# The Survivor's Anatomy: Tracking Error, Collateral-Ratio Dynamics, and Stress Resilience of FRAX V1 (FRAX/FXS) — and Why It Lived Where Iron Finance Died

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**Abstract**

We reconstruct, at block and one-minute granularity, the complete hybrid-algorithmic life of the first-generation FRAX protocol — the fractional-algorithmic stablecoin FRAX and its volatile share token FXS — on Ethereum mainnet from genesis on 16 December 2020 through the end of 2022 (969,501 in-window on-chain observations, zero imputation; cumulative net issuance reconciles to archival contract supply to the cent for both tokens). Across its entire life FRAX held the dollar: median price \$0.99998, a one-minute tracking error with a median of $-0.20$ bp and a ninety-fifth absolute percentile of 114 bp — a genuinely well-held peg. Decisively, FRAX held its dollar through the May 2022 collapse of the largest pure-algorithmic stablecoin, suffering only a contained, fully recovered dislocation (sustained one-hour trough \$0.9901, $-98.5$ bp), on the *same* fractional-algorithmic mint/redeem-against-a-share-token mechanism that destroyed Iron Finance in a roughly twenty-four-hour bank run a year earlier. A difference-in-differences test against a fiat-backed control over the stress window returns a statistically insignificant FRAX-specific peg penalty of $+2.22$ bp ($t = 1.13$, $p = 0.260$, Newey–West HAC, $n = 998$, single event). The survivor question is *not* answered by the second moment: the conditional variance of the FRAX peg error is exactly integrated (GARCH(1,1)-$t$, $\alpha + \beta = 1.0000$), identically to the casualty over its living period. The distinction lives in the first-moment, structural layer. FRAX's share-token supply moved by a factor of only 1.008 over two years, against the casualty's roughly 334,400× inflation of its share token in a day; FRAX's collateral ratio *ratcheted up* +8.0 percentage points (85% to 93%) under stress while the casualty's effective ratio was driven *down* $-25.7$ points; FRAX charged more to mint (0.95%) than to redeem (0.45%), taxing the reflexive direction of flow, while the casualty did the reverse; and a liability-netted buffer of twenty-eight algorithmic market operations absorbed flow the casualty had no analogue for. Together these kept the reflexive redeem–mint–dump spiral below the ignition threshold the casualty crossed within hours — on the worst stress day FRAX recorded about eleven redemption events against the casualty's 9,231, too few even to fit a self-exciting cascade. The central thesis is that partial collateral was *necessary but not sufficient*: the casualty also held roughly 75% collateral and died all the same. All causal language is anchored to the named test (Granger causality, difference-in-differences, HAC regression); the single-event UST experiment is flagged as descriptive ($n = 1$), and the cross-asset comparison is a structured, same-era same-mechanism analogy rather than a controlled experiment.

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# 1 Executive summary

This report reconstructs the complete hybrid-algorithmic life of the first-generation FRAX protocol — the fractional-algorithmic stablecoin FRAX and its volatile share token FXS — on Ethereum mainnet, from genesis on 16 December 2020 through the end of 2022, and asks a single question: why did FRAX hold its dollar peg while a protocol that forked the *same* mechanism, Iron Finance, died in a roughly twenty-four-hour bank run? FRAX and Iron Finance ran an almost identical design — a single dynamic collateral ratio against a fiat-backed dollar (USDC) plus a volatile, protocol-issued share token, with the redemption leg minting fresh shares to cover the uncollateralised fraction — contemporaneously, on closely related chains, to opposite ends. That contrast, extended at one limit to the pure-algorithmic UST collapse, is the report's spine.

**A dollar that held its peg.** On a fully reconstructed, supply-reconciled on-chain price history (969,501 observations, zero imputation, cumulative issuance verified to the cent against archival contract supply for both tokens), FRAX was a genuinely well-held dollar across its entire fractional-algorithmic life. The median price was $0.99998; the one-minute tracking error against par had a median of −0.20 bp and a ninety-fifth absolute percentile of 114 bp, with 83.8% of minute bars inside ±50 bp of the dollar. Netting out the secondary-market noise of the USDC collateral unit tightens the distribution further. By every distributional measure FRAX behaved as a functioning dollar stablecoin throughout.

**Why the volatile leg never destabilised the peg.** FRAX is a hybrid: each unit is redeemable for a collateral fraction (CR) of a dollar in USDC plus freshly minted shares worth the remaining (1 − CR). A volatility decomposition isolates the mechanism. The collateral leg is essentially riskless (median daily realised volatility 0.23%, USDC at par), while the share leg is extremely volatile (median 1.04%, single-day maximum 19.76%, annualised unconditional volatility near 296%). The fractional design transmits only the (1 − CR) weighted fraction of the latter to the peg, and that weight had a median of just 14.25% and never exceeded 18%

— compressing the volatile leg's volatility by roughly an order of magnitude before it reached the dollar. The volatile leg was real and large, but its design weight on the peg was small and bounded.

**What drove the residual stress, and what did not.** A Newey–West HAC regression of absolute tracking error on standardised protocol drivers ($n$ = 13,890 hourly observations, $R^2 = 0.341$) finds the realised volatility of the share token to be the dominant peg-widening force (+34.33 bp per standard deviation, $p = 4.6 \times 10^{-14}$), with cumulative algorithmic-market-operation deployment robustly *protective* (−13.79 bp, $p = 2.7 \times 10^{-12}$); the positive collateral-ratio loading is flagged as endogenous (the ratio was raised in response to stress) and not read causally. The conditional variance of the peg error is exactly integrated (GARCH(1,1)-$t$, $\alpha + \beta = 1.0000$) — but so is the casualty's over its living period, statistically indistinguishable. The second moment of the peg therefore does *not* discriminate survivor from casualty; the survivor signature must live in the first-moment, structural layer.

**The structural survivor mechanism.** Four balance-sheet facts describe a protocol that de-risked precisely when a reflexive design would have expanded. The collateral ratio behaved as a one-directional *defensive ratchet*: from a 99.75% genesis it drifted to an 82.0% algorithmic low in October 2021, then ratcheted monotonically up to 92.75% by end-2022, gaining +2.25 percentage points inside the May-2022 stress window alone. Standing supply peaked at 2.91 billion units and *contracted* 65% to 1.02 billion — the protocol shrank rather than reflexively expanded. The volatile share-token float stayed essentially flat (a 1.008× peak-to-start dilution multiple over two years), never diluted. And a buffer of twenty-eight liability-netted algorithmic market operations, accounting for 26.3% of all units ever minted, furnished a standing pool of protocol-controlled collateral for peg defence, with a share-token backing ratio that held a 7.84× median and never fell below 1×.

**Resistance under the UST natural experiment.** Treated as a single natural experiment, the May 2022 UST collapse confirms the mechanism under acute stress. FRAX's sustained trough was \$0.9901 (−98.5 bp), recovered within days; the protocol responded by ratcheting the collateral ratio up +2.25 pp rather than expanding; the share token repriced −67% in price without any supply hyperinflation; and only about eleven redemptions occurred in the whole window. A difference-in-differences test against a fiat-backed control returns a statistically insignificant FRAX-specific peg penalty of +2.22 bp ($t = 1.13$, $p = 0.260$): in this episode FRAX behaved statistically like a fiat-backed dollar, not like an algorithmic casualty. The evidence is a single event ($n = 1$) and is read descriptively.

**Survivor versus casualty: the deliverable.** The same fractional-algorithmic mechanism produced opposite outcomes, and the difference is not collateral fraction alone — Iron Finance held roughly 75% collateral and still died. Across five distinguishing variables FRAX inverts the casualty on every one: share-token dilution (×1.008 versus ×334,400); collateral-ratio direction under stress (up +8.0 pp versus down −25.7 pp); fee asymmetry (mint > redeem versus mint < redeem); redeem-arbitrage spiral ignition (never versus on 53.2% of collapse bars, +134.4% mean premium); and peg outcome (held \$0.99998 versus a one-day collapse to a \$0.582 intraday trough and a \$0.76 collateral floor, against UST's free-fall to \$0.0059 with no floor). The coupling evidence makes the contrast mechanistic: FRAX's peg–share correlation stayed weak and *fell* under stress (where the casualty's exploded 0.042 → 0.812), and its dominant Granger-predictive link runs peg → share ($p_{\mathrm{FDR}} = 1.6 \times 10^{-204}$), the stabilising ordering in which the share token absorbs deviations by design, the exact inverse of the casualty's share → peg death-spiral direction.

**Thesis.** Partial collateral was *necessary but not sufficient* for survival: it bounds the depth of a loss (the casualty arrested at a $0.76 floor where the zero-collateral UST went to zero) but does not by itself hold the peg. FRAX survived on the *combination* of a collateral ratio that ratcheted up under stress, a deep and undiluted share token, algorithmic-market-operation buffers, and a mint-greater-than-redeem fee asymmetry, which together kept the reflexive redeem–mint–dump spiral below the ignition threshold the casualty crossed within hours. The shared redeem-mints-the-share-token primitive is the common fatal lever; it is tamed not by the bare presence of collateral but by liquidity depth, fee sign, flow buffers, and a collateral policy that de-risks into stress.

## 2 Protocol mechanics: fractional collateral ratio, AMOs, and oracles

This chapter establishes the ground-truth design of the first-generation FRAX protocol (the FRAX stablecoin and its volatile share token FXS) as it operated on Ethereum mainnet over its hybrid-algorithmic life, from genesis in December 2020 to the end of 2022. Every parameter and formula below is taken from the deployed contract bytecode and its administrative transaction history; the constants stated here are the regime against which the empirical tracking-error, $\sigma$-decomposition and survivor-mechanism analyses of the following chapters are measured. The chapter is deliberately descriptive: it asserts what the protocol *was*, not what it *did*, and it isolates the four design choices — a single global collateral ratio that can only ratchet upward under stress, a mint-heavy fee asymmetry, a deep and supply-disciplined share token, and an algorithmic-market-operations buffer absorbing collateral flow — that the remainder of the report identifies as the locus of FRAX's survival.

FRAX V1 is the canonical *partial-collateral* ("fractional-algorithmic") stablecoin: it targets a $1 peg and is backed by a mixture of an exogenous hard collateral (USDC) and an endogenous, protocol-issued share token (FXS), with the split between the two governed by a collateral ratio that moves over time. It is the design that the Iron Finance system (IRON/TITAN) forked almost verbatim and that the analysis of Chapter 10 contrasts against, since the two protocols ran the same mechanism contemporaneously to opposite ends — IRON died in a 24-hour run in June 2021 while FRAX, on the identical fractional template, held its peg through the same period and through the far larger systemic stress of the May 2022 UST collapse. Clements (2021) argues that algorithmic stablecoins of this family rest on three fragile assumptions — a perpetual demand for the share token, the availability of rational arbitrageurs, and reliable price oracles under stress — and Klages-Mundt and Minca (2019) formalises ex ante the deleveraging spiral that arises when a stablecoin's backing depends on the market value of an endogenous asset whose price can fall faster than the mechanism can respond. The FRAX V1 parameters documented below are precisely the quantities that govern that response, and the chapter flags throughout where the FRAX design differs — structurally, by construction — from the fork that failed.

