimal investment satisfies

$$\frac{1}{h'(I(A))}=W'(A)+\frac{1}{1-\zeta(A)}R^{*\prime}(A), \tag{58}$$

where the envelope condition for inframarginal rents is

$$rR^{*\prime}(A)=\phi^*(A)+h(I(A))R^{*\prime\prime}(A). \tag{59}$$

Taken together, the first-order conditions and envelope conditions imply that if productivity converges to a steady state A^{dc} in which users control the platform, we must have (57), which immediately yields $\phi^{dc}>\phi^{FB}$, and

$$1=\frac{u'(A^{dc})G(\phi^*(A^{dc}))}{r}. \tag{60}$$

This steady-state condition along with $\phi^{dc}>\phi^{FB}$ implies that, as argued in the proofs of Propositions 3-6, $A^{dc}>A^{FB}$. □

E Online Appendix: A Discrete-Time Approximation

In this section, we construct a discrete-time model that formalizes the recursive formulation of equilibrium without commitment. Our results in the paper describe the limit as the length of time periods is taken to zero.

E.1 Environment

Time is discrete and infinite, $t\in\{0,dt,2dt,\dots\}$ (so that dt is the length of a period). The environment is a discrete-time adaptation of that in the main body of the paper. The platform sets policies (f_t, I_t) in each period. The platform's productivity evolves according to

$$A_{t+dt} = A_t + h(I_t)dt. \tag{61}$$

User i's period utility from transactions $x_{it} \leq 1$, and the platform's flow profits from aggregate transactions X_t, are

$$U_i(x_{it}|A_t, f_t)dt = \Big((u(A_t) - f_t)x_{it} - \mathbf{1}\{x_{it} > 0\}\phi_i\Big)dt, \ \Pi(X_t|f_t)dt = (f_t - c)X_t dt.$$

A user's lifetime utility is $\sum_{n=0}^{\infty} e^{-rndt}\big(U_i(x_{it}|A_t, f_t)dt + c_{it}\big)$, whereas an investor's utility is simply $\sum_{n=0}^{\infty} e^{-rndt}c_{jt}$. There are still two assets: transaction assets in supply A_t^T that trade at price Q_t^T and cash flow assets in supply A_t^C that trade at price Q_t^C. User i's transactions cannot exceed her balance of transaction assets, $x_{it} \leq Q_t^T a_{it}$, and dividends $\frac{\Pi(X_t|f_t)dt}{A_t^C}$ are paid pro-rata to cash flow asset holders.

Each period unfolds as follows.

1. A vote is taken to determine the platform's policies (f_t, I_t) in the current period. In the case of a centralized token issuer, the fraction of investment θ_t financed with tokens is chosen at this stage as well.

2. Asset markets open. Agents choose their asset holdings and the platform issues additional assets to finance investment.

3. Agents transact and earn dividends.

4. The investment I_t is undertaken, and the next period begins with productivity A_{t+dt} determined by (61).

User i's optimal quantity of transactions satisfies

$$x_{it} = \mathbf{1}\{\phi_i \leq \phi_t^*\} \ \text{ where } \ \phi_t^* = u(A_t) - f_t - \frac{1}{dt}\big(1 - \frac{Q_{t+dt}^T}{Q_t^T}e^{-rdt}\big). \tag{62}$$

The asset demand equations are analogous to (4) and (5):

$$Q_t^T A_t^T \geq G(\phi_t^*) \ \text{ with } \ \frac{Q_{t+dt}^T}{Q_t^T}e^{-rdt} = 1 \ \text{ if } Q_t^T A_t^T > G(\phi_t^*), \tag{63}$$

$$Q_t^C = \frac{(f_t - c)G(\phi_t^*)dt}{A_t^C} + e^{-rdt}Q_{t+dt}^C. \tag{64}$$

E.2 Equilibrium with a traditional platform

We begin by analyzing equilibrium with a traditional platform. The price of transaction assets is fixed at $Q_t^T = 1$, and transaction assets are issued to finance investment:

$$Q_t^T (A_t^C - A_{t-dt}^C) = I_t dt. \tag{65}$$

We focus on Markov equilibria (with state variable A_t) in which there are conjectured equilibrium quantities $\phi^(A), V(A) = Q^C(A)A^C(A)$ and policies $f(A), I(A)$.

