Anatomy of a Run: The Terra Luna Crash

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Abstract

Terra, the third largest cryptocurrency ecosystem after Bitcoin and Ethereum, collapsed in three days in May 2022 and wiped out $50 billion in valuation. At the center of the collapse was a run on a blockchain-based borrowing and lending protocol (Anchor) that promised high yields to its stablecoin (UST) depositors. Using detailed data from the Terra blockchain and trading data from exchanges, we show that the run on Terra was a complex phenomenon that happened across multiple chains and assets. It was unlikely due to concentrated market manipulation by a third party but instead was precipitated by growing concerns about the sustainability of the system. Once a few large holders of UST adjusted their positions on May 7th, 2022, other large traders followed. Blockchain technology allowed investors to monitor each other's actions and amplified the speed of the run. Wealthier and more sophisticated investors were the first to run and experienced much smaller losses. Poorer and less sophisticated investors ran later and had larger losses. The complexity of the system made it difficult even for insiders to understand the buildup of risk. Finally, we draw broader lessons about financial fragility in an environment where a regulatory safety net does not exist, pseudonymous transactions are publicly observable, and market participants are incentivized to monitor the financial health of the system.

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The collapse of Terra in May 2022 was one of the most highly publicized events in the crypto industry. Prior to the crash, Terra's combined market capitalization was $50 billion, with an average daily trading volume of $1 billion, making it the third largest ecosystem after Bitcoin and Ethereum. However, within three days of the crash, its value plummeted to zero. This event marked the first significant run in crypto and triggered a chain reaction that led to the collapse of several other prominent players, including Celsius and Three Arrows, and ultimately contributed to the fall of FTX.

Our study of the Terra crash has two primary objectives. First, the crash provides a unique opportunity to enhance our understanding of runs in the absence of regulatory oversight or safety nets such as the Federal Reserve or FDIC deposit insurance. The previous literature that has examined runs on traditional financial institutions demonstrates, among other things, that regulatory interventions alter the incentives of market participants and can create coordinating events for a run, Iyer and Puri (2012) and Iyer et al. (2016). Since Terra operated outside of the conventional regulatory framework, such reliance on regulatory intervention was impossible. As a result, participants on Terra should have had heightened incentives to monitor the health of the ecosystem and exit if necessary. Blockchain data enables us to investigate in detail how and when various market participants ran.

Our second objective is to extract broader insights on the economics of the ecosystem that extend beyond Terra and apply to the entire crypto space. Cryptocurrencies and decentralized finance (DeFi) aspire to build a new financial architecture. Open access for all users and observability of pseudonymous transactions on the blockchain are among the central building blocks of this ecosystem. These features are frequently regarded as ways to enable all participants to monitor the health of the network, ensure its stability, and promote greater financial inclusion. However, we find that the Terra case revealed several significant fault lines in the typical DeFi architecture that exacerbate the inherent risks in the system and undermine the advertised benefits.

Using detailed data from the Terra blockchain and trading data from off-chain centralized exchanges (CEX), we show that the run on Terra was a complex phenomenon that happened across multiple chains and assets. At the center of the collapse was Terra's algorithmic stablecoin, UST, and a blockchain-based borrowing and lending protocol, Anchor. UST was designed to serve as a stable medium of transactions on the Terra blockchain. In economic terms, it was similar to dollar-denominated convertible debt issued against Terra's native cryptocurrency, LUNA. To incentivize users to adopt UST, the Anchor protocol offered highly subsidized yields to UST depositors, which generated significant inflows of deposits and led to a large increase in UST issuance. The newly issued UST were used to pay the interest on Anchor deposits and fund other activities. However, as the amount of deposits skyrocketed, the level of subsidies required became increasingly unsustainable. The Anchor protocol was therefore exposed to significant risks of insolvency, and its collapse had a domino effect on the entire Terra ecosystem.

Our analysis suggests that the run on Terra was not the result of targeted market manipulation by a single entity, but rather stemmed from growing concerns about the sustainability of the system. Once a few large holders of UST adjusted their positions on May 7^{th}, 2022, other large traders followed suit. Blockchain technology enabled investors to closely monitor each other's actions and amplified the speed of the run. However, the complexity of the system put less sophisticated and poorer individuals at greater informational disadvantage. We show that wealthier and more sophisticated investors were the first to run and experienced much smaller losses. Poorer and less sophisticated investors not only ran later and had larger losses, but a significant fraction of them attempted to buy into the run, hoping to "buy the dip." The system's complexity also made it difficult even for insiders to accurately assess the buildup of risk and adjust system parameters accordingly. Decentralized governance mechanisms added inefficiencies to the system and further exacerbated the instability.

To understand the context of the crash, we briefly need to lay out the design of the Terra network. Terra was developed by TerraForm Labs (TFL), a company founded in 2018 by Do Kwon and Daniel Shin. Like other smart contract blockchains such as Ethereum, the central idea was to build different applications and services on the blockchain to attract a stable user base and generate fees for its cryptocurrency holders. LUNA was the native cryptocurrency of Terra and derived its value from three main factors. First, by delegating their coins to validators, LUNA holders could get a share of Terra's transaction fees and block rewards. Second, using LUNA, users could access Terra applications which generated transaction demand. Finally, demand for LUNA could result from investors speculating on its value.

In an attempt to increase transaction demand on Terra and provide a stable medium of exchange, TFL introduced an algorithmic stablecoin, UST, which was pegged against the dollar.[1] UST was marketed as the first genuine crypto-native stablecoin and was a distinguishing feature of the Terra network.[2] Unlike other major stablecoins such as Tether or Circle, which are backed by off-chain liquid assets, e.g., treasuries, UST was not supported by off-chain collateral but by a smart contract that allowed an exchange

[1]Terra also offered a suite of other stablecoins pegged against other fiat currencies, like Korean Won or Euro, but UST was by far the most prominent one.

[2]Dai could be considered another contender for a crypto-native stablecoin. However, its price frequently de-pegged until it started using a basket of stablecoins backed by traditional assets to support the peg.

of one unit of UST to $1 worth of LUNA and vice versa. The pegging mechanism relied on traders taking advantage of an arbitrage opportunity that would present itself every time UST lost its peg in either direction. For example, if the price of UST falls below $1, arbitrageurs could buy UST at a price below $1 and convert it into $1 worth of LUNA, and in the process, reduce the supply of UST and drive up its price. And vice versa if the UST price is above $1.

In economic terms, UST was like infinite maturity convertible debt with a face value of $1 backed by LUNA. The main danger to the stability of the system was if users suddenly stopped holding UST and converted them to LUNA. While conversion of UST to LUNA reduces the UST supply, it also increases the LUNA supply and dilutes existing holders of LUNA. If this increase in the LUNA supply is expected to lead to a significant decline in the LUNA price, then any LUNA holder would be better off selling LUNA ahead of the conversion resulting in a so-called "death spiral" of both UST and LUNA falling in tandem.

It would be tempting to conclude that any conversion of a significant amount of UST to LUNA must lead to a decrease in the LUNA price. But as in the case of convertible debt, if investors are fully rational and understand that the outstanding supply of UST is a claim on LUNA's value, the conversion of UST to LUNA does not have to have an impact on the LUNA price since the conversion would be already priced in, see e.g., Glasserman and Nouri (2016), Pennacchi and Tchistyi (2019). Of course, for LUNA to successfully back UST, there must be enough value in the Terra system. Hence, one might expect that the instability of the system increases with the amount of the outstanding UST supply.

To increase the adoption of UST, Terra developed a borrowing and savings protocol, Anchor. Unlike other DeFi protocols where the lending yield is generated through interest paid on borrowings, we show that both borrowing and lending rates on Anchor were heavily subsidized. In particular, holders of UST could deposit their UST at Anchor at a stable 19.5% yield which was substantially higher than the yield on other major stablecoins, and the net borrowing rate was consistently below the lending rate.

The high deposit rate attracted significant deposit inflows, which were accompanied by a strong run-up in the price of LUNA and large issuance of UST by TFL. The proceeds from the sale of UST were used to pay the interest on loans on Anchor and fund other activities. Initially, TFL was willing to provide these subsidies, likely with the expectation that new users would continue to utilize the platform and generate future revenues. But it became increasingly apparent that the level of subsidy could not be sustained in the long run. By April 2022, the daily subsidy level had reached $6 million, prompting the Terra community to pass a proposal to gradually decrease the 19.5% interest rate to a more sustainable and market-driven level, starting on May 1, 2022.

Contemporary with these developments, there were additional indications of declining network fundamentals. First, following its peak value of $119.18 on April 5, 2022, the value of LUNA experienced a decline in conjunction with a general downturn in the value of cryptocurrencies, thereby diminishing the relative market valuation of LUNA compared to UST. Second, during the latter half of April 2022, there was a substantial decrease in the entry rate and an increase in the exit rate from Anchor.

Although it is not possible to assert with absolute certainty that the run on Terra was inevitable, our analysis shows that by following unsustainable policies, the Terra network was becoming increasingly fragile. In this situation, models such as Morris and Shin (1998), Goldstein and Pauzner (2005), or Abreu and Brunnermeier (2003) predict that even a small shift in fundamentals or common public signals can act as a coordination mechanism and trigger a run by investors. In the context of cryptocurrencies, where the actions of agents on the blockchain are publicly observable and agents can monitor and react to each other's actions, the actions themselves can serve as a coordination mechanism.

The first signs of the run appeared on May 7, 2022, when two large addresses withdrew 375M UST from Anchor. Following these withdrawals, the UST price began to decrease, and other withdrawals from Anchor intensified. Despite TFL's attempts to stabilize the peg by purchasing UST, investors continued to withdraw their funds from Anchor. The rate of withdrawals from Anchor intensified during the late hours of May 9, 2022, coinciding with the point at which the market capitalization of LUNA became equal to the outstanding supply of UST. As a result, the value of UST plummeted to $0.75. By the end of May 13, Anchor had fewer than 2 billion UST remaining, and the value of UST had declined to below $0.2.

We document how different types of investors behaved during the run and exited from Terra. We exclude all smart contract addresses and classify the remaining addresses by the size of their pre-run balance on Anchor and observed levels of financial sophistication based on the history of their trades. To measure sophistication, we look if an address had previously traded across several exchanges and used bridges to transfer tokens to other blockchains. In addition, we compute the level of trading volume divided by the balance in the account.

We show that large and more sophisticated investors were the first to run, and ran much more decisively, i.e., withdrew most of their coins conditional on running. We also document that large and sophisticated traders effectively used multiple avenues to exit UST and LUNA. In contrast, less sophisticated and smaller wallets were late to the run and sustained much larger losses. In fact, several especially smaller addresses even bought UST on May 9 or 10, when for a short time, it looked like the price was stabilizing at a level below $1, potentially in an attempt to "buy the dip." These addresses fared particularly badly at the end of the run.

Thus, although the prices of UST and LUNA, as well as trades of large wallets, were publicly observable on the blockchain, it did not create a level playing field for all depositors. Our analysis indicates that similar to the findings of studies investigating runs on traditional banks, e.g., Iyer and Puri (2012) and Iyer et al. (2016), wealthier and sophisticated investors were able to leverage this information more effectively and run earlier.

The UST peg design adds an additional dimension how investors could exit UST, by either selling UST at the market price or swapping UST for LUNA and then selling LUNA at the market price. In the absence of frictions, the second option would deliver strictly higher profits that increase with the size of the UST discount. In practice, investors faced several frictions, in particular swap fees, price impact when selling LUNA, and the risk of a delay between the time investors send their funds to an exchange and when they are cleared for trading. We show that during the run, the UST discount and the swap volume closely followed each other. As the UST discount widened investors found it increasingly more profitable to swap UST for LUNA and engage in the UST-LUNA arbitrage. In the period from May 7 to May 13, users swapped UST worth $4.65 billion. As users swapped UST for LUNA, the price of LUNA precipitously fell leading to increasing dilution which further depressed the price of LUNA, and led to a dramatic "death spiral."

Interestingly, we find that Alameda Research, a cryptocurrency trading firm closely affiliated with the FTX exchange, conducted the largest amount of UST-LUNA swaps among Anchor depositors. It seems that the swap fees and uncertainty about the execution price of LUNA on exchanges discouraged most other Anchor depositors from utilizing the native swap contract as an exit strategy. But Alameda Research, with its advantageous access to the FTX exchange, had a competitive advantage over other market participants.

We also analyze an earlier de-pegging incidence in May 2021 and show that it foreshadowed the risks and economic mechanisms that were important during the May 2022 crash. Similar to the May 2022 crash, the de-pegging coincided with LUNA market capitalization declining to a level close to the aggregate market value of UST and investor withdrawals from Anchor. As in May 2022, withdrawals were concentrated among wealthier investors, while low-wealth investors continued pouring their funds into Anchor.

One might ask why the run was avoided in May 2021, but not in May 2022. A critical factor appears to have been that the outstanding supply of UST was much smaller in May 2021, which enabled TFL to function as a lender of last resort. We show that nearly all UST-LUNA swaps were initiated by TFL, which presumably held onto the newly swapped LUNA instead of selling it. Furthermore, as the recent SEC lawsuit against TFL alleges, the peg was restored due to stabilization purchases of UST by a third party, which has been identified as Jump Trading. But market participants were unaware that TFL and Jump Trading were engaging in the stabilization of UST. As a result, when participants saw the price re-pegging, they appear to have interpreted it as a sign of the system's stability. In contrast, in May 2022, traders were aware of the fact that TFL was using funds held in LFG addresses to support the peg. They also knew that the supply of UST and the amount of UST locked in the Anchor protocol was significantly larger than the amount available to support the peg. Thus, traders might not have believed that the stabilization would succeed.

Our paper contributes to several different strands of the literature. First, there is a growing literature that examines the design and operation of stablecoins. For overviews of different design features and stabilization mechanisms, see for example, Eichengreen (2019); Arner et al. (2020); Makarov and Schoar (2022); Gorton and Zhang (2021); and Gorton et al. (2022) provide a comparative analysis of stablecoins and private money creation during the wildcat banking period of 19^{th} century United States.

d'Avernas et al. (2022) and Li and Mayer (2022) develop equilibrium models of the underlying pegging mechanisms for stablecoin protocols and underscore that mechanisms lacking external collateral are vulnerable to run risks if significant negative demand shocks arise, even if they remain stable for small shocks. Lyons and Viswanath-Natraj (2023) analyze the stability mechanisms of Tether and Dai. Uhlig (2022) proposes a model of the Terra-Luna crash.

The pegging mechanism behind UST and LUNA is also related to the literature that studies contingent convertibles, see Glasserman and Nouri (2016), Pennacchi and Tchistyi (2019), and Hillion and Vermaelen (2004).

Second, our results are related to a vast literature on runs on financial institutions, see Brunnermeier and Oehmke (2013) for an excellent recent survey of this literature. One part of this literature, starting with Bryant (1980) and Diamond and Dybvig (1983), posits that bank runs can arise as sunspot phenomena because of the liquidity mismatch and coordination problems among depositors. Another part emphasizes the role of information asymmetry about bank fundamentals, see for example, Chari and Jagannathan (1988) and Jacklin and Bhattacharya (1988). Following Morris and Shin (1998), a growing body of literature explores the interaction between fundamentals and strategic behavior by market participants as for example in Goldstein and Pauzner (2005), Goldstein (2013), and Abreu and Brunnermeier (2003). In these models, agents receive private and public signals about the strength of fundamentals. A common public signal acts as an additional coordination event for agents' actions.

A few recent empirical papers have analyzed the behavior of depositors during bank runs using individual account information. Iyer and Puri (2012) and Iyer et al. (2016) highlight the role that deposit insurance plays in mitigating a run as well as relationships between depositors and the bank. These papers also highlight the importance of depositor composition in accelerating a run. Looking at the run in the money market mutual fund market following the Lehman crash, Schmidt et al. (2016) similarly analyze coordination as a function of incomplete information and strategic complementarities between investors.

Third, the pegging mechanism behind UST and LUNA has some resemblance to the large literature in international finance on the causes and consequences of currency crises in countries with fixed exchange rates. A large body of initial research, commonly referred to as "first generation models", emphasizes the role played by deteriorating fundamentals as in Krugman (1979), Flood and Garber (1984), or Eichengreen et al. (1994). A body of "second generation" models allows currency crises to arise from speculative attacks that are potentially self-fulfilling, see for example Obstfeld (1996), Chamley (2003), or Cukierman et al. (2004). In these models, there is typically an equilibrium under which the peg is sustainable, and another under which the peg can be broken if speculation is sufficiently intense. For a comprehensive review of the extensive literature on currency crises, see Lorenzoni (2014).

Finally, we also relate more broadly to the literature that has tried to model the risk and value of cryptocurrencies such as Abadi and Brunnermeier (2018), Cong et al. (2021); Kogan et al. (2021); Hu et al. (2019); Liu and Tsyvinski (2021), and the benefit to a platform of having a native token such as in Sockin and Xiong (2023); Li and Mann (2018); Gryglewicz et al. (2021).

The rest of the paper is organized as follows. Section 1 describes the data used in this study. Section 2 provides description of the Terra network and the design of Terra's algorithmic stablecoin. In Section 3, we provide an analysis of the economics of Terra leading up to the run. Section 4 documents the run on UST and the collapse of LUNA. In Section 5, we compare the interventions of TFL in the May 2022 crash to the earlier de-pegging event in May 2021. Section 6 concludes.

1. Data

Our primary data source is the Terra blockchain. Like other permissionless cryptocurrencies, the Terra blockchain is publicly available. However, the Terra data are substantially more complex than say the Bitcoin data, which only record bitcoin transfers from one account to another. The structure of Terra data is comparable to Ethereum, since many transactions on Terra are not simply token transfers but the inputs and outputs of smart contracts. One must parse the smart contract data to understand the Terra data successfully. The work is challenging because (1) each smart contract has its own data structure, (2) smart contracts often rely on each other, and (3) some transactions are not settled immediately but require a delay or resolution of other conditions.