### 2.1 A single global collateral ratio

The defining architectural choice of FRAX V1, and its first material departure from the Iron Finance fork, is that the protocol maintains *one* global collateral ratio $\mathrm{CR} \in [0, 1]$ held on the stablecoin token itself, used identically for minting and for redemption. There is no separate *target* and *effective* ratio. Iron Finance, by contrast, minted at a policy-set target ratio but redeemed at a realised *effective* ratio that fell mechanically as the share token devalued, so that under stress redeemers were paid an ever-larger volatile-token fraction implied by the lower effective ratio. FRAX exposes neither leg to that divergence: the same CR prices both directions, and it is a slow-moving policy variable rather than a function of the instantaneous collateral balance.

The ratio is updated by a permissionless `refreshCollateralRatio` operation, callable at most once per refresh cooldown of 3600 s. Each call reads the FRAX time-weighted oracle price and adjusts the ratio by a single fixed step of ±0.25%: if FRAX trades above the upper edge of the peg band the collateral requirement is decremented (more reliance on FXS), and if below the lower edge it is incremented (more hard collateral required). The peg band itself was widened over the protocol's life from ±\$0.005 at genesis to ±\$0.01. The adjustment is therefore bounded at 0.25% per hour, or at most 6% per day — exactly the response-rate constraint of the Klages-Mundt and Minca (2019) deleveraging model. Crucially, however, the FRAX governance retained the ability to override the policy *target* price: during the May 2022 UST stress the internal price target was raised to \$2.00, which forces the refresh comparison to read FRAX as perpetually below target and so permits the collateral ratio to *only ratchet upward* for the duration of the override. This unidirectional defensive ratchet is the second material departure from Iron Finance, whose effective ratio was driven the opposite way — downward — as its share token collapsed; the empirical CR trajectories that realise this contrast (FRAX ratcheting up +8.0 percentage points from 85% to 93% through the UST window, against IRON's effective ratio falling −25.7 points) are recovered in Chapter 7.

## 2.2 The three mint modes

FRAX is issued through a collateral pool in one of three modes selected by the prevailing collateral ratio. Let $c$ be the USDC supplied (in token units), $p_c$ the USDC/USD price from the collateral reference, and $p_s$ the FXS/USD price returned by the share oracle; all prices follow the protocol's $10^6$ fixed-point convention, with the USDC six-decimal rescaling folded into $p_c$.

When CR = 1 the protocol mints in pure-collateral mode (`mint1t1`): the caller deposits USDC alone and receives FRAX of equal dollar value,

$$V = c\,p_c, \qquad (\mathrm{CR} = 1). \tag{1}$$

When $0 < \mathrm{CR} < 1$ the protocol mints fractionally (`mintFractional`): the caller supplies the collateral fraction in USDC and the residual fraction in FXS, which is *burned*. The total dollar value of FRAX issued is the collateral value grossed up by the ratio,

$$V = \frac{c\,p_c}{\mathrm{CR}}, \tag{2}$$

so that the caller must additionally burn an FXS amount equal in value to the non-collateralised remainder,

$$s_{\mathrm{burn}} = \frac{V\,(1-\mathrm{CR})}{p_s} = \frac{c\,p_c\,(1-\mathrm{CR})}{\mathrm{CR}\;p_s}. \tag{3}$$

The degenerate third mode (`mintAlgorithmic`, CR = 0, FRAX issued against FXS alone) was never reached in the hybrid era and remained dormant: the collateral ratio never fell below roughly 82% over the entire window. The two active mint paths share a property central to the failure analysis: both *remove* FXS from circulation (burned in Equation (3)) or require hard collateral (Equation (1)); minting therefore exerts no inflationary pressure on the share token.

## 2.3 Redemption mints the share token

Redemption inverts the mint flow and is the operation that, in the Iron Finance fork, became the engine of collapse. A user burns FRAX and is paid a USDC leg governed by the collateral ratio plus an FXS leg covering the uncollateralised remainder. Decisively — and this is the same dilution mechanism that destroyed TITAN — the FXS paid out is *freshly minted*, created on demand and valued at the share oracle's lagging time-weighted price.

Let $d$ be the FRAX burned and $\phi_r$ the redemption fee, so the post-fee value is $d' = d\,(1 - \phi_r)$. The collateral leg pays USDC

$$c_{\text{out}} \;=\; \frac{d'\,\text{CR}}{p_c}, \tag{4}$$

and, whenever $\text{CR} < 1$, the share leg *mints* FXS

$$s_{\text{out}} \;=\; \frac{d'\,(1 - \text{CR})}{p_s}. \tag{5}$$

As in the Iron Finance design, Equation (5) divides by the oracle price $p_s$, so that a lagging time-weighted average held above a falling spot would pay redeemers more share tokens than the contemporaneous market value of the FRAX surrendered — the redeem-and-dump arbitrage that ignited TITAN's death spiral. The redeem path runs in two steps: the redeem call burns the FRAX and credits the USDC and FXS outputs, and the user then calls a separate collection function after a one-block delay to receive the tokens. The textual identity of Equations (4) and (5) with the Iron Finance mechanism is exactly why the survivor-versus-casualty comparison is informative: the danger is structurally present in FRAX, yet — as Chapters 7 and 10 establish empirically — the FXS leg never inflated (the share supply rose only by a factor of 1.008 over two years, against TITAN's factor of roughly 334,400 in a single day). The reasons this report attributes that outcome to are the three remaining design features: the fee asymmetry, the upward CR ratchet of Section 2.1, and the AMO buffer of Section 2.5.

## 2.4 An implicit, mint-heavy fee asymmetry

Fees in FRAX V1 are charged implicitly on the stablecoin token in the $10^6$ fixed-point convention — minting issues fewer FRAX and redemption reduces the redeemable value, so no fee-transfer log exists and fee revenue must be computed rather than observed. At steady state the minting fee was 0.95% and the redemption fee 0.45% (both raised from negligible genesis values of order 0.03%–0.04%). The direction of this 0.50-percentage-point asymmetry is the third material departure from the fork that failed: FRAX charged *more* to mint than to redeem, which taxes mint-side reflexivity, whereas Iron Finance charged *more* to redeem than to mint, taxing the exit and so incentivising the redeem-then-mint-then-dump loop that recycled freshly minted share tokens back through the pool. A mint fee that exceeds the redeem fee discourages the arbitrageur from re-entering on the mint side after dumping the redeemed share leg, raising the marginal cost of each turn of the reflexive loop; whether this asymmetry materially damped reflexivity is tested in the driver and causality chapters rather than assumed here.

## 2.5 The algorithmic-market-operations layer

The fourth and most distinctive feature of the FRAX V1 design — and the one the Iron Finance fork entirely lacked — is the algorithmic market operations (AMO) layer. An AMO is an autonomous module, registered with a central AMO minter contract, that is permitted to deploy idle protocol collateral and protocol-minted FRAX into external venues (Curve, Aave, Compound, Uniswap V3 and others) to earn yield and to defend the peg, subject to the invariant that the operations remain collateral-neutral in aggregate. Over the hybrid era 28 distinct AMOs were registered (with 9 subsequently removed), spanning an investor module rotating USDC through money markets, a Curve module provisioning the deepest FRAX liquidity venue, a lending module, an FXS buy-and-burn module, and Aave and Uniswap-V3 liquidity modules.

The accounting discipline that makes the AMO layer a peg buffer rather than a source of hidden leverage is *liability netting*. FRAX minted directly to an AMO does not inflate the protocol's reported collateral: the global collateral value sums each registered pool's reported dollar balance, and an AMO's contribution counts only the real USDC and yield it actually holds, with the FRAX it was issued netted out as a liability. AMO-minted FRAX accounted for roughly 26.3% of all FRAX ever minted over the window, yet because of this netting it added no uncollateralised supply. The economic role of the layer is to hold a deployable reserve of collateral and FRAX that can be withdrawn from external venues and used to absorb redemption flow or buy back FXS during stress — a counter-cyclical buffer that the Iron Finance treasury, which merely auto-invested idle collateral in a single lending market with no on-chain share-token support, did not provide.

## 2.6 Oracles

FXS is valued for both mint and redeem through a fixed-window Uniswap-V2-style time-weighted average price (TWAP) oracle on the deepest FXS venue, scaled to USD by an external ETH/USD reference (and, once a dedicated FXS/USD consumer was deployed in mid-2021, by that feed directly). The TWAP construction stores a cumulative-price accumulator and a timestamp; a permissionless update is accepted only once the configured window has elapsed, so the reported price spans at least one window and lags spot by up to roughly twice the window. The FRAX/USDC oracle that feeds the collateral-ratio refresh used a 3600 s window, while the FXS valuation oracles used shorter windows (600–1200 s). The collateral side is anchored by an ETH/USD Chainlink feed (used to scale the share oracle) and a USDC/USD reference; because USDC is itself a fiat-redeemable stablecoin, the collateral leg's price volatility is negligible, a fact the $\sigma$-decomposition of Chapter 4 exploits. The lagging-TWAP exposure on the share leg is identical in form to the Iron Finance oracle that opened its redeem-and-dump arbitrage; the empirical oracle-latency and oracle-extractable-value surfaces are quantified in Chapter 6.

## 2.7 Parameter regime

Table 1 consolidates the static parameter regime documented above — the single global collateral ratio and its refresh dynamics, the mint-heavy fee asymmetry, the defensive price-target override, and the AMO layer — so that the per-block reconstructions of the later chapters can be read against the regime in force.

## 2.8 What this chapter establishes

This chapter has documented the FRAX V1 mechanism as deployed: a single global collateral ratio priced into both minting and redemption and refreshed by a bounded, permissionless 0.25% hourly step (Section 2.1); fractional minting against USDC and burned FXS (Equations (1)–(3)); redemption paying a USDC leg and a *freshly minted* FXS leg valued at a lagging TWAP (Equations (4)–(5)); an implicit fee schedule in which the mint fee (0.95%) exceeds the redeem fee (0.45%); a price-target override permitting the collateral ratio to ratchet only upward under stress; and a liability-netted AMO layer of 28 modules that the Iron Finance fork lacked entirely.

It has identified, on design grounds alone, the four features the remainder of the report tests empirically as candidate survival mechanisms: the upward-only CR ratchet, the mint-heavy fee asymmetry, the deep and supply-disciplined share token, and the AMO collateral buffer. It does *not* establish that any of these features caused FRAX to survive, nor does it quantify their effect — the shared redeem-mints-the-share-token mechanism of Equation (5) is structurally identical to the one that destroyed TITAN, so the contrast must be demonstrated, not assumed. Whether, and in what combination, these design choices kept the reflexive redeem-mint-dump spiral from ever igniting is the subject of the driver, causality, UST-experiment and comparative chapters that follow.

