ISSN 0956-8549

On the Fragility of DeFi Lending

By

Jonathan Chiu
Emre Ozdenoren
Kathy Yuan
Shengxing Zhang

DISCUSSION PAPER NO 883

PAUL WOOLLEY CENTRE WORKING PAPER No 95

August 2023

On the Fragility of DeFi Lending

Jonathan Chiu
Bank of Canada

Emre Ozdenoren
LBS, CEPR

Kathy Yuan
IMF, LSE, FMG, CEPR

Shengxing Zhang*
PHBS, LSE, CEPR

November 2022

Abstract

We develop a dynamic model of DeFi lending that incorporates the following key features: 1) borrowing and lending are decentralized, anonymous, overcollaterlized, and backed by the market value of crypto assets where contract terms are pre-specified and rigid; and 2) information friction exists between borrowers and lenders. We identify a price-liquidity feedback: the market outcome in any given period depends on agents expectations about lending activities in future periods, with higher future price expectations leading to more lending and higher prices in that period. Given the rigidity inherent to smart contracts, this feedback leads to multiple self-fulfilling equilibria where DeFi lending and asset prices co-move with market sentiment. We show that flexible updates of smart contracts can restore equilibrium uniqueness. This finding highlights the difficulty of achieving stability and efficiency in a decentralized environment without a liquidity backstop.

Keywords: Decentralized Finance; DeFi, Smart Contracts; Dynamic Price Feedback; Financial Fragility; Adverse Selection; DeFi trilemma, Stability, Efficiency, and DecentralizationTradeoff.

JEL classification: G10, G01

*Chiu (jchiu@bankofcanada.ca), Ozdenoren (eozdenoren@london.edu), Yuan (k.yuan@lse.ac.uk), and Zhang (oo7zsx@gmail.com). Yuan worked on the revision of the paper during her visit at IMF. We thank our discussants Felix Irresberger, Quentin Vandeweyer and Ganesh Viswanath-Natraj for valuable suggestions, and we thank many conference participants for their comments. We thank Hanna Yu for her research assistance. The views expressed in this paper are solely those of the authors and may differ from official Bank of Canada or IMF views.

1 Introduction

Decentralized finance (DeFi) is an umbrella term for a variety of financial service protocols and applications (e.g., decentralized exchanges, lending platforms, asset management) that operate on blockchain technology. They are anonymous permission-less financial arrangements implemented via smart contracts—immutable, deterministic computer programs—on a blockchain that have been designed to replace traditional financial intermediaries (TradFi).

Among the many promises DeFi offers, two stand out. First, DeFi protocols have the potential to democratize the provision of and also expand access to financial services, especially for individuals who are under-served by TradFi, improving social welfare. Second, by automating contract execution, DeFi could resolve incentive problems associated with human discretion (e.g., fraud, censorship, racial and cultural bias) and hence complement TradFi.[1]

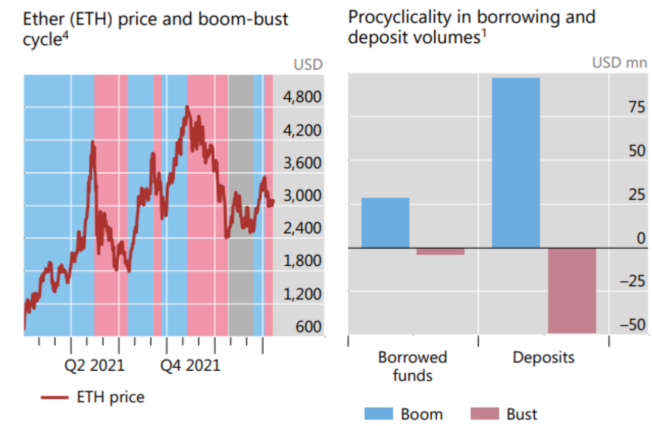
The growth of decentralized finance has been substantial since the "DeFi Summer" of 2020. According to data aggregator DeFiLlama, the total value locked (TVL) of DeFi had risen to 230 billion U.S. dollars as of April 2022, up from less than one billion two years prior to that time. As DeFi grows in scale and scope and becomes more extensively connected to the real economy, its vulnerabilities might undermine financial-sector stability (Aramonte, Huang, and Schrimpf (2021)). As a result, policymakers and regulators have raised concerns about the implications of DeFi for financial stability (FSB 2022; IOSCO 2022).[2] Yet formal economic analysis of this issue remains very limited. In this paper, we examine DeFi lending protocols—an important component of the DeFi eco-system—and the sources and implications of their instability. For example, DeFi lending is much more volatile than traditional lending.[3] In addition, Aramonte et al. (2022) argue that DeFi lending generates "pro-cyclicality"—co-movement between crypto prices and lending activities, as shown in Figure 1. We develop a dynamic model to capture key features of DeFi lending and explore its inherent fragility and its relationship to crypto asset-price dynamics.

[1] The collapse of the cryptocurrency exchange FTX—an unregulated centralized blockchain trading firm—has further pushed investors away from centralized blockchain platforms towards self-custodial DeFi platforms. For example, it has been reported that Uniswap, one of the largest decentralized exchanges, registered a significant spike in trading volume on November 11 2022, the day FTX filed for bankruptcy. The subsequent increase in its trading volume has been much higher than similar increases on many centralized exchanges (https://cointelegraph.com/news/after-ftx-defi-can-go-mainstream-if-it-overcomes-its-flaws).

[2] URLs of reports: https://g20.org/wp-content/uploads/2022/02/FSB-Report-on-Assessment-of-Risks-to-Financial-Stability-from-Crypto-assets_.pdf and https://www.iosco.org/library/pubdocs/pdf/IOSCOPD699.pdf

[3] For instance, the coefficients of variation for the total values of Aave v2 loans and deposits in 2021 were, respectively, 73 and 65. The corresponding statistics for US demand deposits and C&I loans were, respectively 10.4 and 2.7.

Figure 1: Crypto price boom–bust cycle and pro-cyclicality in DeFi lending



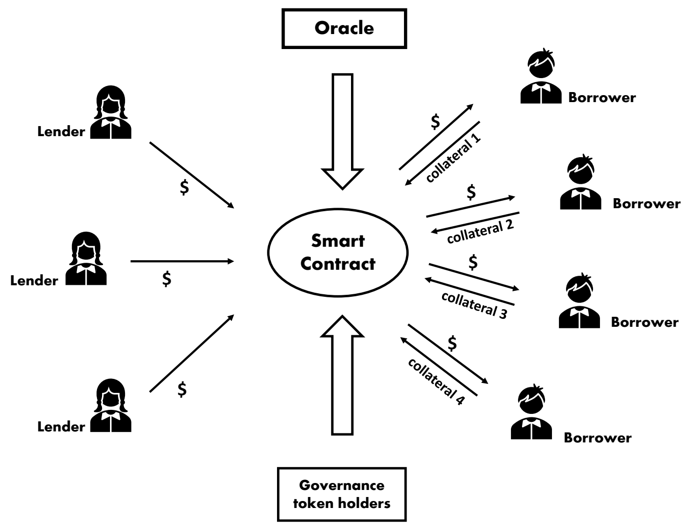
Sources: CryptoCompare; Dune, @echolon166; @zkmark; authors' calculations.

Source: Aramonte et al. (2022)

In Figure 2 we present a stylized display of the structure of lending protocols. Anonymous lenders deposit their crypto assets (e.g., stablecoins denoted as $) via a lending smart contract to the lending pool associated with the corresponding crypto asset. Anonymous borrowers can borrow the crypto asset from its lending pool by pledging *any* crypto collateral accepted by the protocol via a borrowing smart contract. The collateral composition of a lending pool is not readily observable, implying that borrowers are better informed about collateral quality than lenders are. Collateral assets are valued based on price feeds provided by an oracle, which can be either on-chain or off-chain. Since crypto assets are volatile, overcollateralization is a key feature of DeFi borrowing. The rules for setting key parameters (e.g., interest rates and haircuts) are pre-programmed in smart contracts. The protocol is governed in a decentralized fashion by holders of governance tokens. DeFi lending is typically short term because all lending and borrowing can be terminated at any minute.

DeFi lending differs from TradFi lending in four unique respects. The first key difference involves anonymity: TradFi borrowers are typically identified while DeFi agents are anonymous in the crypto space, where credit checks and other borrower-specific evaluations are not feasible. The second difference concerns the collateral asset. In TradFi, standard assets are available as collateral. In DeFi, however, only tokenized assets can be pledged as collateral, and such assets tend to exhibit very high price volatilities. Moreover, these risky assets are often bundled into an opaque asset pool so that, while DeFi borrowers can choose to pledge any acceptable collateral assets, lenders can neither control nor easily monitor the composition of the underlying collateral pool. As a result, DeFi lending is subject

Figure 2: Stylized Structure of a DeFi Lending Protocol



to information asymmetry between borrowers and lenders.[4] The third difference is related to loan contracts. TradFi loan contracts can be quite flexible, with loan officers modifying terms according to the latest hard and soft information. These features help to improve loan quality and enforce loan repayments in TradFi, but are not applicable to DeFi lending, which is based on a public blockchain.[5] In DeFi, a smart contract is used to replace human judgment and all terms (e.g., loan rate formulas, haircuts) need to be pre-programmed and can only be contingent on a small set of quantifiable, real-time data. As a result, DeFi lending typically involves linear, non-recourse debt contracts that feature over-collateralization as the only risk control. Furthermore, the decentralized nature of DeFi implies that

[4]Borrowers can also have an information advantage relative to the lending protocol when a smart contract relies on an inaccurate price oracle. The price feed of an oracle involves a trade-off between latency and accuracy. For example, the reference implementation to Uniswap's oracle averages prices over a twenty-four hour window, meaning that short-lived shocks to the price are largely ignored and even a large and sustained shock (e.g. 20% for an hour) will move the oracle price by less than 1%. When the price falls because of falling fundamentals, the oracle price will lag the asset's "true" price significantly. Because crypto is a volatile asset class, with frequent intraday spikes and drops, informed borrowers can take out large loans backed by a crypto asset with a suddenly inflated price from a delayed oracle and default on loan obligations, leaving the lending protocol with a collateral whose value is far below the face value of the loan. In Appendix D, we discuss several exploit incidents that occurred during the Terra collapse in May 2022 and other price exploits reflecting inflated on-chain collateral prices.

[5]Some intertemporal and/or non-linear features of loan contracts cannot be implemented. For instance, reputational schemes become less effective (individuals can always walk away from a contract without future consequences). If loan size is used to screen borrower types, users may find it optimal to submit multiple transactions from separate addresses.

even a slight modification of a contract can involve a lengthy decision process among the governance token holders. Consequently, smart contract terms are modified only occasionally.[6] The fourth difference concerns regulation. There are so far no meaningful regulatory or oversight controls on DeFi lending, while TradFi is heavily regulated.

Motivated by these observations, we develop a dynamic model of DeFi lending with the following features. Borrowing is decentralized, over-collateralized, backed by the market value of various crypto assets, and governed by a linear borrowing contract, while the terms of the borrowing contract (such as the rule for haircuts) are pre-specified and rigid. Moreover, borrowers are better informed about the fundamental values of the crypto collateral assets than lenders.[7]

In our model, borrowers would like to borrow funds (e.g., stablecoins) from lenders through a lending platform using their crypto asset holdings as collateral. There is asymmetric information regarding the asset's quality between borrowers and lenders. Borrowers who are privately informed that their crypto assets are low quality have stronger incentives to borrow than those who are privately informed that their crypto assets are high quality. Lenders cannot control the collateral mix directly, so this information friction results in the classic lemons problem (Akerlof (1970)) and can severely reduce gains from trade by driving out high-quality borrowers. The DeFi platform imposes a haircut on the crypto asset, which reduces the loan's information sensitivity and mitigates the adverse-selection problem.

Interestingly, the lemons problem gives rise to a feedback effect between price and liquidity: the price of collateral assets affects the borrowing volume which, in turn, affects the equilibrium collateral price. In particular, this feedback is dynamic: the crypto market outcome in any given period depends on agents expectations of crypto market conditions in future periods. Higher expectations regarding future crypto asset prices improves DeFi lending and supports higher crypto prices in the present, leading to multiple self-fulfilling equilibria that makes DeFi lending fragile. There exist "sentiment" equilibria in which sunspots generate fluctuations in crypto asset prices and DeFi lending volume. Assets of lower average quality are used more extensively as collateral during periods when negative sentiment runs

[6]To amend or upgrade smart contracts, proxy contracts and implementation contracts are deployed to swap old for new smart contracts. DeFi protocols are however typically controlled using on-chain governance, where token holders vote to modify certain parameters of the smart contracts, resulting in only occasional risk-parameter changes. We find that, for example, the AAVE protocol was subject to only 13 risk-parameter changes in its first two years of operation. There are calls for technology developments to make decentralized governance semi-automatic and data-driven. So far, however, choosing these parameters has been a manual process (see Xu (2022)).

[7]In fact, this information friction need not reflect the quality of the asset. In the appendix, we show that an alternative information friction, unobservable private valuation, leads to the same price-liquidity feedback effects and multiple equilibria in the outcomes.

high. In addition, crypto asset prices and DeFi loans are more sensitive to fundamental shocks and more volatile.

We then show that the rigidity of a smart contract (e.g., specifying a constant haircut) plays an important role in driving the above mentioned outcomes. Under a flexible smart contract where the haircut can be updated nonlinearly in response to changes in market prices and the information environment, it is possible to support a unique equilibrium with high and stable lending volume and asset prices. Such contracts are however costly and difficult to implement in the decentralized environment, pinpointing the inherent fragility of DeFi lending protocols. To improve stability, it is necessary to give up a certain degree of decentralization in DeFi. For example, some platforms need to re-introduce human actors to provide real-time risk management—an arrangement that forces the decentralized protocol to rely on a trusted third party. While decentralization in participation and governance is fundamental to DeFi's exciting prospects for democratizing finance, our finding highlights the fact that decentralization also imposes limitations on DeFi's efficiency, complexity, and flexibility.

Our study is the first economics paper to develop a dynamic equilibrium model for studying decentralized lending protocols such as Aave and Compound. While there is a young and growing body of literature on decentralized finance, there is limited work on DeFi lending platforms. Most existing DeFi papers study decentralized exchanges to understand how automated market-makers (e.g., Uniswap) function differently from a traditional exchange (e.g., see Aoyagi and Itoy (2021), Capponi and Jia (2021), Lehar and Parlour (2021), Park (2021)). There are also papers investigating the structure of decentralized stablecoins such as Dai issued by the MakerDAO (e.g., d'Avernas, Bourany, and Vandeweyer (2021), Li and Mayer (2021), Kozhan and Viswanath-Natraj (2021)). Lehar and Parlour (2022) empirically study the impact of collateral liquidations on asset prices. For a general overview of DeFi architecture and applications, see Harvey et al. (2021) and Schar (2021). Chiu, Kahn, and Koeppl (2022) study the value propositions and limitations of DeFi. Vulnerabilities that make DeFi lending protocols fragile (e.g., price oracle exploits by borrowers) have been studied in the recent computer science literature. These computer science papers focus mainly on the efficiency of the design features of these protocols (e.g, see Gudgeon et al. (2020), Perez et al. (2021), Qin et al. (2020), Qin et al. (2021)).

Our model is related to existing theoretical work on collateralized borrowing in a general equilibrium setting, such as Geanakoplos (1997), Geanakoplos and Zame (2002), Geanakoplos (2003), and Fostel and Geanakoplos (2012). Building on Ozdenoren, Yuan, and Zhang (2021), our model captures some essential institutional features of DeFi lending to facilitate our study of the joint determination of lending activities and collateral asset prices, which helps us understand how information frictions and smart contract rigidity contribute to the vulnerabilities of crypto prices and DeFi lending.

This paper is organized as follows. In Section 2, we provide a brief description of the features of and frictions that affect lending protocols using Aave as an example to motivate the model assumptions. We describe the model setup in Section 3 and derive the equilibrium lending market in Section 4. In Section 5, we establish the inherent fragility of DeFi lending and discuss how flexible contract design can improve stability and efficiency. Section 6 concludes. In the Online Appendix, we report evidence supporting the case that our model can be useful for understanding the relationship between DeFi lending, crypto prices, and market sentiment.

2 Lending Protocols: Features and Frictions

To motivate our model setup, we now describe some key features of and frictions associated with DeFi protocols based on Aave, the largest DeFi lending protocol.

Key players. The Aave eco-system consists of several types of participants. Depositors can deposit a crypto asset into the corresponding pool of the Aave protocol and collect interest over time. Borrowers can borrow funds from the pool by pledging any acceptable crypto assets as collateral to back the borrowing position. A borrower repays the loan in the same borrowed asset. There is no fixed time period within which to pay back the loan. Partial or full repayments can be made at any time. As long as the position is safe, the loan can continue for an undefined period. As time passes, though, the accrued interest on an unpaid loan will grow, which might make it more likely that the deposited assets are liquidated by liquidators. This eco-system also includes AAVE token holders. Like shareholders, token holders act as residual claimants and vote when necessary to modify the protocol. The daily operations are governed by smart contracts stored on a blockchain that runs when predetermined conditions are met.