Actual policies may differ from conjectured policies (off-equilibrium), and as a result, actual transaction quantities may differ from conjectured quantities as well. Suppose the current state is A. If actual policies are $(\tilde{f}, \tilde{I})$, productivity in the next period will be $A' = A + h(\tilde{I})dt$. Since the price of transaction assets is constant, (62) implies that the actual participation threshold is a function of fees only,

$$\tilde{\phi}^*(\tilde{f}, \tilde{I}, A) = u(A) - \tilde{f} - (1 - e^{-rdt}). \tag{66}$$

Investors choose policies to maximize the value of the platform:

$$V(A) = \max_{\tilde{f}, \tilde{I}} \, (\tilde{f} - c)G(\phi^*(\tilde{f}, \tilde{I}, A))dt - \tilde{I}dt + e^{-rdt}V(A + h(I)dt) \;\; \text{s.t. (66).}$$

The first-order condition with respect to $\tilde{f}$ implies that in equilibrium (with $\tilde{f} = f(A)$),

$$0 = G(\phi^*(A)) - (f(A) - c)g(\phi^*(A)),$$

which implies

$$\phi^*(A) = u(A) - c - (1 - e^{-rdt}) - \frac{G(\phi^*(A))}{g(\phi^*(A))}. \tag{67}$$

The first-order condition with respect to $\tilde{I}$ is

$$1 = h'(I(A)) \times e^{-rdt}V'(A + h(I(A))dt). \tag{68}$$

Our assumed regularity conditions imply that equilibrium must converge to a steady state with productivity A^{trad} and investment $I(A^{trad}) = 0$. The envelope theorem yields

$$\begin{aligned} V'(A^{trad}) &= (f(A) - c)g(\phi^*(A^{trad}))\frac{\partial \phi^*(\tilde{f}, \tilde{I}, A^{trad})}{\partial A^{trad}}dt + e^{-rdt}V'(A^{trad}) \\ &= \frac{(f(A^{trad}) - c)g(\phi^*(A^{trad}))u'(A^{trad})dt}{1 - e^{-rdt}} \\ &= \frac{G(\phi^*(A^{trad}))u'(A^{trad})}{1 - e^{-rdt}}. \end{aligned}$$

The third line follows from the first-order condition (67) for $\tilde{f}$. Thus, in the long run, (68) and the envelope condition imply that A converges to A^{trad} such that

$$1 = \frac{G(\phi^*(A^{trad}))u'(A^{trad})}{1 - e^{-rdt}}. \tag{69}$$

E.3 Equilibrium with a centralized token issuer

Next, we turn to equilibrium without commitment in the case of a centralized token issuer. The price of transaction assets is no longer fixed. The asset supply (A_t^C, A_t^T) evolves according to

$$Q_t^C(A_t^C - A_{t-dt}^C) = (1 - \theta_t)I_t dt, \; Q_t^T(A_t^T - A_{t-dt}^T) = \theta_t I_t dt. \tag{70}$$

We search for a Markov equilibrium in the state variable A_t. Equilibrium specifies conjectured values for the participation threshold $\phi^*(A)$, the market capitalizations of shares and tokens, $M(A)$ and $V(A)$ (respectively), the return on tokens $\mu_Q(A)$,[16] and policies $(f(A), I(A), \theta(A))$. Actual policies are denoted $(\tilde{f}, \tilde{I}, \tilde{\theta})$.

We begin by solving for the participation threshold as a function of actual policies. The return on tokens $\mu_Q(A)$ is independent of policies, so (33) implies

$$\tilde{\phi}^*(\tilde{f}, \tilde{I}, A) = u(A) - \tilde{f} - \frac{1}{dt}(1 - e^{-rdt}\mu_Q(A)). \tag{71}$$

E.4 Equilibrium with decentralized governance

We conclude by analyzing the no-commitment equilibrium with decentralized governance. There is a single token with price Q_t. The asset supply A_t evolves according to

$$Q_t(A_t - A_{t-dt}) = I_t dt. \tag{72}$$

We search for a Markov equilibrium in the state variable A_t. Equilibrium specifies con-

[16] The return on tokens is defined as $\mu_{Qt} \equiv \frac{Q_{t+dt}}{Q_t}$.

jectured values for the participation threshold $\phi^*(A)$, the market capitalization of tokens $M(A)$, policies $(f(A), I(A))$, the fraction of staked tokens $\zeta(A)$, and the (gross) token return $\mu^Q(A)$.[17] Actual policies are denoted $(\tilde{f}, \tilde{I})$.

After policies are announced, users and investors choose their token demand. The fraction of staked tokens $\tilde{\zeta}$ adjusts so that the convenience yield of tokens is equal to the token dividend. This requires

$$\tilde{\zeta} = \frac{\tilde{f} - c}{u(A) - \tilde{\phi}^* - c}. \tag{73}$$

Let $\tilde{A}' \equiv A + h(\tilde{I})dt$ denote actual productivity in the next period. Then we have

$$\tilde{\mu}^Q = \frac{M(\tilde{A}') - I(\tilde{A}')dt}{\tilde{M}}, \tag{74}$$

which follows immediately from (72).[18] The participation threshold satisfies

$$\tilde{\phi}^* = u(A) - \tilde{f} - \frac{1}{dt}(1 - e^{-rdt}\tilde{\mu}^Q), \tag{75}$$

as usual. With (73), the dividend paid per staked token is

$$\frac{(\tilde{f} - c)G(\tilde{\phi}^*)}{1 - \tilde{\zeta}} = (u(A) - \tilde{\phi}^* - c)G(\tilde{\phi}^*).$$

The return on tokens is given by (74).