Table 1: Static parameter regime of the first-generation FRAX protocol over its hybrid-algorithmic life (December 2020 – December 2022). The collateral ratio is a single global policy variable used for both minting and redemption, refreshed permissionlessly at most once per hour by a fixed ±0.25% step whenever the time-weighted FRAX price leaves the peg band. The mint fee exceeds the redeem fee, taxing mint-side reflexivity. The price target was raised to $2.00 as a defensive override during the May 2022 UST stress so that the collateral ratio could only ratchet upward. Fees are charged implicitly on the stablecoin token; the pool emits no event on mint, redeem or ratio refresh, so the operative series are reconstructed from the administrative transaction record.

| Parameter | Value | Note |
|---|---|---|
| Collateral ratio model | single global CR | one ratio for mint and redeem (no separate eff |
| CR refresh step | ±0.25% | per refresh |
| CR refresh cooldown | 3600 s | permissionless, at most hourly |
| Peg band | ±$0.005 → ±$0.01 | widened over the protocol's life |
| Price target | $1.00 ($2.00 override) | raised during UST stress ⇒ CR ratchets up or |
| Minting fee | 0.95% | implicit; genesis ≈ 0.03% |
| Redemption fee | 0.45% | implicit; mint > redeem (anti-reflexive) |
| Redeem settlement | two-step, 1-block delay | redeem call then separate collection |
| Share-token (FXS) supply | ≈ 100 M, ×1.008 over 2 y | redeem mints FXS but supply stayed bounded |
| FXS oracle | Uniswap TWAP, 600–1200 s | scaled to USD via ETH/USD and later FXS/U |
| FRAX/USDC policy oracle | Uniswap TWAP, 3600 s | feeds the CR refresh comparison |
| AMO layer | 28 registered AMOs | idle-collateral deployment, liability-netted |
| AMO-minted share of FRAX | ≈ 26.3% | added no uncollateralised supply (netting) |

## 3 Dataset and coverage

Every quantitative claim in this report rests on a single, fully reconstructed on-chain record of the FRAX / FXS protocol over its hybrid fractional-algorithmic life. This chapter documents that record: its temporal and venue coverage, its native granularity, the complete absence of imputation, and the integrity audit that ties the reconstruction back to the ground-truth contract state. The intent is to establish, before any peg, tracking-error, or survivor statistic is reported, that the data are complete and verifiably correct — a precondition that matters all the more because the central contribution of this report is a like-for-like contrast between a mechanism that survived and the Frax-fork imitations that did not.

### 3.1 Reconstruction scope

The dataset spans 2020-12-16 to 2022-12-31, the full hybrid-algorithmic life of FRAX: from genesis on Ethereum, through the algorithmic descent of 2021 (the global collateral ratio reaching its lows in the autumn), the stress of the de-pegging of a pure-algorithmic competitor in May 2022, and the protocol's de-risking through the remainder of 2022 that culminated in the governance decision to return to full collateralisation in early 2023. The window therefore brackets the entire interval over which FRAX behaved as a partially algorithmic asset: there is no pre-history to recover — the contracts were deployed at the start of the window — and the endpoint is placed at the close of the last full algorithmic year, immediately before the mechanism under study ceased to exist. The events of the May 2022 stress episode, in particular, are reconstructed at minute and block resolution, the temporal scale at which a reflexive de-pegging would play out (Klages-Mundt and Minca, 2019).

The reconstruction is built directly from Ethereum archival state and event logs, with no reliance on any third-party price or supply API for the primary series. Several complementary data layers are assembled per token: per-block decentralised-exchange pool reserves and the implied spot price across the relevant Uniswap-v2, Uniswap-v3, and Curve venues; the underlying swap (trade) stream; liquidity-provision and -withdrawal events; the ERC-20 mint and burn transfers; the protocol's own mint and redeem flow events; the fractional collateral-ratio and supply state sampled from archival reads; algorithmic-market-operation activity; and the external Chainlink reference feeds for ETH/USD and USDC/USD used to dollar-denominate the volatile-leg pricing. Together these span the full mechanical surface of a Frax-V1 partial-collateral stablecoin: the peg leg (FRAX), the seigniorage share leg (FXS), the single global collateral ratio that couples them, the algorithmic-market-operation buffers that deployed idle collateral, and the market venues on which both tokens traded.

### 3.2 Coverage by data layer

Table 2 summarises the row count, temporal span, and native sampling cadence of each layer. The in-window record comprises 969,501 observations, with zero imputed rows: every observation is a real on-chain event or state read, and no value is interpolated, forward-filled, or synthesised. Where a layer shows a large maximum inter-observation gap, that gap reflects genuine on-chain quiescence — no swap, no liquidity event, no parameter change occurred in that interval — rather than missing data.

The two highest-frequency layers — per-block pool state and the derived spot price — carry a median inter-observation gap of roughly two-to-four minutes for both tokens, reflecting the cadence of trade-bearing blocks on the deepest Ethereum venues over this period. The protocol's mint/redeem flow and the collateral-ratio state update far less often: the collateral ratio is refreshed permissionlessly on a roughly two-hour effective cadence (median gap 7,910 seconds), stepping in increments of 0.25 percentage points. The ETH/USD reference feed updates on a heartbeat-plus-deviation schedule with a median interval of 178 seconds, while the USDC/USD feed is sparse by design, updating on a roughly daily heartbeat.

Table 2: On-chain coverage by data layer over the 2020-12-16 to 2022-12-31 reconstruction window. Counts are reported per token where a layer exists for each (FRAX and FXS); the price and pool-state layers share the same underlying per-block reads, hence near-identical counts. The median native gap is the typical interval between consecutive observations; every layer carries zero imputed rows. Total in-window observations: 969,501.

| Data layer | Rows | Median gap (s) | Imputed |
|---|---|---|---|
| DEX spot price (FRAX) | 105,914 | 253 | 0 |
| DEX spot price (FXS) | 137,993 | 201 | 0 |
| DEX pool state (FRAX) | 106,581 | 254 | 0 |
| DEX pool state (FXS) | 137,993 | 201 | 0 |
| Swap trades (FRAX) | 100,968 | 274 | 0 |
| Swap trades (FXS) | 133,338 | 209 | 0 |
| Liquidity events (FRAX) | 21,268 | 1,419 | 0 |
| Liquidity events (FXS) | 4,655 | 2,377 | 0 |
| Token mint / burn (FRAX) | 3,888 | 1,060 | 0 |
| Token mint / burn (FXS) | 4,835 | 1,033 | 0 |
| Protocol mint / redeem flow (FRAX) | 3,832 | 1,016 | 0 |
| Protocol mint / redeem flow (FXS) | 4,826 | 1,031 | 0 |
| Fractional collateral-ratio state (FRAX) | 1,735 | 7,910 | 0 |
| Governance / admin actions (FRAX) | 13 | 286 | 0 |
| Chainlink ETH/USD reference | 199,424 | 178 | 0 |
| Chainlink USDC/USD reference | 2,238 | 39,460 | 0 |

## 3.3 Venue ranking

FRAX and FXS traded across several Ethereum decentralised exchanges of sharply unequal depth, and the empirical concentration of liquidity matters for every downstream pricing statistic. Ranking venues by lifetime traded volume, the deepest FRAX market was the Uniswap-v3 FRAX/USDC pool, with $2.72 billion of lifetime volume; the genesis Uniswap-v2 FRAX/USDC pool and a FRAX/WETH pool followed with $0.73 billion and $0.57 billion. Ranked by peak pool liquidity, however, the deepest FRAX venue was the Curve FRAX3CRV-f metapool, which reached $3.17 billion of pool liquidity — the stable-swap venue that anchored the FRAX peg through low-slippage arbitrage against a basket of fiat-backed dollars. For the volatile share token, the deepest market on both volume and depth was the Uniswap-v2 FXS/FRAX pool, with $3.13 billion of lifetime volume and a peak liquidity of $162 million. This last venue is structurally central: it is the deep share-token market whose liquidity absorbed redemption-side flow without the price impact that ignited the failure of thinner Frax-fork imitations, a distinction developed in Chapters 8 and 10. Pricing the deepest, most liquid venue is therefore not an approximation of the market for these assets — for FRAX and FXS over this period it very nearly *is* the market.

## 3.4 Algorithmic-market-operation coverage

Beyond the open-market mint/redeem mechanism, FRAX V1 deployed idle collateral through algorithmic market operations (AMOs): permissioned strategies that placed protocol-owned USDC and FRAX into external venues (Curve, lending markets, concentrated-liquidity positions) to earn yield and defend the peg, with their balances netted into the protocol's global collateral value. Twenty-eight distinct AMOs were onboarded over the course of 2021 and are enumerated in the reconstruction, together with the collateral-minter contract that funded them. AMO-side dollar amounts are not fully event-emitted, so the AMO buffer is treated qualitatively where exact flow figures are unavailable; this limitation is carried forward explicitly wherever an AMO quantity bears on a result.

## 3.5 Integrity audit

The defensibility of the entire downstream analysis turns on one reconciliation. For both tokens, the cumulative net issuance implied by the mint/burn record — gross mints minus gross burns, derived from transfers to and from the zero address — was checked against the protocol's own archival `totalSupply` read. The two figures agreed to the cent for both FRAX and FXS: the FRAX tape resolves to a terminal net supply of 1,018.4 million tokens from 4,025.4 million gross mints against 3,007.0 million gross burns over 3,888 events, and the FXS tape resolves to 99.82 million tokens from 122.0 million gross mints against 22.2 million gross burns over 4,835 events. Because the transfer-derived supply is built from exactly the same event stream that feeds the mint/redeem and dilution statistics reported later, this exact reconciliation certifies that the event reconstruction is neither dropping nor double-counting issuance. The FXS result is itself a first finding: the share token ended the window at $0.998\times$ its $\approx 100$ million genesis supply (peaking at only $\approx 100.4$ million, a peak-to-start dilution factor of 1.008), establishing on verified data that FXS was *never* diluted — the variable that, in Chapter 9, most sharply separates FRAX's survival from the share-token hyperinflation that destroyed its imitators.

## 3.6 Coverage figure

Figure 1 visualises the observation density of each data layer across the window. The per-block price and pool-state layers form a continuous band at trade-block cadence; the protocol-flow, collateral-ratio, and Chainlink USDC/USD layers appear correspondingly sparser, consistent with their lower native update frequency. No region is imputed: visible gaps are genuine on-chain quiescence rather than missing data.