Loan rate and liquidation threshold. Loan and deposit rates are set based on current supply and demand in the pool according to formulas specified in the smart contracts. In particular, as the utilization rate of the deposits in a pool rises (i.e., a larger fraction of deposits are borrowed), both rates will rise in a deterministic fashion. The loan-to-value (LTV) ratio defines the maximum amount that can be borrowed with specific collateral. For example, at LTV = .75, for every 1 ETH of collateral, borrowers can borrow 0.75 ETHs' worth of funds. The protocol also defines a liquidation threshold, called the health factor. When the health factor is below 1, a loan is considered undercollateralized and can be liquidated by collateral liquidators. The collateral assets are valued based on price feeds provided by Chainlink's decentralized oracles.

Risky collateral. Aave currently accepts more than 20 distinct crypto assets as collateral, including WETH, WBTC, USDC, and UNI. The market value of most non-stablecoin collateral assets is highly volatile. As shown in table 3 in the Appendix, the prices of stablecoins such as USDC and DAI (top panel) are not particularly volatile and they are typically loaned out by lenders. Other crypto assets, which are used as collateral to back borrowings, are extremely volatile compared with collateral assets commonly used in TradFi (bottom panel). For example, ETH, which accounts for about 50% of non-stablecoin deposits in Aave, exhibits daily volatility of 5.69%. The maximum daily price drop was over 26% during the sample period. The most volatile asset is CRV, the governance token for the decentralized exchange and automated market-maker protocol Curve DAO. The maximum CRV price change within a day was over 40%. For risk-management purposes, Aave has imposed very high haircuts on these crypto assets. For example, the haircuts for YFI and SNX are, respectively, 60% and 85%.[8]

Collateral pool. Loans are backed by a pool of collateral assets. While the borrower can pledge any one of the acceptable assets as collateral, lenders cannot control or easily monitor the quality of the underlying collateral pool. As a result, DeFi lending is subject to asymmetric information: borrowers can freely modify the underlying collateral mix without notifying lenders. Naturally, borrowers and lenders have asymmetric incentives to expend effort acquiring information about pledged collateral (e.g., monitoring new information, conducting data analytics).

Pre-specified loan terms. Aave lending pools follow pre-specified rules to set loan rates and haircuts. As a smart contract is isolated from the outside world, it cannot be contingent on all available real-time information. While asset prices are periodically queried from an oracle (Chainlink), the loan terms do not depend on other soft information (e.g., regulatory changes, projections, statements of future plans, rumors, market commentary) as they cannot be readily quantified and fed into a contract.

Decentralized governance. Like many other DeFi protocols, Aave has deferred governance to the user community by setting up a decentralized autonomous organization, or DAO. Holders of the AAVE token can vote on matters such as adjustments of interest rate functions, addition or removal of assets, and modification of risk parameters such as margin requirements. To implement such protocol changes, token holders need to make proposals, discuss them with the community, and obtain enough support in a

[8]More recently, Aave has begun accepting tokenized real-world assets (https://medium.com/centrifuge/rwa-market-the-aave-market-for-real-world-assets-goes-live-48976b984dde). Aave also plans to accept non-fungible tokens (NFTs) as collateral (https://twitter.com/StaniKulechov/status/1400638828264710144). As non-standardized assets, NFTs are likely to be subject to even more severe informational frictions. Popular DeFi lending platforms for NFTs include NFTfi, Arcade, and Nexo.

vote. This process helps protect the system against censorship and collusion. Decentralized governance by a large group of token holders is, however, costly in both time and resources. Hence it is not possible to update the protocol or the smart contract terms very frequently. As a result, when compared with a centralized organization, a DeFi protocol may be slower to make necessary adjustments in response to certain unexpected external changes (e.g., changes in market sentiment) in a timely manner. This problem is well documented. For instance, a risk-assessment report issued by Aave in April 2021 pointed out that, "As market conditions change, the optimal parameters and suggestions will need to dynamically shift as well. Our results suggest that monitoring and adjustment of protocol parameters is crucial for reducing risk to lenders and slashing in the safety module."[9] In practice, between the setup of Aave v2 in late 2020 and May 2022, the risk parameters have been updated only 13 times (see Table 2 in the Appendix for some of the key changes). All updates were conducted after Aave DAO elected Gauntlet, a centralized entity, to provide dynamic risk-parameter recommendations.

These features of Aave are common among the DeFi lending protocols, highlighting three key frictions that affect DeFi lending. First, there is a lack of commitment from DeFi borrowers and hence the borrowings have to be (over-)collateralized. Second, information asymmetry between DeFi borrowers and lenders can occur because lenders cannot control the collateral mix in the collateral pool. Third, DeFi contracts are rigid and based on quantifiable information stored on the blockchain.

3 The Model Setup

The economy is set in discrete time and lasts forever.[10] There are many infinitely lived borrowers with identical preferences. There is a fixed set of crypto assets. Every borrower can hold at most one unit. There are also potential lenders who live for a single period and are replaced every period. The lending protocol intermediates DeFi lending via smart contracts. All agents can consume/produce a numeraire good at the end of each period with a constant per-unit utility/cost.

Gains from Trade and the Lending Platform A borrower needs funding that can be provided by lenders. There are gains from trade as the value per-unit of funding to a borrower is $z > 1$, while the per-unit cost of providing funding by lenders is normalized to one. In the DeFi setting, borrowers are anonymous and cannot commit to paying their debt. To overcome the commitment problem, loans

[9] Source: https://gauntlet.network/reports/aave

[10] In reality, interest payments on the borrowing in the lending protocols are compounded continuously and can be terminated at any time. Therefore, time periods in our model are relatively brief.

must be backed by collateral. DeFi lending relies on smart contracts to implement collateralized loans. The DeFi intermediary determines the terms of a smart contract. Collateral is locked into the smart contract and released to the borrower if and only if repayment is received.[11]

In DeFi lending protocols such as Aave, borrowers borrow predominantly stablecoins such as USDT and USDC using risky crypto assets as collateral (e.g. ETH, BTC, YFI, YNX). As stablecoins are regarded as a medium of exchange and a unit of account in DeFi, they are used to fund various transactions or to increase leverage in crypto investment. We interpret z as the value accrued to borrowers when using stablecoins borrowed from lenders for speculative or productive purposes.[12]

Crypto Asset Properties and the Information Environment We assume that all crypto assets are ex-ante identical and pay random dividends $\widetilde{\delta}$ in each period and survive to the next period with random probability $\widetilde{s}$.[13] The dividend δ captures both the pecuniary payoff that the asset generates (e.g., staking returns to the holder) and other private benefits that accrue from holding the crypto asset (e.g., governance rights). At the beginning of a period, each asset receives an iid quality shock that determines its current- and future-period payoffs. Specifically, with probability $1-\lambda$, the quality of an asset is high (H) and with probability λ it is low (L). The distribution of $(\widetilde{\delta}, \widetilde{s})$ is F_Q if asset quality is $Q \in \{H, L\}$. We assume that F_H first-order stochastically dominates F_L and denote expectation with respect to F_Q by $\mathbb{E}_Q$.

To simplify the analysis we make further assumptions regarding the distributions. We assume that a high-quality asset pays dividend $\delta > 0$ at the end of the period and survives to the next period with probability $s = 1$. A low-quality asset does not pay any dividends in the present ($\delta = 0$) and survives to the next period with probability $s \in [0, 1]$. The survival probability of the low-quality asset, s, is drawn from a distribution F before the end of the period. Here, $1 - s$ captures whether the quality shock has persistent effects on the dividend flow from the crypto asset.

We assume that the crypto asset pays positive dividends in some states. The main role of this assumption is to eliminate a non-monetary equilibrium. In our model the asset has collateral service and can have a positive price even if it pays no dividend. There can also however be an equilibrium where the asset is worthless because current lenders believe future lenders will not accept the asset as collateral. A

[11] Chiu, Kahn, and Koeppl (2022) study how a smart contract helps mitigate commitment problems in decentralized lending.

[12] It is straightforward to introduce governance tokens issued by the intermediary—the lending platform. Governance token holders then provide insurance to lenders by acting as residual claimants. Given risk neutrality, the equilibrium outcome remains the same.

[13] We use ˜ to denote random variables.

positive dividend eliminates the latter equilibrium. As we show later, in our model multiple monetary equilibria emerge when there is asymmetric information about the asset's payoff (which includes the asset's dividend and price) and its survival probability.[14][15]

At the beginning of each period, the borrower of a crypto asset privately learns the asset's quality (i.e., whether it is high or low). After observing the quality shock, the borrower decides whether and how much to borrow from the platform. The borrower then receives the private return from the loan (which is z times the loan size) and observes the realization of $(\widetilde{\delta}, \widetilde{s})$. Given the information, the borrower decides whether to repay the loan or default. The asset's quality and the state $(\widetilde{\delta}, \widetilde{s})$ are both publicly revealed at the end of each period. In the next period, some low-type assets do not survive and are replaced by new assets that are ex-ante identical. In the main model, we assume that borrowers receive private information in every period. In the Appendix, we consider the more general case where private information arrives only infrequently with probability χ, which captures the degree of information imperfection.

Asset Price At the end of each period, agents meet in a centralized market to trade the assets by transferring the numeraire good. At this point, the private information is revealed publicly. The end-of-period ex-dividend price of a crypto asset that will survive to the next period is denoted as ϕ_t. The pre-dividend price is thus $\Phi_t = \delta + \phi_t$ for a good asset and $s\phi_t$ for a bad asset with survival probability s. In the centralized market, each borrower can acquire at most one unit of the crypto asset that is held into the next period.[16]

Smart Contracts As discussed in the introduction, DeFi lending is anonymous and collateralized via smart contracts. A smart contract is a debt contract that specifies, at each time t, the haircut and interest rate (h, R_t) set by the lending protocol. The haircut defines the debt limit per unit of collateral according to

$$D_t \equiv \Phi_t(1 - h), \tag{1}$$

where $\Phi_t = \delta + \phi_t$.

[14]Although we demonstrate existence of multiple equilibria in a setting with asymmetric information about both components, the result would go through as long as there is asymmetric information about either one of these components.

[15]Our results do not depend on asymmetric information about the common value component of the dividends. In Appendix A.6, we explore an alternative setup where there is asymmetric information concerning borrowers' private valuations. The main results hold. In Appendix A.7, we show that our setup can also be extended to time-varying information frictions.

[16]The dynamic structure of the model is based on Lagos and Wright (2005).

In reality, the floating loan interest rate in the smart contract is a function of the utilization ratio, i.e., the ratio of demand and supply for funding, and the collateral-specific haircut is updated infrequently. To capture the economic impact of these features, we assume in our main model that the smart contract specifies a flexible market-clearing interest rate and a fixed haircut. We investigate the flexible haircut case in an extension.

DeFi Lending & Borrowers In each period, if the borrower borrows ℓ_t units of funding, the face value of the debt is $R_t \ell_t$. After observing the asset quality, the borrower raises funding from a DeFi protocol by executing the lending contract. Given (R_t, D_t), a type $Q = H, L$ borrower chooses the amount of collateral a_t to pledge and the size of the loan ℓ_t to take from the pool,

$$\max_{a_t, \ell_t} z\ell_t - \mathbb{E}_Q \min\{\ell_t R_t, a_t(\widetilde{\delta} + \widetilde{s}\phi_t)\},$$

subject to collateral constraint

$$\ell_t R_t \leq a_t D_t,$$

where D_t is the debt limit pinned down by (1). By borrowing ℓ_t and pledging a_t, the borrower obtains $z\ell_t$ from the loan but needs to either repay $\ell_t R_t$ or lose the collateral value $a_t(\widetilde{\delta} + \widetilde{s}\phi_t)$. The collateral value discounted by the haircut needs to be sufficiently high to cover the loan repayment. Note that, without loss of generality, we assume that the collateral constraint is binding: $\ell_t R_t = a_t D_t$.[17] So the solution for the borrowing decision is given by

$$a_{it} \in \arg\max_{a_t \in [0,1]} a_t[zD_t/R_t - \mathbb{E}_Q \min\{D_t, \widetilde{\delta} + \widetilde{s}\phi_t\}]. \tag{2}$$

Hence, it is optimal to set $a_t \in \{0, 1\}$. When the term inside the square bracket is positive, the borrower pledges $a_t = 1$ to borrow $\ell_t = D_t/R_t$ and promises to repay D_t. Default occurs whenever $D_t > \widetilde{\delta} + \widetilde{s}\phi_t$. When the term inside the square bracket is non-positive, the borrower does not borrow: $a_t = \ell_t = 0$. Because $\mathbb{E}_H \min\{D_t, \delta + \phi_t\} = D_t \geq \mathbb{E}_L \min\{D_t, \widetilde{s}\phi_t\}$, we have $a_{Lt} \geq a_{Ht}$ and $\ell_{Lt} \geq \ell_{Ht}$. That is, the low-type borrowers have stronger incentives to borrow than high-type borrowers. When both types borrow, we have a *pooling* outcome. When only the low-type borrowers borrow, we have a *separating* outcome.

DeFi Lending and Lenders The intermediary has no initial funding. It obtains funding q_t from lenders to finance loans to borrowers. When a loan matures, the intermediary passes the cash flows—either a borrower's repayment or the resale value of the collateral (in case of a default)—to the lenders

[17] To see this, suppose (ℓ^*, a^*) is optimal and $\ell^* R < a^* D$. Because the objective function is (weakly) decreasing in a, lowering a (weakly) increases the objective. The increase is strict if $as\phi < \ell R$ for some realization of s.

after collecting an intermediation fee (discussed below). Note that the borrower's borrowing decision, $a_{i,t}$ where $i \in \{L, H\}$, is quality-dependent, meaning that lenders face adverse selection in DeFi lending. Inasmuch as lenders are unable to distinguish between low- and high-quality borrowers at the time of lending, the choice of funding size q_t does not depend on the underlying asset quality. Of course, in equilibrium, lenders account for the expected quality of the collateral mix that backs the loan.

We assume that the lending market is competitive. That is, given $\{a_{i,t}\}_{i\in\{L,H\}}$, D_t, and ϕ_t, funding supply q_t satisfies the following zero-profit condition,

$$q_t = \frac{1}{1+f}\left\{\frac{1}{a_{L,t}\lambda + a_{H,t}(1-\lambda)}\left[a_{L,t}\lambda\mathbb{E}_L\min\{D_t, \widetilde{s}\phi_t\} + a_{H,t}(1-\lambda)\min\{D_t, \delta+\phi_t\}\right]\right\}, \quad (3)$$

where $f < z - 1$ is a fixed fee charged by the intermediary per unit of loan.[18]

When $a_{L,t} = a_{H,t} = 1$ (both types are borrowing) or when $a_{L,t} = 1$, $a_{H,t} = 0$ and the realized type is L, the funding supply is fully utilized and the funding market clears. In the separating case, if the realized type is H then there is no demand for funding. In this case, we assume that the intermediary returns the funding supply to the lenders without charging a fee.

The intermediary's payoff is given by

$$f[\lambda a_{L,t} + (1-\lambda)a_{H,t}]q_t. \quad (4)$$

In section 5.5, we consider the case where the intermediary flexibly chooses the haircut. In that case, the intermediary chooses h_t to maximize (4), taking $(a_{i,t})_{i\in\{L,H\}}$ and ϕ_t as given.

Determination of the Crypto Asset Price The price of a crypto asset at the end of period t, ϕ_t,, is given by

$$\begin{aligned}\phi_t = \beta &\underbrace{\{\lambda(\mathbb{E}_L\widetilde{s})\phi_{t+1} + (1-\lambda)(\delta+\phi_{t+1})\}}_{\text{Fundamental Value}} \\ +\beta &\underbrace{\left\{\begin{array}{c}\lambda\left(a_{L,t+1}\mathbb{E}_L\left(zD_{t+1}/R_{t+1} - \min\{D_{t+1}, \widetilde{s}\phi_{t+1}\}\right)\right) \\ +(1-\lambda)a_{H,t+1}\left(zD_{t+1}/R_{t+1} - \min\{D_{t+1}, \delta+\phi_{t+1}\}\right)\end{array}\right\}}_{\text{Collateral Value}},\end{aligned} \quad (5)$$

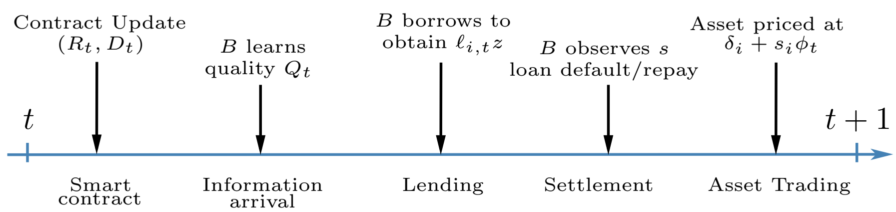
where β is the discount factor such that $0 < \beta < 1/z$. The continuation value of the asset is simply the sum of two terms: the fundamental value of the asset, which is the discounted value of the future dividend and asset resale price, and the collateral value. Importantly, the collateral value of the asset

[18] When the loan matures, the intermediary takes qf either from the repayment or from the resale value of the collateral. The remaining amount goes to the lender. The assumption of $f < z - 1$ ensures that the net gain from the loan is positive.

depends on endogenous variables, $(a_{i,t+1})_{i\in\{L,H\}}$, D_{t+1}, R_{t+1} and ϕ_{t+1}, which in turn depend on the extent of asymmetric information in future DeFi lending markets.