We are unaware of any data source that provides fully processed Terra data. In our research, we work closely with two leading blockchain data analytics companies, Nansen and Flipside.[3] We learned from them how to process the blockchain transactions and use their data to help with validating our data processing.

We use several data in our analysis. First, we use Terra token transfers from October 2021 to August 2022 that come from transaction logs. When a transaction is settled, the blockchain records logs that contain the transfer, minting (creating), and burning (destroying) of tokens. The tokens include LUNA, Terra stablecoins, and CW20 standard tokens.[4] To collect the logs, we run a Terra Classic node using data from ChainLayer Quicksync that stores copies of blockchains to speed up synchronization.[5] We use Terra Classic's API to query the data in each block. We first use the LCD (Light Client Daemon) API to query transactions, fees, and the log of transactions. Next, we parse the logs into structured data. We record the time of transfer, the source account, the destination account, the token, and the transfer amount. For transactions that require a delay or condition to settle, we use the RPC (Remote Procedure Call) API to query the list of settlement events in each block.[6]

Second, we use genesis files from Terra's online code repository.[7] Genesis files are snapshots of the blockchain state at each upgrade, i.e., each fork. When the Terra

[3] See https://flipsidecrypto.xyz/ and https://www.nansen.ai/.

[4] CW20 is the standard for fungible tokens on Terra such as aUST, bLUNA, and ANC. The data do not cover transfers of NFTs that follow the CW721 standard. Both CW20 and CW721 standards closely resemble the equivalent ERC20 and ERC721 standards on Ethereum. See https://github.com/CosmWasm/cw-plus/blob/main/packages/cw20/README.md for more detail.

[5] See https://www.chainlayer.io/quicksync/

[6] For example, LUNA un-delegation requires a 21-day delay. Spending from the community pool requires approval of the on-chain governance.

[7] See https://github.com/terra-money/classic-mainnet.

developers release a major software upgrade, validators take a snapshot of the state of the blockchain and resume from there. Therefore, a snapshot fully characterizes the blockchain state before an upgrade. We collect five snapshots that date back to April 23, 2019 (Columbus-1), June 6, 2019 (Columbus-2), December 13, 2019 (Columbus-3), October 3, 2020 (Columbus-4), and September 30, 2021 (Columbus-5). We reconstruct the daily balances of UST, LUNA, and CW20 tokens since Columbus-5 by finding the cumulative sum of token transfers and adding the initial balance.

Third, we use Flipside pre-processed data of specific transactions. These data include (1) Terraswap, Astroport, and the Terra native swaps, (2) LUNA delegation and un-delegation, (3) airdrops of ANC, MIR, and MINE, and (4) governance proposals and voting records on both Terra and Anchor.

To link pseudonymous addresses with real-world entities we use Flipside and Nansen address labels as well as labels obtained from searching online forums, social media, and open-source code repositories. We also manually label some addresses by examining their transaction logs and graphs. For example, centralized exchanges usually ask users to specify their account number in deposit transactions, which makes it possible to identify them in the data. We also identify unnamed smart contracts from transaction logs. We collect their addresses from transactions that are smart contract instantiation or execution.

We also use the Ethereum blockchain data. We parse transactions that correspond to trades on the Curve pool between UST and other stablecoins, and trace UST and LUNA bridge transfers between Terra and Ethereum blockchains.

Finally, we obtain exchange trading data from Kaiko, a leading data provider of trading data on centralized exchanges. Kaiko provides data on minute-level order book depths, tick-level trading records, and the minute-level funding rates of perpetual futures. The data cover 19 exchanges and 131 trading pairs for UST, LUNA, ANC, and MIR tokens.

Put together, our data cover 7.5 million blocks that contain 228 million transactions from October 3, 2020, to May 15, 2022. One transaction can result in multiple logs on the blockchain. We collect 657 million transaction logs. These logs cover 367 million voting records of oracle prices, 109 million records of LUNA and UST transfers, and 162 million records of smart contract execution results (including 40 million records of CW20 token transfers). Among these transactions, there are 5.4 million Anchor transactions, 1.8 million native swap records, and 97 thousand bridge transfers from Terra to Ethereum.

Our data cover 3.7 million addresses. Among them are 25 centralized exchanges (CEXs), 864 trading pairs on 4 decentralized exchanges (DEXs), 10 inter-chain bridges, 58 DeFi protocols, 319 blockchain validators, 69 other entities including hedge funds and venture capitals, 4,498 CW20 tokens, and 58,941 unnamed smart contracts.

2. Terra Network

In this section we lay out the evolution of the Terra blockchain and its main building blocks. The architecture of Terra shared many features with other cryptocurrency platforms such as Ethereum, which makes it an interesting object of study. Although smaller than the Ethereum network, Terra's smart contract platform enabled developers to build a similar array of applications. The Terra blockchain was created with the intention of supporting a decentralized financial architecture with several key use cases, ranging from borrowing and lending protocols to savings and trading applications. The original network was named Terra but is currently referred to as TerraClassic. For ease of reference, we continue to use the name Terra to describe the network.

The Terra network was developed by TerraForm Labs (TFL), a company started by Do Kwon and Daniel Shin in 2018. TFL raised $32 million in seed capital from a number of venture funds and some of the largest cryptocurrency exchanges such as Binance and Huobi. In January 2019, TFL raised $62 million in an initial coin offering (ICO) by selling Terra's native cryptocurrency, LUNA, at a price of $0.8 per LUNA. The initial supply of LUNA was set to 1B, with seed and other investors receiving 188M LUNA and TFL the rest. TFL used this initial allocation to provide block rewards to validators and fund other projects.

The Terra blockchain was a proof-of-stake (PoS) blockchain built using the Cosmos's software development kit (SDK). In a PoS protocol, validators of transactions pledge their coins, which can be forfeited if the validator fails to verify transactions promptly or if their actions are found to be malicious. This process of pledging coins is known as staking. Validators are rewarded with transaction fees and block rewards for their services. Validators who stake a larger number of coins are more likely to be selected to verify transactions and receive rewards. Users can delegate their coins to validators and share the rewards with them.

The native token of the Terra network, LUNA, could be staked by users. Holders of LUNA could delegate their tokens to validators of their choosing and receive rewards in proportion to their stake. Staking LUNA also permitted holders to propose and vote on governance proposals. One of the notable characteristics of the Terra blockchain was that it provided a range of algorithmic stablecoins that were pegged to different fiat currencies. Among these stablecoins, TerraUSD (UST), pegged to the US Dollar, was the most prominent. Unlike other major stablecoins such as Tether or Circle, which were backed by off-chain liquid assets such as treasuries, UST was not supported by off-chain collateral but by a smart contract that facilitated the exchange of one unit of UST to $1 worth of LUNA and vice versa. Terra's stablecoins became a distinctive aspect of the Terra network. We describe them further in Section 2.1.

The applications on the blockchain benefit from having a reliable stablecoin as a medium of change and store of value, but they also drive the demand for the stablecoin. Some of the more notable protocols built on the Terra network included (1) borrowing and lending protocols like Anchor or Mars, (2) decentralized exchanges (DEX) such as Astroport and Terraswap, (3) payment applications like Chai and Memepay, or (4) the creation of synthetic assets that could track prices of stocks and other securities, as in the Mirror protocol. One of the most widely used application on the Terra platform was the Anchor protocol which provided lenders with a stable interest of 19.5%. We will describe its economics in more detail in Section 3.2. Another prominent application on the Terra network was Chai, which was marketed as a mobile payment app supported by the Terra blockchain. However, a recent SEC case against Terra alleges that these payments were never processed on the blockchain and that Terra fabricated fake transactions.[8]

The Terra blockchain also allowed for easy cross-chain transfers of assets, tokens and data to other highly used blockchains. As a blockchain built on the Cosmos SDK, it was interoperable with other blockchains built on the IBC (Inter-Blockchain Communication) protocol. In addition, Terra also facilitated interoperability with other blockchain applications through the so-called bridges (a form of message passing protocol).[9] Terra Shuttle bridge was the first Ethereum bridge followed by the Wormhole bridges that connected Terra with Solana, Ethereum, Binance Smart Chain, and others. This interoperability became very important for Terra, since it allowed traders on the Terra blockchain to access liquidity on DeFi apps on other blockchains, in particular the Curve protocol on Ethereum, which emerged as the DEX with the deepest liquidity to trade an array of stablecoins including UST (in the UST/3CRV Curve meta pool).[10]

In January 2022, Do Kwon announced the launch of the Luna Foundation Guard (LFG) a non-profit organization "to build reserves supporting the $/UST peg amid volatile market condition". This was prompted by concerns arising about price dislocations of UST stemming from large trades or coordinated attacks on Curve and other

[8] See `https://www.sec.gov/news/press-release/2023-32`.

[9] These bridges operate as a decentralized, intermediary oracle network that observes and verifies messages on one chain (i.e., Terra) and relays them to the other chain (i.e., Ethereum). This solution allows tokens to move between blockchains without relying on centralized exchanges.

[10] See `https://resources.curve.fi/` for more detail.

DEX or centralized exchanges like Binance. LFG was overseen by a governing council including several TFL co-founders and the lead investors. LFG originally raised $1 billion through the sale of LUNA tokens, with Jump Trading and Three Arrows Capital as the lead investors. It set up a pool of exogenous reserve assets (mostly denominated in BTC) to support the stability mechanism for the UST stablecoin, UST. Through a series of further LUNA sales and transfers from Terraform Labs LFG built a significant reserve pool. The audit report by JS Held conducted after the crash confirms that as of May 6th 2022, LFG held about 80,300 BTC, USDT 26 million, and USDC 24 million, as well as minor allotments in a few other coins.[11]

Figure 1 shows the timeline of the main Terra events. Terra went through several protocol upgrades, the so-called forks in the crypto parlance. Early upgrades were mostly concerned with tweaking protocol parameters. Columbus-4 launched on Oct 3, 2020, allowed users to write and upload smart contracts that led to a rapid growth of DeFi protocols. Columbus-5 launched on September 30, 2021, improved the interoperability of Terra with other networks and changed the economics of UST-LUNA swaps. Prior to Columbus-5, when LUNA was swapped for UST, 5% of LUNA was burnt and the rest was sent to the community pool. Funds from the community pool were used to finance various community projects. Starting from Columbus-5, all LUNA swapped for UST have been burnt.

[Fig. 1 About Here]

2.1. Terra stablecoins

Starting in March 2020 Terra introduced a suite of algorithmic stablecoins pegged against different fiat currencies, the most prominent being UST which was pegged against the US Dollar.[12] Unlike custodial stablecoins such as Tether and Circle, which are backed by non-crypto assets, UST was backed by LUNA via a peg mechanism that is meant to incentivize traders to engage in arbitrage whenever the stablecoin deviates from the peg.

At the core of the peg mechanism is a *native swap* smart contract that allows users to exchange, say $1 worth of a stablecoin, UST, for the dollar-equivalent amount of LUNA, and vice versa. Thus, when UST is traded above $1, users could buy LUNA, swap LUNA for UST, which amounts to burning (destroying) LUNA and mint (creating) new UST, and sell UST at a premium above $1, pocketing the difference as profit. In

[11] See https://lfg.sg/audit/LFG-Audit-2022-11-14.pdf for the audit report.

[12] Others included TerraCNY (Chinese yuan), TerraEUR (euro), TerraBGP (British pound), TerraJPY (Japanese yen), or TerraKWR (South Korean won).

contrast, when UST trades below $1, users could buy UST, burn UST to mint new LUNA, and then sell LUNA with a profit.

The LUNA price, necessary for the native swap to work, is supplied by an oracle of off-chain centralized exchanges every 30 seconds.[13] To prevent oracle price manipulation, the fees associated with the native swap are designed to increase with the volume. Without swap fees, a user could have done the following. Sell LUNA on off-chain exchanges to temporarily depress the price of LUNA. Then use the native swap contract to swap a large quantity of UST for LUNA at a lower LUNA price, buy LUNA on off-chain exchanges to bid up the LUNA price, and finally use the native swap contract to swap back a large quantity of LUNA for more UST.

The swap fees have been set so that the on-chain liquidity provided by the native swap stays below the liquidity of the off-chain exchanges used by the oracle. The swap fees have decreased over time as the liquidity of the off-chain exchanges increased. Initially, the Terra protocol allowed swapping $400 thousand per day with a 2% spread, with the spread increasing if the volume exceeds the daily limit. The daily limit was increased to $20 million in Feb 2021 (Terra proposal 36). Following the May 2021 de-pegging event, proposal 90 was passed to increase the daily limit to $135 million and decrease the spread to 0.5%, and then to increase the daily limit to $293 million in Feb 2022 (Terra proposal 185).

2.2. Viability of Peg Mechanism

For the peg mechanism to work it has to be that (1) the price of LUNA supplied by oracles is accurate, (2) arbitrageurs have incentives to defend the peg, and (3) any negative feedback from converting UST to LUNA on the price of LUNA is limited. To understand the last condition, notice that if a swap of UST for LUNA, which decreases the supply of UST and increases the supply of LUNA is expected to lead to a significant decline in the LUNA price then any LUNA holder would be better off selling LUNA ahead of the swap resulting in a run on LUNA.

When do we expect condition (3) to hold? First imagine a situation where the supply of UST is negligible relative to the market cap of LUNA. Here converting UST into LUNA will only lead to small changes in the aggregate LUNA supply and thus the expected dilution should be minimal and it would be reasonable to expect condition (3) to hold. Now lets imagine the case where the supply of UST is more significant relative to the market cap of LUNA. Here the situation is more complicated and it can be useful to draw an analogy with warrants that give their owners the right to buy

[13] Blockchain oracles are services that provide smart contracts with external information. They serve as bridges between blockchains and outside data.

company stock at a prespecified price. Similar to UST, which increases the supply of LUNA if converted, warrants are dilutive — when investors exercise their warrant, they receive newly issued stock. To the extent that exercising warrants does not change the total value of the firm, it would be tempting to conclude the stock price should decline following warrant exercise. However, if investors are rational and understand that outstanding warrants are a claim on the firm's value then the exercising of warrants would not have any impact on the stock price. But the price would decline at the time that the warrants are issued.

Similarly, if Terra investors are rational and understand that UST is a claim on LUNA, swapping even large quantities UST for LUNA could have no effect on the LUNA price. However, if Terra investors price LUNA without fully taking into account the dilutive nature of UST, swapping large quantities of UST for LUNA is likely to have a large impact on the price of LUNA. In the latter scenario, the states of the world where the market cap of UST is close to that of LUNA are expected to be fragile and prone to a run on LUNA.

The above discussion raises an important question of the determinants of the value of LUNA. First, by staking LUNA, one gets a claim to the transaction fees on Terra and the rights to decide on the future development of the network. This makes it possible to express the value of LUNA as the sum of the discounted future transaction fees, see Kogan et al. (2021) for details. Second, LUNA also gives access to the services offered on the Terra network, which creates transaction demand and with it validation fees. Finally, demand for LUNA can be the result of investors speculating on its value.

The demand for UST can be broken down to the interest rate it offers and transaction demand. With their value pegged, stablecoins serve as a natural choice of collateral and benchmark asset in the crypto space. Being native to the Terra network, UST faced no direct competition from other stablecoins on Terra. However, on other chains like Ethereum, UST had to compete with stablecoins like Tether, USDC, or Dai.

In what follows, we present evidence that shows that the main factor behind the demand for LUNA was speculative demand and for UST was the artificially inflated interest rate on Anchor.

3. Terra Prior to the Run

We now analyze the transaction flow on Terra and their underlying economics prior to the run. Like other (payment) platform businesses Terra aimed to provide a suite of services that draw in users and generate fees for the token holders. If more users participate on the blockchain, it becomes more attractive for users to be on the network and for developers to create additional applications on the platform, which in turn attract more users and so on. If these network externalities are expected to be strong, start ups in the tech or social media industry often subsidize customer acquisitions initially to achieve critical mass, after which the marginal value of new customers should turn positive to justify the investments.

We show that one of the main attractions on Terra was a borrowing and lending protocol, Anchor, which provided heavily subsidized deposit rates and drew many users to the platform. While it might have originally been intended as a way to generate network externalities, our analysis shows that users on the platform did not start utilizing other services extensively, and instead the subsidies on Anchor remained the main attractor to Terra. While the level of subsidy was unsustainable, the complex structure of the subsidies, might have made it difficult for many network participants to understand their origin.

3.1. Network Structure and Transaction Volume

In this section, we provide an analysis of transaction volumes on the Terra network using on-chain data. We focus on the period starting with the Columbus-5 fork on September 30, 2021 and finished before the crash, on May 6, 2022. Our goal is to understand how different tokens and smart contracts were used on the Terra network prior to the crash.

To compute volume, we treat any single address as a separate entity unless we have information that several addresses belong to the same entity. As a result, our calculation of the network volume is likely to be biased upwards since some entities might control several addresses. The situation is not as severe as in the case of the Bitcoin network where as Makarov and Schoar (2021) show one entity can control ten and more million addresses. Being a *account*-based network like Ethereum, Terra has a much smaller number of addresses than Bitcoin network. A typical entity on the Terra network usually controls one or only a few addresses.

Some smart contracts like Nexus often adjust a position by rebalancing the whole position. For example, in the following sample transaction, Nexus smart contract adjust the amount borrowed from Anchor from 16,226,512 UST to 16,227,559 UST by first repaying the outstanding balance and then borrowing the new amount.[14] The net effect is an increase in the borrowed position by 1,047 UST. Computing volume simply as the sum of the two transfers would grossly overstate the real volume on the

[14] See https://finder.terra.money/classic/tx/e874a1d3824854bbdb4f8743f18484fdc07361bc62538b10369c8dc9fe7a3faf.

network. Therefore, in our volume calculation, we first net token transfers between any two addresses that happened at the same time.

The aggregate UST and LUNA volumes during the pre-crash period are $360 and $217 billion, respectively. The tokens with the next two largest volumes are aUST and bLUNA, at $114 and $50 billion. As we explain in the next section the volume in these coins is closely related to transactions related to Anchor. For this reason, in what follows we only focus on the UST and LUNA volumes. Table 1 reports the total volume of transactions for each token in detail.