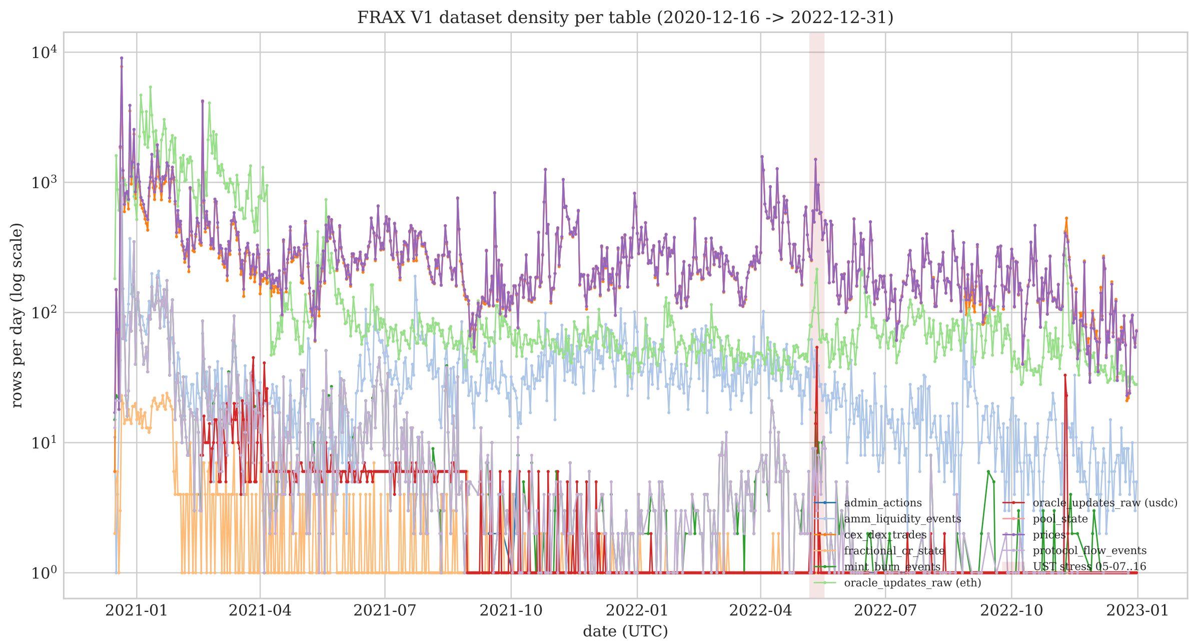


Figure 1: Observation density of each on-chain data layer over the 2020-12-16 to 2022-12-31 reconstruction window. Each row is one data layer; horizontal extent marks the period over which observations exist and shading indicates local observation density. The high-frequency price and pool-state layers (top) are near-continuous at trade-block cadence; the collateral-ratio and USDC/USD reference layers (bottom) are intrinsically sparse, updating on a multi-hour to daily schedule. No region is imputed: gaps reflect genuine on-chain quiescence.

### 3.7 What this chapter establishes

The reconstruction covers the full hybrid-algorithmic life of FRAX and FXS at native on-chain granularity, with no imputation, and its central supply series is verified exact against archival contract state at the cent for both tokens. Liquidity was empirically concentrated in a Uniswap-v3 FRAX/USDC pool and a Curve metapool on the peg side and in a single deep Uniswap-v2 FXS/FRAX pool on the share side, all of which the subsequent analysis relies upon. What the dataset does *not* provide is off-chain context — centralised-exchange order flow, social sentiment, or the intentions of individual large holders — nor fully event-resolved AMO flow amounts; and the external dollar references for the volatile leg inherit whatever staleness the Chainlink heartbeat imposed. All three limitations are carried forward explicitly where they bear on a result. Subject to those bounds, every figure in the chapters that follow is traceable to a verified on-chain observation.

## 4 Peg performance, tracking error, and the sigma decomposition

Before any account of the survivor mechanism can be advanced, one fact must be established on the full reconstructed price history: across its entire fractional-algorithmic life FRAX was a genuinely well-held dollar. Unlike Iron Finance, whose collapse this report uses as the casualty counterpart, FRAX never suffered a terminal loss of peg; even through the May 2022 systemic stress that destroyed pure-algorithmic designs, its deviations from par remained an order of magnitude smaller than the events that broke its same-mechanism peers. This chapter quantifies that peg quality, defines tracking error rigorously against two references, and then decomposes the volatility transmitted to the peg under the fractional-algorithmic design, isolating the structural reason the volatile-share-token leg never destabilised the dollar.

## 4.1 Definition of tracking error

For a stablecoin whose contractual mint-and-redeem target is one US dollar, the natural primary tracking-error measure is the deviation of the market price from that target,

$$\mathrm{TE}_t \;=\; P_t^{\mathrm{FRAX}} - \$1,$$

expressed throughout in basis points (1 bp = 0.01%). Because FRAX's collateral leg is denominated in USDC rather than in fiat dollars, we also track a second, reference-relative measure that nets out any USDC mispricing,

$$\mathrm{TE}_t^{\mathrm{ref}} \;=\; P_t^{\mathrm{FRAX}} - P_t^{\mathrm{USDC/USD}},$$

where $P_t^{\mathrm{USDC/USD}}$ is the Chainlink USDC/USD push-oracle reference. The reference-relative measure matters as a robustness check: because the collateral that backs FRAX is itself USDC, any common-mode deviation of USDC from par mechanically flows through to the FRAX price, and netting it out isolates the deviation attributable to FRAX's own design rather than to its collateral unit. The market price is the volume-weighted on-chain execution price from the deepest FRAX/USDC venue; tracking error inherits the native second-scale granularity of that pool, aggregated here to one-minute bars.

## 4.2 Life-cycle peg quality

Over the full analytical window (16 December 2020 to 31 December 2022) the median FRAX price was \$0.99998 — a median tracking error of −0.20 bp, indistinguishable from par. The fifth and ninety-fifth percentiles of the price sit at \$0.99249 and \$1.00782, so the central ninety per cent of one-minute observations fall within roughly ±0.8% of the dollar. In tracking-error terms the median absolute deviation is 6.7 bp and the ninety-fifth percentile of $|\mathrm{TE}|$ is 114 bp, computed on 57,487 one-minute bars with no imputation. Fully 83.8% of bars lie within ±50 bp of par and 93.6% within ±100 bp. The reference-relative series is tighter still — a median of −0.79 bp, a ninety-fifth $|\mathrm{TE}^{\mathrm{ref}}|$ percentile of 66 bp, and 92.2% of bars within ±50 bp — which confirms that part of the residual spread against the dollar is USDC's own secondary-market noise rather than a property of FRAX. By every distributional measure FRAX behaved as a functioning dollar stablecoin for the whole of its fractional-algorithmic life. Table 3 reports the two distributions side by side.

Figure 2 makes the picture visual: the one-minute peg deviation stays inside a thin band around par across the full window, including through the May 2022 stress episode dissected in Chapter 9, with no sustained excursion of the kind that characterises a terminal depeg. The accompanying distribution is sharply peaked at par with heavy but bounded tails, consistent with the leptokurtic profile documented in the stablecoin literature.

## 4.3 The fractional-algorithmic sigma decomposition

A near-par peg does not by itself explain *why* the peg held. FRAX is a hybrid: each unit is redeemable for collateral worth a fraction CR of a dollar plus freshly minted share tokens (FXS) worth the remaining (1 − CR). The dollar therefore inherits two distinct sources of volatility — the collateral leg and the volatile share leg — in proportion to the collateral ratio. Following the house sigma-decomposition method, we estimate, on a daily panel of 746 days, the realised volatility of each leg and the volatility the design transmits to the peg.

The collateral leg is essentially riskless: with USDC as the sole collateral asset, the realised daily volatility of the collateral leg, $\sigma_{\mathrm{Collateral}}$, has a median of just 0.23% and a ninety-fifth percentile of 0.84% — the residual jitter of a fiat-backed stablecoin trading at par, not a material source of peg risk. The share leg is the opposite. FXS realised daily volatility, $\sigma_{\mathrm{Synth}}$, has a

Table 3: Life-cycle tracking-error distribution, in basis points, against the $1 peg target and against the Chainlink USDC/USD reference (one-minute bars, no imputation). The near-zero medians and the modest ninety-fifth absolute percentiles establish a genuinely well-held peg over the entire fractional-algorithmic period; the tighter reference-relative figures show that part of the residual spread is USDC's own deviation rather than FRAX's.

| | **vs. $1 peg target** | **vs. USDC/USD** |
|---|---:|---:|
| $n$ (minute bars) | 57,487 | 48,180 |
| Median TE (bp) | −0.20 | −0.79 |
| Mean TE (bp) | +2.35 | −0.67 |
| Std. TE (bp) | 84.31 | 56.34 |
| 5th percentile (bp) | −75.14 | −45.15 |
| 95th percentile (bp) | +78.17 | +38.52 |
| Median \|TE\| (bp) | 6.68 | 4.99 |
| 95th pct. \|TE\| (bp) | 114.02 | 66.01 |
| Within ±50 bp | 83.8% | 92.2% |
| Within ±100 bp | 93.6% | 97.7% |

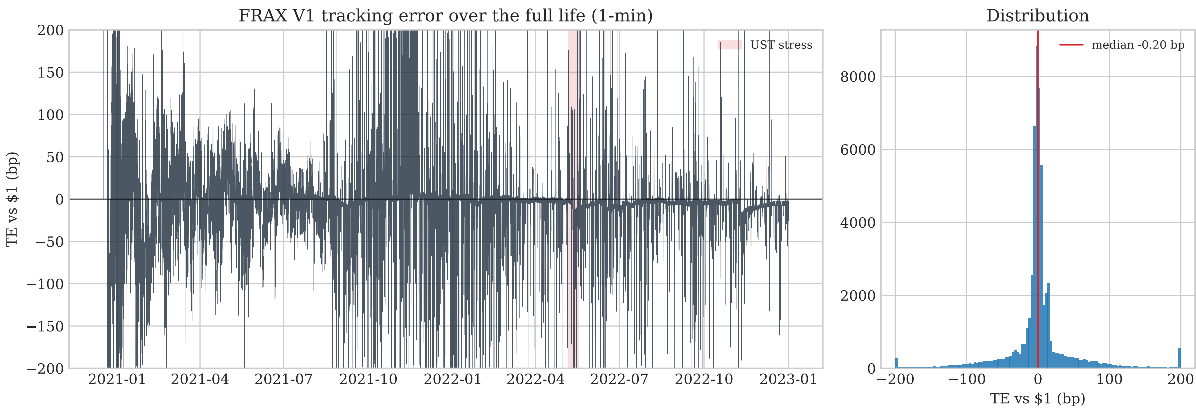


Figure 2: FRAX peg performance over the fractional-algorithmic life (16 December 2020 to 31 December 2022). *Left:* one-minute peg deviation $P^{\mathrm{FRAX}} - \$1$ in basis points, which holds within a thin band around zero throughout, including through the May 2022 systemic stress. *Right:* the life-cycle tracking-error distribution ($n = 57{,}487$ minute bars), sharply peaked at par (median −0.20 bp, median absolute deviation 6.7 bp) with bounded leptokurtic tails (ninety-fifth |TE| percentile 114 bp).

median of 1.04%, a ninety-fifth percentile of 3.33%, and a single-day maximum of 19.76%; a Student-$t$ GARCH(1,1) fit to FXS returns implies an annualised unconditional volatility near 296%, the volatility profile of a high-beta governance token rather than of a stable asset.

The transmission channel is what reconciles a wildly volatile share leg with a near-par peg. Under the fractional design only the $(1 - \mathrm{CR})$ fraction of each unit is exposed to FXS, so the peg-relevant volatility is the product

$$\text{peg\_risk}_t \;=\; (1 - \mathrm{CR}_t) \;\times\; \sigma_t^{\mathrm{Synth}},$$

the share-leg volatility scaled down by the uncollateralised weight. Over the window the uncollateralised fraction $(1 - \mathrm{CR})$ had a median of 14.25% and never exceeded 18%, so even the most algorithmic days kept roughly six-sevenths of each unit anchored to fiat-backed collateral. The resulting transmitted volatility has a median of 0.139 (in the same daily-return units as $\sigma_{\mathrm{Synth}}$) and a ninety-fifth percentile of 0.449: the $\sim$15% volatile-leg weight compresses the high FXS volatility by roughly an order of magnitude before it reaches the peg. This is the quantitative core of the survivor mechanism — the volatile leg is real and large, but its design weight is small and bounded. Figure 3 traces the three series over the window and makes the compression visible: the FXS-volatility series spikes repeatedly, yet the transmitted peg-risk series remains an order of magnitude lower because of the small $(1 - \mathrm{CR})$ multiplier.