Timing The time line is summarized in Figure (3). At the beginning of each period, the smart contract specifies the debt limit D_t (or equivalently the haircut h) and the loan interest rate. Next, the borrower receives private information about the quality of the asset and decides whether to borrow from the lending platform by pledging collateral to the smart contract. Lenders supply funding subject to the zero-profit condition. After this stage, the borrower's type is revealed and the borrower either repays the loan or defaults and loses the collateral. If the asset survives, then its price is determined, consumption occurs, and the borrower works to acquire assets for the next period.

Figure 3: Time Line



Note that on this time line the lending platform is exposed to information friction, the asset market is frictionless, and we assume that they do not open simultaneously, which reflects the natural timing of the information-revelation process. In reality, a privately informed borrower can choose to offload the underlying asset to a lending platform by borrowing a stablecoin loan against it or conducting an outright sale in an exchange (that is, an asset market). Theoretically, however, it may not be optimal for a borrower to conduct an outright sale to raise money when there is adverse selection about the asset quality. The adverse-selection problem is more severe in an asset exchange because the borrower is selling an equity contract but less so in a lending platform because the borrower is selling a debt contract.[19] Empirically, other technical frictions occur when selling crypto assets on decentralized and centralized exchanges on blockchains. Transferring crypto assets to an off-chain centralized exchange is often subject to a long time lag before the assets can be traded, while transactions on an on-chain decentralized exchange are often subject to market illiquidity and price slippage. Therefore, for expositional clarity and without loss of generality, we assume that the asset market with frictions does not open simultaneously

[19] Ozdenoren, Yuan, and Zhang (2021) have shown the optimal security for privately informed borrowers to sell in a similar setting consists of a debt contract (which both high- and low-quality borrowers sell) and a residual equity contract (which only low-quality borrowers sell).

with the lending platform.

Equilibrium Definition Given haircut h and fee f, an equilibrium consists of asset prices $\{\phi_{t,}\}_{t=0}^{\infty}$, debt thresholds $\{D_t\}_{t=0}^{\infty}$, loan rates $\{R_t\}_{t=0}^{\infty}$, funding size $\{q_t\}_{t=0}^{\infty}$ and collateral quantities $\{a_{Lt}, a_{Ht}\}_{t=0}^{\infty}$ such that

1. borrowers' loan decisions are optimal (condition 2),
2. lenders earn zero profit (condition 3),
3. funding supply equals funding demand, i.e. $q_t = D_t/R_t$, and
4. the asset-pricing equation is satisfied (condition 5).

4 Equilibrium in the Lending Market

We begin the analysis by describing the equilibrium in the DeFi lending market for a given asset price ϕ.[20] To study the borrowers' decision, we first define the degree of *information insensitivity* as the ratio of the expected value of the debt contract for type L to the expected value of the debt contract for type H, i.e., $\zeta(\phi; h) = \mathbb{E}_L \min\{D, \widetilde{s}\phi\}/D \in (0, 1]$, where $D = (\delta + \phi)(1 - h)$. As this ratio increases, the expected values of the debt under the low- and high-type borrowers become closer and the adverse-selection problem becomes less severe.

There are two cases, depending on whether the high-type borrowers are active. In the pooling case, condition (3) implies that the equilibrium funding supplied by lenders is

$$q^P = \frac{1}{1+f}[\lambda \mathbb{E}_L \min\{D, \widetilde{s}\phi\} + (1-\lambda)D].$$

The interest rate is pinned down by $q^P = D/R^P$, that is,

$$R^P = \frac{D(1+f)}{\lambda \mathbb{E}_L [\min\{D, \widetilde{s}\phi\}] + (1-\lambda)D}.$$

In the separating case, the funding from lenders is given by

$$q^S = \frac{1}{1+f}\mathbb{E}_L \min\{D, \widetilde{s}\phi\},$$

and the interest rate is pinned down by $q^S = D/R^S$, that is,

$$R^S = \frac{D(1+f)}{\mathbb{E}_L [\min\{D, \widetilde{s}\phi\}]}.$$

[20] In this section, for ease of notation, we drop the time subscript t from all the variables.

Define $\overline{\zeta} \equiv 1 - \frac{z-1-f}{z\lambda}$. The next proposition characterizes the equilibrium in the DeFi lending market for a given asset price ϕ.

Proposition 1. *Given asset price ϕ, if the degree of information insensitivity $\zeta(\phi; h) > \overline{\zeta}$, then borrowers' equilibrium funding obtained from DeFi lending is $q = q^P$, the interest rate is $R = R^P$ and collateral choices for H-type borrowers and L-type borrowers are $a_L = a_H = 1$. If the degree of information insensitivity $\zeta(\phi; h) < \overline{\zeta}$, then borrowers' equilibrium funding from DeFi lending is $q = q^S$, the interest rate is $R = R^S$, and the collateral choices for H-type borrowers and L-type borrowers are $a_L = 1$ and $a_H = 0$. The former condition, for a pooling equilibrium, is easier to satisfy when asset price ϕ, haircut h, or productivity from borrowers' private investment z is higher.*

Proposition 1 implies that, given asset price ϕ, there is a unique equilibrium in DeFi lending. This equilibrium is pooling (separating) when the debt contract is sufficiently informationally insensitive (sensitive). In particular, when the degree of information insensitivity $\zeta(\phi; h)$ is above the threshold ζ, the adverse-selection problem is not particularly severe and both types of borrowers borrow. In this case, the loan size is the pooling quantity $q = q^P$. When the degree of information insensitivity is below the threshold, the adverse-selection problem is severe and only the low-type borrower borrows. In this case, the loan size is the separating amount $q = q^S$. Furthermore, the loan rate in a pooling equilibrium is lower than that in a separating equilibrium.

Note that $\zeta(\phi; h) = \mathbb{E}_L \min\{1, \frac{\widetilde{s}\phi}{(\delta+\phi)(1-h)}\}$. As a result, the debt contract becomes informationally less sensitive for a high ϕ and a high h. The above proposition also indicates that, in addition to the parameter λ that characterizes type heterogeneity, the net gains from trade, $z/(1+f)$, is also an important determinant of adverse selection: a lower $z/(1+f)$ leads to a higher $\overline{\zeta}$. In particular, even if there is very little asymmetric information about the quality of the debt contract (i.e., when $\zeta(\phi; h)$ is slightly below 1), as $z/(1+f)$ approaches 1 (so that $\overline{\zeta}$ is close to 1), the DeFi lending will be in a separating equilibrium. In other words, when net gains from trade are low, even a slight degree of information asymmetry results in an adverse-selection problem.

5 Multiple Equilibria in Dynamic DeFi Lending

The analysis presented in the previous section takes the asset price as given. In this section, we characterize the stationary equilibrium where asset prices are endogenously determined. We demonstrate that DeFi lending is fragile in the sense that it exhibits dynamic multiplicity in prices. Specifically, we show that there might be multiple equilibria in the DeFi lending market justified by varying crypto asset prices. The multiple asset prices are in turn justified by the multiple equilibria in DeFi lending. Inasmuch as we are focusing on stationary equilibria, we drop the time subscripts.

5.1 Characterization of Stationary Equilibria

5.1.1 Pooling equilibrium

In a stationary pooling equilibrium, all borrowers borrow ($a_L = a_H = 1$). This equilibrium exists when there is an asset price ϕ^P that satisfies the equation

$$\phi^P = \beta\left[(z-1-f)q^P\right] + \beta(1-\lambda)\delta + \beta(\lambda\mathbb{E}_L\widetilde{s} + (1-\lambda))\phi^P. \tag{6}$$

The loan size is given by

$$q^P = \frac{1}{1+f}\left(\lambda\mathbb{E}_L\left[\min\{D^P, \widetilde{s}\phi^P\}\right] + (1-\lambda)D^P\right),$$

where $D^P = \left(\delta + \phi^P\right)(1-h)$. In addition, the high-type borrower's incentive constraint to pool with the low-type borrower must hold:

$$\zeta\left(\phi^P; h\right) = \mathbb{E}_L\min\{1, \frac{\widetilde{s}\phi^P}{(\delta+\phi^P)(1-h)}\} \geq \overline{\zeta}. \tag{7}$$

5.1.2 Separating Equilibrium

In a separating equilibrium, only the low-type borrowers borrow (i.e., $a_H = 0$, $a_L = 1$). This equilibrium exists when there is an asset price ϕ^S that satisfies the equation

$$\phi^S = \beta\left(\lambda(z-1-f)q^S + (1-\lambda)\delta + (\lambda\mathbb{E}_L\widetilde{s} + (1-\lambda))\phi^S\right). \tag{8}$$

The loan size is given by

$$\frac{D^S}{R} = q^S = \frac{1}{1+f}\mathbb{E}_L\left[\min\{D^S, \widetilde{s}\phi^S\}\right],$$

where $D^S = \left(\delta + \phi^S\right)(1-h)$. In addition, pooling violates the high-type borrower's incentive constraint:

$$\zeta\left(\phi^S; h\right) < \overline{\zeta}. \tag{9}$$

5.2 Existence and Uniqueness

We first focus on the asset-pricing equations (6) and (8).

Lemma 1. *Equation (6) has a unique solution ϕ^P and equation (8) has a unique solution ϕ^S. Also, $\phi^P \geq \phi^S$.*

Lemma 1 implies that there exists at most one pooling and one separating stationary equilibrium. If these equilbria co-exist, the price in the pooling equilibrium is higher than that in the separating equilibrium. It is also easy to show that both prices are higher than the fundamental price of the asset in autarky, $\underline{\phi} = \frac{\beta(1-\lambda)\delta}{1-\beta(\lambda\mathbb{E}(s_L)+(1-\lambda))}$. This means that the introduction of DeFi lending raises the equilibrium asset price above its fundamental level. Lemma 1 implies that $\zeta(\phi^P; h) \geq \zeta(\phi^S; h)$. Hence, we have the following proposition.

Proposition 2. *There always exists at least one stationary equilibrium:*

- *it is a unique pooling equilibrium when* $\overline{\zeta} < \zeta(\phi^S; h)$,
- *it is a unique separating equilibrium when* $\overline{\zeta} > \zeta(\phi^P; h)$,
- *a pooling equilibrium and a separating equilibrium coexist when* $\overline{\zeta} \in [\zeta(\phi^S; h), \zeta(\phi^P; h)]$.

In the next section, we examine the conditions under which the multiplicity arises.

5.3 Haircuts and Multiplicity

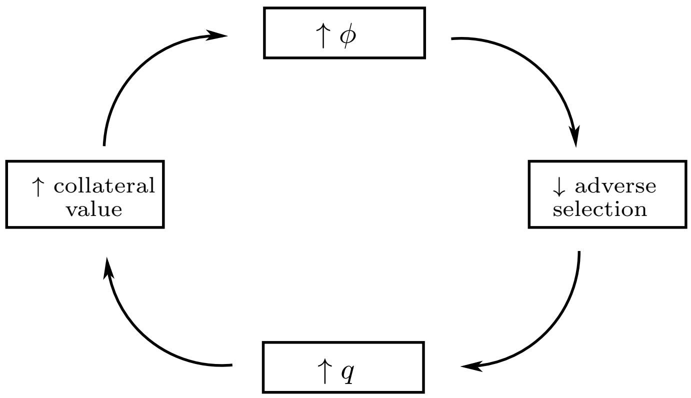
In Proposition 2, multiplicity arises as a result of a dynamic price–feedback effect described in Figure 4. When the collateral asset price is high, the degree of information insensitivity of the debt contract, $\zeta(\phi^P; h)$, is above the threshold $\overline{\zeta}$. Hence, the adverse-selection problem is mild and the high-type borrowers are willing to pool with the low type borrowers. In turn, if agents anticipate a pooling equilibrium in future periods, the expected liquidity value of the asset in the next period is high, and hence the asset price in the present is high. Conversely, when the asset price is low, the degree of information insensitivity of the debt contract, $\zeta(\phi^S; h)$, is below the threshold $\overline{\zeta}$. Therefore, the adverse-selection problem is severe and the high type borrower retains the asset and chooses not to borrow. In turn, if agents anticipate separating equilibria in future periods, the liquidity value of the asset is limited and thus the present asset price is low. As a result, the asset prices in this economy are self-fulfilling.

The haircut is a key parameter that controls the degree of information sensitivity. Setting a lower haircut makes the debt contract informationally more sensitive, magnifying the adverse-selection problem. Defining two thresholds

$$\kappa_P \equiv \frac{\zeta}{\beta z[(1-\lambda) + \zeta\lambda]}$$
$$\kappa_S \equiv \frac{\zeta}{\beta[(1-\lambda) + \zeta\lambda z]} < \kappa_P,$$

we have the following result.

Figure 4: Dynamic Feedback Loop



Proposition 3. *Suppose that the expected survival probability of the crypto asset satisfies* $\mathbb{E}_L \widetilde{s} \in (\kappa_P, \kappa_S)$. *There exists a threshold for the haircut such that when h is below this threshold, there are multiple equilibria.*

5.3.1 Example: Two-point distribution

We now use an example to illustrate the effects of h on the equilibrium outcome. The full analysis is given in the Appendix. Suppose $\widetilde{s}$ is drawn from a two-point distribution such that $s = 1$ with probability π and $s = 0$ with probability $1 - \pi$. Consider the separating equilibrium. When $s = 0$, a low-type borrower always defaults. When $s = 1$, the low-type borrower defaults if $D^S = \left(\delta + \phi^S\right)(1 - h) > \phi^S$ and repays if $D^S \leq \phi^S$. We can rewrite this condition to show that there exists a threshold level $\underline{h}^S$ such that, when $s = 1$, the low-type borrower defaults if $h < \underline{h}^S$ and repays if $h \geq \underline{h}^S$. In the former case, the low-type borrower always defaults so neither the face value of the loan nor, consequently, the loan size depends on the haircut. In the latter case, the low-type borrower repays the loan in the good state (i.e., $s = 1$); hence, the loan size depends on the face value of the debt. The face value of debt declines as the haircut increases, so the loan size decreases in h.

We define $\zeta^S(h) \equiv \zeta(\phi^S(h); h)$. That is, we obtain $\zeta^S(h)$ by substituting the price ϕ^S as a function of the haircut given fixed values for all other exogenous variables. We define $\zeta^P(h)$ similarly. Using (9), a separating equilibrium exists if $\zeta^S(h) \leq \overline{\zeta}$. The threshold $\zeta^S(h)$ is strictly increasing in h for $h < \underline{h}^S$ because the high-type borrower never defaults, so the expected value of the contract with the high-type borrower declines as h increases. The low-type borrower, on the other hand, always defaults and the expected value of the contract with the low-type borrower is independent of h. Hence, the information sensitivity of the contract decreases as h increases and it becomes harder to support a separating equilibrium. For $h \geq \underline{h}^S$, $\zeta^S(h) = \pi$ and a separating equilibrium exists whenever $\pi < \overline{\zeta}$. That is, once the haircut is large enough, increasing it further does not affect the information sensitivity of the contract because, in this case, the high-type borrower always pays the face value and the low-type borrower pays the face value only in the good state. As the haircut increases, the face value decreases but the value of the contract declines at the same rate for both types of borrowers so its information sensitivity remains constant.

We analyze the pooling equilibrium similarly and find a threshold $\underline{h}^P < \underline{h}^S$ such that, when $s = 1$, the low-type borrower defaults if $h < \underline{h}^P$ and repays if $h \geq \underline{h}^P$. A pooling equilibrium exists if $\zeta^P(h) \geq \overline{\zeta}$. The threshold $\zeta^P(h)$ is strictly increasing in h and $\zeta^P(h) > \zeta^S(h)$ for $h < \underline{h}^P$. For $h \geq \underline{h}^P$, $\zeta^P(h) = \pi$ and a pooling equilibrium exists whenever $\pi > \overline{\zeta}$.

Putting these facts together, we see that, whenever $h < \underline{h}^S$, we have $\zeta^S(h) < \zeta^P(h)$. Hence, when $\overline{\zeta}$ is in this range the two equilibria coexist. When the haircut exceeds $\underline{h}^S$, only a unique equilibrium can exist, depending on whether $\overline{\zeta}$ is above or below π.