Figure 2 we now show the decomposition of the trading volumes for UST (left panel) and LUNA (right) between different addresses on the Terra blockchain. We classify addresses into broad groups that are associated with the main participants on the blockchain. In particular, "Admin" addresses denote those of network administration accounts and Terra insiders, including the community pool, Terra's native swap, addresses for transaction fees and LFG wallets. "TFL" addresses are those used to issue new UST and to defend the peg. "Anchor" denotes addresses through which transactions belonging to the Anchor protocol are conducted, such as its yield service, money market transactions, staking accounts and other operations related to Anchor. "Other" captures the accounts of regular users on Terra including retail individual traders, hedge funds and large traders. CEX, DEX, and Bridges signify the wallets of these entities. And DeFi captures smart contracts of entities that are not CEX, DEX or Bridges, for example NFT market places or crowdfunding platforms. For a more detailed description of the categories, see Appendix Table 7.

The size of the node reflects the total volume of the category. Similarly, the edge size between nodes is proportional to the volume between the two categories. The number next to an edge shows the corresponding volume. For clarity, we show only categories with at least $10 billion of total volume in the UST network and $5 billion in the LUNA network, and edges with at least $1 billion of volume.

The left panel shows that Anchor was by far the most important protocol in the UST network accounting for 46% of the total network volume. The decomposition of flows on the network also shows that the next two categories, centralized exchanges (CEX) and decentralized exchanges (DEX), together account for 26% of the volume. All unlabeled addresses are assigned to the 'Other' category, which contains addresses of individual users on the network. We also see that the largest flow between nodes is between Anchor and Other, again highlighting the importance of Anchor on the network.

Similarly, in the right panel we map transactions on the LUNA network. In this case, we observe that CEX, DEX, and addresses affiliated with TFL and Admin accounts account for 84% of aggregate volume. This finding indicates that the majority of transactions utilizing LUNA are associated with trading on exchanges, which reinforces the notion that a significant portion of the demand for LUNA stems from speculative activities.

[Fig. 2 About Here]

3.2. Anchor

The previous section shows that Anchor was the main attraction in the Terra network. Its design shares many characteristics with other decentralized lending platforms such lending and borrowing are automated by smart contracts, similar to Aave or Compound on Ethereum. However, as we show in this section, while Aave or Compound lending rates are financed by borrowing rates, both lending and borrowing on Anchor were heavily subsidized by TFL.

3.2.1. Lending

We will now discuss the mechanics of the smart contracts underlying the Anchor protocol. The Anchor contract aggregates stablecoin deposits with matching denominations into a pool, which is called markets. Borrows are proceeded from this pool, and interest gained from them is equally shared among all the units of stablecoin deposits. Deposits can be withdrawn anytime, unless every stablecoin in a market is borrowed.

When an address lends to Anchor, it transfers, say 100 UST to the Anchor UST market address. The Anchor UST market contract mints (issues) the appropriate amount of aUST, and transfers it to the depositor's address. The aUST token is a claim on UST stored in Anchor. It is freely tradable and transferable. The conversion rate between aUST and UST is only a function of time with the interest rate on the Anchor UST deposit being embedded in the aUST/UST conversion rate. When the address wants to withdraw its UST from Anchor, it sends aUST tokens back to the Anchor UST market contract, which burns (destroys) the aUST and returns UST along with interest. The interest on each aUST token is the difference between the aUST/UST conversion rates at the time of the deposit versus withdrawal. The rate was 1 when Anchor was launched in March 2021 and was 1.213 one year later in March 2022.

3.2.2. Borrowing

Borrowing on Anchor is over-collateralized. For the period we consider, Anchor allowed two types of collateral, bLUNA and bETH. These types of bAssets are liquid, tokenized representations of staked (bonded) assets in a PoS blockchain. Since the native token in a PoS blockchain can be staked to earn a reward, it is more efficient to hold staked LUNA or ETH as collateral rather than their unstaked counterparts. The main obstacle with using staked tokens as collateral is their illiquidity — staked tokens can be unstaked only with a delay because the Terra network has a lockup period of 21 days.

The built-in delay serves an important function in a PoS protocol of providing validators and delegators with proper incentives to verify transactions on the blockchain. But by restricting the timely access to the token, the built-in delay reduces its collateral value. One solution that emerged to the above problem, is to introduce a derivative contract, which is a claim on the staked tokens and which can be freely traded in the market. This was implemented by the Lido Liquid Staking Protocol in the form of bAssets.[15]

When an address borrows UST from the Anchor UST market, it first sends bLUNA (bETH) as collateral to the Anchor bLUNA (bETH) Custody Contract, which then records the address and the amount of collateral provided. The borrowing limit depends on the value of the collateral and cannot exceed the maximum allowed loan-to-value (LTV) ratio. The maximum LTV for bLUNA was initially set to 50%, then raised to 60% in July 2021, and to 80% in Feb 2022. Smilarly the LTV for bETH was raised to 75% at the peak. Naturally, the borrowing limit fluctuates with the oracle-reported bAsset price. When the borrowing limit exceeds the maximum LTV the loan gets liquidated. Liquidation is implemented via what is called a Liquidation Queue, where liquidators bid in a first-price auction for the right to liquidate the collateral and repay the loan.

3.2.3. Anchor Rates

The Anchor lending rate was primarily a function of two main rates, *target deposit rate* and *threshold deposit rate*.[16] The target deposit rate, known as the Anchor rate, was the rate, which the protocol attempts to achieve from the interest gained from the borrowers. The threshold deposit rate served as a floor to the deposit rate triggering a direct deposit rate subsidy from the *yield reserve* pool of Terra if the current deposit rate is below this value.

When Anchor was originally launched, the Target Deposit Rate and the Threshold

[15] The Lido Protocol also allowed a second set of derivative contracts called stAssets. The differences are not important for our purpose, but details can be found in Lido Terra Docs at https://docs.terra.lido.fi/introduction/tokens.

[16] https://docs.anchorprotocol.com/anchor-2/protocol/anchor-governance/modify-market-parameters.

Deposit Rate were set at 20% and 18%, respectively, and later changed to 20.5% and 19.5%. Following widespread discussions that the 20% Anchor rate is unsustainable, there was a series of proposal starting in March 2022 to lower the Anchor deposit rate. Eventually, Anchor Proposition 20 was passed on March 23 and implemented on May 1st, 2022, which tied the deposit rate to the change in the yield reserve over a one month period. If the yield reserve is growing, the deposit rate would increase and vice versa if the yield reserve is falling. The maximum amount the deposit rate could change per month was set to 1.5%.[17]

On the other side of the Anchor platform, the annualized borrowing rate was an increasing function of the proportion of outstanding loans to outstanding deposits and given by the following formula:

$$2\% + 42\% \times \frac{\text{outstanding loans}}{\text{outstanding deposits}}$$

and was adjusted every three hours.

Figure 3 shows the Anchor lending and borrowing rates from April 2021 when Anchor was launched until the beginning of the crash on May 7, 2022. We can see that the lending rate had been consistently around 20%. Comparing the lending and borrowing rates shown in Figure 3, one can also see that the borrowing rate was often below the lending rate. But this simple comparison does not reflect the full cost to a borrower, since the borrowing rate does not include the opportunity cost of losing the staking yield on the collateral that was required to borrow from Anchor.

[Fig. 3 About Here]

The LUNA staking yield comes from two main sources: (1) block rewards and (2) airdrops. Block rewards are the sum of swap fees and gas fees, minus validator commissions. Airdrops, a practice of giving away tokens to active members of the blockchain community, is a popular marketing strategy in the crypto space to reward participants and promote awareness of new tokens.

LUNA delegators received three main airdrops — ANC (Anchor native token), MIR (Mirror native token), and MINE (Pylon native token). To compute the resulting staking yield, we assume that delegators claim all available airdrops of the three tracked tokens every week and sell them over that week for LUNA. Figure 4 left panel shows the LUNA staking yield by source. Through most of 2021 LUNA block rewards were stable but constituted less than 50% of the rewards from staking. The other half of the rewards to staking came from the airdrops. The burning of LUNA for UST in

[17] https://twitter.com/anchor_protocol/status/1507052921745256449?lang=en-GB.

the community pool in November 2021, which we describe in Section 3.2.4, lead to a significant increase in LUNA staking yield.

[Fig. 4 About Here]

To compensate borrowers for the opportunity cost of collateral, Anchor implemented a subsidy scheme which distributed Anchor native token ANC to borrowers. Anchor initially sent 87,000 ANC to all borrowers per day in proportion to their loan balance. But following the May 2021 LUNA crash (see Section 5 for more detail) that lead to a large number of liquidations over a span of four days and sharp decline in borrowing activity, the rate was dynamically adjusted at 50% per week until it reached the upper limit of 260,000 ANC per day on June 8 2021, and stayed at this level thereafter.

The right panel of Figure 4 shows the annualized ANC subsidy rate, where we assume that borrows sell the daily ANC incentive at the market price. The subsidy rate was as high as 300% when it was first introduced. It led to a sharp rise in lending. As more investors borrowed from Anchor, the subsidy rate declined slightly in May 2021, but still was around 80%. After the mini crash in May 2021, it increased again, and then slowly decreased as borrowing activity recovered.

Figure 5 shows the net borrowing rate. To compute it, we assume that the borrower takes a loan with the maximum LTV. This would be the case if users use intermediary protocols like Nexus that are designed to be as efficient as possible by constantly monitoring the LTV and making sure that it stays below the level that triggers liquidation. Standalone users typically choose lower LTVs. For these users, the opportunity cost of borrowing are higher.

[Fig. 5 About Here]

Figure 5 reveals a striking fact that the net borrowing rate on Anchor has been below the lending rate at all times. In other words, Anchor was never self-sustaining but relied from significant subsidies from TFL. This imbalance was primarily driven by the deposit rate on Anchor having been set exogenously and artificially high. Early on, the high deposit rate might have been intended as a marketing tool to attract users to the Terra ecosystem. But our analysis suggests that these users did not start generating more fees over time to support the high deposit rate.

In fact, many users took advantage of the low net borrowing rate by borrowing funds from Anchor and immediately posting them back. We call these exploiting loans. Figure 5 shows the share of exploiting loans among all loans. We can see that the share of exploiting loans varies inversely with the difference between the lending and the net borrowing rates, with the lowest value being 20% and often being as high as 60%. In other words, participants engaged in exploiting loans more heavily when the gains from this activity were greater.

3.2.4. Anchor Balance

The highly subsidized Anchor rates were very high even by the crypto standards. Figure 6 shows the average lending rates on thee major stablecoins, USDT, USDC, and DAI on Aave and Compound platforms, which are the main borrowing and lending market places in the Ethereum network. We can see that the Aave and Compound rates were around 2-3% in Jan-May 2022, which stand in stark contrast to the 20% Anchor rate.

[Fig. 6 About Here]

Not surprisingly, the high Anchor rates were one of the main drivers for the demand for UST and the Terra network in general. The left panel of Figure 7 plots the number of new addresses on Terra each day from April 2021 until the crash in May 2022. The lowest (blue) line of the graph indicates the number of addresses that start using Anchor from the first day that they are on the Terra blockchain. We interpret this as a sign that the main attraction for these users was the opportunity to gain access to the subsidized borrowing and lending rates on Anchor. The next lines plot users who started using Anchor within a week, within a month, and more than a month to use Anchor, and those that never used Anchor. These users are increasingly less likely to be participating on Terra only for the yield on Anchor but might have a broader interest in the ecosystem. The right panel shows the share of each group that eventually used Anchor.

[Fig. 7 About Here]

Figure 7 shows that the number of new addresses on Terra and those that use Anchor have been growing over time and that the majority of addresses that ever use Anchor do so on their first day. This dynamic supports the hypothesis that from the date of its creation, Anchor has been one of the main attractions for new users on Terra and the source of demand for UST.

In response to the increasing demand for UST, TFL significantly expanded UST supply. Figure 8 shows the aggregate supply of UST broken down by entities that swapped LUNA for UST. The entities include TFL and Admin addresses, Anchor, Bridges, CEX, DEX, and UST and LUNA locked in other DeFi protocols. The category 'Other' includes user accounts that are not part of the above categories.

[Fig. 8 About Here]

Recall that swapping LUNA for UST is the only way to create new UST. The top panel of Figure 9 shows the daily amounts of UST and LUNA swapped along with the cumulative net UST supply. The net volume is computed according to the following formula: swap amount + fee amount - offer amount, where swap amount + fee amount are from LUNA for UST swaps and offer amount is from UST for LUNA swaps. The bottom panel shows the UST dollar price. We can see that except for May 19-25 and January 27 when UST lost its peg, the volume of LUNA being swapped into UST significantly exceeds that of UST for LUNA swaps.

[Fig. 9 About Here]

The first large increase in the supply of UST occurred in February–March 2021 when the launch of Mirror protocol created a large increase in the demand for UST that led to the UST price to be significantly above $1. Because of the peg mechanism, these large deviations presented arbitrage opportunities and led to LUNA being swapped for UST. After March 2021, the supply of UST stayed around 2-2.5 billion until the next fork, the Columbus-5 upgrade.

The Columbus-5 upgrade introduced an important change in the economics of the Terra network. Prior to Columbus-5, only five percent of LUNA was burnt (destroyed) and the rest was sent to the community pool. Starting from Columbus-5, all LUNA swapped for UST were burnt. Terra Proposals 133 and 134 introduced by Terra founder Do Kwon and passed on November 10, 2021, directed that the 88.675 million Pre-Columbus-5 LUNA accumulated in the community pool should be swapped for UST. The immediate effect was a sharp increase in the supply of UST from 2.5 billion to 6.5 billion (which was placed in Admin accounts). The burning of the community pool also had important implications for the LUNA staking yield. Figure 9 shows that burning the community pool happened within a few days with volumes that far exceeded the daily swap limit of $135 million set at that time. As a result, these swaps incurred very large swap fees of 30% that were used to increase the LUNA staking yield to 10%, see Figure 4.

The supply of UST continued to increase and reached 18.5 billion by the time of the May 2022 crash. Figure 8 reveals that the majority of newly created UST ended up in the Anchor protocol. Right before the crash, Anchor held around 12 billion UST and the community account held another 3 billion.

The LUNA for UST swap fees after the burning of the community pool stayed around 1%. Figure 9 bottom panel shows that while the UST price was consistently above $1 during that period, the deviations were modest, typically within 25-50bp, which precluded any trading gains from swapping LUNA to UST.

This raises a questions of who was swapping LUNA for UST. Table 4 documents the top 26 addresses that swapped the highest amount of LUNA to UST. These addresses swapped 90% of the aggregate volume of swaps of LUNA into UST. Table 4 shows that except for the addresses of Terraswap route and Jump trading, the top 26 addresses are all controlled by TFL.

3.2.5. Concentration of the Anchor Holdings

Considering the substantial amount of UST that was locked in the Anchor protocol, it is important to understand the concentration of Anchor deposits. The more concentrated the funds on Anchor, the greater could be the potential impact could be from a single large participant moving funds from Anchor and exiting Terra.

The left panel of Figure 10 plots the percentage of deposits that the top 10, 100 and 1000 users constitute on Anchor on a given day, we filter out intermediary addresses fomr this analysis. We can see that the holdings were highly concentrated. Starting from January 2022, the top 10 addresses controlled between 15% and 20%, the top 100 addresses between 30% and 40%, and the top 1000 addresses around 60%. These numbers are similar to the concentration of bitcoin holdings and substantially higher than the concentration of wealth among the US households, see Makarov and Schoar (2021).

The right panel of Figure 10 shows the histogram of non-intermediary address balances on May 6, 2022. Among the total 160 thousand addresses, there are 109 addresses with the balance above 10 million UST with the aggregate balance of 5 billion UST, 1230 addresses with the balance between 1 and 10 million UST and the aggregate balance of 3 billion UST, 10,397 addresses with the balance between 100 thousand and 1 million UST and the aggregate balance of 2.7 billion UST, 40,688 addresses with the balance between 10 thousand and 100 thousand UST and the aggregate balance of 1.3 billion UST, and 63,360 addresses with the balance between 1 thousand and 10 thousand UST and the aggregate balance of 236 million UST.

[Fig. 10 About Here]

3.2.6. Anchor Accounting

We now show what subsidy rates mean for the daily cashflows of the Anchor protocol. Figure 11 shows the cumulative Anchor inflows and outflows. The inflows include the interests on the outstanding loans (blue line), the staking rewards produced by the staked collateral LUNA (red line) or ETH (yellow line), and proportional fees charged on the liquidated loans (green line). The outflows include the interests paid to depositors (gray line), and the buyback of ANC tokens from the Astroport DEX (teal line). The solid black line shows that net cash flows. We can see that starting from December 2021 the outflows vastly outpaced inflows. The difference was made up by the Anchor's yield reserve. The yield reserve makes up the difference when the cash flow is negative and receives the overhead when the net cash flow is positive.

The right panel of Figure 11 shows the balance of Anchor's yield reserve. Since the Anchor protocol was not self-sustaining, i.e. borrowing rates were not above lending rates, the yield reserve was depleting most of the time. As a result, TFL had to top up the balance of the yield reserve several times. the TFL first injected $71 million in July 2021 and LFG injected $510 million UST in Feb 2022 to the yield reserve. Both injections were funded by swapping LUNA for UST.

[Fig. 11 About Here]

3.2.7. Anchor Governance

Like many other protocols on Terra, Anchor was set up as a decentralized autonomous organization (DAO) with its own native governance token, ANC. Holders of ANC could stake their tokens to vote or propose changes to the protocol, and their voting power was proportional to the amount of ANC staked in the vote. ANC tokens were designed to capture a portion of Anchor's yield, scaling up linearly with the assets under management.