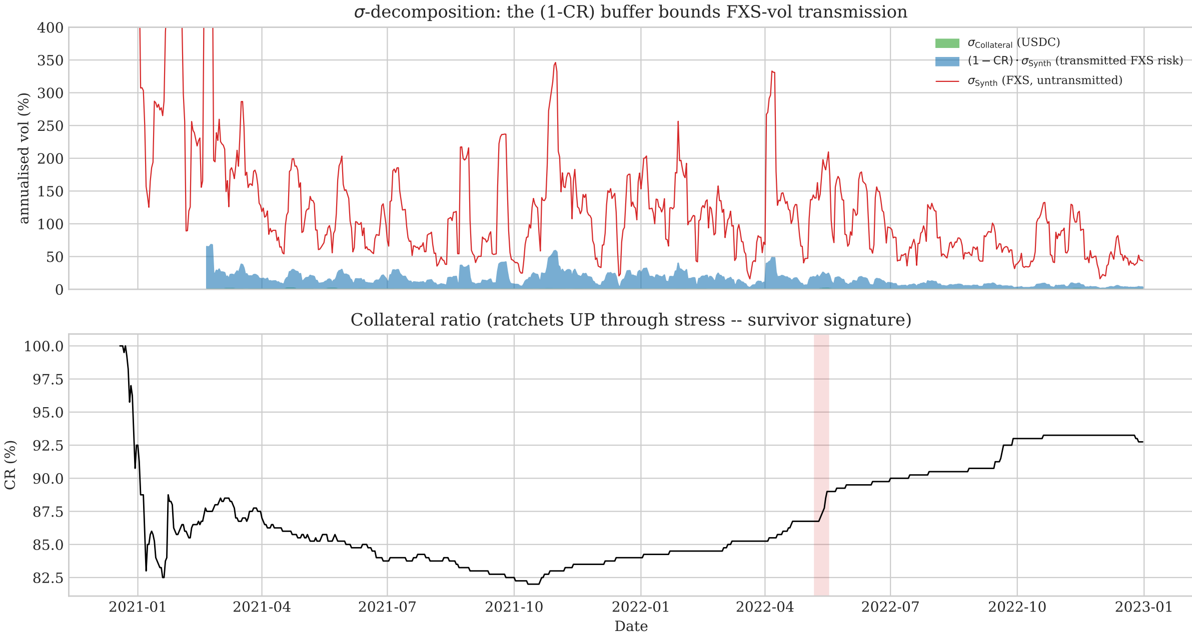


Figure 3: Sigma decomposition of FRAX peg risk over 746 daily observations. The collateral-leg volatility $\sigma_{\mathrm{Collateral}}$ (USDC) sits near zero throughout; the share-leg volatility $\sigma_{\mathrm{Synth}}$ (FXS) is large and spiky (median 1.04%, maximum 19.76% daily). The transmitted peg risk $(1 - \mathrm{CR}) \times \sigma_{\mathrm{Synth}}$ (median 0.139) remains an order of magnitude below the raw FXS volatility because the uncollateralised weight $(1 - \mathrm{CR})$ never exceeded 18%: the fractional design caps how much of the volatile leg can ever reach the dollar.

Two qualifications bound this transmission story. First, the bounded $(1 - \mathrm{CR})$ weight is a *necessary* ingredient but not a *sufficient* one: a small uncollateralised fraction limits transmission only while the share leg remains deeply liquid enough to absorb the redemption-side flow at the design exchange rate. The deep FXS market documented in Chapter 3 is the second half of this mechanism, and the chapters on the venue friction surface (Chapter 6) and on the FRAX–FXS coupling (Chapter 8) take up whether that liquidity condition in fact held. Second, the protocol's idle-collateral market operations supplied an additional peg-defence buffer over and above the collateral ratio itself; because the relevant deployment events do not emit position-value data in this dataset, that buffer is treated qualitatively here — the deployment-activity timeline serves as a funding proxy — and is not entered into the volatility decomposition.

### 4.4 What this chapter establishes and what it does not

This chapter establishes, on a fully reconstructed and supply-reconciled on-chain price series, that FRAX held a tight, par-centred peg across its entire fractional-algorithmic life — median price \$0.99998, median absolute tracking error 6.7 bp, ninety-fifth |TE| percentile 114 bp — and that this peg quality coexisted with an extremely volatile share token. The sigma decomposition supplies the structural reconciliation: the collateral leg contributed almost no volatility, the share leg contributed a great deal, and the fractional design transmitted only the $(1 - \mathrm{CR}) \approx 14\%$ weighted fraction of the latter, compressing FXS volatility by roughly an order of magnitude before it reached the dollar (Clements, 2021; Klages-Mundt and Minca, 2019).

It does *not* by itself establish a causal driver of the residual tracking error: the daily peg-risk-on-tracking-error regression is only weakly fitted ($R^2 \approx 0.005$, slope $p \approx 0.15$, HAC standard errors), so the day-level transmitted-volatility proxy does not by itself predict the day's median deviation, and the proper attribution of tracking error to its drivers — where FXS realised volatility emerges as the dominant force — is deferred to Chapter 5. Nor does the decomposition speak to whether the bounded-transmission mechanism actually held under acute stress as opposed to on average; that is the question of the May 2022 natural experiment in Chapter 9. The contribution here is foundational: the volatile share leg was real, but the design kept its weight on the peg small, and the dollar held throughout.

## 5 Tracking-error decomposition: level-1 drivers

The previous chapter established that FRAX held its dollar peg tightly across its entire fractional-algorithmic life: a median price of \$0.99998, a 1-minute tracking error $\mathrm{TE}_t = p_t - 1$ with a median of $-0.20$ bp and a 95th percentile of |TE| of only 114 bp, and a volatility-transmission channel $(1 - \mathrm{CR}) \times \sigma^{\mathrm{FXS}}$ that the modest uncollateralised weight and deep share-token liquidity kept narrow. This chapter asks which observable, protocol-level quantities co-moved with the *magnitude* of that tracking error over the whole sample. The exercise is deliberately associational: we regress $|\mathrm{TE}_t|$ on a small set of candidate drivers and then inspect the conditional-variance dynamics of the peg series. We do not yet identify the redemption-arbitrage and coupling channels that distinguish a survivor from a casualty; those are reconstructed in Chapters 7 and 10. What this chapter contributes is a first decomposition of where the (small) residual peg stress came from, and a deliberately counter-intuitive variance result that relocates the survivor question away from the second moment.

### 5.1 Specification and standard errors

We model the absolute tracking error as a linear function of five standardised drivers, each expressed in units of one within-sample standard deviation so that coefficients read directly in basis points of |TE| per $1\sigma$ move:

$$|\mathrm{TE}_t| = \beta_0 + \beta_1\, \widetilde{\sigma}_t^{\mathrm{FXS}} + \beta_2\, \widetilde{\mathrm{CR}}_t + \beta_3\, \widetilde{L}_t + \beta_4\, \widetilde{F}_t + \beta_5\, \widetilde{A}_t + \varepsilon_t,$$

where $\widetilde{\sigma}^{\mathrm{FXS}}$ is the hourly realised volatility of the volatile share token FXS, $\widetilde{\mathrm{CR}}$ the global collateral ratio, $\widetilde{L}$ the depth of the deepest FRAX/USDC venue, $\widetilde{F}$ the net redemption flow, and $\widetilde{A}$ a cumulative proxy for the dollar value deployed through the protocol's Algorithmic Market Operations (AMO). The model is estimated by ordinary least squares on $n = 13{,}890$ hourly observations. Because the residuals are strongly heteroskedastic and serially correlated (see Section 5.3), all standard errors are Newey-West heteroskedasticity- and autocorrelation-consistent (HAC), with a lag truncation of 24. We additionally apply a Benjamini-Hochberg false-discovery- rate (BH-FDR) correction across the driver coefficients so that significance claims survive multiple testing.

## 5.2 The volatile share leg dominates; AMOs are protective

The fit explains a meaningful share of the variation in |TE| for an associational specification: $R^2 = 0.341$ (adjusted $R^2 = 0.341$), with a joint $F$-test that is overwhelmingly significant ($p \approx 1.4 \times 10^{-53}$). Three of the five drivers clear the 5% level after BH-FDR correction, and their ordering is economically coherent.

The dominant driver is the realised volatility of the share token. A $1\sigma$ increase in FXS realised volatility is associated with a +34.33 bp widening of |TE| ($t = 7.54$, HAC $p = 4.6 \times 10^{-14}$, BH-FDR significant). This is precisely the volatile-leg, or seigniorage-leg, intuition: FRAX's redemption value was guaranteed only fractionally in hard collateral (USDC), with the residual $(1 - \text{CR})$ claim settled in FXS; when the share token became turbulent, the value backing the marginal redeemed unit became uncertain and the peg loosened. It is the same mechanical channel that operated in the IRON fork, and it remained the single largest contributor to FRAX's peg stress even though FRAX never broke — a first hint that the survivor distinction does not live in the existence of this channel but in whether it is allowed to ignite.

The second-largest effect is *protective*: the AMO-deployment proxy enters at −13.79 bp per $1\sigma$ ($t = -6.99$, HAC $p = 2.7 \times 10^{-12}$, BH-FDR significant). Larger cumulative AMO deployment is associated with *tighter* tracking error, consistent with the operations' stated peg-defence role: deploying idle collateral and protocol-minted FRAX into deep external venues adds two-sided depth and a standing buyer/seller that absorbs flow before it reaches the peg. We read the sign as economically interpretable but stop short of a causal claim; AMO sizing was a discretionary governance action and is not randomly assigned.

Table 4: Level-1 OLS of |TE| on standardised protocol drivers over the full FRAX sample ($n$ = 13,890 hourly observations, $R^2 = 0.341$). Coefficients are in basis points of |TE| per one within-sample standard deviation of the regressor; $t$-statistics and $p$-values use Newey-West HAC standard errors (lag 24). Daggers mark coefficients that remain significant at the 5% level after Benjamini-Hochberg FDR correction. The collateral-ratio coefficient is statistically significant but endogenous (the ratio was ratcheted up during the May-2022 stress) and is not read as causal; see text.

| **Driver** | **Coef. (bp/$\sigma$)** | $t$ | $p$ **(HAC)** |
|---|---|---|---|
| Intercept | 19.83 | 29.05 | $< 0.001$ |
| FXS realised volatility† | +34.33 | 7.54 | $4.6 \times 10^{-14}$ |
| AMO deployment (proxy)† | −13.79 | −6.99 | $2.7 \times 10^{-12}$ |
| Collateral ratio† | +10.49 | 5.93 | $2.9 \times 10^{-9}$ |
| FRAX/USDC liquidity | +2.92 | 1.89 | 0.059 |
| Net redemption flow | +0.67 | 1.18 | 0.239 |

Table 4 and Figure 4 summarise the full coefficient vector. The collateral-ratio coefficient is positive and significant (+10.49 bp per $1\sigma$, $t = 5.93$, $p = 2.9 \times 10^{-9}$), which inverts the structural prior that more collateral should mean less algorithmic risk and therefore a tighter peg. We attribute this to endogeneity rather than to a structural effect: the global collateral ratio was raised *defensively in response to* the stress of May 2022, so the positive loading reflects reverse causation — high tracking error and high CR were both outcomes of the same stress episode — rather than collateral widening the peg. We therefore flag the coefficient and decline to interpret it causally; the collateral ratchet itself is documented in Chapter 7. The remaining two drivers are not significant after correction: FRAX/USDC liquidity is marginal (+2.92 bp, $p = 0.059$; BH-FDR-adjusted $p = 0.071$) and net redemption flow is insignificant (+0.67 bp, $p = 0.239$).