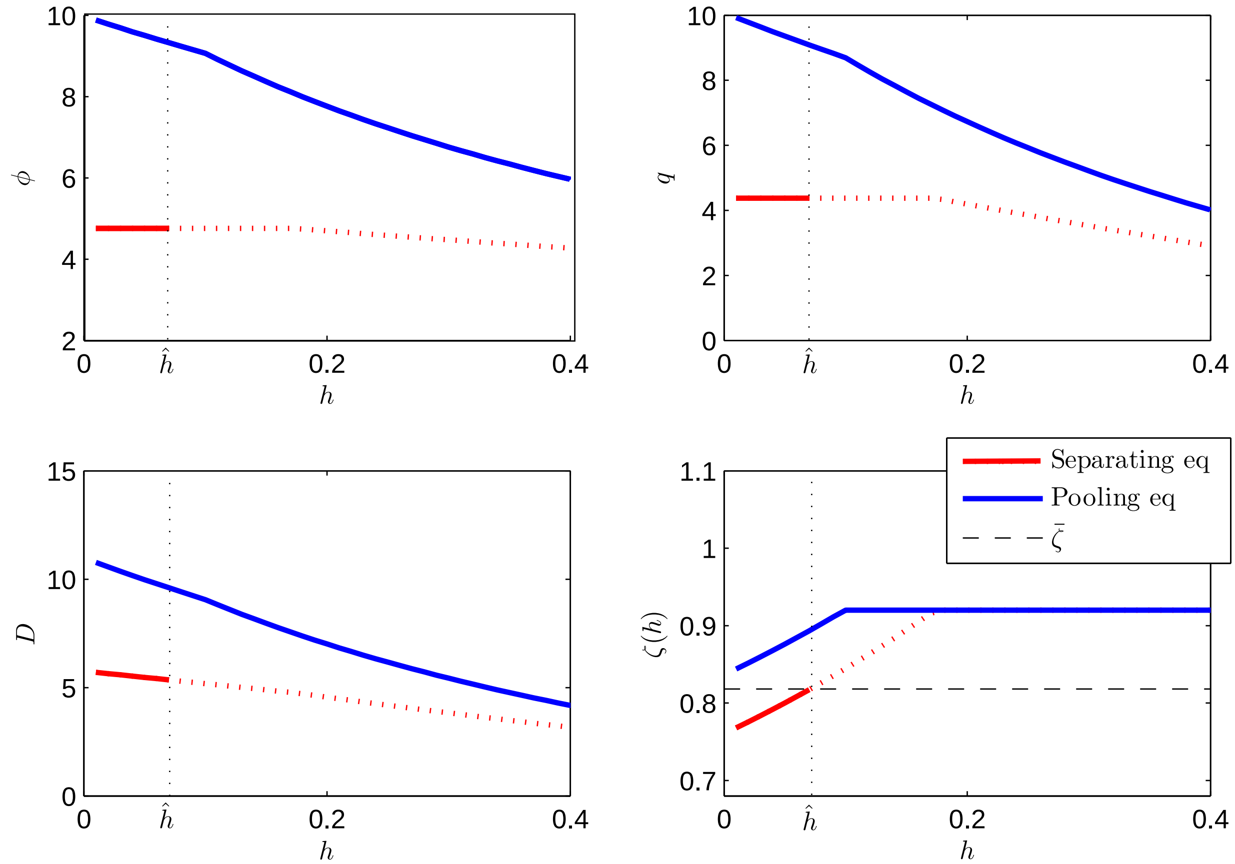
In Figure 5 we plot the effects of h on the asset price, the loan size, the debt limit, and the degree of information insensitivity of the contract. The red and blue curves indicate, respectively, the separating and pooling equilibria, assuming their existence. The parameter values used are $z = 1.1$, $\lambda = 0.5$, $\beta = 0.9$, $\delta = 1$, $\pi = 0.92$, $f = 0$, which satisfy the condition $\mathbb{E}_L\widetilde{s} \in (\kappa_P, \kappa_S)$ in Proposition 3. In the bottom right plot we compare the degrees of information insensitivity to the threshold $\overline{\zeta}$, which is captured by the dashed horizontal line. When h is close to zero, the dashed line appears above the red curve and below the blue curve, confirming the multiplicity result specified in Proposition 3. The other three plots also confirm the earlier result that the asset price, loan size, and debt limit are all higher in a pooling equilibrium. In this example, multiplicity can be ruled out and pooling can be supported by setting $h > \hat{h} = 7.1\%$ where $\overline{\zeta} = \zeta^S(\hat{h})$.[21]

5.4 Sentiment Equilibrium

In the middle region where multiple self-fulfilling equilibria coexist, it is possible to construct *sentiment equilibria* where agents' expectations depend on non-fundamental sunspot states (Asriyan, Fuchs, and Green (2017)). Suppose that there are K sentiment states indexed from 1 through K. We let $\sigma_{kk'}$ be

[21] When $h > \hat{h}$, the separating equilibrium cannot be sustained and hence, in Figure 5, the red lines depicting separating equilibria become red dotted lines in this region.

Figure 5: Effects of Haircut h



the Markov transition probability from sentiment state k to k'.

In the presence of sentiments we modify the model as follows. Let ϕ^k be the price of the asset, R^k be the loan rate, and $D^k = \left(\delta + \phi^k\right)(1-h)$ be the debt limit in sentiment state k. Quantities of collateral a_L^k, a_H^k chosen by each borrower type must be optimal given the asset price and loan rate at each sentiment state k. The loan size chosen by the lender in sentiment state k is given by:

$$q^k = \lambda E_L \left[\min\{D^k, s\phi^k\}\right] + (1-\lambda)D^k.$$

The price of the crypto asset in sentiment state k is given by:

$$\phi^k = \beta \sum_{k=1}^{K} \sigma_{kk'} \left\{ \lambda \int_{\underline{s}}^{\bar{s}} s_L \phi^{k'} dF(s_L) + (1-\lambda) \left(\delta + \phi^{k'}\right) \right.$$
$$\left. + \lambda a_L^{k'} \int_{\underline{s}}^{\bar{s}} \left(zD^{k'}/R^{k'} - \min\{D^{k'}, s_L \phi^{k'})\} \right) dF(s_L) + (1-\lambda)\, a_H^{k'} \left(zD^{k'}/R^{k'} - D^{k'} \right) \right\}.$$

We want to construct a *non-trivial sentiment equilibrium* such that the economy supports a pooling outcome in states $k = 1, ..., \bar{k}$ and a separating outcome in states $k = \bar{k}+1, ..., K$. By continuity, we can obtain the following result.

Proposition 4. *Suppose that $\mathbb{E}(s) \in (\kappa_P, \kappa_S)$ and the haircut is not too large. Then, for sufficiently large σ_{kk}, there exists a non-trivial sentiment equilibrium.*

To demonstrate the non-trivial sentiment equilibrium and examine equilibrium properties, we provide the following two numerical examples. In both examples we assume that $\widetilde{s}$ is drawn from a two-point distribution such that $s = 1$ with probability π and $s = 0$ with probability $1 - \pi$.

Example 1. Suppose that $K = 3$ and $\bar{k} = 1$. The economy remains in the same state with probability σ and moves to the next state with probability $1 - \sigma$, where the next state from 1 is 2, that from 2 is 3, and that from 3 is 1. We can interpret the three states as follows:

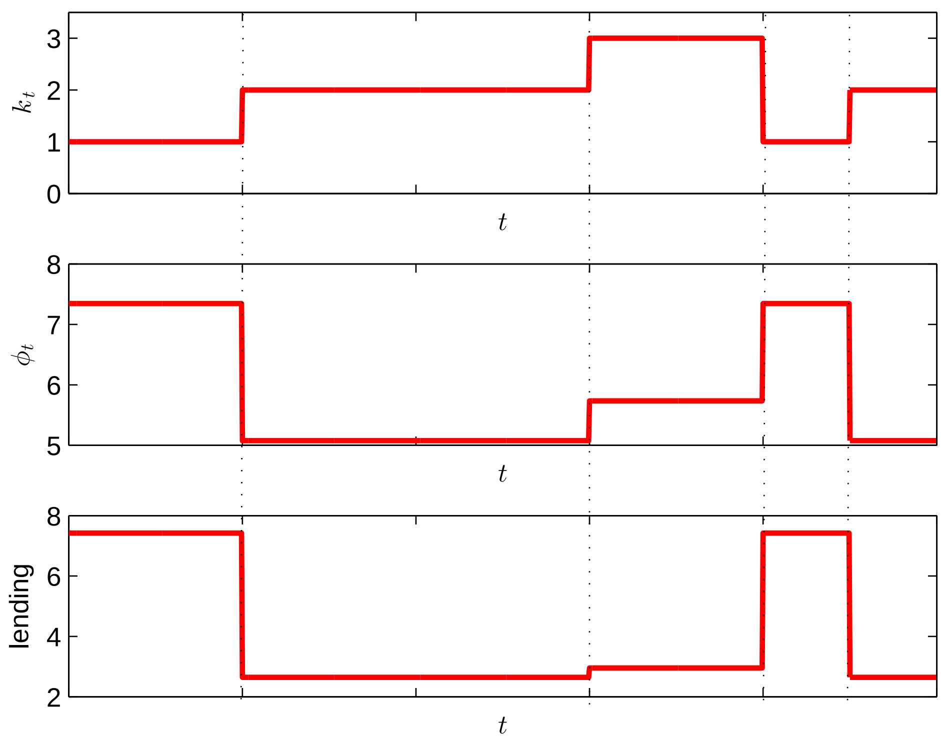
- $k = 1$: Boom state
  - $a_L^1 = a_H^1 = 1$, $q^1 = \lambda\pi \min\{(\delta + \phi^1)(1-h), \phi^1\} + (1-\lambda)(\delta+\phi^1)(1-h)$
- $k = 2$: Crash state
  - $a_L^2 = 1, a_H^2 = 0$, $q^2 = \pi \min\{(\delta + \phi^2)(1-h), \phi^2\}$
- $k = 3$: Recovery state
  - $a_L^3 = 1, a_H^3 = 0$, $q^3 = \pi \min\{(\delta + \phi^3)(1-h), \phi^3\}$

The asset prices are then given by

$$\begin{aligned}\phi^k =& \beta\sigma_{k1} \left[(z-1)q^1 + (1-\lambda)\delta + (\lambda\pi + (1-\lambda))\phi^1\right] \\ &+ \beta\sigma_{k2} \left[\lambda(z-1)q^2 + (1-\lambda)\delta + (\lambda\pi + (1-\lambda))\phi^2\right] \\ &+ \beta\sigma_{k3} \left[\lambda(z-1)q^3 + (1-\lambda)\delta + (\lambda\pi + (1-\lambda))\phi^3\right].\end{aligned}$$

Figure 6 plots the effects of sentiment states on asset prices and total lending. When $\sigma = 0.95$, the sentiment state is sufficiently persistent so that the above sentiment equilibrium exists. As shown, the sentiment dynamics drive the endogenous asset-price cycle: The asset price declines when the economy enters the crash state, jumps up when the economy moves from the crash state to the recovery state, and jumps up further when the economy returns to the boom state. Note that the total lending, $\left(\lambda a_L^k + (1-\lambda) a_H^k\right) q^k$, is "pro-cyclical" in the sense that it is positively correlated with the asset price.

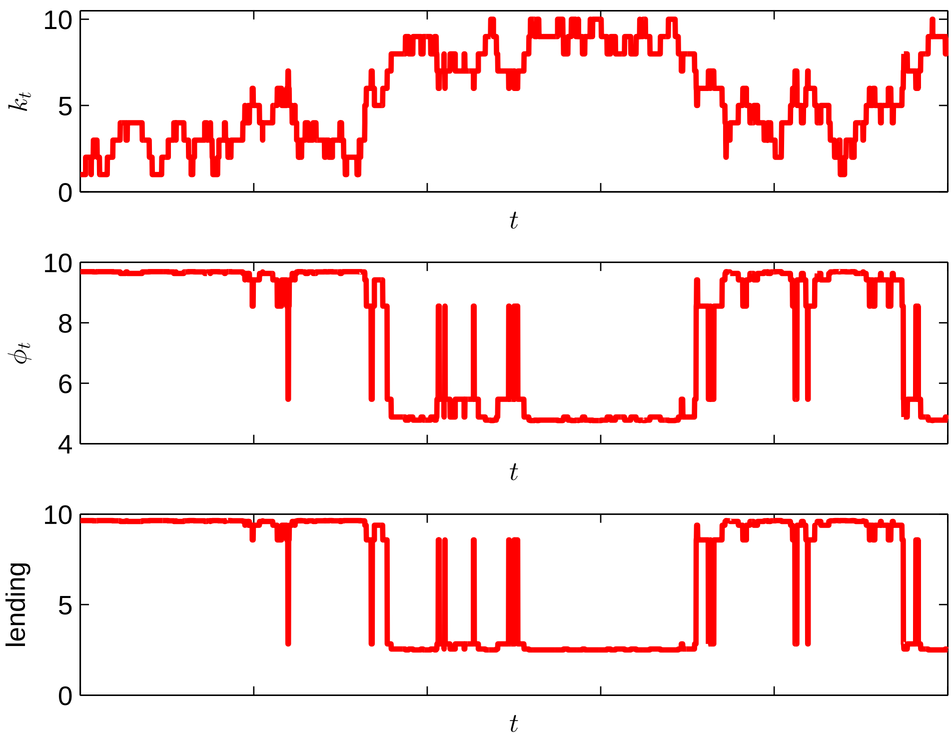
Figure 6: Sentiment Equilibrium Example 1



Next, we reveal a similar pro-cyclical pattern of lending and asset prices in an example where there are more (than three) states and a state moves to an up or down state with equal probability. In this example, equilibrium lending and asset prices are more volatile.

Example 2. Let $K = 10$. If the economy is in state k in a given period, in the next period sentiment remains the same with probability σ. From states $k \in \{2, \ldots, K-1\}$ the economy moves to state $k-1$ with probability $(1-\sigma)/2$ and to state $k+1$ with probability $(1-\sigma)/2$. From state 1 the economy moves to state 2 with probability $1-\sigma$. From state K the economy moves to state $K-1$ with probability $1-\sigma$. Figure 7 plots a simulation for 5,000 periods when $\sigma = 0.95$ and $\bar{k} = 6$.

Figure 7: Sentiment Equilibrium Example 2



5.5 Uniqueness under Flexible Design of the Debt Limit

We have shown that when DeFi lending is subject to a rigid haircut, multiplicity occurs if the debt contract is too informationally sensitive. We now show that a flexible contract design supports a unique equilibrium and generates higher social surplus from lending than in the case with a rigid haircut.

Under flexible design, the smart contract is no longer subject to constraint (1). Instead, in each period the intermediary, in this case the DeFi protocol, can choose any feasible debt contract, $y(D_t, \widetilde{\delta} + \widetilde{s}\phi_t) = \min(D_t, \widetilde{\delta} + \widetilde{s}\phi_t)$ for $0 \leq D_t \leq \delta + \phi_t$. Let $\widehat{z}$ denote the marginal value of obtaining funding from lenders after deducting the intermediation fee f that is paid to the intermediary,

$$\widehat{z} = \frac{z}{1+f}.$$

Recall from (4) that the intermediary maximizes the expected loan size times the intermediation fee:

$$f[\lambda + (1-\lambda)\, a_{H,t}]q_t \left(y(D_t, \widetilde{\delta} + \widetilde{s}\phi_t) \right).$$

The loan size is

$$q_t\left(y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)\right)=\frac{1}{1+f}\frac{\left[\lambda\mathbb{E}_L+a_{H,t}\left(1-\lambda\right)\mathbb{E}_H\right]y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)}{\lambda+a_{H,t}\left(1-\lambda\right)} \tag{10}$$

where

$$a_{H,t}=\begin{cases}1 & \text{if } \widehat{z}\left[\lambda\mathbb{E}_L+(1-\lambda)\mathbb{E}_H\right]y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)\geq\mathbb{E}_H y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)\\ 0 & \text{otherwise}\end{cases}. \tag{11}$$

Equivalently, the intermediary maximizes

$$\left[\lambda\mathbb{E}_L+a_{H,t}\left(1-\lambda\right)\mathbb{E}_H\right]y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t), \tag{12}$$

subject to (11). In other words, the intermediary takes the price ϕ_t as given and sets the debt threshold D to maximize the expected loan size, taking into account the impact of the contract on the funding that lenders are willing to supply. The value of the asset to the borrower is:

$$\begin{aligned}V_t=\max_{0\leq D\leq\delta+\phi_t}\lambda&\left[\widehat{z}q_t\left(y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)\right)-\mathbb{E}_L y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)+\mathbb{E}_L\left(\widetilde{\delta}+\widetilde{s}\phi_t\right)\right] \\ &+(1-\lambda)\left[a_{H,t}\left\{\widehat{z}q_t\left(y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)\right)-\mathbb{E}_H y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)\right\}+\mathbb{E}_H\left(\widetilde{\delta}+\widetilde{s}\phi_t\right)\right].\end{aligned} \tag{13}$$

Given the optimal design, the asset price at the end of the previous period equals

$$\phi_{t-1}=\beta V_t. \tag{14}$$

An equilibrium under flexible smart contract design is debt face value D_t, the borrower's value for the asset at the beginning of period t V_t and the resale price of the asset at the end of period t ϕ_t such that (i) D_t maximizes (12) taking ϕ_t as given, and (ii) V_t, and ϕ_t satisfy (13) and (14).

We also make the same simplifying assumptions regarding the distribution of $\left(\widetilde{\delta},\widetilde{s}\right)$ that we make in the rigid haircut case. That is, we assume that a high-quality asset pays dividend $\delta>0$ at the end of the period and survives to the next period with certainty, which implies

$$\mathbb{E}_H y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)=y(D_t,\delta+\phi_t);$$

and the low-type asset pays no dividends and it survives to the next period with probability $s\in[0,1]$, which is drawn from a distribution F, which implies

$$\mathbb{E}_L y(D_t,\widetilde{\delta}+\widetilde{s}\phi_t)=\int_{\underline{s}}^{\bar{s}}y(D_t,s_L\phi_t)dF\left(s_L\right).$$

The following proposition describes the optimal debt threshold and the implied haircut as a function of the asset price ϕ_t.