However, this design generated a misalignment in objectives between ANC and LUNA token holders. Maintaining a high and subsidized deposit rate on Anchor benefited ANC holders by driving demand to ANC, increasing assets under management, and with it, the fees going to ANC holders. But as noted earlier, this also contributed to the risks building up in the system and reduced the going concern of LUNA. ANC holders did not fully internalize the negative impact on the survival of the system. This misalignment became more pronounced when ANC holders had to decide whether to reduce the subsidized deposit rate and bring it in line with the fees generated from borrowing. This example illustrates one of the potential inefficiencies arising in a decentralized governance system, where it becomes more challenging to reconcile competing objectives between different parts of the ecosystem. For a more detailed discussion of DAOs and DeFi applications, see for example Makarov and Schoar (2022).

3.2.8. Anchor Entry and Exit Rates

Finally, we analyze how the participation of depositors and borrowers on Anchor evolved over time. Our goal is to understand what factors affected the growth of Anchor. Figure 12 plots the number of depositors that enter or exit Anchor as a fraction of the existing depositors on the previous day. The graph highlights that the depositor inflow was very high originally when Anchor was introduced in March 2021. We also see that periods of price increases of LUNA seem to be accompanied by more deposits on Anchor. We also observe the sharp spike in entry rates in November 2021, which is due to TFL minting lots of UST as discussed above. Similarly we see that the exit rate spiked around the two prior de-pegging events in May 19-25 2021 and January 27, 2022. But exit rates dropped again after each of these events, and entry resumed, once the peg was reestablished and market participants became more comfortable again. Finally, we see that starting in April 2022, exit rates started accelerating and entry dropped sharply. We interpret this dynamic as an indication that some traders started having concerns about the sustainability of Anchor rates.

[Fig. 12 About Here]

4. LUNA and UST Run

While we cannot say with certainty whether the run on UST was inevitable, our analysis shows a pattern of events that closely resembles models of runs which highlight the interaction of worsening fundamentals and strategic behavior by traders, such as Morris and Shin (1998) or Goldstein and Pauzner (2005) and Goldstein (2013), Abreu and Brunnermeier (2003). In these models agents receive private and public signals about the strength of fundamentals. A common public signal acts as an additional coordination device for agents' actions. In the context of cryptocurrencies, since actions of the agents on the blockchain are observable, agents can also monitor each others actions and react to them.

Our analysis above documents a set of worsening fundamentals of the network over the first few months of 2022, which investors could have observed. These include the balance of the Anchor yield reserve dropping as the subsidies to Anchor were becoming increasingly harder to sustain, as well as the price of LUNA declining in line with a general drop in cryptocurrency prices which reduced the relative market valuation of LUNA versus UST outstanding. We show that already in April 2022, some investors seem to have become concerned about the health of the network as evidenced by a sharp decline in the entry rate an increase in the exit rate from Anchor.

Following a general decline in cryptocurrency prices the gap between the market cap of LUNA and UST had been shrinking since mid-April. On May 7, the gap was around $4 billion, as shown in Figure 13. It closed completely in the evening of May 9 and coincided with the time when the UST price plummeted to $0.75. As we discussed in Section 4, if investors were fully rational and took into account the dilutive effect of UST on LUNA the crossing point would not necessarily play a significant role for the valuation of LUNA. However, if investors priced LUNA independently from UST and the conversion of UST to LUNA has a negative effect on the LUNA price, the crossing point could serve as a salient synchronization event. The synchronization between the market cap of LUNA and UST equalizing and the drop in the price of UST suggests that it might have been another coordinating event for holders of UST. The discussions on many social media sites indicate that many market participants viewed LUNA pricing largely independent from the outstanding supply of UST. In their mind, the moment the market capitalization of LUNA and UST crossed, is a signal that there was not enough value in the LUNA network to support the value of all the UST outstanding.

[Fig. 13 About Here]

Finally, the beginning of the run coincided with the re-balancing of the UST-3Crv pool, since TFL was planning to establish a new liquidity pool on Curve involving a different set of stable coins. While the re-balancing of the Curve pool is not an adverse event, when fundamentals are weak, even an apparently innocuous event could serve as a coordinating event for the run. All these were warning signs that should have made market participants start paying attention to mounting risks on Terra.

4.1. The Timing of the Run

The first signs of the run appeared on May 7, 2022, as has been reported in several industry reports and on social media.[18] On that day, two addresses dubbed wallet A and B withdrew 400M UST from Anchor.[19] The withdrawals were made in batches and sent to Curve and Binance, which were the most liquid UST DEX and CEX exchanges, respectively. The top two panels of Figure 14 show the exact timing of these withdrawals. Wallet A was the first to withdraw 45M UST around 5am UTC and it sent the funds to Binance. Following this event, wallet B withdrew 175M UST around noon and sent the funds to Ethereum using the Wormhole bridge, but did not

[18] See for example, an insightful report by Nansen at https://www.nansen.ai/research/on-chain-forensics-demystifying-terrausd-de-peg.

[19] The wallets A and B allegedly belong to Jane Street and Celsius, see https://twitter.com/FrankResearcher/status/1630545591397670916.

make any trades at that time. Next, wallet A withdrew another 35M around 5pm, and then another 20M around 8:30pm and 9:30pm, again sending all the funds to Binance. Finally, at 21:48pm wallet A withdrew the last 85M and send them to Curve. The bottom panel of Figure 14 shows the timing of all other Anchor deposits and withdrawals on May 7. The deposits are colored in green and withdrawals in red. We can see that starting from 12pm other large wallets started moving out of Anchor.

[Fig. 14 About Here]

Concurrent with an increase in Anchor withdrawals, the UST price on both Curve and Binance began falling. The top panel of Figure 15 shows the swap transactions price of UST against three major stablecoins, USDT, USDC, and DAI on May 7, 2022. Swap transactions of UST into the other three stablecoins are colored in red, and swaps into UST in green. The y-scale is logarithmic. The bottom panel of Figure 15 shows the net signed volume and the deviation of the UST price from $1 in basis points.

Figure 15 highlight that during the day on May 7, swapping out of UST intensified, leading to a gradual increase in the UST discount. The selling activity increased sharply after 21:44pm, which is marked by the dashed gray line and corresponds to the moment when TFL removed 150M UST from the UST-3Crv pool to send it to a new UST-4Crv pool. This was a preplanned transition, since the new pool was supposed to go live on Ethereum the week after. Terra together with FRAX, another algorithmic stablecoin that was growing at the time, aimed to set up a separate Curve pool to create more liquidity and generate higher yields for their stablecoins.

Note that the withdrawal of 150M UST from the UST-3Crv by itself is not an adverse event for investors who are worried about the convertibility of UST into other stablecoins because the amount of other stablecoins available to withdraw remains unchanged. In fact, the removal of UST increases the UST price vis-a-vis other stablecoins because it decreases the supply of UST relative to the supply of other stablecoins, which is reflected in the small decrease in the UST discount immediately following the event.

The withdrawal of 150M UST by TFL was followed as we describe above by wallet A withdrawing 85M UST from Anchor and selling the whole amount on Curve in one transaction. The immediate effect of this trade was a widening of the UST discount to 80bp. This event was succeeded by a flood of other large sales, in particular a trade by wallet B, which sold 150M UST transferred to Ethereum earlier that day. It is interesting that while wallet B seemingly prepared for a possible sale earlier that day, it only started actively selling its UST once other large traders started exiting and the price dropped. As a result, the UST discount on Curve reached 250bp. In response, TFL Curve bots started actively trading in an attempt to restore the peg. We see that they partially succeeded by reducing the UST discount to 50bp for the rest of the day on May 7.

[Fig. 15 About Here]

The UST discount on Curve was mirrored by that on Binance. The top panel of Figure 16 shows the UST/USDT trades. Sell-initiated trades are marked in red and buy-initiated ones in green. The y-scale is logarithmic. Similar to the Curve graph, the bottom panel shows the net signed volume and the deviation of the UST price from $1 in basis points.

Comparing trades on Curve and Binance we can see that there were many more trades on Binance, but they were smaller in size. Because of Curve's pricing mechanism large orders have smaller price impact on Curve than on Binance and therefore Curve attracted larger traders. Another reason for the smaller trade size might be that there were more retail investors on Binance, who usually trade in smaller quantities. Interestingly, while the UST discounts on both exchanges were highly correlated, the signed volume moved in the opposite direction. The cumulative net selling volume on Curve was around 200M UST. This in in contrast to the net buying volume of 200M UST on Binance. Thus, the UST price and signed volume moved in the opposite direction on Binance on May 7, which is contrary to what is normally observed in many markets.[20] This negative relation could realize, if sellers on Binance placed large limit orders at the current price, which has been filled by buy market orders. The buy market orders could have come either from "noise traders" who tried to "buy the dip", or from parties like TFL that tried to defend the peg.

[Fig. 16 About Here]

Finally, Figure 17 plots the evolution of the aggregate hourly balance of total deposits on Anchor and the price of UST in the week after May 7. It shows that investors continued to withdraw funds from Anchor, but the UST price remained close to $1 until the evening of May 9th. During that time, TFL and LFG tried to defend the peg by a series of actions aimed at buying UST and support the price. The LFG audit report documents that during this period TFL and LFG spent a total of about $2.5 billion (80,071BTC, 26,281,671USDT, and 23,555,590 USDC) on purchases of UST and LUNA.[21] Late on May 9, the withdrawals from Anchor accelerated and the UST price

[20] See for example, Evans and Lyons (2002), Chordia et al. (2002), Hasbrouck (1995) or Hendershott and Menkveld (2014) or for crypto markets see Makarov and Schoar (2020)

[21] See the Audit Report by JS Heldt, Analysis – Terraform Labs' and Luna Foundation Guard's Defense of the UST Price Peg, November 2022.

dropped precipitously to \$0.75. It hovered between \$0.2 and \$0.9 for a few days before completely imploding. By the end of May 13, less than 2B UST remained on Anchor and the UST price fell below \$0.2.

[Fig. 17 About Here]

4.2. Swapping of UST and LUNA

The UST peg design added an additional dimension to the investors' strategy space. Whenever the price of UST falls below \$1, investors who no longer wish to hold it could follow two main strategies. They could either (1) sell UST at the market price or (2) could swap UST for LUNA for its nominal value and then sell LUNA at the market price. In the absence of frictions, the second option would deliver them strictly higher profits, which increases with the size of the UST discount.

In practice, investors faced several frictions. First, as discussed in Section 2.2, to prevent oracle price manipulation the native swap contract had built-in fees that were designed to increase with the volume. Second, trades in both the LUNA and UST markets were subject to price impact — a co-movement of prices in the direction of trades. Finally, there could be a delay between the time investors send their funds to an exchange and the time their funds are cleared for trading. This delay becomes especially important if investors anticipate that other investors will sell their LUNA holdings, which would result in a predictable decline in the future price of LUNA.

Figure 18 documents the trading activity in the native swap market from May 7, 2022 to May 13, 2022, when the convertibility between UST and LUNA got suspended. The top panel plots the UST discount and the swap fees over time. The middle panel shows the difference between the UST discount and the swap fees that measures the attractiveness of swapping UST for LUNA over selling UST at the market price. The difference can also be thought as an arbitrage spread from buying UST at the market price, swapping it for LUNA, and selling LUNA at the market price. Finally, the bottom panel shows the dollar amount of UST that were swapped in a given minute.

[Fig. 18 About Here]

Figure 18 shows that the UST discount, the swap fees, and swap volume closely followed each other. As the UST discount widened investors found it increasingly more profitable to swap UST for LUNA and engage in the UST-LUNA arbitrage. In the May 7–13 period, users swapped 7.42 billion UST worth \$4.65 billion.

Table 5 shows the top 20 addresses that swapped the largest amount of UST over the run period. The largest amounts were swapped by two unknown smart contracts that arbitraged the relative price of UST and LUNA between Terra's main DEX, Astroport and the native swap contract. Alameda Research, a cryptocurrency trading firm co-founded by Sam Bankman-Fried and closely linked to FTX exchange, swapped the third largest amount. The case of Alameda Research is interesting because most of the top addresses did not have exposure to Anchor and used swaps to perform the UST-LUNA arbitrage. We estimate that out of 12 UST billion Anchor balances at most 700 million UST were routed to the native swap with the majority of funds sent to CEXs and DEXs. Out of the top 20 addresses in Table 5, only Alameda Research and terra1…4c2t held a balance on Anchor (311M and 73M UST, respectively). It seems that the swap fees and uncertainty about the execution price of LUNA on CEXs prevented most market participants from using the native swap contract as an escape rout. But Alameda Research with its favorable access to the FTX exchange had an advantage over other players and appears to have exploited it.

Figure 19 shows that as users swapped UST for LUNA, the price of LUNA precipitously declined leading to a situation where the ever increasing amounts of LUNA were swapped in exchange for UST. From May 11 to May 13, the LUNA supply increased from less than 1 billion to 5.89 trillion, while the price of LUNA dropped from \$50 to $\$10^{-6}$. In economic terms, the falling price of LUNA meant that investors running from UST into LUNA created increasing dilution and with it further depressed the price of LUNA, which led to a dramatic "death spiral."

[Fig. 19 About Here]

The enormous increase in the LUNA supply also had important implications for Terra's governance. Since Terra uses a system of one LUNA-one vote, owners of newly issued LUNA de facto obtained control over the Terra network as they were diluting the positions of existing holder of LUNA. To defend its dominant position in the network, TFL swapped a large amount of UST for LUNA.

4.3. How Did Investors Run?

We finally study how investors ran and the magnitude of the losses they experienced at the end of the run. Since one of the main premises of Terra and permissionless blockchains more generally is the equal access and democratization of finance, we want to evaluate how different types of investors were able to exit through the run. An important advantage of the observability of transactions on the blockchain is that we can observe the transactions of individual investors over time. This information allows us to infer investors characteristics such as wealth and sophistication. We can build a proxy for investor wealth, since we observe the balance of each address prior to the run. To sort investors according to their sophistication, we assume that the usage of complex protocols (such as bridges) or complex strategies (such as using multiple CEX and DEX) are signs of investor sophistication.

We first analyze withdrawals from Anchor broken out by the size of the deposit balance of addresses before the run, as of May 6th. We drop from the sample any addresses held by intermediaries or large institutions and focus on individual addresses. We also remove addresses with less than 100 UST in Anchor. Figure 20 shows a stark gradation by size, with the largest addresses running first and the smaller groups lagging. The largest group, addresses with more than 10 million UST, withdrew their funds on average much earlier and more decisively, so by the end of May 12 that group had withdrawn almost 100% of their balance. In contrast, addresses with 1,000 to 10,000 UST started running almost two days later and by the end of May 12 still had about 50% of their balance still on Anchor. In fact, the smallest category, addresses with below 1,000 UST on average kept adding deposits to Anchor until May 10th, after which date they also started decreasing their balances. But by May 11 they still had about 80% of their pre-run balances on Anchor.

[Fig. 20 About Here]

The total loss that different depositors encountered not only depends on the speed with which people ran but also how decisively they exited their holding. We see that some people even added deposits during the early part of the run, maybe in a misunderstood attempt to "buy the dip".

To calculate the total loss for each address we adopt the following strategy. We calculate the USD value of each address' token portfolio at the start of May 6 and mark it to market. The portfolio covers UST, LUNA, aUST, bLUNA, bETH, and ANC holdings. Then we calculate the USD value of inflows and outflows of these five tokens over the days of the run, where we again mark every token transfer to market. Since some addresses have token holdings outside of the Terra blockchain, such as Ethereum bridges or CEX, we also regard any inflows before the first outflow as part of the initial balance, which we call the balance adjustment. Finally, we calculate the ending balance at the end of May 13 and again mark it to market. We compute the loss as:

$$\text{loss} = \left(1 - \frac{\text{post-run USD balance} + \text{USD outflow} - \text{USD inflow} + \text{adjustment}}{\text{pre-run USD balance} + \text{adjustment}}\right) \times 100\% \tag{1}$$

Since we do not have reliable price data for some of the minor tokens, there are a small number of addresses that have outliers in the losses. We winsorize the losses at the 0.5th and the 99.5th percentiles.

We first tabulate the average size of the loss by the pre-run size of the address in Table 2. Losses decrease monotonically in size, with the addresses above 10 million experiencing a 26% loss and the addresses above 1 million experiencing a 32% loss. In contrast the smallest addresses with below 10,000 UST or even below 1,000 UST lost an average of 60% and 76%, respectively.

Since size might be correlated with other characteristics, especially financial sophistication, we now analyze the percentage loss of an address as a function of size, financial sophistication, and the age of the address. Age is measured as the months since the address was established. As discussed before, participants can set up new addresses if they choose to. Therefore, the measure of age is probably a lower bound on the true age of a participant. Some older participants might have set up new addresses which means we might have attenuation in the age measure. Our measures of sophistication are derived from observed prior transactions on the blockchain. In particular, we construct (1) a measure of how many different CEXs the address had used as a proxy for arbitrage trading, (2) a dummy for whether the address had ever used a bridge, like Wormhole or Shuttle, to move assets across blockchains, and finally (3) we measure the trading activity as the volume of token inflows in US dollars divided by the token balance in US dollars before the run.

Table 3 Column (1) shows the results from a multivariate regression of the percentage loss of an address over the period from May 6 to the end of May 13 on log size, log age in months plus one on Terra, and our measures of sophistication. Column (2) repeats the same regression but uses dummies for different size bins instead of continuous variable of log size. As in the descriptive statistics, there is a strongly negative and significant relationship between the balance at the beginning of the run and the loss an address experienced. Columns (2) shows that the largest addresses with balances above \$10M had a 45% smaller loss compared to the smallest addresses with balances below \$1K.

Column (2) also shows the variation in losses that is explained by our measures of financial sophistication controlling for size. The ratio of trading volume divided by the balance, the number of CEX used by an address and whether it ever used bridges have a large and significant relation with the loss during the run. In contrast, log age has a positive and significant relationship with losses. While age of an address is only a noisy proxy for whether the owner of the address is new to Terra Luna, it suggests that older addresses might have been more willing to believe in the stability of the system. This might be a reflection that their owners are more committed to the ecosystem overall and thus did not want to destabilize it or they experienced the first crash in May 2021 and thus felt that they had seen stability in the system. But the fact that the estimated coefficient is positive on age also suggests that experience alone is not the reason why some depositors fair better during the run. In other words, our measures of sophistication appears to be distinct from just experience with Anchor or the Terra ecosystem.