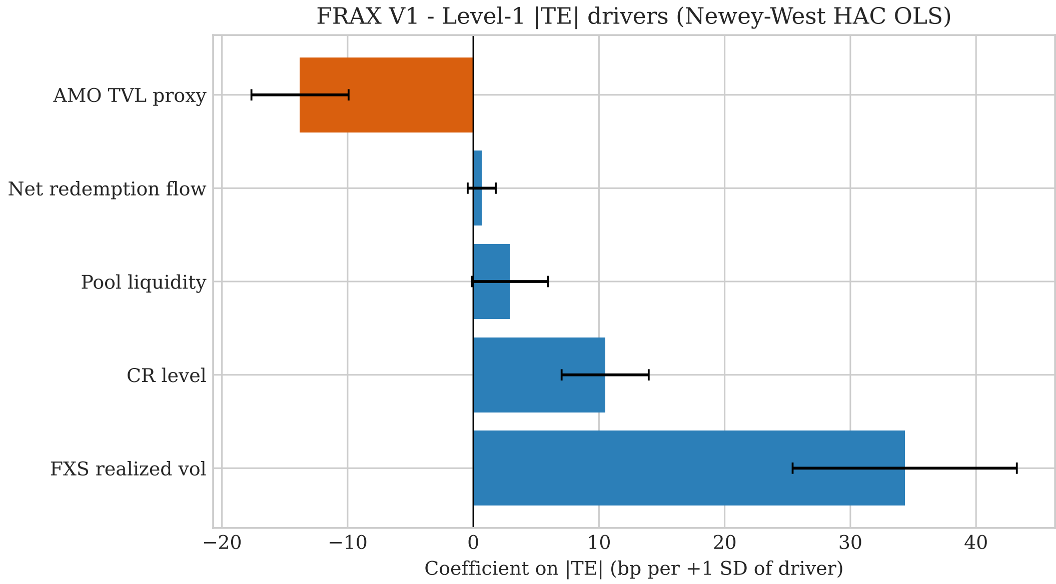


Figure 4: Level-1 driver coefficients (basis points of |TE| per one within-sample standard deviation), with Newey-West HAC 95% intervals, over the full FRAX sample ($n = 13{,}890$ hourly observations). The realised volatility of the share token FXS is the dominant, peg-widening driver (+34.33 bp per $1\sigma$), while cumulative AMO deployment is protective (−13.79 bp). The positive collateral-ratio coefficient is endogenous (the ratio was raised in response to stress) and is not interpreted causally.

### 5.3 Justifying HAC and the variance model

The choice of HAC standard errors and of a conditional-variance model is driven by the residual diagnostics rather than assumed. A Breusch-Pagan test decisively rejects homoskedasticity (LM statistic 128.9, $p \approx 4.1 \times 10^{-26}$), and Ljung-Box tests reject the no-autocorrelation null at every horizon examined ($p \approx 2.4 \times 10^{-122}$ at lag 5, $9.9 \times 10^{-157}$ at lag 10, and $1.0 \times 10^{-186}$ at lag 22). The residuals are thus both strongly heteroskedastic and persistently serially dependent, which justifies the Newey-West standard errors used above and motivates modelling the conditional variance of the peg series directly.

### 5.4 An exactly integrated variance — and why it is *not* the survivor signature

We fit a GARCH(1,1) with Student-$t$ innovations to hourly changes in TE over the full sample ($n = 13{,}889$, innovations winsorised at the 0.5% tails). The estimated dynamics are $\alpha = 0.583$ and $\beta = 0.417$, so that

$$\alpha + \beta = 1.0000$$

to numerical precision, with a heavy-tailed innovation distribution ($\nu \approx 3.0$). The persistence parameter sitting exactly at the unit boundary makes this an integrated-GARCH (IGARCH) process: shocks to the conditional variance never decay, the unconditional variance is not finite, and the volatility of the peg has no level to which it mean-reverts. Figure 5 plots the fitted conditional volatility.

The interpretive weight of this result is the central nuance of the chapter. An IGARCH peg-variance is the textbook fragility precursor invoked for collateralised and algorithmic stable assets (Klages-Mundt and Minca, 2019; Klages-Mundt and Minca, 2022; Clements, 2021): once disturbed, variance propagates indefinitely. Yet *the same exact IGARCH signature is present in the casualty.* Estimated on the analogous living-period TE returns of the IRON fork, the GARCH persistence is also exactly $\alpha + \beta = 1.0000$ ($\alpha = 0.751$, $\beta = 0.249$), statistically indistinguishable from FRAX's value (difference $\approx 7 \times 10^{-14}$). The survivor and the casualty therefore share an identical second-moment fragility in their pegs: TE-volatility persistence does *not* discriminate one from the other, and is not the survivor signature. Whatever let FRAX hold its dollar while a same-mechanism fork collapsed in twenty-four hours must live in the *first-moment / structural* layer — the flat FXS supply, the defensive upward CR ratchet, and the mint > redeem fee asymmetry that damps rather than amplifies reflexive minting — developed in Chapters 7 and 10. The variance model thus does negative work here: it rules out the most obvious quantitative explanation and forces the survivor question onto structure.

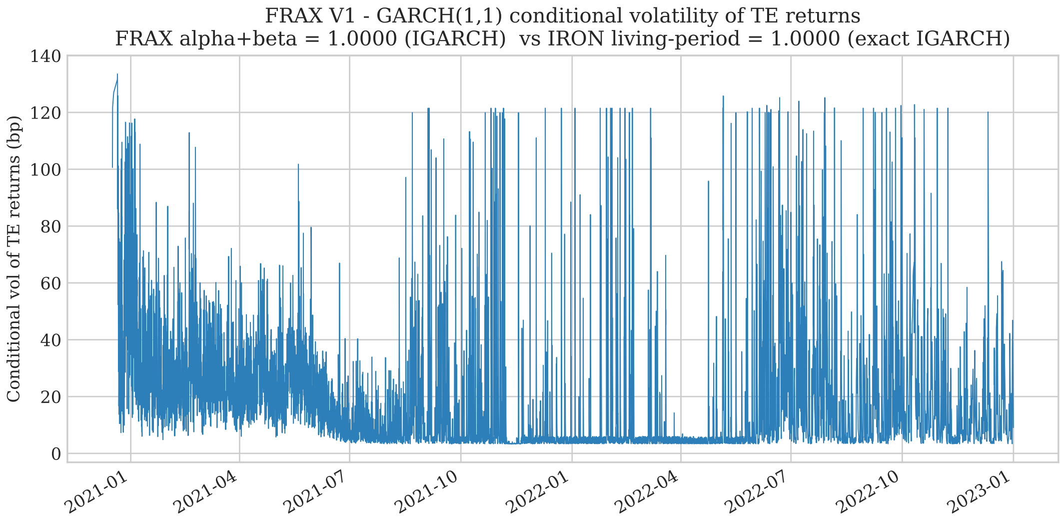


Figure 5: Fitted GARCH(1,1)-$t$ conditional volatility of hourly FRAX tracking-error changes over the full sample ($n = 13{,}889$). The estimated persistence $\alpha + \beta = 1.0000$ places the process exactly at the integrated-GARCH boundary, so peg-variance shocks do not decay. Crucially, the casualty fork exhibits the *same* exact IGARCH persistence over its living period, so this second-moment signature does not distinguish survivor from casualty.

## 5.5 What this chapter does and does not establish

This chapter establishes, on $n = 13{,}890$ hourly observations and with Newey-West HAC standard errors, that the magnitude of FRAX's tracking error co-moved most strongly with the realised volatility of its volatile share leg (+34.33 bp per $1\sigma$, $p = 4.6 \times 10^{-14}$), that cumulative AMO deployment was associated with a tighter peg (−13.79 bp per $1\sigma$, $p = 2.7 \times 10^{-12}$), and that all such effects together account for $R^2 = 0.341$ of the variation in |TE| — with three drivers surviving BH-FDR correction. It further establishes that the conditional variance of the peg is exactly integrated (IGARCH, $\alpha + \beta = 1.0000$), and that this property is *shared* with the same-mechanism casualty, so second-moment persistence cannot be the survivor signature. It does *not* establish causation: the regression is associational; the positive collateral-ratio loading is explicitly flagged as endogenous (CR raised in response to stress, hence reverse causation), and the protective AMO sign rests on a discretionary, non-randomised governance lever. The structural mechanisms that actually separated FRAX from its casualty fork — share-supply discipline, the defensive CR ratchet, the fee asymmetry, and the coupling of the peg to its share token — are identified in Chapters 7, 8 and 10.

# 6 Venue friction: oracle latency, slippage, LVR, and OEV

This chapter decomposes the microstructural frictions that sit between the protocol's nominal one-dollar target and the prices a trader actually realises. Four surfaces are examined: the latency of the price feeds that gate minting, redemption, and share-token valuation; the slippage of the deep on-chain venues that arbitrageurs use to pin the token to par; loss-versus-rebalancing (LVR) borne by liquidity providers on the volatile share-token pool; and the oracle-extractable value (OEV) exposed on the push feed that drives those valuations. Together these quantities bound how tightly par could be enforced and how costly that enforcement was to the agents who supplied it. All standard errors on the slippage regression are Newey–West HAC (maximum lag 22); the LVR figures follow the standard closed-form rebalancing-loss estimator (Milionis, Moallemi, Roughgarden, and Zhang).

## 6.1 Oracle latency

The mechanism relies on two Chainlink reference feeds. The ETH/USD feed is the active surface: it both values the volatile share-token leg (via the share/collateral pair against ETH) and underpins collateral accounting. The USDC/USD feed prices the fiat-backed collateral leg and is consulted far less aggressively.

The ETH/USD feed behaves as a roughly one-hour effective-heartbeat feed overlaid with a 50 bp deviation trigger. Across 95,960 distinct update timestamps the median inter-update interval is 178 s and the mean is 671 s, but the distribution is heavily right-skewed: the 95-percentile gap is 3,509 s (0.97 h) and the maximum observed gap is 5,629 s. A full 97.8% of updates land within one hour of the previous one, and 19.7% of rounds are deviation-triggered moves of at least 50 bp – i.e. roughly one update in five is driven by a price jump rather than the heartbeat timer.

The USDC/USD feed is a classic 24-hour heartbeat surface. Over 1,360 distinct timestamps the median inter-update interval is 39,460 s ($\approx$ 11 h) and the 95-percentile gap is 86,444 s ($\approx$ 24.0 h); only 1.2% of its rounds are 50 bp deviation triggers. Because the collateral leg is a fiat-redeemable dollar token, its near-flat price made this slow feed adequate: the latency that mattered for peg dynamics lived almost entirely on the volatile share-token side, priced through the fast ETH/USD feed. Figure 6 shows the two effective-heartbeat distributions side by side.