Proposition 5. *If* $\mathbb{E}_L s < 1 + \frac{1}{\lambda\widehat{z}} - \frac{1}{\lambda}$*, then let* s^* *be the unique solution to*

$$\widehat{z}\,[\lambda\mathbb{E}_L \min(s^*, s) + (1-\lambda)s^*] = s^*.$$

In this case, the equilibrium contract is a pooling contract ($a_{H,t} = 1$*) with face value* $D_t = s^*\phi_t$ *when*

$$\lambda\mathbb{E}_L \min(s^*, s) + (1-\lambda)\,s^* - \lambda\mathbb{E}_L s \geq 0.$$

Otherwise, the equilibrium contract is a separating contract ($a_{H,t} = 0$*) with face value* $D_t = \delta + \phi_t$*. The implied haircut is:*

$$h_t = \begin{cases} 0 & \text{if } \lambda\mathbb{E}_L \min(s^*, s) + (1-\lambda)\,s^* - \lambda\mathbb{E}_L s < 0, \\ 1 - \frac{s^*\phi_t}{\delta+\phi_t} & \text{if } \lambda\mathbb{E}_L \min(s^*, s) + (1-\lambda)\,s^* - \lambda\mathbb{E}_L s \geq 0. \end{cases}$$

If $\mathbb{E}_L s > 1 + \frac{1}{\lambda\widehat{z}} - \frac{1}{\lambda}$*, the equilibrium contract is a pooling contract with face value* $D = d^* + \phi$*, where*

$$d^* = \min\left\{\delta, \frac{\widehat{z}\,[\lambda E_L s + (1-\lambda)] - 1}{1 - \widehat{z}(1-\lambda)}\phi\right\}.$$

The implied haircut is

$$h_t = \max\left\{0, 1 - \frac{\widehat{z}\lambda E_L s}{1 - \widehat{z}(1-\lambda)}\frac{\phi_t}{\delta + \phi_t}\right\}.$$

Moreover, given any end-of-period price ϕ_t*, the asset price in the previous period and the lending volume are higher than those under the rigid DeFi contract.*

Note that the optimal haircut rule is not a fixed number or a simple linear rule but is non-linear in price ϕ_t. The proposition shows that a flexible contract generates a higher social surplus. For example, when ϕ_t is high (which makes the debt contract informationally less sensitive), the intermediary can increase D_t to induce a higher lending volume, which raises the surplus gained from lending. In contrast, when ϕ_t is low (which makes the contract informationally more sensitive), the intermediary may choose to lower D_t to maintain a pooling outcome. Depending on the parameter values, the intermediary may also choose to raise D_t to induce a separating equilibrium. This flexibility in adjusting D_t implies that, given any end-of-period price ϕ_t, the price of the asset in the previous period and the loan size are weakly greater than those under the rigid DeFi contract.

The following proposition shows that flexibility in setting the haircut optimally in response to changes in the asset price leads to a unique stationary equilibrium with a fixed realized equilibrium haircut.

Proposition 6. *Under a flexible optimal debt limit there exists a unique stationary equilibrium that Pareto dominates the equilibrium under DeFi.*

The above result suggests that the rigid haircut rule (1) imposed by the DeFi smart contract generates financial instability in the form of multiple equilibria and potentially sentiment-driven equilibria (e.g. Asriyan, Fuchs, and Green (2017)) while reducing welfare. Can a DeFi smart contract be preprogrammed to replicate the flexible contract design? This can be challenging to execute in practice. First, a flexible contract cannot be implemented using simple linear haircut rules that are typically encoded in DeFi contracts. Second, the optimal debt threshold depends on information that may not be readily available on the blockchain (e.g., z, λ). Alternatively, the lending protocol can replace the algorithm with a human risk manager who can adjust risk parameters in real time according to the latest information. Relying fully on a trusted third party, however, can be controversial for a DeFi protocol. Our results highlight the difficulty involved in achieving stability and efficiency in a decentralized environment that is subject to informational frictions.

6 Conclusion

In this paper, we study sources of fragility in DeFi lending caused by several of its fundamental features. These features are informational frictions, such as asymmetric information about collateral quality, oracle problems, and rigid contract terms. We demonstrate the inherent instability of DeFi lending that results from price–liquidity feedback exacerbated by informational frictions, leading to self-fulfilling sentiment-driven cycles. Stability requires flexible and state-contingent smart contracts. To achieve that end, a smart contract may take a complex form. Such a contract also requires a reliable oracle to feed real-time hard and soft information from the off-chain world. Alternatively, DeFi lending could abandon complete decentralization and re-introduce human intervention to provide real-time risk management—an arrangement that would force the protocol to rely on a trusted third party. Our finding highlights a trilemma faced by DeFi protocols: the difficulty involved in achieving simplicity in smart contracts and stability in asset prices while maintaining a high degree of decentralization.

References

Akerlof, George A (1970). "The Market for" Lemons": Quality Uncertainty and the Market Mechanism". *Quarterly Journal of Economics* 84.3, pp. 488–500.

Aoyagi, J. and Y. Itoy (2021). *Coexisting Exchange Platforms: Limit Order Books and Automated Market Makers.* URL: https://ssrn.com/abstract=3808755.

Aramonte, Sirio, Wenqian Huang, and Andreas Schrimpf (2021). "DeFi Risks and the Decentralisation Illusion". *BIS Quarterly Review*.

Aramonte, Sirio et al. (2022). "DeFi lending: intermediation without information?" *BIS Bulletin*.

Asriyan, Vladimir, William Fuchs, and Brett Green (2017). "Liquidity sentiments". *Working paper*.

Capponi, A. and R. Jia (2021). *Decentralized Stablecoins and Collateral Risk*. URL: arXiv:2103.08842.

Chiu, J., C. Kahn, and T. Koeppl (2022). *Grasping De(centralized) Fi(nance) through the Lens of Economic Theory*. URL: https://ssrn.com/abstract=4221027.

d'Avernas, A., T. Bourany, and Q. Vandeweyer (2021). *Are Stablecoins Stable?* URL: https://www.banque-france.fr/sites/default/files/media/2021/06/10/gdre_bounary.pdf.

Fostel, Ana and John Geanakoplos (2012). "Tranching, CDS, and asset prices: how financial innovation can cause bubbles and crashes". *American Economic Journal: Macroeconomics* 4.1, pp. 190–225. DOI: 10.1257/mac.4.1.190.

Geanakoplos, John (1997). "Promises, promises". *The economy as an evolving complex system II* 1997, pp. 285–320.

— (2003). "Liquidity, default, and crashes endogenous contracts in general". In: *Advances in economics and econometrics: theory and applications: eighth World Congress*. Vol. 170.

Geanakoplos, John and William Zame (2002). *Collateral and the enforcement of intertemporal contracts*. Yale University working paper.

Gudgeon, Lewis et al. (2020). "DeFi Protocols for Loanable Funds: Interest Rates, Liquidity and Market Efficiency". In: *Proceedings of the 2nd ACM Conference on Advances in Financial Technologies*. AFT '20. New York, NY, USA: Association for Computing Machinery, 92?112. ISBN: 9781450381390. DOI: 10.1145/3419614.3423254. URL: https://doi.org/10.1145/3419614.3423254.

Harvey, C.R. et al. (2021). *DeFi and the Future of Finance*. Wiley. ISBN: 9781119836018. URL: https://books.google.co.uk/books?id=CGM4EAAAQBAJ.

Kozhan, R. and G.F. Viswanath-Natraj (2021). *Decentralized Stablecoins and Collateral Risk*. WBS Finance Group Research Paper.

Lagos, Ricardo and Randall Wright (2005). "A unified framework for monetary theory and policy analysis". *Journal of Political Economy* 113.3, pp. 463–484.

Lehar, Alfred and Christine A. Parlour (2021). *Decentralized exchanges*. University of Calgary and University of California, Berkeley.

— (2022). *Systemic Fragility in Decentralized Markets*. University of Calgary and University of California, Berkeley.

Li, Ye and Simon Mayer (2021). *Money creation in decentralized finance: A dynamic model of stablecoin and crypto shadow banking*. CESifo Working Paper No. 9260.

Ozdenoren, Emre, Kathy Yuan, and Shengxing Zhang (2021). *Dynamic Asset-Backed Security Design*. London School of Economics.

Park, Andrea (2021). *The Conceptual Flaws of Constant Product Automated Market Making*. University of Toronto.

Perez, Daniel et al. (2021). "Liquidations: DeFi on a Knife-Edge". In: *Financial Cryptography and Data Security: 25th International Conference, FC 2021, Virtual Event, March 1?5, 2021, Revised Selected Papers, Part II*. Berlin, Heidelberg: Springer-Verlag, 457?476. ISBN: 978-3-662-64330-3. DOI: 10.1007/978-3-662-64331-0_24. URL: https://doi.org/10.1007/978-3-662-64331-0_24.

Qin, Kaihua et al. (2020). *Attacking the DeFi Ecosystem with Flash Loans for Fun and Profit*. DOI: 10.48550/ARXIV.2003.03810. URL: https://arxiv.org/abs/2003.03810.

Qin, Kaihua et al. (2021). "An empirical study of DeFi liquidations". In: *Proceedings of the 21st ACM Internet Measurement Conference*. ACM. DOI: 10.1145/3487552.3487811. URL: https://doi.org/10.1145%2F3487552.3487811.

Schar, Fabian (2021). "Decentralized finance: On blockchain-and smart contract-based financial markets.n". *FRB of St. Louis Review*.

Xu, Jiahua (2022). *Auto.gov: Optimal On-chain Governance for DeFi*. Tech. rep. UCL.

A Appendix

A.1 Proof of Proposition 1

Condition (2) implies that, in a pooling equilibrium, the high-type borrower is willing to borrow if and only if

$$zq^P \geq \mathbb{E}\min\{D, \delta + \phi\},$$

which is equivalent to

$$\mathbb{E}y_L(s_L, \phi)/\mathbb{E}y_H(\phi) \geq \zeta.$$

If $\mathbb{E}y_L(s_L, \phi)/\mathbb{E}y_H(\phi) > \zeta$, then it is optimal for the intermediary to set $R = R^P$. To see this, note that at this rate lenders provide loan q^P and, by assumption, the high-type borrower indeed chooses to borrow. This is clearly optimal because setting a higher rate reduces total lending and at a lower rate lenders do not break even. If $\mathbb{E}y_L(s_L, \phi)/\mathbb{E}y_H(\phi) < \zeta$, then the intermediary's problem is solved by setting $R = R^S$. In this case, if the intermediary lowers the rate sufficiently below R^P, then the high-type borrower will borrow. At that rate, however, lenders would earn negative profit.

$\mathbb{E}y_L(s_L,\phi)/\mathbb{E}y_H(\phi) = \mathbb{E}\min\{1, \frac{s_L\phi}{(\delta+\phi)(1-h)}\}$, so a higher ϕ or h will make it easier to satisfy the condition for the pooling outcome.

A.2 Proof of Proposition 2

First, we define functions

$$\hat{q}^S(\phi) = \frac{1}{1+f}\mathbb{E}\left[\min\{(1-h)(\phi+\delta), s_L\phi\}\right],$$
$$\hat{q}^P(\phi) = \frac{1}{1+f}\mathbb{E}\left[\lambda\min\{(1-h)(\phi+\delta), s_L\phi\} + (1-\lambda)(1-h)(\phi+\delta)\right].$$

Note that their difference is

$$\begin{aligned}&\hat{q}^P(\phi) - \hat{q}^S(\phi)\\ =&\frac{1-\lambda}{1+f}[(1-\lambda)(1-h)(\phi+\delta) - \mathbb{E}\min\{(1-\lambda)(1-h)(\phi+\delta), s_L\phi\}]\\ \geq&0,\end{aligned}$$

and $0 < \hat{q}^{S\prime}(\phi) < \hat{q}^{P\prime}(\phi) < 1$. Similarly, we define functions

$$\hat{\phi}^P(\phi) = \beta\left[(z-1-f)\hat{q}^P(\phi)\right] + \beta(1-\lambda)\delta + \beta(\lambda\mathbb{E}(s_L) + (1-\lambda))\phi,$$

$$\hat{\phi}^S(\phi) = \beta\lambda(z-1-f)\hat{q}^S(\phi) + \beta(1-\lambda)\delta + \beta(\lambda\mathbb{E}(s_L) + (1-\lambda))\phi,$$

which have the following properties,

$$\hat{\phi}^P(0) = \beta(1-\lambda)\delta + \beta\frac{(z-1-f)(1-\lambda)(1-h)\delta}{1+f} > \beta(1-\lambda)\delta = \hat{\phi}^S(0),$$
$$\hat{\phi}^{P\prime}(\phi) > \hat{\phi}^{S\prime}(\phi) > 0,$$
$$\hat{\phi}^{P\prime}(\phi) = \beta\left[(z-1-f)\hat{q}^{P\prime}(\phi)\right] + \beta(\lambda\mathbb{E}(s_L) + (1-\lambda)) < 1,$$
$$\hat{\phi}^{S\prime}(\phi) = \beta\lambda(z-1-f)\hat{q}^{S\prime}(\phi) + \beta(\lambda\mathbb{E}(s_L) + (1-\lambda)) < 1,$$

and the difference between the two functions is

$$\begin{aligned}&\hat{\phi}^P(\phi) - \hat{\phi}^S(\phi)\\ =&\beta(1-\lambda)(z-1-f)\hat{q}^P(\phi) + \beta\lambda(z-1-f)(\hat{q}^P(\phi) - \hat{q}^S(\phi)) > 0.\end{aligned}$$

The above properties imply that both functions have a unique fixed point and that $\phi^P > \phi^S$.

A.3 Proof of Proposition 3

Separating equilibrium

Consider first a separating equilibrium where a borrower chooses $a_L = 1$ and $a_H = 0$:

Debt limit:

$$D^S = \left(\delta + \phi^S\right)(1 - h)$$

Loan size:

$$\ell_L = q^S = \mathbb{E}\left[\min\{D^S, s\phi^S\}\right]$$

Asset price:

$$\phi^S = \beta\left(\lambda\left[zq^S - \mathbb{E}\min\{D^S, s\phi^S\}\right] + (1-\lambda)\delta + (\lambda\mathbb{E}(s) + (1-\lambda))\phi^S\right)$$

Existence of separating equilibrium:

$$\frac{E_L y}{E_H y} = \frac{\mathbb{E}\min\{D^S, s\phi^S\}}{(\delta + \phi^S)(1-h)} < \zeta$$

We now look at the limiting case as $h \to 0$:

Debt limit:

$$D^S = \left(\delta + \phi^S\right)$$

Loan size:

$$q^S = \mathbb{E}(s)\phi^S$$

Asset price:

$$\phi^S = \frac{\beta(1-\lambda)\delta}{1 - \beta[\lambda z\mathbb{E}(s) + (1-\lambda)]}$$

Existence of separating equilibrium:

$$\frac{E_L y}{E_H y} = \frac{\mathbb{E}\min\{D^S, s\phi^S\}}{(\delta + \phi^S)(1-h)} = \frac{\mathbb{E}(s)\phi^S}{(\delta + \phi^S)} < \zeta$$

Hence, a separating equilibrium exists when

$$\mathbb{E}(s) < \frac{\zeta}{\beta[(1-\lambda) + \zeta\lambda z]} \equiv \kappa_S.$$

Pooling equilibrium

We now consider a pooling equilibrium where $a_L = 1$ and $a_H = 1$:

Debt limit:

$$D^P = \left(\delta + \phi^P\right)(1 - h)$$

Loan size:

$$\ell_L = \ell_H = q^P = \lambda \mathbb{E}\left[\min\{D^P, s\phi^P\}\right] + (1 - \lambda)D^P$$

Asset price:

$$\begin{aligned}\phi^P = &\beta\left[zq^P - \lambda \mathbb{E}\min\{D^P, s\phi^P\} - (1 - \lambda)D^P\right] \\ &+ \beta(1 - \lambda)\delta + \beta(\lambda \mathbb{E}(s) + (1 - \lambda))\phi^P\end{aligned}$$

Existence of pooling equilibrium:

$$\frac{E_L y}{E_H y} = \frac{\mathbb{E}\min\{D^P, s\phi^P\}}{(\delta + \phi^P)(1 - h)} > \zeta$$

As $h \to 0$, we have

Debt limit:

$$D^P = \left(\delta + \phi^P\right)$$

Loan size:

$$\ell_L = \ell_H = q^P = \lambda \mathbb{E}(s)\phi^P + (1 - \lambda)(\delta + \phi^P)$$

Asset price:

$$\phi^P = \frac{\beta z(1 - \lambda)\delta}{1 - \beta z[\lambda \mathbb{E}(s) + (1 - \lambda)]}$$

Existence of pooling equilibrium:

$$\frac{E_L y}{E_H y} = \frac{\mathbb{E}\min\{D^S, s\phi^S\}}{(\delta + \phi^S)(1 - h)} = \frac{\mathbb{E}(s)\phi^P}{(\delta + \phi^P)} > \zeta$$

Hence a pooling equilibrium exists when

$$\mathbb{E}(s) > \frac{\zeta}{\beta z[(1 - \lambda) + \zeta\lambda]} \equiv \kappa_P < \kappa_S$$

Therefore, when $\mathbb{E}(s) \in (\kappa_P, \kappa_S)$, there are multiple equilibria in the neighborhood of $h = 0$.