In Columns (3) to (8), we now analyze if the importance of sophistication measures varies across the size distribution. For this purpose, we repeat the same specification but we break out addresses by the size of the balance before the run started. We use the following size bins in UST: below 1,000, 1,000 – 10 thousand, 10 – 100 thousand, 100 thousand – 1 million, 1 – 10 million, and above 10 million UST. We see that across the size distribution, addresses which score higher on sophistication as measure by the use of bridges, a larger number of centralized exchanges or a higher fraction of trading volume to balance, experienced smaller losses. Interestingly the importance of sophistication seems higher for smaller and mid-sized addresses, while for the very largest addresses, above $10M, none of the sophistication measures are significant. Similarly, the positive relationship between losses and the age of an address is significant and comparable in magnitude across addresses with different balances. Thus independent of the size of the balance, older addresses are more likely to experience losses since they tended to run later. Again the exemption is the subsample of the very largest addresses, above $10M, where we do not see a correlation between age and the size of the loss. The results suggest that for the very largest addresses our metrics of sophistication do not capture the difference in their trading strategies, most likely since they are all relatively sophisticated and were aware of the changes on Terra. In addition, since this group only includes 109 addresses, idiosyncratic differences may play a larger role here than for the other subgroups.

In summary, our findings have important implications for understanding the risks and benefits of the open blockchain architecture in creating a level financial playing field. Although information about prices and trades of large wallets on the Terra blockchain was observable to all depositors, outcomes were highly uneven. The larger losses experienced by smaller and less sophisticated depositors are not explained by some depositors having unfair access to bank representatives or insiders, an issue that has been highlighted for traditional banks, an issue that has been highlighted for traditional banks. For example, Iyer et al. (2016) shows that bank staff or depositors connected to bank insiders experienced smaller losses in a run. Instead, our results suggest that many participants lacked the ability or founded too costly to process information in real time. As we have shown, many small depositors re-entered Anchor to "buy the dip" while large wallets were withdrawing. Thus, open access and the transparency of the blockchain do not compensate for differences in financial literacy and wealth and may even exacerbate them.

5. De-pegging Event in May 2021

As mentioned in Section 3.2.4, May 2022 was not the first time UST de-pegged from parity with the US dollar. Terra experienced a prior de-pegging event between May 19 and May 25, 2021.[22] The comparison with the May 2022 crash is interesting since it foreshadowed some of the risks and economic mechanisms that were important later on. It also allows us to analyze why some of the interventions that TFL undertook to stabilize the price of UST might have worked during the first de-pegging event but not during the crash in May 2022.

The de-pegging started on May 19 2021, when China announced a crackdown on the use of cryptocurrencies, and the price of LUNA fell from \$16 to \$4. Many other cryptocurrencies also experienced a drop in price at this time. The significant drop in the price of LUNA resulted in its market capitalization declining to a level close to the aggregate market value of UST, as illustrated in Figure 21. As discussed before, the market capitalization of the two coins approaching each other may not hold any particular significance for fully rational investors who up front factor in the potential dilution from swapping UST into LUNA. But many investors appeared to have bought into the narrative that this point signaled insufficient value in LUNA to support the value of UST, thereby serving as a strong indication to sell.

[Fig. 21 About Here]

The upper panel of Figure 22 documents swap transactions of UST against three major stablecoins, USDT, USDC, and DAI, occurring between May 17$^{\text{th}}$ and May 29$^{\text{th}}$, 2021, on the UST-3Crv pool. During the period of the first de-pegging event, this was the most liquid marketplace where UST could be exchanged for other stablecoins. The bottom panel shows the net signed volume (blue) and the deviation of the UST price from \$1 in basis points (black).

[Fig. 22 About Here]

Similar to the later de-pegging event in May 2022, we initially see intensified selling in particular by larger addresses. Between 19$^{\text{th}}$ and May 24$^{\text{th}}$, investors sold a net value

[22] There was also a second smaller de-pegging on January 27, 2022. But this episode was short lived and relatively minor.

of 25 million UST, resulting in a 10% discount on UST. In addition, we show that there were four addresses, which purchased a combined 135 million UST during this period. Had it not been for the aggressive support of UST by these addresses, the discount on UST would have been significantly greater.[23] The swaps into UST initiated by the four addresses are represented by blue triangles, while the swaps into UST initiated by other addresses are represented by green circles. Swaps of UST into the other three stablecoins are depicted by red circles.

In addition, we see that similar to the May 2022 crash, the decline in the UST price coincided with investor withdrawals from Anchor. Figure 24 shows the outstanding deposit balance in Anchor.

[Fig. 24 About Here]

When we decompose how different participants ran, we see that as in the May 2022 crash, withdrawals were concentrated among wealthier investors, while low-wealth investors continued pouring their funds into Anchor, see Figure 25.

[Fig. 25 About Here]

Lastly, we examine the effectiveness of the native swap mechanism in safeguarding the peg. When the price of UST drops below 1, the peg mechanism is designed to incentivize arbitrageurs to purchase the discounted UST, swap it for LUNA, and receive the equivalent of $1. First, we note that because of the swap fees, as in May 2022, the swap spread closely tracked the UST discount restricting the ability of arbitrageurs to participate in the mechanism, see Figure 23. In fact, many participants in the Terra ecosystem were worried at the time about the potential disincentive effects of the protocol design, and several articles on social media even blamed the de-pegging event itself on the design of the on-chain redemption cap.[24]

But as discussed in Section 4.2, while the mechanism can support the price of UST, it can also contribute to a death spiral if investors who swap UST for LUNA decide to sell their LUNA holdings. Thus, it is important to understand as to why the run was avoided in May 2021, but not in May 2022.

A critical factor appears to be that the outstanding supply of UST was much smaller in May 2021, which enabled TFL to function as a lender of last resort. Table 6

[23] These four addresses are 0x5dd09afc9ca51b46d6cda2189478b505ace7f37b, 0xe3bdda6413313ed58585e47441815e9662bdd818, 0x2747363d886c7fdcc5187217f1ca493922aa4940, and 0xaf7bbcfb1c1f987e0ae409c684289b332a425254. They bought 66M, 33M, 19M, and 17M, respectively.

[24] See, for example, https://medium.com/coinmonks/should-depositors-in-anchor-protocol-pay-attention-to-ust-de-peg-risk-8b59849d75bf.

displays the top 20 addresses that swapped the largest quantity of UST during the de-pegging period. In contrast to May 2022, nearly all swaps were initiated by TFL, which presumably held onto the newly swapped LUNA instead of selling it.

The lawsuit initiated by the SEC against TFL provides further insight into the events. The SEC alleges that the peg was restored due to purchases of UST by a third party, which has been identified as Jump Trading. Over the period of the run, between May 23 through May 27, Jump made net purchases of over 62 million UST across at least two crypto asset trading platforms. In return, Jump allegedly received allocations of UST from TFL at a heavily discounted price of $0.4 to compensate them for the stabilization trades.

If the SEC allegation is correct, the fact that market participants in May 2021 were unaware that TFL and Jump Trading were engaging in the stabilization of UST could be an additional important factor why the run was avoided in May 2021. When market participants saw the price re-pegging, they interpreted it as a sign of the system's stability. In contrast, in May 2022, traders were aware of the fact that TFL was using funds held in LFG addresses to support the peg. They also knew that the supply of UST and the amount of UST locked in the Anchor protocol was significantly larger than the amount available to support the peg. Thus, traders might not have believed that the stabilization would succeed.

6. Conclusion

This paper provides a detailed analysis of the run on Terra and identifies the underlying economic mechanisms and risks within the ecosystem that led to the crash. We show that the significant increase in UST issuances combined with the highly subsidized deposit rates on Anchor created an unsustainable and fragile system. The price of LUNA initially rose strongly with the rapid inflow of depositors to Anchor, but participants may not have fully understood the underlying economics and not have priced in the potential dilution from the outstanding supply of UST. Our analysis suggests that the run on Terra was not due to targeted market manipulation by a single entity, but rather emerged from increasing concerns regarding the viability of the system.

The run on Terra on May 7th began with a few large investors withdrawing their UST deposits from Anchor and selling them on exchanges. We observe large differences in the run behavior across sophisticated and less sophisticated investors, with the latter group being much slower to run and often did not fully exit even conditional on withdrawing some funds. Some of these participants even reinvested during the run in an apparent attempt to "buy the dip."

In contrast to traditional financial institutions, blockchain and price data were in principle observable to all investors. However, we find that larger and more sophisticated investors withdrew their funds more quickly and decisively. These results underscore the fact that observability and free access do not, by themselves, level the playing field for investors if there are significant differences in their ability to process and interpret information.

The highly subsidized deposit rate on Anchor made some observers compare the economics of Terra-Luna to a Ponzi scheme. Our analysis does show that the Anchor protocol was a major factor driving the strong demand for UST. It likely also contributed to the high price of LUNA since UST was issued by converting LUNA into UST. But it is important to note that unlike in a classical Ponzi scheme, the amount of subsidies provided by TFL was recorded on the Terra blockchain and, in principle, observable by all investors. However, it is unclear to what extent investors understood the precarious nature of UST claims and the possible impact of UST conversion on the LUNA price. By aggressively underplaying the risks building up in the system on social media and other outlets, Terra insiders likely contributed to the hype about the network.[25] This highlights the limitation of transparency, especially for complex systems like Terra-Luna. Ultimately, the sustainability of the DeFi ecosystem depends on the ability of investors to make informed decisions and hold projects accountable for their actions.

[25] https://markets.businessinsider.com/news/currencies/terra-usd-ust-luna-do-kwon-poor-critics-crypto-crash-2022-5

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Figures

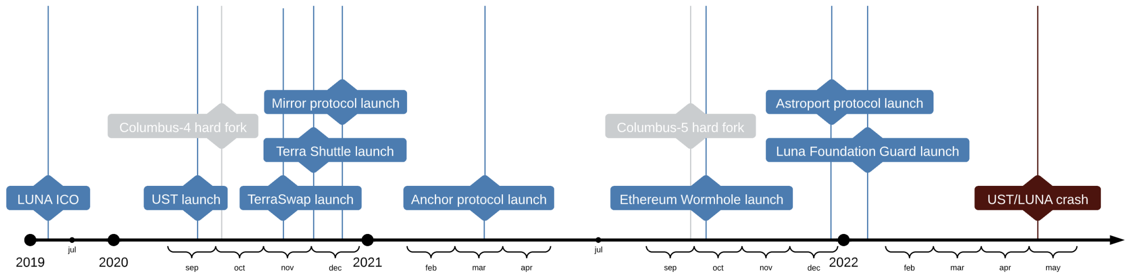

Figure 1: Terra timeline. This figure shows the timeline of major events in the development of the Terra Luna network. Blue markers represent the launch of various protocols. Gray markers indicate major network upgrades, also known as hard forks. The depeg event is marked in red.

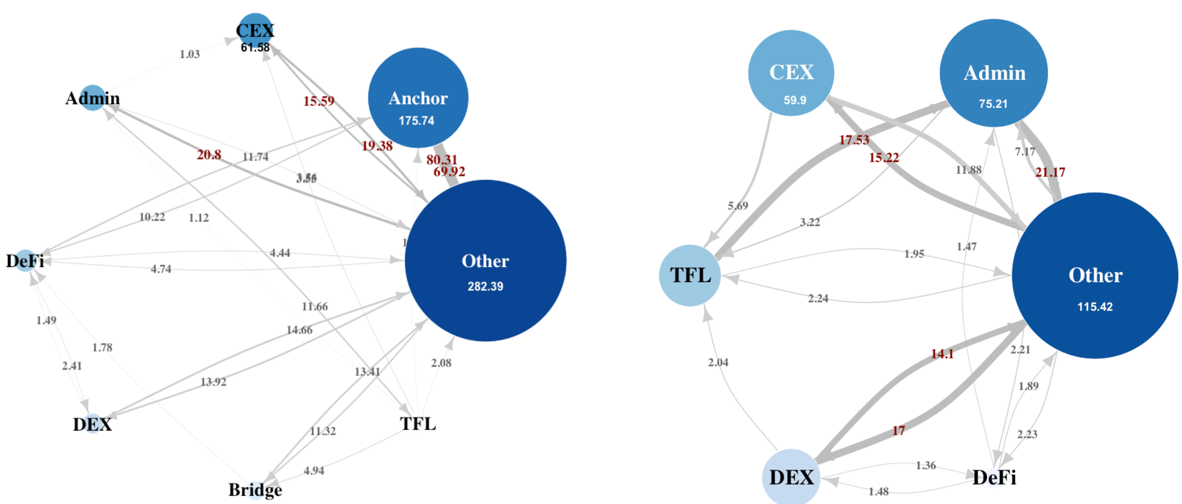

Figure 2: Network volume of UST (left) and LUNA (right). This figure shows the largest nodes in the Terra Luna network by transaction volume and the flow of volume between nodes. The size of the node reflects the total volume that flows through the category. The (grey) edge size between nodes is proportional to the volume between the two nodes. The numbers next to an edge show the corresponding volume. Definitions of the entity groups are in the text. We only show categories with at least \$10 billion of total volume in the UST network and \$5 billion in the LUNA network, and edges with at least \$1 billion of volume.

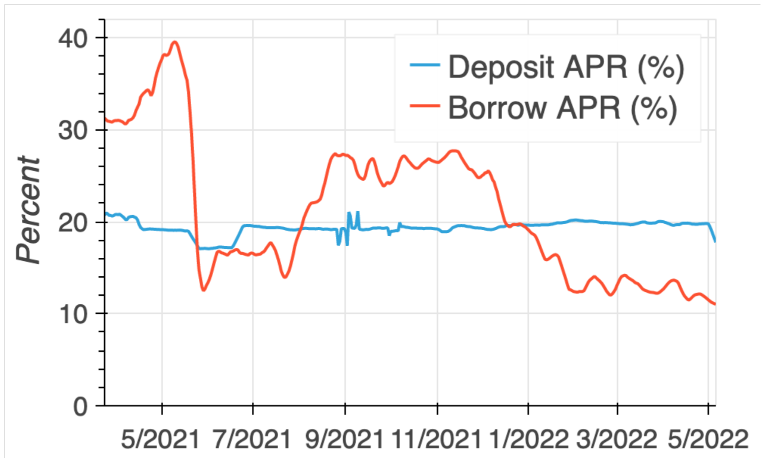

Figure 3: Anchor gross rates. This figure shows the daily APR of lending and borrowing on Anchor before subsidies by TFL and collateral yield. The annual deposit rate was set at 19.5%. The annualized borrowing rate was set as an increasing function of the proportion of outstanding loans to outstanding deposits. The series are smoothed with 7-day rolling averages.

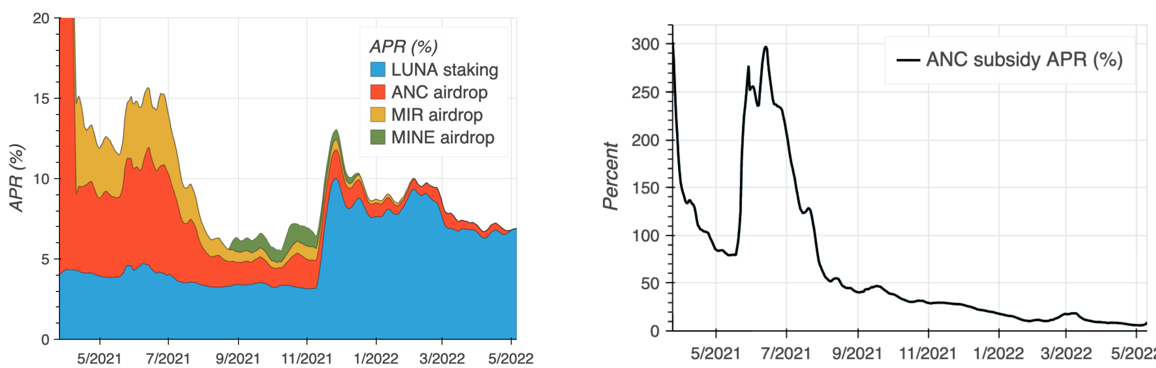

Figure 4: Anchor borrowing costs and incentives. The left figure shows the opportunity cost of LUNA collateral broken out by the source of the yield on LUNA tokens. The two main sources are block rewards and airdrops, which are token allocations to reward participants. To value the airdrops we assume a borrower sells weekly token airdrops during the week after receiving them. The right panel shows the annualized subsidy rate on Anchor, which was distributed to borrowers via ANC, Anchor native token. The series are smoothed with 7-day rolling averages.

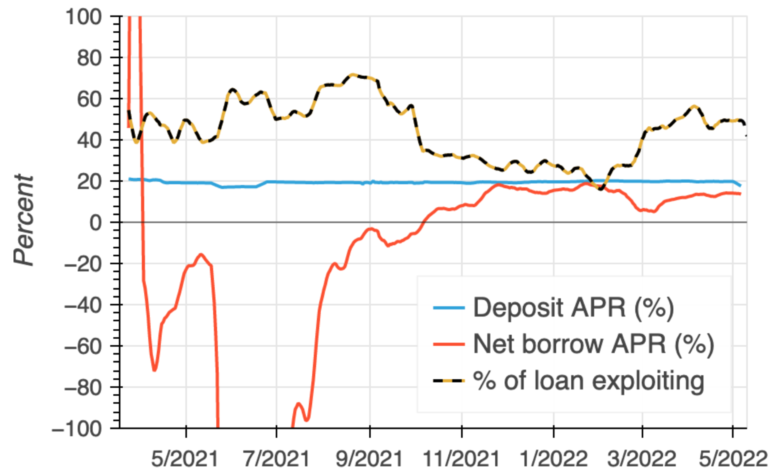

Figure 5: Anchor net rates and exploiting loans. This figures shows the daily APR of lending (blue line) and borrowing (red line) on Anchor after considering the opportunity cost of the collateral and the ANC subsidy. We assume borrowers use the minimum permitted amount of collateral by the LTV limit and sell ANC subsidies after receiving them. The dashed line shows the proportion of loans from Anchor that are posted back to Anchor as deposits. The series are smoothed with 7-day rolling averages.