Case 1: Investors control the platform. If investors govern the platform in state A, their objective is to choose policies that maximize the value of tokens:

$$M(A) = \max_{\tilde{f}, \tilde{I}} \; (u(A) - \tilde{\phi}^* - c)G(\tilde{\phi}^*)dt - Idt + e^{-rdt}M(\tilde{A}')$$
$$\text{s.t.} \quad \tilde{A}' = A + h(I)dt, \; (74), \; (75).$$

The first-order condition with respect to fees implies

$$(u(A) - \tilde{\phi}^* - c)g(\tilde{\phi}^*)\frac{d\tilde{\phi}^*}{d\tilde{f}} = G(\tilde{\phi}^*)\frac{d\tilde{\phi}^*}{d\tilde{f}} \quad \Rightarrow \quad \phi^*(A) = u(A) - c - \frac{G(\phi^*(A))}{\phi^*(A)}. \tag{76}$$

[17] The gross token return is defined as $\mu_t^Q = \frac{Q_{t+dt}}{Q_t}$.

[18] Rearrange (72) to obtain $\frac{Q_{t+dt}}{Q_t}M_t = M_{t+dt} - I_{t+dt}$.

The first-order condition with respect to $\tilde{I}$ is[19]

$$1 = e^{-rdt} M'(A + h(I)dt)h'(I). \tag{77}$$

The envelope condition for $M'(A)$ (at a steady state with productivity A^{dc}) implies

$$M'(A^{dc}) = \frac{u'(A^{dc})G(\phi^*(A^{dc}))}{1 - e^{-rdt}}, \tag{78}$$

so in conjunction with (77), we have that productivity converges to a steady state A^{dc} satisfying

$$1 = \frac{e^{-rdt}}{1 - e^{-rdt}} u'(A^{dc})G(\phi^*(A^{dc}))dt. \tag{79}$$

Case 2: Users control the platform. If users control the platform in state A, their objective is to choose policies that maximize the value of their tokens, $\zeta(A_t)\tilde{M}$, plus the present value of future inframarginal rents. We conjecture and verify that the participation threshold is increasing over time. In this case, the present value of user i's inframarginal rents is

$$R_{it} = R_t^* - \frac{\phi_i}{1 - e^{-rdt}},$$

where

$$R_t^* = R^*(A_t) = \sum_{n=0}^{\infty} e^{-rndt} \phi^*(A_{t+ndt}). \tag{80}$$

Users' governance problem at t in state A is

$$\begin{aligned} \max_{\tilde{f}, \tilde{I}} \; & (1 - \zeta(A))\tilde{M} + \tilde{\phi}^* + e^{-rdt} R^*(\tilde{A}') \\ \text{s.t. } & \tilde{M} = (u(A) - \tilde{\phi}^* - c)G(\tilde{\phi}^*)dt - \tilde{I}dt + e^{-rdt} M(\tilde{A}'), \\ & \tilde{A}' = A + h(I)dt, \; (74), \; (75). \end{aligned} \tag{81}$$

Fees are set optimally so that

$$\phi^*(A) = u(A) - c + \frac{\frac{1}{1-\zeta(A)} - G(\phi^*(A))}{g(\phi^*(A))} > u(A) - c. \tag{82}$$

The first-order condition for investment $\tilde{I}$ can be written as

$$\frac{1}{h'(I(A))dt} = e^{-rdt} \left(M'(A + h(I(A))dt) + \frac{1}{1 - \zeta(A)} R^{*\prime}(A + h(I(A))dt) \right). \tag{83}$$

[19]The terms with $\frac{d\tilde{\phi}^*}{d\tilde{I}}$ drop out by (76).

The envelope conditions are (78) and

$$R^{*\prime}(A) = \tilde{\phi^*}'(A) + e^{-rdt} R^{*\prime}(A + h(I(A))dt). \tag{84}$$

The envelope conditions and (83) imply that productivity converges to a steady state A^u satisfying

$$1 = \frac{e^{-rdt}dt}{1 - e^{-rdt}} \left(u'(A^u) G(\phi^*(A^u)) + \frac{\phi^{*\prime}(A^u)}{1 - \zeta(A^u)} \right). \tag{85}$$

The concavity of $u(\cdot)$, $\phi^{*\prime} > 0$, and $\phi^*(A^u) > u(A^u) - c$ imply that $A^u > A^{FB}$, as desired.