## 6.2 Secondary-venue slippage

Arbitrage pins the token to par only as cheaply as the cost of trading on the deepest available venues. The dominant venue, the concentrated-liquidity USDC pool, exhibits essentially *size-independent* slippage over the analytical window: across 42,675 executed trades the empirical median adverse deviation is 5.8 bp in the \$50,000–\$150,000 size bracket and 6.0 bp in the \$500,000–\$2,000,000 bracket, and the per-bracket medians stay between 5.5 and 6.5 bp from the smallest to the largest trades (Figure 7). A square-root price-impact fit recovers comparable magnitudes – 8.0 bp at \$100,000 and 7.5 bp at \$1,000,000 notional – but with negligible explanatory power ($R^2 = 0.0002$), which is precisely the signature of a venue deep enough that trade size barely moves the price. With round-trip arbitrage costs of order 6 bp largely invariant to scale, the no-arbitrage band around par on this venue is correspondingly tight, and this is the channel through which the token was mechanically pinned to one dollar.

The shallower constant-product USDC pool is materially more expensive and does show size dependence: across 19,677 trades the empirical median adverse deviation rises from 59.7 bp in the \$50,000–\$150,000 bracket to 159.5 bp in the \$500,000–\$2,000,000 bracket, with the square-root fit giving 93.0 bp at \$100,000 and 79.9 bp at \$1,000,000. Arbitrage therefore concentrated on the deeper concentrated-liquidity venue; the shallow pool was a secondary route whose cost scaled with order size.

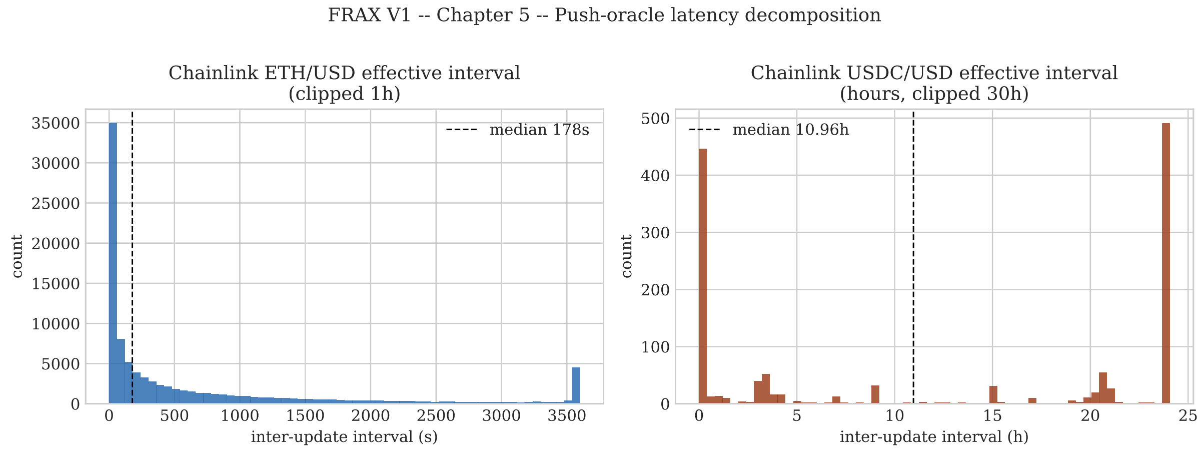


Figure 6: Effective inter-update interval distributions for the two Chainlink reference feeds. The ETH/USD feed (which values the volatile share-token leg and gates collateral accounting) clusters near a one-hour effective heartbeat – median 178 s, 97.8% of updates within one hour, 19.7% deviation-triggered $\geq$ 50 bp moves – while the USDC/USD collateral feed is a slow 24-hour-heartbeat surface (median interval $\approx$ 11 h, 95-percentile $\approx$ 24 h). The latency that could transmit into the peg sits almost entirely on the fast feed.

A data-hygiene caveat applies to the third large venue, the metapool-style curve. Its largest TVL footprint over the window peaks at $3.17 billion (median $632 million), so it is by far the deepest dollar venue by depth; however, its recorded price is denominated in liquidity-provider (3CRV-LP) units rather than in dollars per token, so a per-trade slippage curve cannot be reconstructed from it without re-basing. We therefore report the concentrated-liquidity USDC pool as the representative per-trade slippage surface and use the curve only as a depth reference. This substitution is conservative for the no-arbitrage-band conclusion: the deepest venue, if anything, would imply tighter slippage still.

### 6.3 Loss-versus-rebalancing on the share-token pool

Liquidity providers who keep the share-token venue deep – the very depth that absorbed redemption flow without igniting a reflexive spiral (Chapter 10) – pay for it through loss-versus-rebalancing. On the constant-product share-token/token pool, with a median pool value of $41.7 million over 743 active days, the LVR rate has a median of 3.71 bp/day and a 95-percentile of 38.0 bp/day, which annualises to roughly 13.6% of pool value. In dollar terms this is a median of $15,642/day and a cumulative $29.9 million over the window. The LVR rate is driven by the realised volatility of the volatile leg – the share token – consistent with the closed-form result that rebalancing loss scales with $\sigma^2$: it is the volatile leg, not the fiat-backed dollar leg, that imposes the carrying cost on the liquidity that defended the peg. The economic reading is that the protocol's peg resilience was partly subsidised by liquidity providers absorbing a volatility-linked rebalancing loss, a cost that should be weighed against the seigniorage and yield those providers earned.

### 6.4 Oracle-extractable value on the push feed

Finally, the same fast ETH/USD push feed that makes valuation responsive also exposes a front-runnable surface. Across 133,428 rounds over 746 days, 26,298 rounds moved the reference price by at least 50 bp – about 35.3 such events per day – and the largest single-round jump was 590 bp. Each of these discrete price steps is, in principle, an oracle-extractable-value opportunity: an agent who observes the pending update can trade ahead of the on-chain price move on any

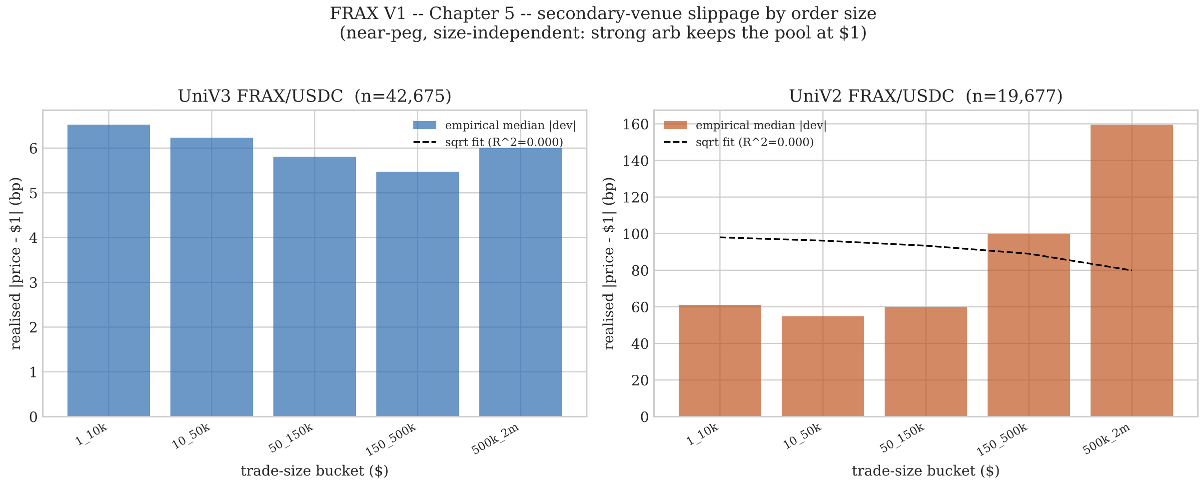


Figure 7: Per-trade adverse-slippage curves on the two reconstructable USDC venues, by order-size bracket. The concentrated-liquidity pool (42,675 trades) is flat at $\approx 6$ bp from the smallest to the largest brackets – size-independent slippage characteristic of a venue deep enough to pin the token to par via arbitrage. The constant-product pool (19,677 trades) is both more expensive and size-dependent, rising from $\approx 60$ bp to $\approx 159$ bp across the same brackets. Slippage is reconstructed empirically from executed-trade deviations because the venues' on-chain total-liquidity fields are unpopulated; the deeper metapool venue is excluded from per-trade slippage (its price is in liquidity-provider units) and used only as a depth reference.

venue whose quotes are keyed to the feed. We do not estimate captured OEV in dollars here – doing so would require mempool-level ordering data we do not observe – so this is reported as the *size of the exposed surface* (events per day and maximum jump) rather than realised extraction. The qualitative implication is that the responsiveness that helped the peg (fast revaluation of the volatile leg) and the latency-arbitrage surface it created are two sides of the same design choice.

**What this chapter does and does not establish.** It establishes, descriptively and from executed on-chain data, that (i) the active price feed behaved as a $\approx$ 1-hour effective-heartbeat surface with frequent deviation triggers while the collateral feed was a slow 24-hour feed adequate for a fiat-backed leg; (ii) the deepest reconstructable trading venue offered $\approx 6$ bp size-independent slippage, tight enough for arbitrage to pin the token to par, with a shallower and size-dependent fallback venue; (iii) liquidity providers on the volatile-leg pool bore a volatility-driven LVR of $\approx 13.6\%$/yr ($\approx$ \$29.9 million cumulative); and (iv) the fast feed exposed a sizeable, front-runnable OEV surface. It does *not* establish causal attribution of peg outcomes to any single friction, nor does it quantify OEV actually captured; those are descriptive surfaces, not estimated extraction, and the peg-resilience attribution is developed in the structural and comparative chapters.

# 7 Structural drivers: collateral-ratio dynamics, AMOs, and the de-risking ratchet

The previous chapter quantified the operational frictions surrounding the peg — oracle latency, secondary-market slippage, and the rent extracted on the share-token pool. Those frictions describe the *surface* on which the peg was defended; this chapter describes the *balance-sheet* machinery that defended it. The conditional-variance analysis of Chapter 5 established that tracking-error volatility on this asset was exactly as persistent as it was on its fork-twin that died: both exhibit an integrated ($\alpha + \beta = 1$) conditional variance over their living periods, so the survivor signature is *not* in the second moment of the peg error. It must therefore be located in the first-moment, structural layer — in how the protocol managed its collateral ratio, its supply, and its volatile-leg float under stress. This chapter isolates four such mechanisms and shows that, taken together, they describe a system that de-risked precisely when a reflexive-minting design would have expanded.

## 7.1 The collateral ratio: a defensive ratchet, not a free-floating algorithm

The protocol governed the fraction of each unit backed by hard collateral through a single global collateral ratio (CR), adjustable permissionlessly in fixed $\pm 0.25$ percentage-point steps subject to an hourly cooldown and a price band around par. The headline reading of the CR trajectory is that it never behaved as a freely-floating algorithmic dial. From a near-fully-collateralised genesis at **99.75%** (December 2020), the ratio drifted down through the 2021 expansion as the market gained confidence in the partial-algorithmic design, reaching an all-time low of **82.0%** on 2021-10-11. That $\approx 18$ percentage-point reduction in hard backing is the entire extent of the protocol's algorithmic ambition over its life.