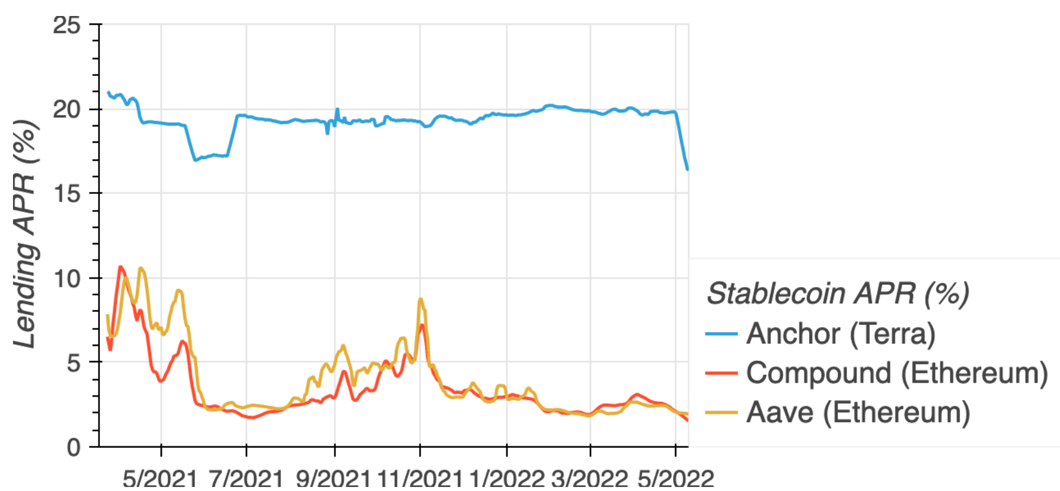

Figure 6: Stablecoin rates on competing platforms. The figure compares the lending rates on Anchor, Compound, and Aave from May 2021 to the end of May 2022. The rates on Compound and Aave are the average rates of Tether (USDT), USD Coin (USDC), and Dai. The series are smoothed with 7-day rolling averages.

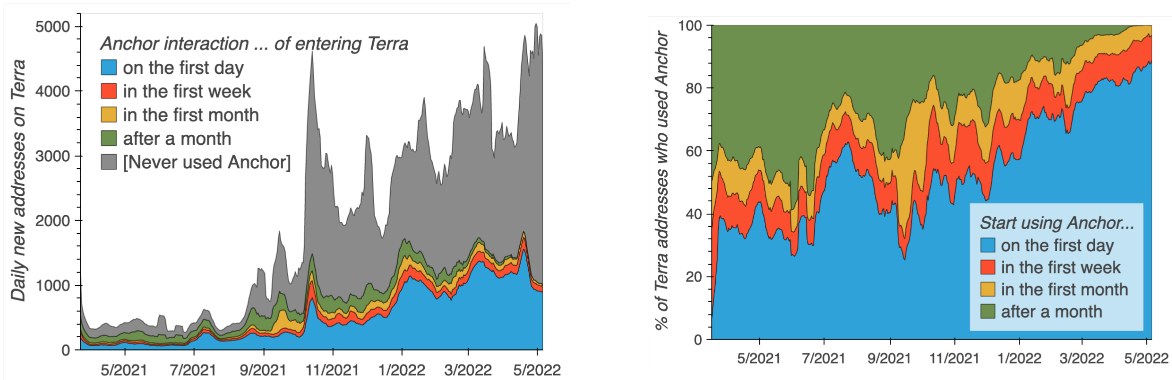

Figure 7: New Terra addresses and time to joining Anchor. This figure shows the number of new addresses on TerraUSD each day, broken out by how soon they start using Anchor. The lowest blue line are users who start using Anchor immediately on their their first day, then next group are those who start using it within a week, etc. The gray ribbon shows the addresses who joined the network but never used Anchor. The series are smoothed with 7-day rolling averages. The right panel shows the share of each group that eventually used Anchor.

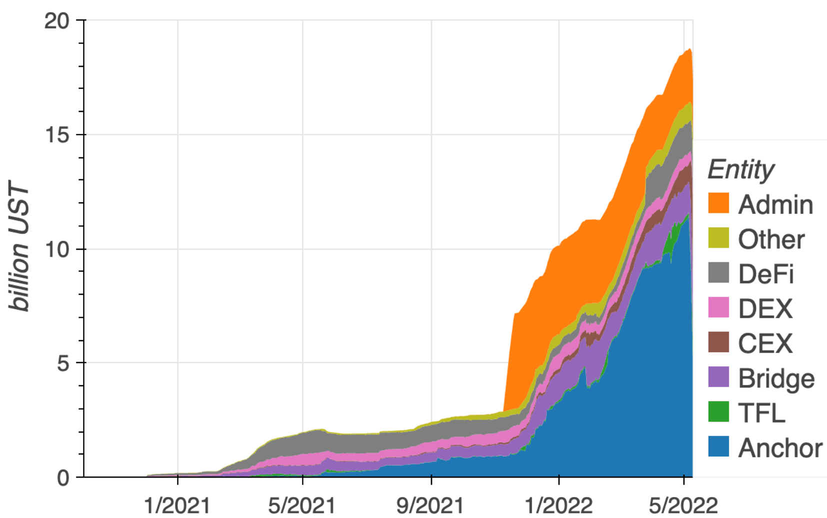

Figure 8: UST supply by entity. This Figure breaks out the aggregate supply of UST by the types of entities that held them. Definitions of the entity groups are in the text.

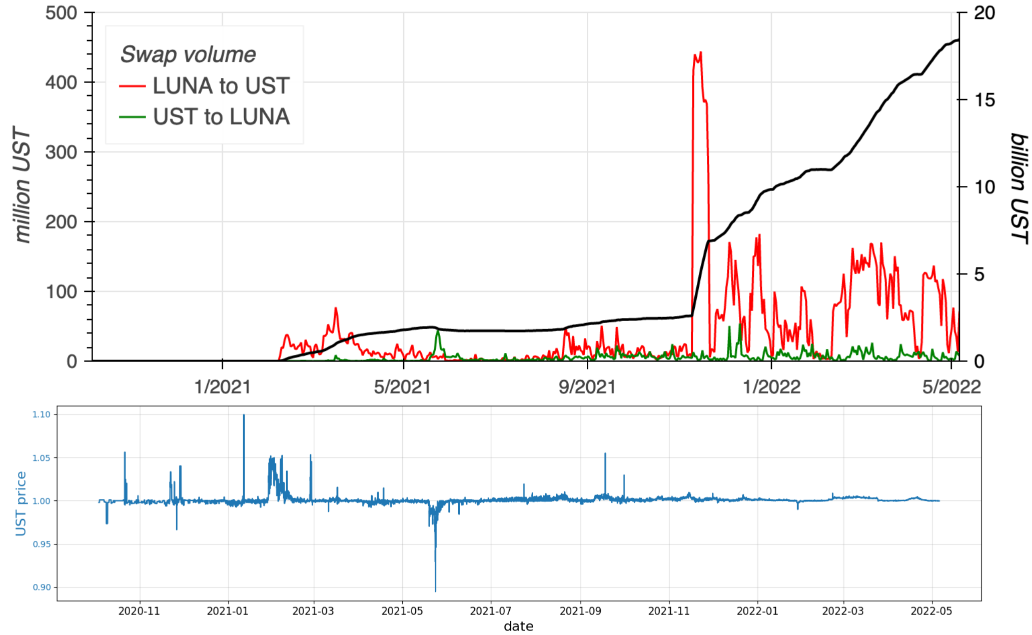

Figure 9: UST-LUNA swap volume and UST price. The top panel shows the daily amount of UST and LUNA swapped (left axis) along with the cumulative net UST supply (right axis). The net volume is computed as: swap amount + fee amount - offer amount. The bottom panel shows the UST dollar price.

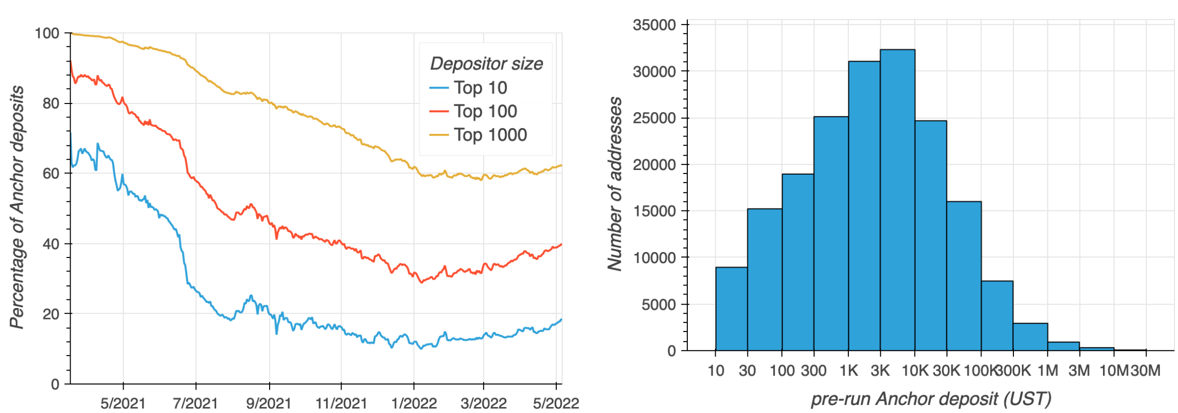

Figure 10: Concentration of Anchor deposits. The left panel plots the percentage of deposits held by the top 10, 100 and 1000 users on Anchor on a given day between May 2021 and May 2022. The right panel plots the histogram of the number of wallets by size of deposits on Anchor before the run on May 6, 2022. We exclude addresses that are exchanges, smart contracts, or other intermediaries.

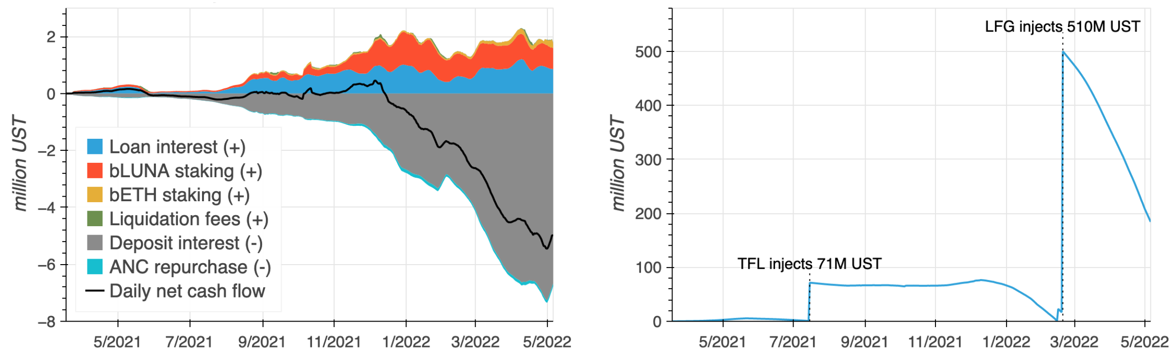

Figure 11: Cash flow decomposition on Anchor. The left panel shows the daily inflows (positive) and outflows (negative) on Anchor in billion UST broken out by their sources. Inflows include the interest on outstanding loans (blue), the staking rewards produced by the staked LUNA as collateral (red) or ETH as collateral (yellow), and proportional fees charged on the liquidated loans (green). Outflows include the interest paid to depositors (gray), and the buyback of ANC tokens from the Astroport DEX (teal). The black line plots the daily net cashflow. The right panel shows the balance of the Anchor's yield reserve address, as well as two waves of UST injections by TFL and LFG into the address.

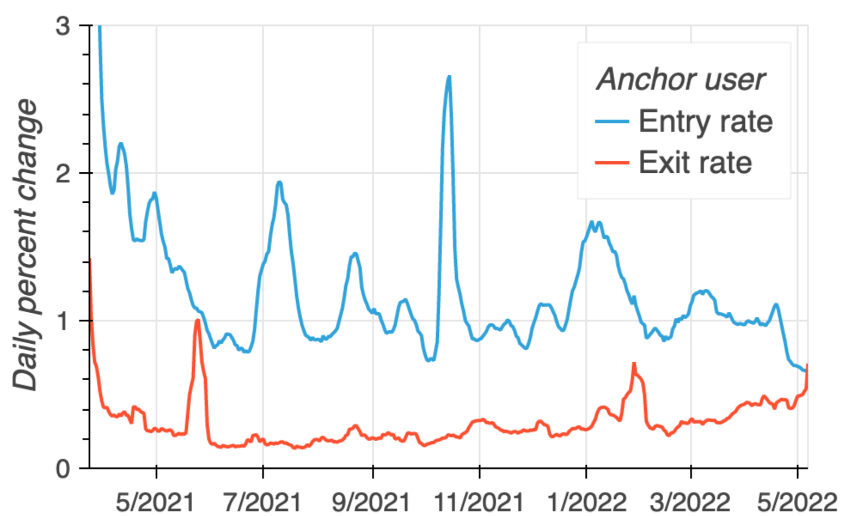

Figure 12: Entry and exit rates of Anchor users. This figure plots the number of depositors that enter or exit Anchor as a fraction of the existing depositors on the previous day. The series are smoothed with 7-day rolling averages.

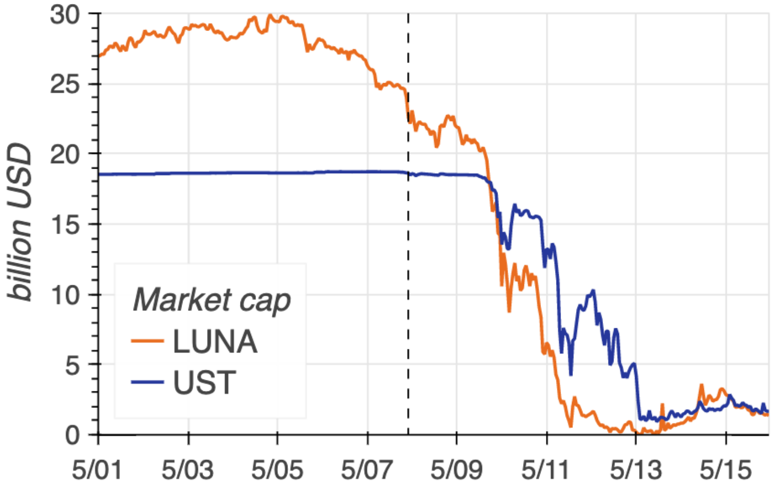

Figure 13: LUNA and UST market capitalization during the run. This figure shows the circulating market capitalization of UST (blue) and LUNA (orange) in billions of US dollars from May 1 to May 15, 2022.

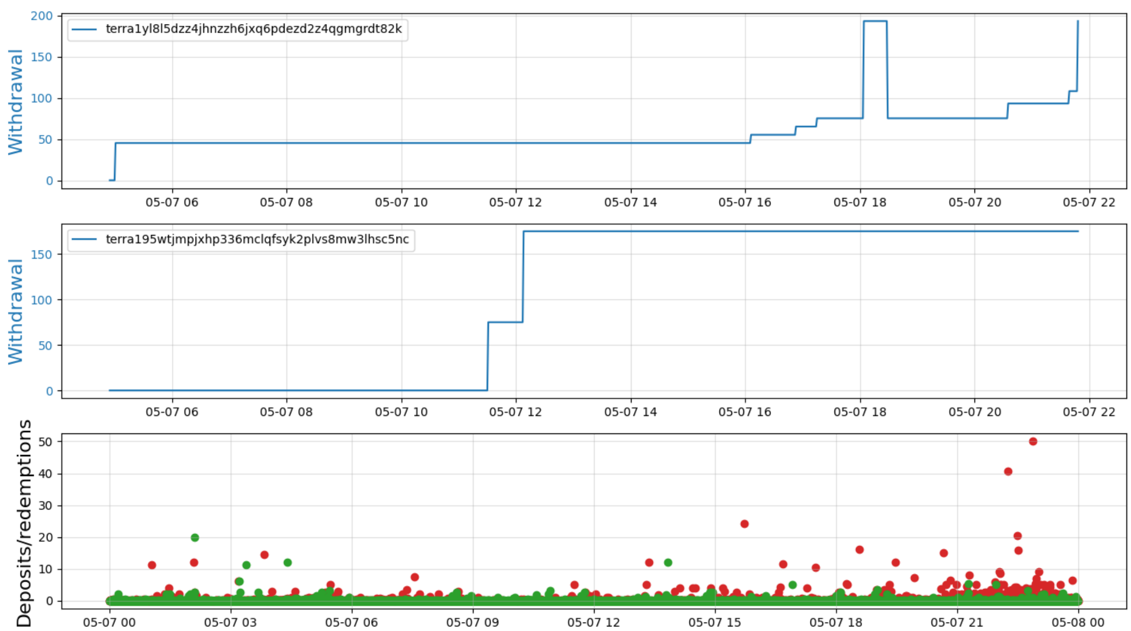

Figure 14: Anchor flows on May 7, 2022. The top two panels show the exact timing of the withdrawals by Wallet A and Wallet B from Anchor which constitute the beginning of the run. The bottom panel shows the timing of all other Anchor deposits (green) and withdrawals (red) on May 7. The y-axis denotes the size of each trade in millions of US dollars.