A.4 Two-point Distribution Example

A.4.1 Separating Equilibrium

Suppose that $s_L = 1$ w.p. π, and $s_L = 0$ w.p. $1 - \pi$.

In a separating equilibrium:

Debt limit:

$$D^S = \left(\delta + \phi^S\right)(1 - h)$$

Loan size:

$$\ell_L = q^S = \mathbb{E}\left[\min\{D^S, s\phi^S\}\right] = \pi \min\{D^S, \phi^S\}$$

There are two cases.

Case (i) $D^S > \phi^S$

This is true when

$$\delta \frac{1-h}{h} > \phi^S.$$

We then have

$$q^S = \pi\phi^S,$$
$$\phi^S = \frac{\beta(1-\lambda)\delta}{1 - \beta[\lambda z\pi + (1-\lambda)]}.$$

The existence of a separating equilibrium requires

$$\zeta^S(h) = \frac{\pi\phi^S}{(\delta + \phi^S)(1-h)} < \zeta.$$

We define a threshold

$$\underline{h}^S \equiv \frac{\delta}{\phi^S + \delta} = \frac{1 - \beta[\lambda z\pi + (1-\lambda)]}{1 - \beta\lambda z\pi}.$$

When the haircut is lower than the threshold $\underline{h}$, the low-type borrowers default even when $s_L = 1$. In this case, the loan size is equal to the expected value of the asset, $\pi\phi^S$, which does not depend on the haircut. Hence, the asset price is also independent of h. An increase in h, however, makes it harder to support a separating equilibrium as the contract becomes less informationally sensitive.

Case (ii) $D^S < \phi^S$

This is true when

$$\delta \frac{1-h}{h} < \phi^S.$$

We then have

$$q^S = \pi(\delta + \phi^S)(1-h)$$
$$\phi^S = \frac{\beta(\lambda(z-1)\pi(1-h) + (1-\lambda))\delta}{1-\beta[\lambda(z-1)\pi(1-h) + (1-\lambda) + \lambda\pi]}.$$

The existence of a separating equilibrium requires

$$\zeta^S(h) = \pi < \zeta.$$

When the haircut is higher than the threshold $\underline{h}$, the low-type borrower pays back the loan to retain the collateral when $s_L = 1$. In this case, the loan size is equal to the πD. Hence, the asset price is decreasing in h. A separating equilibrium exists whenever $\pi < \zeta$. as h does not affect the information sensitivity of the contract.

A.4.2 Pooling Equilibrium

In a pooling equilibrium:

Debt limit:

$$D^P = \left(\delta + \phi^P\right)(1-h)$$

Loan size:

$$q^P = \lambda\mathbb{E}\left[\min\{D^P, s\phi^P\}\right] + (1-\lambda)D^P = \lambda\pi\min\{D^P, \phi^P\} + (1-\lambda)D^P$$

There are two cases.

Case (i) $D^P > \phi^P$

This is true when

$$\delta\frac{1-h}{h} > \phi^P.$$

We then have

$$q^P = \lambda\pi\phi^P + (1-\lambda)D^P$$
$$\phi^P = \frac{\beta(1-\lambda)\delta[(z-1)(1-h)+1]}{1-\beta[\lambda(z-1)\pi + (z-1)(1-\lambda)(1-h) + \lambda\pi + 1 - \lambda]}$$

The existence of a separating equilibrium requires

$$\zeta^P(h) = \frac{\pi\phi^P}{(\delta + \phi^P)(1-h)} > \zeta.$$

We can again define a threshold

$$\underline{h}^P \equiv \frac{1-\beta[\lambda(z-1)\pi+(z-1)(1-\lambda)+\lambda\pi+1-\lambda]}{1-z\beta\lambda\pi-\beta(z-1)(1-\lambda)} < \underline{h}^S,$$

such that this case holds when $h < \underline{h}^P$.

Case (ii) $D^P < \phi^P$

This is true when

$$\delta\frac{1-h}{h} < \phi^P.$$

We then have

$$q^P = \lambda\pi D^P + (1-\lambda)D^P$$
$$\phi^P = \beta\delta\frac{(z-1)(\lambda\pi+1-\lambda)(1-h)+(1-\lambda)}{1-\beta[(z-1)(\lambda\pi+1-\lambda)(1-h)+\lambda\pi+1-\lambda]}$$

The existence of a pooling equilibrium requires

$$\zeta^P(h) = \pi > \zeta.$$

A.5 Proof of Uniqueness Under a Flexible Smart Contract

Denote the debt contract as $y(D, \widetilde{\delta}+\widetilde{s}\phi) = \min(D, \widetilde{\delta}+\widetilde{s}\phi)$. We prove the result for the main model where

$$\mathbb{E}_H y(D, \widetilde{\delta}+\widetilde{s}\phi) = y(D, \delta+\phi);$$

and

$$\mathbb{E}_L y(D, \widetilde{\delta}+\widetilde{s}\phi) = \int_{\underline{s}}^{\bar{s}} y(D, s\phi)dF(s).$$

The arguments, however, generalize to the more general case with modifications.

Denote $D^* \leq \delta+\phi$, the maximum face value, such that the incentive constraint of the high type borrower is satisfied, as

$$\widehat{z}\left[\lambda\mathbb{E}_L y(D, \widetilde{\delta}+\widetilde{s}\phi) + (1-\lambda)\mathbb{E}_H y(D, \widetilde{\delta}+\widetilde{s}\phi)\right] \geq \mathbb{E}_H y(D, \widetilde{\delta}+\widetilde{s}\phi),$$

in which case there is a pooling equilibrium.

When the intermediary designs the smart deposit contract flexibly, it aims to maximize the expected trading volume. Specifically, the intermediary chooses D, or equivalently a haircut, to maximize expected trade volume $[\lambda\mathbb{E}_L + a_{H,t}(1-\lambda)\mathbb{E}_H]\min(D, \widetilde{\delta}+\widetilde{s}\phi)$, taking ϕ as given. Note that the intermediary's payoff is increasing in D as long as the equilibrium does not switch from pooling to separating. Hence, if the intermediary chooses a contract that leads to a pooling outcome, then $D = D^*$, and if the intermediary chooses a contract that leads to a separating outcome, then $D = \delta + \phi$.

Next we look at the two cases:

Pooling case:

If $D < \phi$, we can denote $\hat{s} = D/\phi$. In this case, all terms in the incentive constraint for the high-type borrower are proportional to the asset price ϕ, which drops out of the constraint. So, the high-type borrower's incentive constraint is satisfied iff

$$\widehat{z}\left[\lambda \mathbb{E}_L \min(\hat{s}, s) + (1-\lambda)\hat{s}\right] \geq \hat{s}$$

Let $\mathcal{F}(\hat{s}) \equiv \widehat{z}\left[\lambda \mathbb{E}_L \min(\hat{s}, s) + (1-\lambda)\hat{s}\right] - \hat{s}$ and note that the high-type borrower's incentive constraint is satisfied iff $\mathcal{F}(\hat{s}) \geq 0$. $\mathcal{F}(\hat{s})$ has the following properties:

$$\mathcal{F}(0) \geq 0$$
$$\mathcal{F}'(0) = \widehat{z} - 1 > 0$$
$$\mathcal{F}''(\hat{s}) = -\widehat{z}\lambda f(\hat{s}) < 0$$

So, $\mathcal{F}(\hat{s})$ is concave and strictly positive when $\hat{s}$ is close to 0. Suppose that the information friction is severe enough so that $\mathcal{F}(1) = \widehat{z}(\lambda \mathbb{E}_L s + (1-\lambda)) - 1 < 0$, or equivalently $\mathbb{E}_L s < \frac{1-(1-\lambda)\widehat{z}}{\lambda \widehat{z}} = 1 + \frac{1}{\lambda \widehat{z}} - \frac{1}{\lambda} < 1$. In this case, there exists a unique threshold $0 < s^* < 1$ such that $\mathcal{F}(s^*) = 0$. Because the asset price ϕ drops out, threshold s^* does not depend on ϕ.

Taking the next period asset price ϕ as given, the asset price in the current period under a pooling equilibrium is

$$\phi^P(\phi) = \beta\left[(\widehat{z} - 1)\left(\lambda \mathbb{E}_L \min(s^*, s) + (1-\lambda)\, s^*\right)\phi + \lambda \phi \mathbb{E}_L s + (1-\lambda)(\delta + \phi)\right] \tag{A.1}$$

which has the following property

$$\frac{\partial \phi^P(\phi)}{\partial \phi} = \beta\left[(\widehat{z} - 1)\left(\lambda \mathbb{E}_L \min(s^*, s) + (1-\lambda)\, s^*\right) + \lambda \mathbb{E}_L s + (1-\lambda)\right] < 1$$
$$\phi^P(0) = \beta(1-\lambda)\delta.$$

So, $\phi^P(\phi)$ is a straight line with slope $\frac{\partial \phi^P(\phi)}{\partial \phi}$ and intercept $\phi^P(0) = \beta(1-\lambda)\delta$. Hence there is a unique steady-state price that satisfies $\phi^P(\phi) = \phi$.

Suppose that information friction is too severe so that $\mathcal{F}(1) > 0$, or equivalently, $1 > \mathbb{E}_L s > 1 + \frac{1}{\lambda \widehat{z}} - \frac{1}{\lambda}$. In this case, the face value of the debt is $D^* \geq \phi$. Let $d^*(\phi) = D^* - \phi$. There are two possibilities:

either the high-type borrower's incentive constraint is binding and there is $d^*(\phi) \leq \delta$ that satisfies

$$\widehat{z}\left[\lambda\phi\mathbb{E}_L s + (1-\lambda)(d^*(\phi)+\phi)\right] = d^*(\phi)+\phi,$$

or the high-type borrower's incentive constraint is slack for all D. In the former case

$$d^*(\phi) = \frac{\widehat{z}\left[\lambda\mathbb{E}_L s + (1-\lambda)\right]-1}{1-\widehat{z}(1-\lambda)}\phi.$$

In the latter case $d^*(\phi) = \delta$. If $\frac{\widehat{z}[\lambda\mathbb{E}_L s+(1-\lambda)]-1}{1-\widehat{z}(1-\lambda)}\phi < \delta$,

$$\phi^P(\phi) = \beta\left[\frac{\lambda\widehat{z}}{1-\widehat{z}(1-\lambda)}\lambda\mathbb{E}_L s\phi + (1-\lambda)(\delta+\phi)\right]. \tag{A.2}$$

Note that

$$\phi^P(0) = \beta(1-\lambda)\delta,$$
$$\frac{\partial\phi^P(\phi)}{\partial\phi} = \beta\left(\frac{\lambda\widehat{z}}{1-\widehat{z}(1-\lambda)}\lambda\mathbb{E}_L s + 1-\lambda\right).$$

Hence $\phi^P(\phi)$ is a straight line with slope $\frac{\partial\phi^P(\phi)}{\partial\phi}$ and intercept $\phi^P(0)$.

If $\frac{\widehat{z}[\lambda\mathbb{E}_L s+(1-\lambda)]}{1-\widehat{z}(1-\lambda)}\phi > \delta$,

$$\begin{aligned}\phi^P(\phi) &= \beta\widehat{z}\left[\lambda\mathbb{E}_L s\phi + (1-\lambda)(\delta+\phi)\right] \\ &= \beta\widehat{z}\left[(1-\lambda)\delta + (\lambda\mathbb{E}_L s + 1-\lambda)\phi\right].\end{aligned}$$

Note that

$$\phi^P(0) = \beta\widehat{z}(1-\lambda)\delta,$$
$$\frac{\partial\phi^P(\phi)}{\partial\phi} = \beta\widehat{z}(\lambda\mathbb{E}_L s + 1-\lambda) < 1.$$

By comparing the slopes of $\phi^P(\phi)$ when $\frac{\widehat{z}[\lambda\mathbb{E}_L s+(1-\lambda)]}{1-\widehat{z}(1-\lambda)}\phi$ is below and above δ, we can see that $\phi^P(\phi)$ is concave with a slope of less than 1 when $\frac{\widehat{z}[\lambda\mathbb{E}_L s+(1-\lambda)]}{1-\widehat{z}(1-\lambda)}\phi > \delta$.

Note that, when $D^* \geq \phi$ in a pooling equilibrium or $\mathbb{E}_L s > 1 + \frac{1}{\lambda\widehat{z}} - \frac{1}{\lambda}$, the value of a pooling contract is always greater than that of a separating contract. This is because the intermediary designs the contract optimally to maximize the expected trade volume. The expected value of a loan to a low-type borrower is the same in a separating equilibrium and a pooling equilibrium when $D^* \geq \phi$. So the intermediary strictly prefers designing a pooling contract, as the revenue from the pooling contract strictly dominates that of a separating contract.

Hence, when $\mathbb{E}_L s > 1 + \frac{1}{\lambda\widehat{z}} - \frac{1}{\lambda}$, we can focus on the pooling equilibrium. From the analysis above, we know that $\phi^P(\phi)$ is concave with a slope of less than 1 when $\frac{\widehat{z}[\lambda\mathbb{E}_L s+(1-\lambda)]}{1-\widehat{z}(1-\lambda)}\phi > \delta$. Hence, in this part of the parameter space there exists a unique equilibrium where the loan is traded in a pooling equilibrium.

Separating case:

As argued above, when analyzing the optimal contract in a separating equilibrium, we can focus on the parameter space where

$$E_L s < 1 + \frac{1}{\lambda \widehat{z}} - \frac{1}{\lambda}. \tag{A.3}$$

If the optimal contract supports a separating equilibrium, the intermediary would set $D = \delta + \phi$ to maximize the loan size to the low-type borrower. In the special parameterization of the model, any face value between ϕ and $\delta + \phi$ generates the same revenue from borrowing because a low-quality asset pays no dividend. More generally, low-quality assets could pay positive dividends. So the maximum face value $D = \delta + \phi$ is a more robust form of debt design in the separating case.

Given face value $D = \delta + \phi$, the incentive constraint for the high-type borrower not to borrow is

$$\delta + \phi \geq \widehat{z} \mathbb{E}_L s \phi \tag{A.4}$$

Note that condition (A.3) implies that

$$\widehat{z} \mathbb{E}_L s < 1 + (\widehat{z} - 1)\,(1 - \frac{1}{\lambda}) < 1.$$

The condition for the existence of a separating equilibrium,(A.4), always holds.

In a separating equilibrium, the asset price is

$$\phi^S(\phi) = \beta\left[(\widehat{z} - 1)\lambda \mathbb{E}_L s \phi + \lambda \mathbb{E}_L s \phi + (1 - \lambda)(\delta + \phi)\right], \tag{A.5}$$

which has the following property:

$$\phi^S(0) = \beta(1 - \lambda)\delta$$

$$\frac{\partial \phi^S(\phi)}{\partial \phi} = \beta\left(\widehat{z} \lambda \mathbb{E}_L s + 1 - \lambda\right).$$

So, in this case, $\phi^S(\phi)$ is a straight line with slope $\frac{\partial \phi^S(\phi)}{\partial \phi}$ and intercept $\phi^S(0) = \beta(1 - \lambda)\delta$.

The intermediary chooses the pooling contract if and only if

$$\left[\lambda \mathbb{E}_L + (1 - \lambda)\, \mathbb{E}_H\right] y(D, \widetilde{\delta} + \widetilde{s} \phi^P) \geq \lambda \mathbb{E}_L y(D, \widetilde{\delta} + \widetilde{s} \phi^S)$$

or

$$\left[\lambda \mathbb{E}_L \min(s^*, s) + (1 - \lambda)\, s^*\right] \phi^P \geq \phi^S \lambda \mathbb{E}_L s,$$

where s^* is the unique solution to

$$\widehat{z}\left[\lambda \mathbb{E}_L \min(s^*, s) + (1 - \lambda) s^*\right] = s^*.$$

Plugging in for ϕ^P and ϕ^S, we can rewrite the inequality as

$$\frac{[\lambda \mathbb{E}_L \min(s^*, s) + (1-\lambda)\, s^*]}{1-\beta\left[(\widehat{z}-1)\left(\lambda \mathbb{E}_L \min(s^*, s) + (1-\lambda)\, s^*\right) + \lambda \mathbb{E}_L s + (1-\lambda)\right]} \geq \frac{\lambda \mathbb{E}_L s}{1-\beta\left[(\widehat{z}-1)\lambda \mathbb{E}_L s + \lambda \mathbb{E}_L s + (1-\lambda)\right]}$$

which holds iff

$$\lambda \mathbb{E}_L \min(s^*, s) + (1-\lambda)\, s^* - \lambda \mathbb{E}_L s \geq 0. \tag{A.6}$$

In either case, the equilibrium is unique.

To summarize the equilibrium characterization, when $\mathbb{E}_L s < 1 + \frac{1}{\lambda \widehat{z}} - \frac{1}{\lambda}$, the equilibrium contract is a pooling one with face value $D = s^* \phi < \phi$ when condition (A.6) holds. Otherwise, the equilibrium contract is a separating one with face value $D = \delta + \phi$.