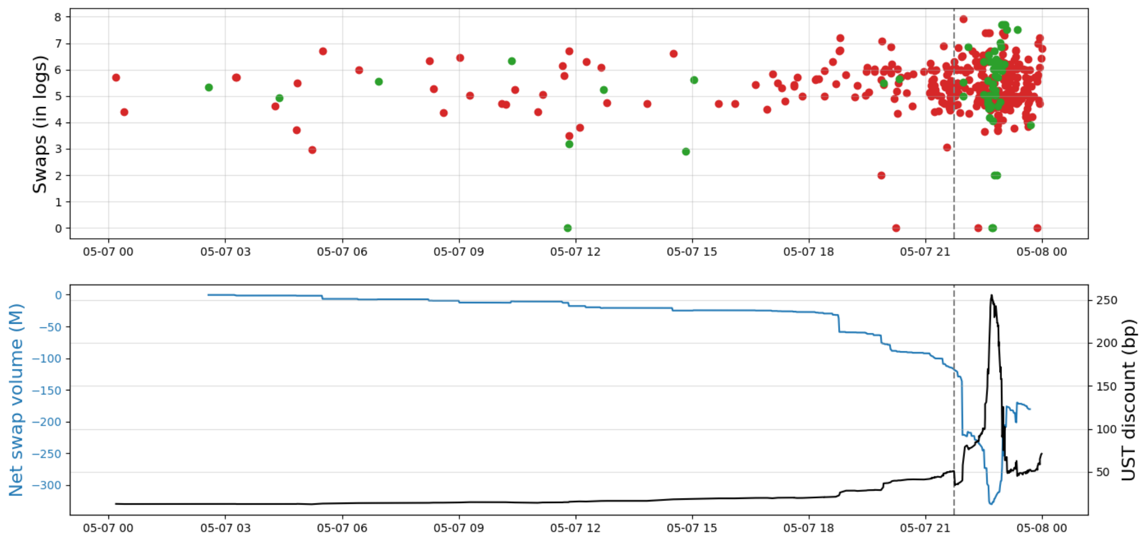

Figure 15: ***UST-3Crv swap transactions.*** *The top panel shows the UST swap transactions price against three major stablecoins, USDT, USDC, and DAI on May 7, 2022. Swap transactions of UST into the other three stablecoins are in red, and swaps into UST in green. The y-scale is logarithmic. The bottom panel shows the net signed volume (blue) and the deviation of the UST price from $1 in basis points (black).*

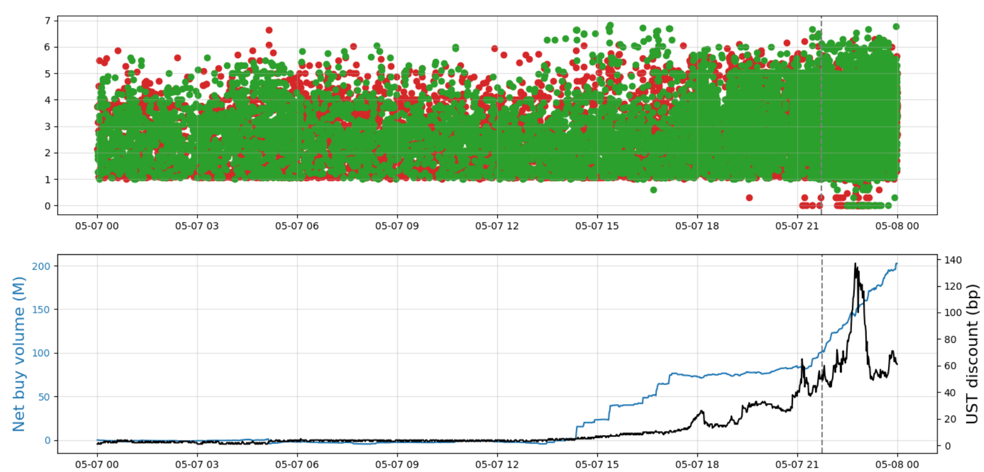

Figure 16: ***Binance UST/USDT trades.*** *The top panel shows the UST/USDT trades on May 7, 2022. Sell-initiated trades are in red and buy-initiated ones in green. The y-scale is logarithmic. The bottom panel shows the net signed volume (blue) and the deviation of the UST price from $1 in basis points (black).*

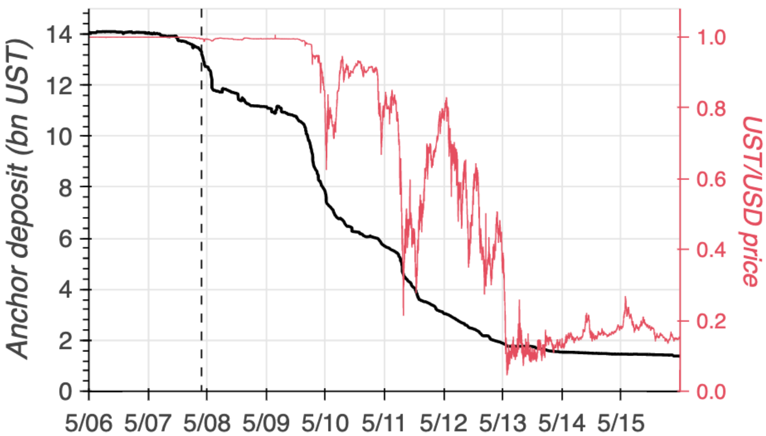

Figure 17: Anchor outflows. This figure shows the outstanding deposit balance in Anchor (black line, left axis) and the price of UST (red line, right axis) during the run in May 2022.

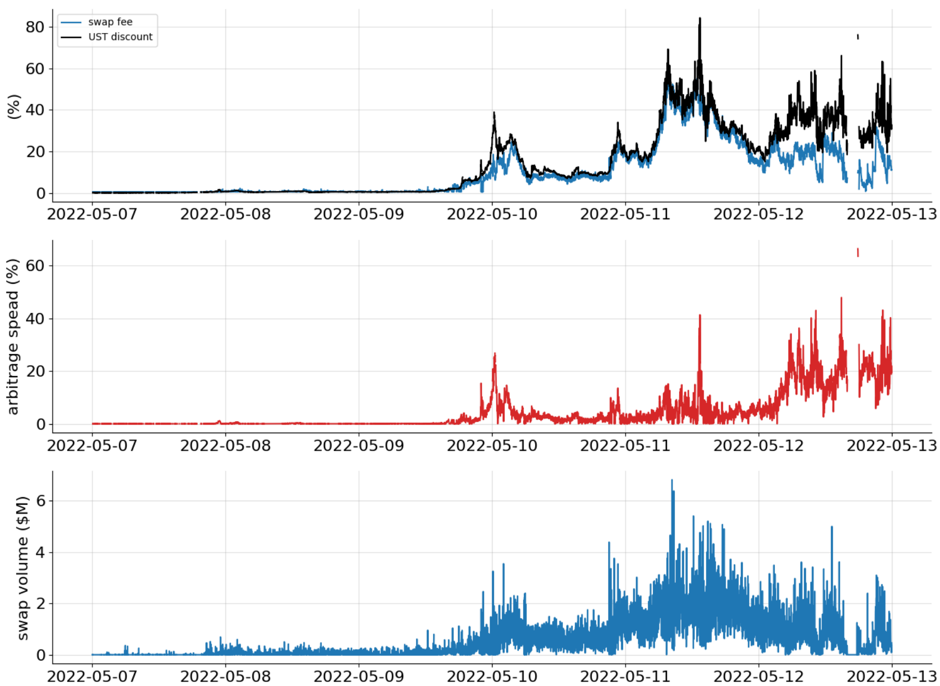

Figure 18: Swap arbitrage. This figure shows the trading activity on the native swap market. The top panel plots the UST discount and the swap fees over time. The middle panel shows the difference between the UST discount and the swap fees, which is a measure for the attractiveness of swapping UST for LUNA over selling UST at the market price. The bottom panel shows the dollar amount of UST that were swapped in a given minute.

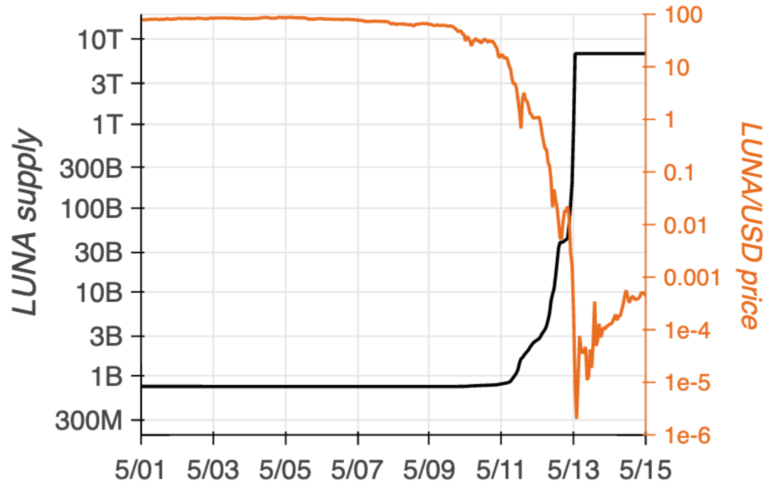

Figure 19: LUNA death spiral. This figure shows and the circulating supply (black line, left axis) and the price (orange line, right axis) of LUNA during the run, both in log scales. The convertibility between LUNA and UST was suspended on May 13.

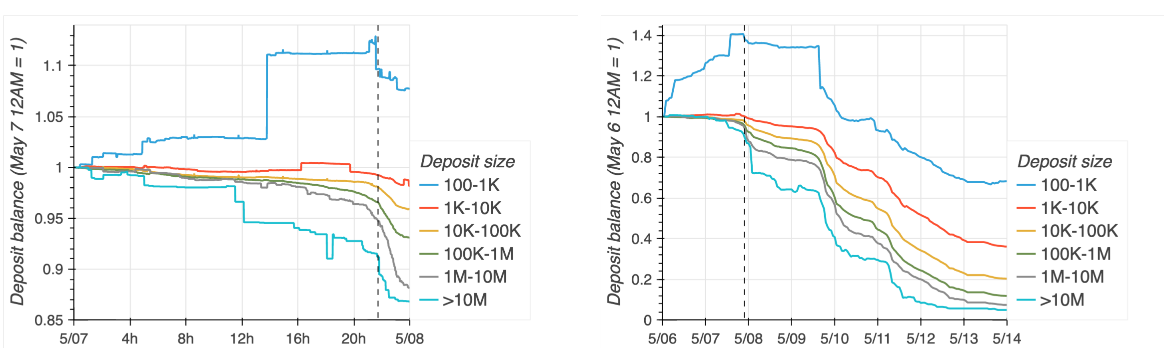

Figure 20: Anchor outflows by size. The left panel shows withdrawals from Anchor over the day of May 7 2022, broken out by the size of the deposit balance of addresses as of May 6th, before the run. The sample excludes any addresses held by intermediaries or large institutions and focuses on individual addresses. We also remove addresses with less than 100 UST in Anchor. The right panel shows the same analysis over the period from May 6 to May 14, 2022.

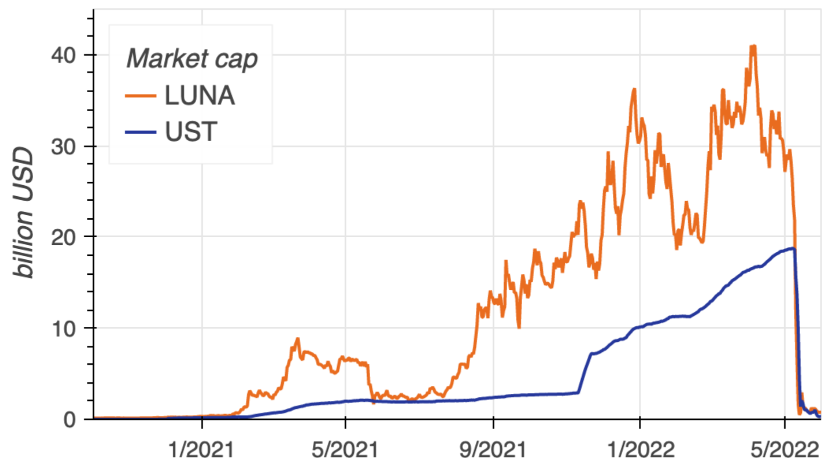

Figure 21: LUNA and UST Market Capitalization. This figure shows the circulating market capitalization of UST (blue) and LUNA (orange) in billions of US dollars from October 2020 to May 2022.

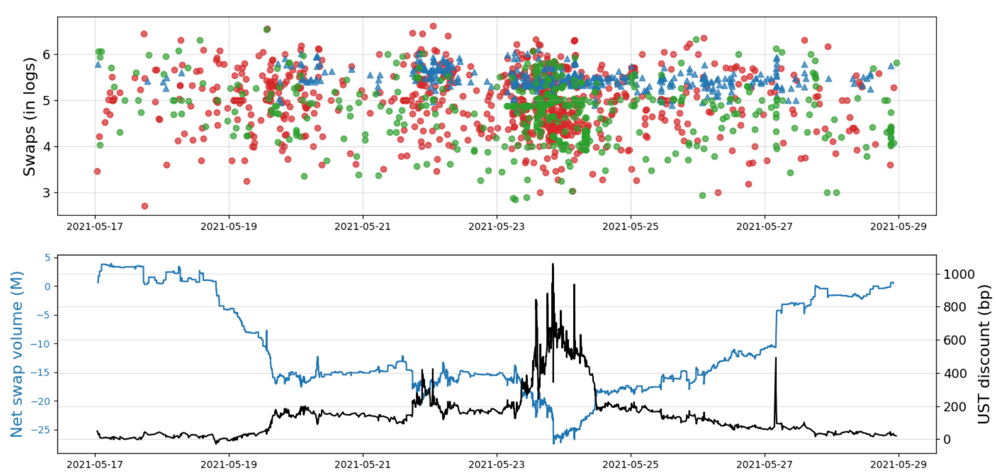

Figure 22: UST-3Crv swap transactions. *The top panel shows the UST swap transactions price against three major stablecoins, USDT, USDC, and DAI on May 17–29, 2021. Swap transactions of UST into the other three stablecoins are in red, and swaps into UST in green and blue. The blue triangles are swaps into UST by four addresses: 0x5dd09afc9ca51b46d6cda2189478b505ace7f37b, 0xe3bdda6413313ed58585e47441815e9662bdd818, 0x2747363d886c7fdcc5187217f1ca493922aa4940, and 0xaf7bbcfb1c1f987e0ae409c684289b332a425254. The y-scale is logarithmic. The bottom panel shows the net signed volume (blue) and the deviation of the UST price from $1 in basis points (black).*

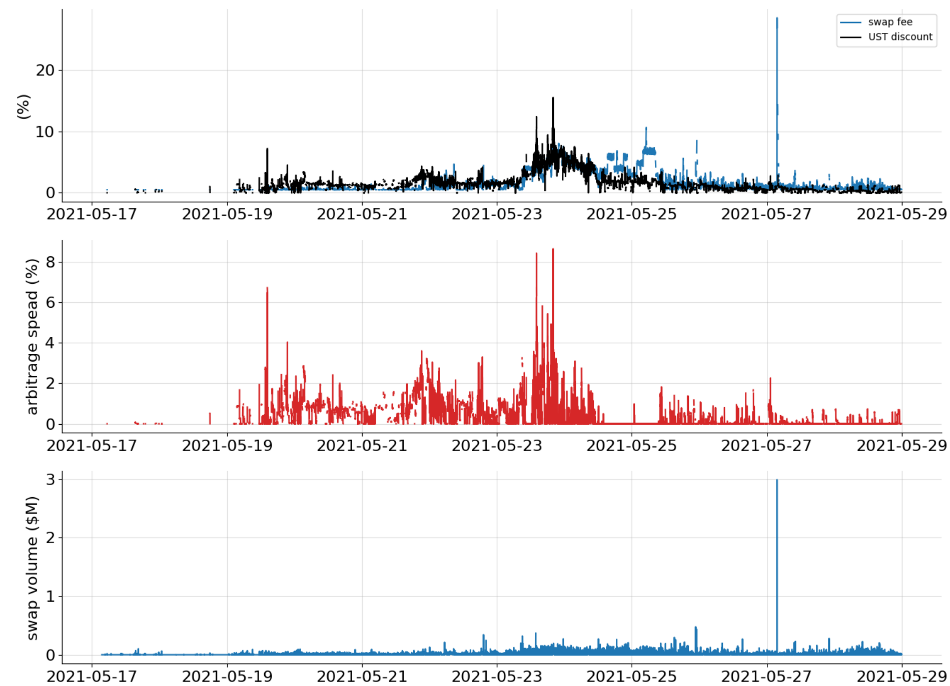

Figure 23: Swap arbitrage, May 2021. This figure shows the trading activity on the native swap market. The top panel plots the UST discount and the swap fees over time. The middle panel shows the difference between the UST discount and the swap fees, which is a measure for the attractiveness of swapping UST for LUNA over selling UST at the market price. The bottom panel shows the dollar amount of UST that were swapped in a given minute.

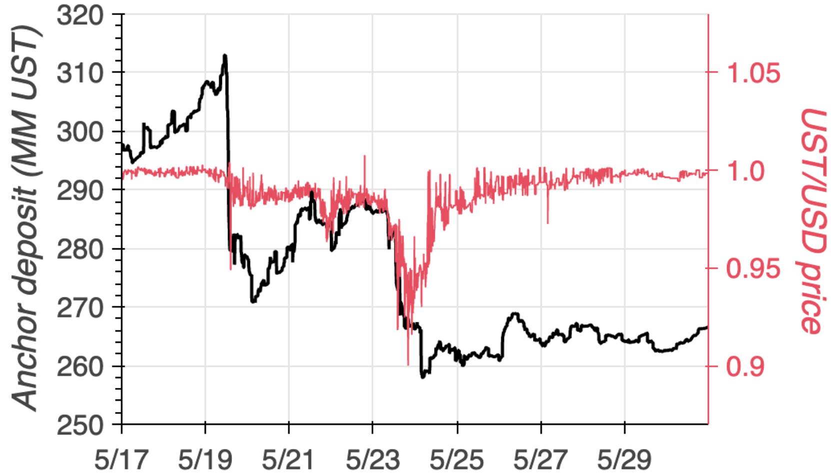

Figure 24: May 2021 De-pegging event. This figure shows the outstanding deposit balance in Anchor (black line, left axis) and the price of UST (red line, right axis) during the run in May 2021.