When $\mathbb{E}_L s > 1 + \frac{1}{\lambda \widehat{z}} - \frac{1}{\lambda}$, the equilibrium contract is a pooling one with face value $D = d^* + \phi$ where

$$d^* = \min\left\{\delta, \frac{\widehat{z}\left[\lambda E_L s + (1-\lambda)\right] - 1}{1 - \widehat{z}(1-\lambda)} \phi\right\}.$$

A.6 An Alternative Setup with Unobservable Private Valuation

We briefly consider an alternative setup where the private information is related to borrowers' private valuations of the asset instead of to the asset's common value. We show that the main results hold.

Suppose that, with probability $1-\varepsilon$, the state is good ($s = 1$) and the asset pays dividend δ. With probability ε, the state is bad ($s = 0$) and the asset pays no dividends. In addition, the borrower has unobservable private valuation. A type-$i = H, L$ borrower, if holding an asset, receives a private value $v_i(s)$ before the asset market opens and after the loan is settled. The type-i borrower is determined before the loan is made and the information is private. With probability λ, the borrower is of type $i = L$ and the private valuation is $v_L(1) = v$ in the good state and $v_L(0) = 0$ in the bad state. With probability $1-\lambda$, the borrower's type is $i = H$ and the private valuation is $v_H(1) = v_H(0) = v$. After observing the private information, the borrower borrows from the platform. After observing the realization of δ, the borrower decides whether to repay or default. After the loan is settled, the borrower, if holding the asset, receives the private valuation. At the end of the period, the asset is traded at $\delta+\phi$ in the good state and at ϕ in the bad state.

The debt limit is given by $D = (\delta + \phi)(1-h)$. We assume that $v > \delta$. As a result, all borrowers repay in the good state. A low-type borrower defaults in the bad state when $D > \phi$. Our analysis will focus on the case of $D \geq \phi$, as it is suboptimal to set $D < \phi$.

In the separating equilibrium, the loan size is

$$q^S = D^S - \varepsilon(D^S - \phi^S)$$

and the asset price is

$$\phi^S = \beta \frac{\lambda(z-1)(1-h)(1-\varepsilon)\delta + (1-\varepsilon)\delta + (1-\varepsilon\lambda)v}{1-\beta-\beta\lambda(z-1)(1-h(1-\varepsilon))}.$$

The separating equilibrium exists when

$$\frac{(1-\varepsilon)D^S + \varepsilon\phi^S}{D^S} < \zeta.$$

In the pooling equilibrium, the loan size is

$$q^P = D^P + \lambda\varepsilon(\phi^P - D^P)$$

and the asset price is

$$\phi^P = \beta \frac{(z-1)\delta(1-h)(1-\varepsilon\lambda) + \beta(1-\varepsilon)\delta + \beta(1-\varepsilon\lambda)v}{1-\beta-\beta(z-1)(1-h(1-\varepsilon\lambda))}.$$

The pooling equilibrium exists when

$$\frac{(1-\varepsilon)D^P + \varepsilon\phi^P}{D^P} > \zeta.$$

Hence we can reproduce the main multiplicity result.

Proposition 7. *For h that is not too large, $\phi^P > \phi^S$ and multiplicity exists when*

$$1 - \frac{\varepsilon\delta}{\delta + \phi^P} > \zeta > 1 - \frac{\varepsilon\delta}{\delta + \phi^S}.$$

A.7 Private Information Parameter $\chi < 1$

We have considered the case where there is private information in each period. We now introduce a parameter, χ, to control the degree of information imperfection. With probability $1-\chi$, there is no private information in the sense that there are no low-quality assets (denoted by state 0). All the equilibrium conditions remain the same except that the asset prices satisfy

$$\begin{aligned}
\phi_t = \beta\chi \Big\{ \lambda \Big[\int_{\underline{s}}^{\bar{s}} (z\ell_{L,t+1} - \min\{\ell_{L,t+1}R_{t+1}, a_{L,t+1}s_L\phi_{t+1})\} + s_L\phi_{t+1})\, dF(s_L) \Big] \\
+\chi(1-\lambda)\left[z\ell_{H,t+1} - \min\{\ell_{H,t+1}R_{t+1}, a_{H,t+1}(\delta+\phi_{t+1})\} + \delta + \phi_{t+1}\right]\Big\} \\
+\beta(1-\chi)\left[z\ell^0_{t+1} - \min\{\ell^0_{t+1}R^0_{t+1}, a^0_{t+1}(\delta+\phi_{t+1})\} + \delta + \phi_{t+1}\right],
\end{aligned}$$

where $a^0 = 1$, $\ell_t^0 = q_t^0 = \frac{1}{1+f}(\delta + \phi_t)(1-h)$ and $R_t^0 = (\delta + \phi_t)(1-h)/q_t^0$. By continuity, all results hold when χ is sufficiently close to 1.

B Additional Details Regarding the Aave Lending Protocol

According to DeFiLlama, there were 1,485 DeFi protocols running on distinct blockchains (e.g., Ethereum, Terra, BSC, Avalanche, Fantom, Solana) as of April 2022. The TVL of these protocols are 237 billion USD with lending protocols accounting for about 20%. (Figure 8).[22] In Table 1 we report basic statistics for the three main lending protocols: Compound, which operates on Ethereum; Venus, which operates on the BSC; and Aave, which operates on multiple chains. Operating on multiple blockchains, Aave is the largest among the three in terms of TVL, deposits and borrows, and the market capitalization of its governance tokens. Below, we provide a brief overview of key features of the Aave lending protocol.

Table 1: Major Decentralized Lending Platforms (April 17, 2022)

	Aave	**Compound**	**Venus**
Total value locked (USD)	13.35 B	6.35 B	1.51 B
Blockchain	Multi	Ethereum	BSC
Total deposits (USD)	15.37 B	9.51 B	1.51 B
Total borrows (USD)	5.93 B	3.21 B	0.82 B
Governance Token	AAVE	COMP	XVS
Market Cap (USD)	2.38 B	0.99 B	0.13 B

Data Source: DefiLlamma; Aavewatch; Compound.finance; Venus.io; Glassnode.

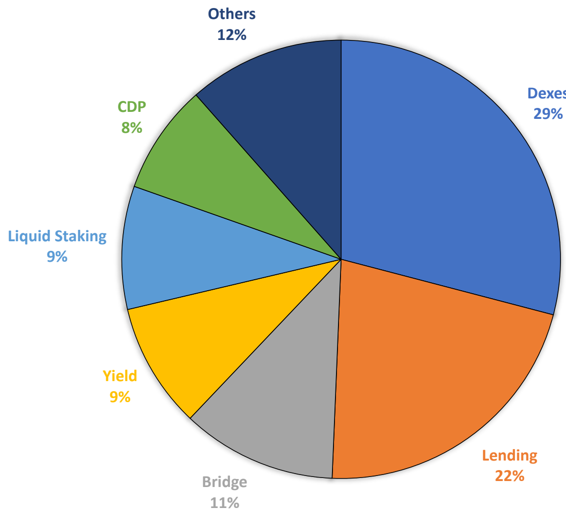
B.1 Tokens

Aave issues two types of tokens: (i) aTokens, which are issued to lenders so they can collect interest on deposits, and (ii) AAVE tokens, which are Aave's native tokens.[23] **aTokens** are interest-bearing tokens that are minted upon deposit and burned at withdrawal. An aToken's value is pegged to the value of the corresponding deposited asset at a 1:1 ratio; it can be safely stored, transferred, or traded. Withdrawals

[22] Collateralized debt positions (CDPs), e.g., MakerDAO, account for 8% of the TVL. Both lending and CDP protocols support collateralized lending. The key difference is that a lending protocol lends out assets deposited by lenders while a CDP lends out assets (e.g., stablecoins) minted by the protocol.

[23] aTokens can be interpeted as bank deposits and AAVE tokens can be interpreted as bank equity shares.

Figure 8: Composition of TVL of all DeFi Protocols on all Chains (April 2022)



Data Sources: DefiLlamma.

of the deposited assets burn the aTokens. **AAVE tokens** are used to vote and influence the governance of the protocol. AAVE holders can also lock (known as "staking") the tokens to provide insurance to the protocol/depositors and earn staking rewards and fees from the protocol (additional details below).

B.2 Deposits and loans

By depositing a certain amount of an asset into the protocol, a **depositor** mints and receives the same amount in corresponding aTokens. All interest earned by these aTokens are distributed directly to the depositor.

Borrowers can borrow these funds with collateral backing the borrowing position. A borrower repays the loan in the borrowed asset. There is no fixed time period within which to pay back the loan. Partial or full repayments can be made at any time. As long as the position is safe, the loan can continue for an undefined period. As time passes, though, the accrued interest on an unpaid loan will grow, as a result of which it is more likely that the deposited assets will be liquidated.

Every borrowing position can be opened with a stable or variable rate. The **loan rate** follows the model

$$Rate = \begin{cases} R_0 + \frac{U}{U_{optimal}} R_{slope1} & \text{, if } U \leq U_{optimal} \\ R_0 + R_{slope1} + \frac{U - U_{optimal}}{1 - U_{optimal}} R_{slope2} & \text{, if } U > U_{optimal}, \end{cases}$$

where $U = Total\ Borrows/Total\ Liquidity$ is the share of the liquidity borrowed.[24]

The **variable rate** is the rate based on current supply and demand in Aave. **Stable rates** act as a fixed rate.[25] The current model parameters for stable and variable interest rates are given in Figure 9. Figure 10 shows Dai's rate schedule as an example.

Figure 9: Current Rate Parameters

		Variable Rate			Stable Rate Rebalance if U > 95% + Average APY < 25%		
	Uoptimal	Base	Slope 1	Slope 2	Average Market Rate	Slope 1	Slope 2
BUSD	80%	0%	4%	100%			
DAI	80%	0%	4%	75%	4%	2%	75%
sUSD	80%	0%	4%	100%			
TUSD	80%	0%	4%	75%	4%	2%	75%
USDC	90%	0%	4%	60%	4%	2%	60%
USDT	90%	0%	4%	60%	4%	2%	60%
AAVE							
BAT	45%	0%	7%	300%	3%	10%	300%
ENJ	45%	0%	7%	300%			
ETH	65%	0%	8%	100%	3%	10%	100%
KNC	65%	0%	8%	300%	3%	10%	300%
LINK	45%	0%	7%	300%	3%	10%	300%
MANA	45%	0%	8%	300%	3%	10%	300%
MKR	45%	0%	7%	300%	3%	10%	300%
REN	45%	0%	7%	300%			
SNX	80%	3%	12%	100%			
UNI	45%	0%	7%	300%			
WBTC	65%	0%	8%	100%	3%	10%	100%
YFI	45%	0%	7%	300%			
ZRX	45%	0%	7%	300%	3%	10%	300%

Table Source: Aave.com

The **deposit rate** is given by

$$\text{Deposit Rate}_t = U_t(SB_t \times S_t + VB_t \times V_t)(1 - R_t,$$

[24]Total "liquidity" refers to the total deposits of a loanable asset.

[25]The stable rate for new loans varies over time. Once a stable loan is taken out, however, borrowers will not experience interest-rate volatility. There is one caveat, though: if the protocol is in dire need of liquidity, then some stable rate loans might undergo a procedure called rebalancing. In particular, rebalancing will occur if the average borrowing rate is lower than 25% APY and the utilization rate is above 95%.

Figure 10: Stable vs Variable Rates for Dai

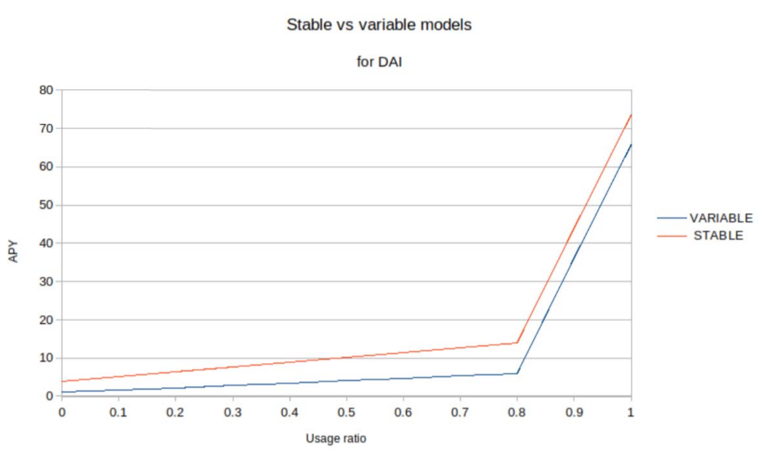


Figure Source: Aave.com

where SB_t is the share of stable loans, S_t is average stable rate, VB_t is the share of variable loans, V_t is the average variable rate, and R_t is the reserve factor (a fraction of interests allocated to mitigate shortfall events discussed below). The **Loan-to-Value** (LTV) ratio defines the maximum amount that can be borrowed with specific collateral and is expressed in percentages: at $LTV = 75\%$, for every 1 ETH's worth of collateral, borrowers will be able to borrow 0.75 ETHs' worth of the corresponding currency in which the loan is denominated. The current risk parameters are given in Figure 11.

B.3 Collateral and Liquidation

The **liquidation threshold** (LQ) is the percentage at which a loan is defined as undercollateralized. For example, a LQ of 80% means that, if the value rises above 80% of the collateral, the loan is undercollateralised and could be liquidated. The LQ of a borrower's position is the weighted average of those of the collateral assets:

$$LQ = \frac{\sum_i \text{Collateral i in ETH} * LQ_i}{\text{Total Borrows in ETH}}.$$

The difference between the LTV and the LQ is a safety cushion for borrowers. The values of assets are based on **price feeds** provided by Chainlink's decentralized oracles. The LQ is also called the **health factor** *(Hf)*. When $Hf < 1$, a loan is considered undercollateralized and can be liquidated. When the health factor of a position is below 1, **liquidators** repay part or all of the outstanding borrowed amount on behalf of the borrower while receiving an equivalent amount of collateral in return plus a

Figure 11: Current Risk Parameters

	LTV	Liquidation Threshold	Liquidation Bonus	Overall Risks	Reserve Factor
BUSD				B	10%
DAI	75%	80%	5%	B	10%
sUSD				C+	20%
TUSD	75%	80%	5%	B	10%
USDC	80%	85%	5%	B+	10%
USDT				B+	10%
AAVE	50%	65%	10%	C+	
BAT	70%	75%	10%	B+	20%
ENJ	55%	60%	10%	B+	20%
ETH	80%	82.5%	5%	A+	10%
KNC	60%	65%	10%	B+	20%
LINK	70%	75%	10%	B+	20%
MANA	60%	65%	10%	B-	35%
MKR	60%	65%	10%	B-	20%
REN	55%	60%	10%	B	20%
SNX	15%	40%	10%	C+	35%
UNI	60%	65%	10%	B	20%
WBTC	70%	75%	10%	B-	20%
YFI	40%	55%	15%	B-	20%
ZRX	60%	65%	10%	B+	20%

Table Source: Aave.com

liquidation "bonus" (see Figure 11).[26] When the liquidation is completed successfully, the health factor of the position rises, bringing the health factor above 1.

B.4 Infrequent Updates of Risk Parameters in Smart Contracts

B.5 Shortfall Events

The primary mechanism for securing the Aave Protocol is the incentivization of AAVE holders (stakers) to lock tokens into Smart Contract–based components called **Safety Modules** (SMs). The locked AAVE will be used as a mitigation tool in case of a Shortfall Event (i.e., when there is a deficit). If a Shortfall Event occurs, a portion of the locked AAVE are auctioned on the market to be sold against the assets needed to mitigate the incurred deficit. To contribute to the safety of the protocol and receive incentives, AAVE holders will deposit their tokens into the SM. In return, they receive rewards (periodic issuance of AAVE known as Safety Incentives (SIs)) and fees generated from the protocol (see the reserve factor

[26]Example: Bob deposits 5 ETHs' and 4 ETHs' worth of YFI, and borrows 5 ETHs' worth of DAI. If Bob's Health Factor drops below 1 his loan will be eligible for liquidation. A liquidator can repay up to 50% of a single borrowed amount = 2.5 ETHs' worth of DAI. In return, the liquidator can claim a single collateral unit, as the liquidation bonus is higher for YFI (15%) than for ETH (5%) the liquidator chooses to claim YFI. The liquidator claims 2.5 + 0.375 ETHs' worth of YFI for repaying 2.5 ETHs' worth of DAI.