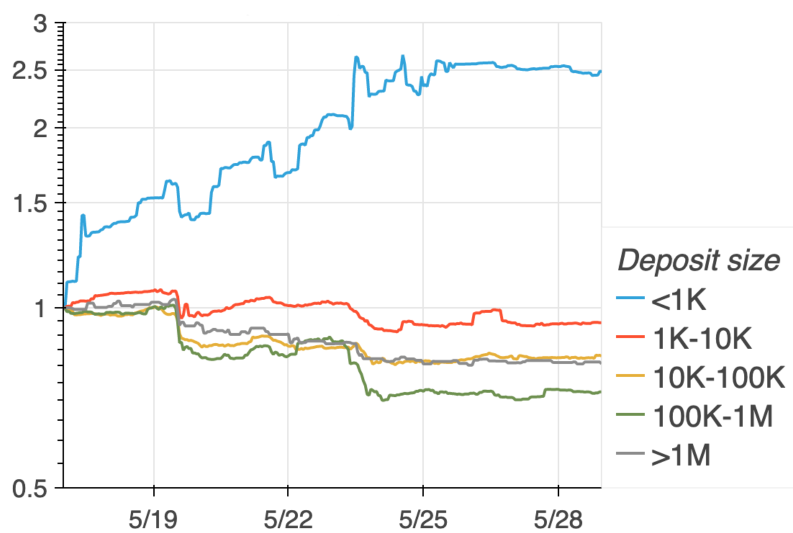

Figure 25: Anchor May 2021 outflows by size. The figure shows withdrawals from Anchor over the period of the first de-pegging event, May 17 to 28, 2021, broken out by the size of the deposit balance of addresses as of May 17th, 2021. The sample excludes any addresses held by intermediaries or large institutions and focuses on individual addresses. We also remove addresses with less than 100 UST in Anchor.

Tables

Token	Volume ($ billion)	Transaction count
UST	359.638	20272983
LUNA	216.698	9540155
aUST (Anchor UST deposit)	114.507	1581845
bLUNA (Anchor bonded LUNA)	49.569	1548061
ANC (Anchor token)	13.161	2983677
bETH (Anchor bonded ETH)	9.214	191050
Astroport ANC-UST LP	5.983	177590
Terraswap ANC-UST LP	5.068	170849
ASTRO (Astroport token)	3.988	1348552
VKR (Valkyrie token)	3.795	737877
SD (Stader token)	2.578	95102
MIR (Mirror token)	2.446	867647
Astroport ASTRO-UST LP	1.236	238299
PSI (Nexus token)	1.077	1175289
MINE (Pylon token)	1.065	593806

Table 1: ***Token volume.*** *This table reports the volume (in billion US dollars) and the transaction count of the top 15 tokens on the Terra Luna network from September 30, 2021 to May 6, 2022. The volume is collected from transaction logs of type "transfer" and "send" in the network. We net any transfer of the same token between the same counterparties at the same time. The USD price is the closing price of the token on the day of transfer. The transaction count is the number of transactions that contain that token.*

	Full sample	Pre-run balance						Exited
		<1K	10K	100K	1M	10M	>10M	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Address count	159669	43885	63360	40688	10397	1230	109	78859
Percent loss	59.31	76.49	60.05	46.29	36.74	31.85	26.58	
Age in months	4.56	4.06	4.43	5.01	5.58	6.10	6.92	
No. of CEXs	1.26	0.99	1.24	1.49	1.60	1.50	1.48	
Used Bridges?	0.30	0.21	0.28	0.36	0.47	0.60	0.65	

Table 2: ***Summary statistics: individual addresses.*** *This table reports the summary statistics for individual addresses prior to the run. We report the number of addresses, the percentage loss in the deposits on the address over the period of the run from May 6 to 13, Age in month is the number of months the address has been on the Terra blockchain, N of CEX is the number of centralized exchanges an address has traded with over the time of its existence, Used Bridges is a dummy for whether the address ever used Terra Shuttle or Wormhole Bridges. In Column (1) we show the full sample and in the remaining columns we break out the sample by the balance in the address on the day before the run.*

	Percent loss							
	Full sample		Balance subgroup					
			<1K	10K	100K	1M	10M	>10M
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
log balance	-6.00							
	(0.05)							
Size[1K-10K]		-15.24						
		(0.24)						
Size[10K-100K]		-27.98						
		(0.27)						
Size[100K-1M]		-37.00						
		(0.43)						
Size[1M-10M]		-41.97						
		(1.11)						
Size[>10M]		-47.08						
		(3.67)						
log(volume/balance)	1.10	1.30	3.57	0.85	-1.97	-3.92	-0.25	-1.27
	(0.09)	(0.09)	(0.16)	(0.16)	(0.21)	(0.39)	(1.08)	(3.73)
log age	5.74	5.63	6.26	5.95	5.18	5.67	6.29	0.41
	(0.16)	(0.16)	(0.31)	(0.26)	(0.30)	(0.53)	(1.36)	(3.58)
No. of CEXs used	-4.39	-4.68	-4.80	-5.48	-3.75	-2.44	-2.81	1.93
	(0.10)	(0.10)	(0.24)	(0.17)	(0.17)	(0.28)	(0.76)	(2.49)
Used bridges?	-3.02	-3.72	-3.33	-4.48	-2.29	-2.49	-4.71	-8.01
	(0.22)	(0.22)	(0.49)	(0.36)	(0.40)	(0.70)	(2.01)	(6.04)
Constant	105.30	72.04	67.86	58.12	47.06	37.47	28.74	29.75
	(0.44)	(0.28)	(0.49)	(0.41)	(0.48)	(0.89)	(2.43)	(7.28)
R^2	0.12	0.12	0.03	0.02	0.02	0.03	0.02	0.02
N	159669	159669	43885	63360	40688	10397	1230	109

Table 3: ***Percentage loss of Anchor depositors.*** *This table reports the results from a regression of the loss in the value of an address experienced over the period of the run, from May 6 to May 13, on the size of the balance of the address before the run and measures of the financial sophistication of traders. Columns 1 and 2 report use the full sample. Columns 3 to 8 report subsamples by the size of the address.*

Address	Volume ($B)	Transaction count	Address label
terra10kjnhhsgm4jfakr85673and3aw2y4a03598e0m	2.71	171	prop 44 swap/burn address
terra1cymh5ywgn4azak74h4gsrnakqgel4y9ssersvx	2.06	23749	LFG/TFL Burning Wallet
terra1dtzfwgzt8xa70zkm8gqzwz0n4zrqtngdpqejx5	1.76	36083	Jump
terra17p4mqd7yl9m0r7cfv0nf9s9zae3d3gm4tmyg2a	0.61	26607	TFL bot/UST Peg Defender
terra13h0qevzm8r5q0yknaamlq6m3k8kuluce7yf5lj	0.51	9462	reserve funder (LFG)
terra1t8szgklntcwxyfyflucuq895gpjr8wn6tsqxye	0.49	22368	TFL bot/UST Peg Defender
terra1v49w0m38fe87edhqdv30w96wq0pz6u6548q9gj	0.48	21393	TFL bot/UST Peg Defender
terra1lewnh53gt0hzgjejrtwdz8q7dennz09s6ds4k2	0.48	21943	TFL bot/UST Peg Defender
terra14tlthgtg6ep6xnqptyg8dp3gcq4jxvgqmskwkd	0.48	21293	TFL bot/UST Peg Defender
terra14ny376fe7hys2zqxwc87zp2achp9tju5q6jul4	0.48	21401	TFL bot/UST Peg Defender
terra1g5dmf4qpmdrcw77d3ty6djrgujt8r2n3lgyknj	0.48	21801	TFL bot/UST Peg Defender
terra1nexqdq252acp09m9eler7jhg9kd3rqfzkek9r0	0.48	21465	TFL bot/UST Peg Defender
terra1mer7nd843n5g3v37xxtd3hude6t5rf4cq3mnae	0.47	21209	TFL bot/UST Peg Defender
terra12qmfcxy8kahwt44tn4aq4t6kdmtyer38xnrh7m	0.46	21079	TFL bot/UST Peg Defender
terra19qx5xe6q9ll4w0890ux7lv2p4mf3csd4qvt3ex	0.43	109878	Terraswap route swap
terra1qy36laaky2ns9n98naha2r0nvt3j7q3fpxfs2e	0.42	5000	LFG reserve address
terra1zz2nf34fjkjygkg0kplkrr29ycxarmct6kafvj	0.42	13455	delegator(TFL)
terra1e028300g5kaef05vycatgz8tnrvmwmfstafk52	0.41	12871	Jump/TFL swap addr
terra1g9p9c5hjw4m3v9l65lmxt2g89vheashp6yfukm	0.40	12441	Jump/TFL swap addr
terra13vpm23s7rw5gqp9ckhqngjesxcuzatytknqpfg	0.40	12478	delegator(TFL)
terra1tdu6f7nffenxw7aahumtjklnzfcdw24k8836q5	0.40	12385	Jump/TFL swap addr
terra1anllr0tt8r2my88kp6kmdwdnewnja5246djj99	0.40	12271	delegator(TFL)
terra1r3mdl2q46mx5z8y8d6enm35t6g76wqtn43008u	0.40	12359	Jump/TFL swap addr
terra13u3p30c2tn9m8dmru6mfyhmqs379qm43vrx7l7	0.39	12545	delegator(TFL)
terra10zzfuednzhkmwn4tqks2mukstr02r5jklpmh2f	0.39	12290	delegator(TFL)
terra1zd46n9v45lsqsxrcje3ke6ejlxm7nhtqr2dlgq	0.39	12473	Jump/TFL swap addr
terra189rgutrsul7dm47u5h4y7hsraxnr9q4dk2fhjs	0.18	20140	Jump/TFL swap addr
terra1q9cs4d4x67u6yvsaswecf0usp2rygdnmrflzfj	0.11	3527	bLUNA Core - Rewards Dispatcher

Table 4: ***Top LUNA for UST swap addresses.*** *This table reports the list of top addresses that swapped the largest amount of LUNA for UST.*

Address	Vol (UST M)	Vol ($M)	Transaction count	Address label
terra1cjjwzcer7qpx4uj9s70fcdwpz9lecrqsxmmtun	687	449	19122	unknown smart contract 12
terra139y02s9urkkyesukndrqdjmqj7gkk5dltd05v8	446	276	6513	unknown smart contract 5
terra1hz0q2qgsgetaqwxds95angslxfyvkpzcfr4j9z	314	154	157	Alameda Research
terra14yzejwu639x5ntud98zsnl6caejqmns2vvfhs4	133	82	278	UST/LUNA arbitrageur
terra1ead9mwsw4efs64z4vz4sq2vp28q4wdsp3swpk4	119	70	134	UST/LUNA arbitrageur
terra1yvu32he5xprd5yea8dmagalaluases0z3x7dlv	122	68	184	UST/LUNA arbitrageur
terra1wlfagw79h0tushlz7uhvg3kxg5qq6zeg6axazf	86	66	2793	UST/LUNA arbitrageur
terra14tlthgtg6ep6xnqptyg8dp3gcq4jxvgqmskwkd	97	62	649	TFL bot/UST Peg Defender
terra1w92zvqhrplwalnj6ke7n28jfqp8fwsdjlajyvc	83	57	2173	UST/LUNA arbitrageur
terra1zdm0cayj9y0vsvt4x60zp9eq9nh2uwxuht7jw0	78	55	7323	UST/LUNA arbitrageur
terra1jus3ldxzjx4d42vzzw7yj5nzu2ghm6yz8k4c2t	90	54	1607	UST/LUNA arbitrageur
terra1wl5pwfj6zuqra2rhjs9eyufke3a0fjdckafxfu	96	51	304	UST/LUNA arbitrageur
terra1nexqdq252acp09m9eler7jhg9kd3rqfzkek9r0	83	50	526	TFL bot/UST Peg Defender
terra14ny376fe7hys2zqxwc87zp2achp9tju5q6jul4	81	50	504	TFL bot/UST Peg Defender
terra12qmfcxy8kahwt44tn4aq4t6kdmtyer38xnrh7m	81	49	518	TFL bot/UST Peg Defender
terra1mer7nd843n5g3v37xxtd3hude6t5rf4cq3mnae	81	49	516	TFL bot/UST Peg Defender
terra1lewnh53gt0hzgjejrtwdz8q7dennz09s6ds4k2	81	49	518	TFL bot/UST Peg Defender
terra1t8szgklntcwxyfyflucuq895gpjr8wn6tsqxye	80	49	505	TFL bot/UST Peg Defender
terra17p4mqd7yl9m0r7cfv0nf9s9zae3d3gm4tmyg2a	80	48	506	TFL bot/UST Peg Defender
terra1g5dmf4qpmdrcw77d3ty6djrgujt8r2n3lgyknj	81	48	529	TFL bot/UST Peg Defender
terra1v49w0m38fe87edhqdv30w96wq0pz6u6548q9gj	80	48	498	TFL bot/UST Peg Defender

Table 5: ***Top LUNA for UST swap addresses during the May 2022 Terra run.*** *This table reports the list of top addresses that swapped the largest amount of LUNA for UST over the period of the run, from May 7 to May 13.*

Address	Vol (UST M)	Transaction count	Address label
terra189rgutrsul7dm47u5h4y7hsraxnr9q4dk2fhjs	63	11536	Jump/TFL swap addr
terra14ny376fe7hys2zqxwc87zp2achp9tju5q6jul4	9	214	TFL bot/UST Peg Defender
terra1lewnh53gt0hzgjejrtwdz8q7dennz09s6ds4k2	8	180	TFL bot/UST Peg Defender
terra1mer7nd843n5g3v37xxtd3hude6t5rf4cq3mnae	8	201	TFL bot/UST Peg Defender
terra1pemrznzc6kup38n294nd5q39k2c8qhl6lthet4	8	4988	UST/LUNA arbitrageur
terra1hsh3ve4vrqnluccws9gwh5sg4jchuc352md2kw	8	4713	UST/LUNA arbitrageur
terra1nexqdq252acp09m9eler7jhg9kd3rqfzkek9r0	7	180	TFL bot/UST Peg Defender
terra1v49w0m38fe87edhqdv30w96wq0pz6u6548q9gj	7	180	TFL bot/UST Peg Defender
terra12qmfcxy8kahwt44tn4aq4t6kdmtyer38xnrh7m	7	168	TFL bot/UST Peg Defender
terra1g5dmf4qpmdrcw77d3ty6djrgujt8r2n3lgyknj	7	163	TFL bot/UST Peg Defender
terra17p4mqd7yl9m0r7cfv0nf9s9zae3d3gm4tmyg2a	7	164	TFL bot/UST Peg Defender
terra1t8szgklntcwxyfyflucuq895gpjr8wn6tsqxye	7	160	TFL bot/UST Peg Defender
terra1cgq04kwfpckhlxvw3uw2ug43a5xur3shaxcl8e	7	2649	UST/LUNA arbitrageur
terra14tlthgtg6ep6xnqptyg8dp3gcq4jxvgqmskwkd	7	149	TFL bot/UST Peg Defender
terra1m3cxucxdkg2p8h7fk3ztwrwqw0fjnr07yxwvuf	5	1909	UST/LUNA arbitrageur
terra1pm37tvmac8khvfr500fzvuj7z0pu73d6mphepy	5	1743	UST/LUNA arbitrageur
terra1x04xgtwlw72gtfzrq7nfwmr6eexla8ecljw28z	4	2	TFL market making
terra1m2rylkksr05r3z7myzhldz59x9j0c5ffagzd5y	3	1281	UST/LUNA arbitrageur
terra1d6yuxj62qefw8wwmmskmfm8503g59fxdrr0z8s	2	1185	UST/LUNA arbitrageur
terra10jycqs3qn6vlxkacqm9lyhzadwk0p03a6de8jm	1	393	UST/LUNA arbitrageur

Table 6: ***Top LUNA for UST swap addresses during the May 2021 de-pegging event.*** *This table reports the list of top addresses that swapped the largest amount of LUNA for UST over the period of the May 2021 de-pegging event, from May 19 to May 27.*

Appendix I

Name	Description
Admin	Addresses of network administration accounts and Terra insiders. This category includes addresses of the community pool, Terra's native swap, the transaction fee collector, the native swap fee collector, LUNA staking master account, the Proposal 44 swap address, TFL's main wallet, LFG's main wallet, TFL and Do Kwon's shadow wallets, TFL's salary distribution wallet, TFL's market marker wallet, and LFG's reserve address.
TFL	Addresses that TFL, LFG, and Jump used to issue UST and defend the peg.
CEX	Addresses of centralized exchanges are regular wallets that belong to a traditional cryptocurrency exchange. CEXs hold custody of cryptocurrencies. We cover 25 known exchanges: Binance, Bitfinex, Bithumb, Bitkub, Bitrue, Bittrex, Bkex, Bybit, Coinex, Coinone, Coinspot, Cryptex, Crypto.com, FTX, Gate.io, Gopax, Hotcoin, Huobi, Kraken, Kucoin, LBank, MEXC, Newton, Upbit, Whitebit. We also identify some unknown exchanges by their transaction patterns and label them as CEXs.
DEX	Addresses of decentralized exchanges are smart contracts that allow traders to trade between pairs of tokens. Each token pair is a smart contract address. We cover trading pairs on Astroport, Terraswap, Loop, and Prism.
Anchor	Addresses that belong to Anchor, including Anchor's UST money market account, Anchor's UST yield reserve, bLUNA and bETH staking accounts, Anchor's loan liquidation auctioneer, the ANC incentive payment account, the ANC airdrop account, the ANC repurchase acount, Anchor's community pool, and Anchor's governance staking account.
Bridge	Addresses that connect Terra to other blockchains, including Wormhole and Shuttle bridges that connect to Ethereum. Terra users can send tokens to these bridges, and they issue tokens on Ethereum.
DeFi	Smart contract addresses that are not DEXs, bridges, or Anchor. This includes crowdfunding platforms, NFT marketplaces, and arbitrage bots.
Other	Addresses of regular users on the blockchain, include hedge funds, venture capitals, blockchain validators, and all unnamed regular accounts on Terra.

Table 7: ***Categories of Terra addresses.*** *This table reports the categories of Terra addresses in Figure 2 and their descriptions.*