Table 2: Historical AAVE V1 Risk Parameter Changes

Date	Asset	LTV	Liquidation threshold	Liquidation Bonus	Comment
10/21/20	MKR	50%	65%	10%	Decreased volatility
10/21/20	TUSD	75%	80%	5%	Following reivew of smart contract
7/22/20	LEND	50%	65%	10%	LEND cannot be borrowed due to migration incoming
7/16/20	LEND	50%	65%	10%	Improved risk parameter
7/16/20	SNX	15%	40%	10%	New Collateral
7/16/20	ENJ	55%	65%	10%	New Asset
7/16/20	REN	50%	65%	10%	New Asset
6/19/20	TUSD	1%	80%	5%	Unaudited update

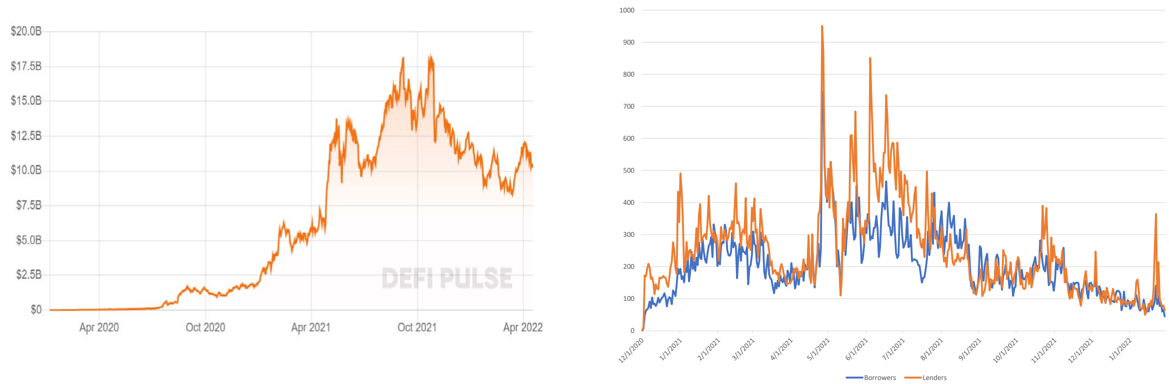
above).

B.6 Recovery Issuance

In case the SM is not able to cover all of the deficit incurred, an ad-hoc Recovery Issuance event is triggered where new AAVE are issued and sold in an open auction.

B.7 Some Basic Statistics

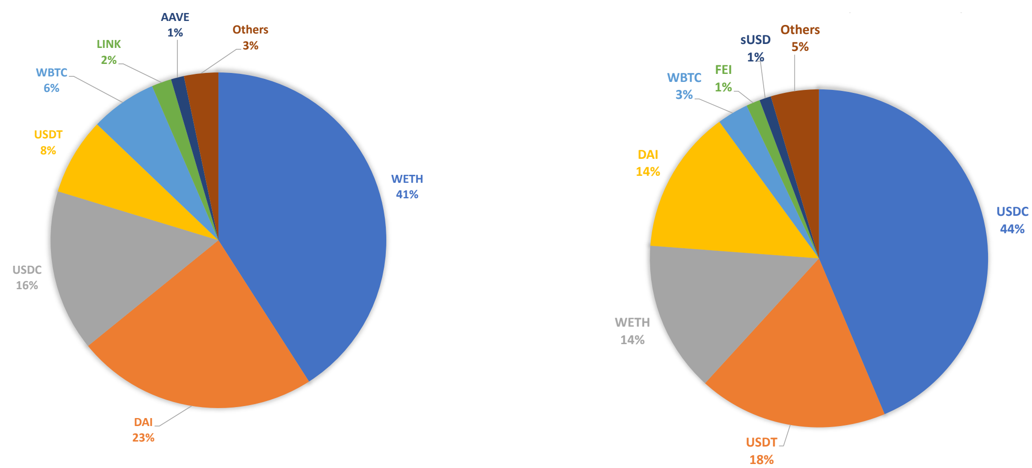
Figures 12–14 display basic statistics describing the Aave lending protocol. In April 2022, Aave supported the lending of 31 tokens and the total market size was about 11 billion USD. As shown in Figure 12 (a), the total value locked in Aave increased substantially between mid-2020 and mid-2021 and has experienced several ups and downs since then. The numbers of active lenders and borrowers, reported in panel (b), have also fluctuated over time. Figure 13 shows the average compositions of deposits and loans. Aave does not show explicitly which deposited crypto assets are used as collateral. These graphs suggest however that stablecoins such as USDC and USDT are borrowed disproportionately relative to their deposits. Stablecoins account for over 75% of loans. At the same time, the frequencies at which assets like ETH and BTC (WETH and WBTC in the figures) are borrowed are lower than those for depositing them, suggesting that they are used mostly as collateral. It is also observed that the leverage associated with these loans is relatively high because the distribution of the health factors is skewed



(a) Total Value (USD) Locked in Aave

(b) Number of Unique Users per Day

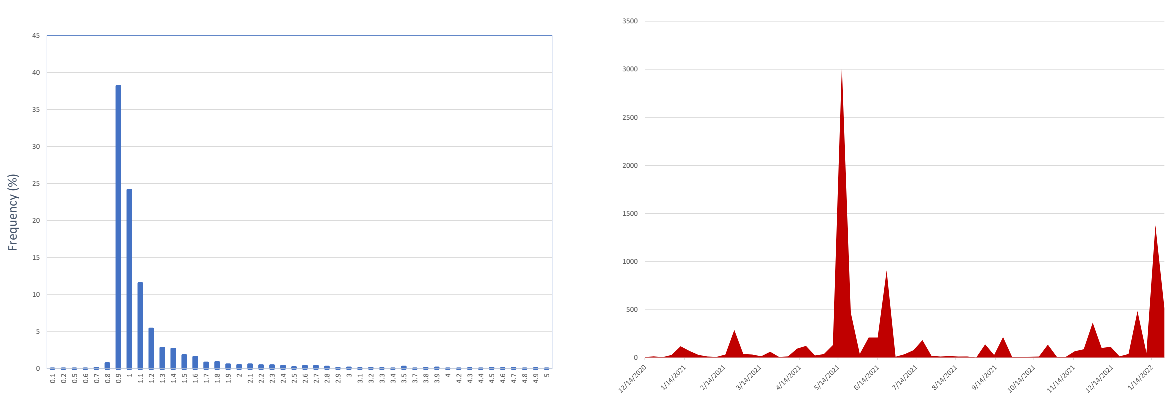
Figure 12: Aave v2 TVL and Users Over time



(a) Avg. Deposit Composition (Jan 2021-Jan 2022)

(b) Avg. Loan Composition (Jan 2021-Jan 2022)

Figure 13: Asset Compositions in Aave v2



(a) Health Factor (January 2022)

(b) Number of Liquidtions per Week

Figure 14: Liquidation Risk in Aave v2

towards the left in Figure 14 (a), at 40% with a health factor below 1.[27] Liquidations happen frequently as a result of the volatile collateral prices and high leverage. Panel (b) shows the time series of collateral liquidations.

[27]In practice, a position with a health factor below one may not be liquidated immediately given the execution costs involved.

C Volatility of Collateral Value

Table 3: The Volatility of Collateral Value (January 2021 - April 2022)

	Daily Volatility	Largest daily increase	Largest daily decrease
Stable Coins			
DAI	0.32%	1.26%	-1.33%
TUSD	0.39%	2.97%	-2.01%
USDC	0.34%	1.94%	-1.57%
Other Coins			
AAVE	7.15%	31.33%	-33.47%
BAT	7.48%	47.60%	-31.05%
BAL	6.62%	22.65%	-31.03%
CRV	8.89%	51.18%	-43.16%
ENJ	8.96%	56.46%	-35.61%
ETH	5.19%	24.53%	-26.30%
KNC	7.19%	30.57%	-31.98%
LINK	6.66%	30.38%	-35.65%
MANA	10.92%	151.66%	-29.79%
MKR	7.10%	51.31%	-24.24%
REN	8.05%	44.84%	-35.82%
SNX	7.36%	25.22%	-36.24%
UNI	7.14%	45.32%	-32.94%
WBTC	4.01%	19.04%	-13.75%
WETH	5.21%	25.96%	-26.12%
XSUSHI	7.65%	33.19%	-29.54%
YFI	6.82%	46.00%	-36.35%
ZRX	7.57%	56.02%	-36.31%
Other Benchmarks			
Stock Market (SPY ETF)	1.00%	2.68%	-3.70%
Treasury (BATS ETF)	0.35%	1.25%	-1.72%
AAA Bond (QLTA ETF)	0.41%	1.11%	-1.33%
Gold (GLD ETF)	0.89%	2.74%	-3.42%

Source: CoinGecko.

D Price Exploits

Here we discuss evidence of borrowers' pledging inflated collateral assets to obtain loans from lending protocols that later suffered major financial losses because of the bad debt.

As discussed in the Introduction, borrowers can have information advantage over a lending protocol when a smart contract relies on an inaccurate price feeds. For example, during the Terra collapse of May 2022, as a result of the extreme volatility in the price of LUNA tokens the price feed used by DeFi smart contracts for the LUNA token was significantly higher than the actual market value of the token. Attackers exploited the price discrepancy to take out loans collateralized against inflated LUNA from the Venus Protocol, the largest lending platform on BSC, leading to a loss of about $11.2 million to the protocol. The protocol later increased the LUNA haircut from 45% to 100%. Similar exploits have depleted the entire lending pool of the Avalanche lending protocol Blizz Finance, which has lost about $8.28 million as a result of this incident.

Similar price exploits can also occur when price oracles are based on on-chain AMMs that are subject to liquidity problems or price manipulation. At times, token prices on DEX can deviate substantially from those on CEX. Multiple incidents indicating that borrowers exploit lending protocols by borrowing against over-valued collateral assets have occurred. For instance, on May 18, 2021 the Venus Protocol faced a massive collateral liquidation. This incident occurred because a large sum of XVS was collateralized at a high price (possibly after price manipulation caused the price to shoot up from $80 to $145 in three hours) to borrow 4,100 BTC and nearly 10,000 ETH from the lending protocol. When the price of XVS dropped four hours later, the loans became undercollateralized, resulting in $200 million in liquidations and more than $100 million in bad debt, with the borrowers profiting from this exploit. In this particular episode, borrowers were able to exploit their information advantage based on the overpricing of XVS while lenders were unable to prevent XVS from being used as collateral. Similar exploits affected the Ethereum-based lending protocols Cheese Bank (with a $3.3 million loss in November 2020), Vesper Finance (with a $3 million loss in November 2021), and Inverse Finance (with a $15.6 million loss in April 2022).

E Empirical evidence (for Online Appendix)

Here we report evidence that supports the case that our model can be useful for understanding the relationship between DeFi lending, crypto prices, and market sentiment.

E.1 Effects of DeFi Lending on ETH Prices

Our model predicts that DeFi lending should be positively correlated with crypto prices because of the price–liquidity feedback loop. Because the Ethereum blockchain is the main platform for DeFi, we use WETH TVL data from DeFiLlama to test this hypothesis. The sample period runs from January 2018 through March 2022. Figure 15 shows that such lending accounts for about 23% of DeFi TVL. We run an OLS,

$$log(ETHP) = \alpha_0 + \alpha_1 log(LTCP) + \alpha_2 BURN + \alpha_3 DEFI + \alpha_4 LEND,$$

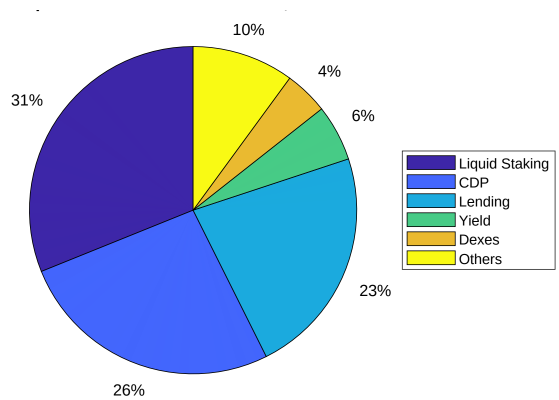
where $ETHP$ is the price of ETH, $LTCP$ is the price of Litecoin (LTC), $BURN$ is the amount of ETH burned since the London Fork as a percentage of the ETH supply, $DEFI$ is the fraction of WETH locked into DeFi protocols, and $LEND$ is the fraction of WETH locked into DeFi lending. Inasmuch as Litecoin has limited use in DeFi, we use its price to capture non-DeFi factors that can influence the price of ETH. As expected, results reported in Table 2 suggest that the prices of ETH and LTC are highly correlated. Also, unsurprisingly, by removing tokens from the circulating supply, BURN has a positive effect on the ETH price. Finally, after controlling for the general effects of DeFi on the price of ETH, TVL in DeFi lending is still positively correlated with the price of ETH, consistent with our model's prediction.

E.2 Collateral Composition and Market Sentiment

Our model predicts that good market sentiment can help mitigate adverse selection, improving the quality of the collateral pool. We use Aave platform data to examine the relationship between collateral composition and market sentiment. Market sentiment is measured by the "Crypto Fear & Greed Index" (FGI) for Bitcoin and other major cryptocurrencies.[28] The construction of the Index is based on measures of market volatility, market momentum/volume, social media, surveys, and token dominance

[28] The Index was developed by the "Alternative.me" website in early 2018 (https://alternative.me/crypto/fear-and-greed-index/).

Figure 15: Composition of WETH TVL in DeFi (March 2022)



Data Source: DefiLlamma.

Table 4: **DeFi Lending and Crypto Prices**

	Estimate	Std. Err.	T-Stat	p
Intercept	1.0845	0.07905	13.72	1.6765e-40
Log(LTCP)	1.0545	0.017673	59.665	0
BURN	0.42739	0.027956	15.288	3.1158e-49
DEFI	4.9181	0.92868	5.2957	1.3566e-07
LEND	36.438	2.5999	14.015	4.3029e-42
No. obs. :	1546			
R^2	0.925	Adj. R^2	0.925	

as well as Google Trends data. The Index was designed to measure market-related emotions and sentiments from various sources, with a value of 0 indicating "Extreme Fear" and a value of 100 indicating "Extreme Greed". Since Aave does not provide collateral data, we need to use outstanding deposits of collateralizable tokens as a proxy. Based on its internal risk assessment, Aave assigns risk ratings ranging from C+ to A+ to each token. We use these risk parameters to measure the quality of these assets. Figure 16 shows how the composition changes over time. Note that tokens have varying USD prices. Hence, changing prices will affect their (nominal) shares in the pool. To remove the effects of token price changes on the composition, we fix their prices at the median level over the sample period (Jan 2021–April 2022). Therefore, the results derived below capture variations only in token quantities, not in their prices.

Figure 16: Composition of Collateralizable Asset Mix

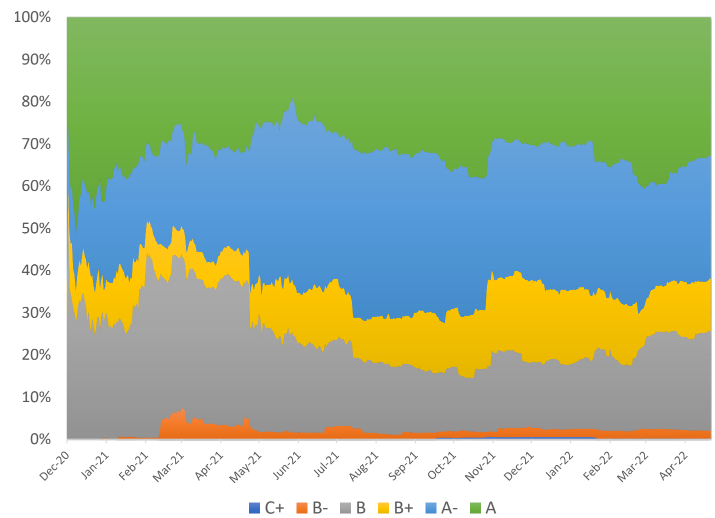


Figure Source: Dune Analytics

We study how sentiment is related to the overall quality of the collateral pool proxied by the weighted average of the ratings of all outstanding collateralizable deposits.[29] We run an OLS regressing log(Rating) on a dummy and log(FGI) as follows,

$$Log(Rating) = \alpha_0 + \alpha_1 Dummy + \alpha_2 log(FGI)$$

where Dummy=1 for days after April 26 (the date when Aave provided incentives to users who borrow/lend certain tokens). We report the results in Table 4. Both variables are significant, suggesting that the average rating of the collateral mix rises when the sentiment captured by the FGI is high, as predicted by our model.

[29]We convert ratings into numerical values as follows: Rating = 6 for "A", = 5 for "A-", ..., =1 for "C+".

Figure 17: Effects of FG Index on Average Risk Rating

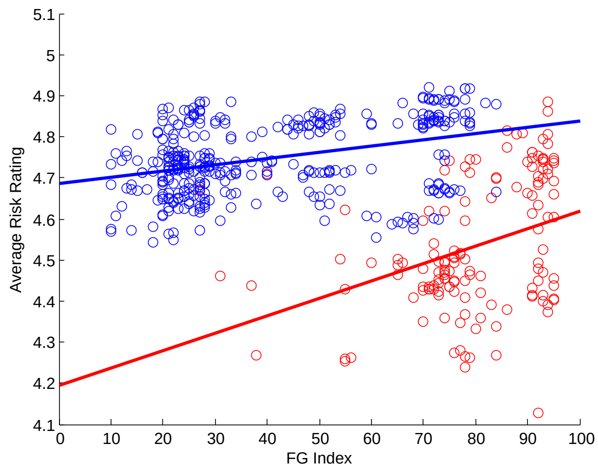


Figure Source: Dune Analytics

Blue (red) markers denote the sample period with (without) incentives

Table 5: **Sentiment and Collateral Ratings**

	Estimate	Std. Err.	T-Stat	p
Intercept	1.4469	0.010123	142.93	0
Dummy	0.058287	0.0029707	19.62	4.2179e-64
Log(FGI)	0.01467	0.0022778	6.4405	2.7814e-10
No. obs. :	507			
R^2	0.464	Adj. R^2	0.461	