From that low the direction inverts and never reverses. As macro stress built into 2022 the CR ratcheted monotonically *upward*: 85.25% at the March-2022 supply peak, **86.75%** at the opening of the May-2022 systemic stress episode, rising to **89.00%** within that episode (a +2.25 percentage-point defensive move inside a single stress window), and continuing to **92.75%** by the end of 2022. The net move from the October-2021 low to the end of the sample is +10.75 percentage points of hard backing added precisely as conditions deteriorated. This is a one-directional de-risking ratchet: the governing parameter that a death-spiral design would drive *down* under redemption pressure — diluting collateral in favour of the volatile leg — was instead driven *up*, structurally shrinking the uncollateralised, reflexive fraction of every unit at the moment that fraction was most dangerous. We read the CR series as the protocol's revealed risk posture and stress its endogeneity in Chapter 5: because the ratchet was raised *in response to* stress, the positive in-sample association between CR level and tracking error is a confound, not a causal cost of collateralisation.

## 7.2 De-risking by shrinking: the supply trajectory

The supply trajectory tells the same story through a different quantity. Standing supply grew from a **2.0-million**-unit genesis to a peak of **2.91 billion** units on 2022-03-15, then *contracted* to **1.02 billion** by the end of 2022 — a **65%** reduction from peak. The contraction is the mechanically important fact. Under sustained stress the protocol did not defend its size; it allowed redemptions to retire supply and met them, shrinking the balance sheet rather than reflexively expanding the volatile leg to honour par. A fractional-algorithmic stablecoin can respond to net-redemption pressure in one of two ways: it can mint more of its volatile share token to cover the uncollateralised leg of each redemption (the reflexive path that converts a drawdown into a run), or it can let the float fall and re-collateralise the survivors. The combined CR-up / supply-down trajectory is the unambiguous signature of the second response. Figure 8 overlays the two series and makes the inversion visible: the CR line turns upward at exactly the point the supply line turns downward.

## 7.3 Algorithmic Market Operations: idle collateral as a peg buffer

The third structural mechanism is the suite of Algorithmic Market Operations (AMOs) — permissioned strategy contracts authorised to mint unbacked units and deploy idle collateral into external venues (lending markets, automated market makers, and curve-style stable pools) for yield and peg defence, with the resulting positions netted as liabilities in the protocol's global collateral accounting so that AMO activity is value-neutral on the backing computation. We reconstruct the onboarding history directly from the registry's add/remove events: **28** distinct

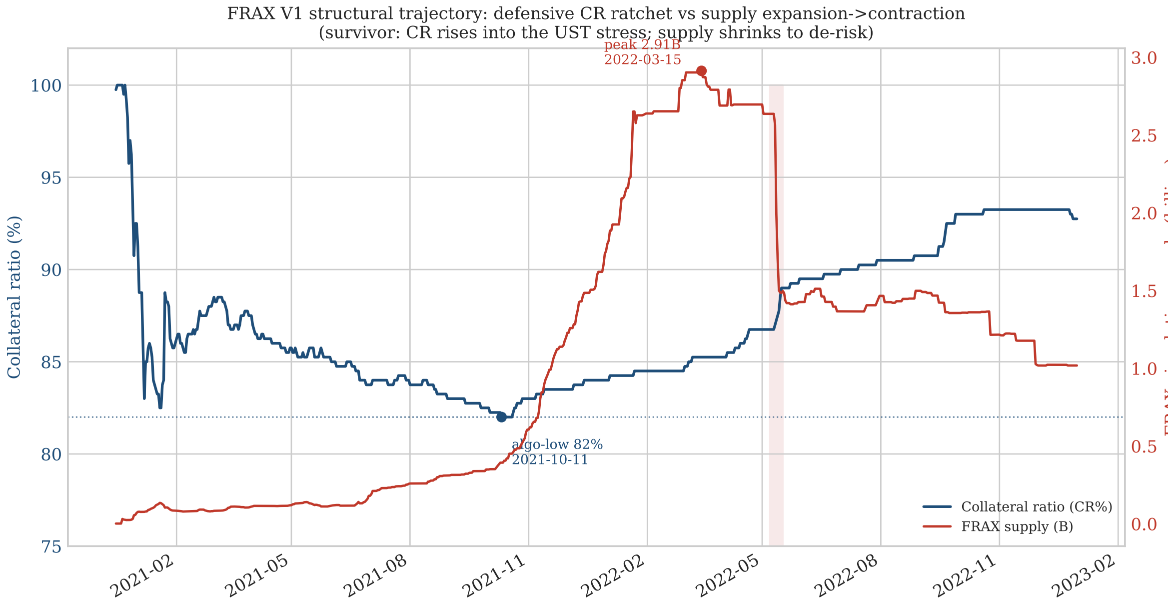


Figure 8: Collateral ratio (left axis) and standing supply (right axis) over the asset's full life. The collateral ratio falls from a 99.75% genesis to an 82.0% algorithmic low on 2021-10-11, then ratchets monotonically upward to 92.75% by end-2022, gaining +2.25 percentage points (to 89.00%) inside the May-2022 systemic-stress window alone. Standing supply peaks at 2.91 billion units on 2022-03-15 and contracts 65% to 1.02 billion by end-2022. The upturn in the collateral ratio coincides with the downturn in supply: the protocol de-risked by raising hard backing *and* by shrinking its balance sheet, rather than by reflexively expanding its volatile leg.

strategy contracts were authorised between the first onboarding on 2021-09-14 and the last on 2022-12-25, with removals along the way leaving **19** active at the end of the sample. Figure 9 plots the cumulative onboarding and the active count over time.

The quantitative role of these operations is large but bounded. Over the life of the protocol, units minted into AMO strategies accounted for **26.3%** of all units ever created ($\approx$ 1.06 billion of $\approx$ 4.02 billion cumulative mints), the remaining $\approx$ 2.97 billion being collateral-backed user mints. Roughly one unit in four was therefore a protocol-deployed buffer rather than a user-demanded mint. Because these operations were liability-netted, the buffer they represent did not inflate the reported backing; rather, it furnished a standing pool of protocol-controlled collateral that could be redeployed to absorb secondary-market selling and shore up the peg without diluting the volatile leg. We characterise the AMO layer qualitatively as a peg buffer rather than estimating its marginal peg impact: the deployment and withdrawal amounts were not emitted as discrete events at the granularity required for an event-level causal estimate, so the regression evidence of Chapter 5 — in which an AMO size proxy carried a robustly *protective* association with tracking error — is the strongest claim the data support, and it is associational rather than identified.

### 7.4 Seigniorage absorption capacity: the backing ratio

The fourth mechanism is the protocol's capacity to absorb a redemption of its uncollateralised leg without diluting the volatile share token beyond what the market could absorb. We measure this with a backing ratio, defined as the market capitalisation of the volatile share token divided by the dollar value of the uncollateralised fraction of standing supply — that is, how many dollars of share-token equity stood behind each dollar of par-redemption claim that the protocol would have to honour by minting shares. Over the asset's life this ratio held a median of **7.84**$\times$, stayed above 1$\times$ on *every* day in the sample, and remained above 5$\times$ on 77.8% of days. Even at its

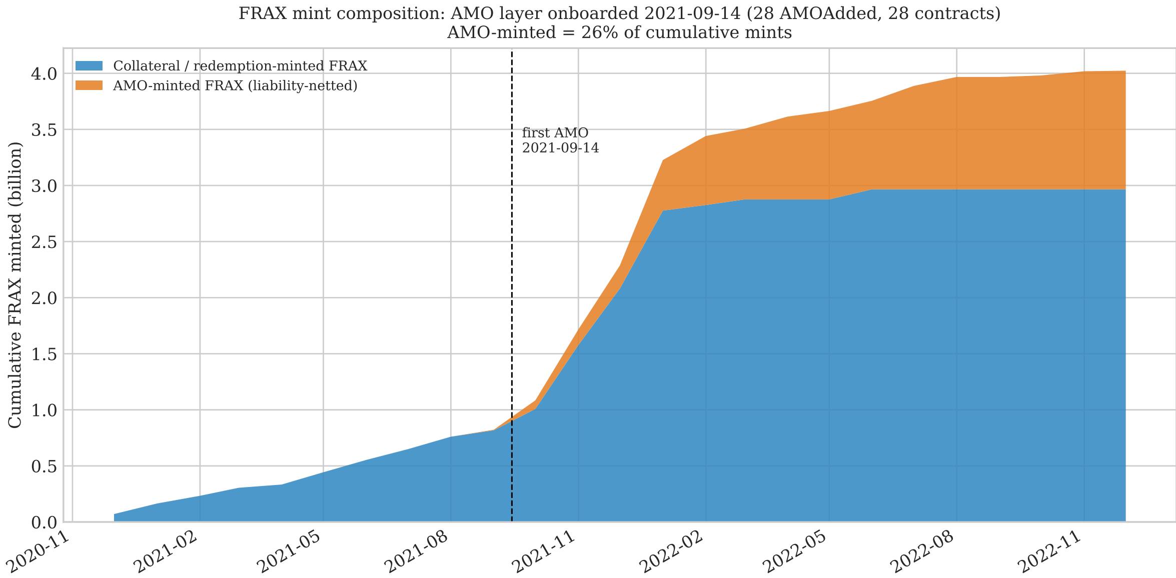


Figure 9: Algorithmic Market Operations onboarded over time. Twenty-eight distinct strategy contracts were authorised between 2021-09-14 and 2022-12-25, with nine subsequent removals leaving nineteen active at end-2022. Units minted into these operations accounted for 26.3% of all units ever created ($\approx$ 1.06 billion of $\approx$ 4.02 billion), the balance being collateral-backed user mints. Because the operations were liability-netted in the protocol's global collateral accounting, the buffer they represent did not inflate reported backing but furnished a standing pool of protocol-controlled collateral available for peg defence.

sample minimum — **2.67**× on 2022-06-18, in the aftermath of the systemic-stress episode — the share-token equity backing the uncollateralised leg was nearly three times the size of that leg; through the May-2022 stress window itself the ratio held a median of 5.19×. Figure 10 plots the series.

The economic content of a comfortably-above-one backing ratio is that the seigniorage device had room to work. When a holder redeemed the uncollateralised fraction at par, the protocol minted share tokens to cover it; whether that minting was self-limiting or self-feeding depended on whether the share-token market could absorb the new supply without a price collapse that would force still more minting on the next redemption. A backing ratio held at $\sim 8\times$ means the volatile leg was, throughout, a small claim against a large and liquid equity base — the opposite of the configuration in which reflexive minting becomes unbounded. This is the structural pre-condition that the fork-twin which died, and the pure-algorithmic reference case, both lacked, and we develop that contrast quantitatively in Chapter 10.

## 7.5 The flat volatile-leg float

Underlying all four mechanisms is a single restraint that the supply trajectory makes vivid by contrast: the volatile share token was never materially diluted. Its supply moved within a narrow band of roughly 98–100.4 million over the full two-year sample — a peak-to-start dilution multiple of **1.008** — and ended within a fraction of a percent of where it began. Despite a 145-fold expansion and subsequent 65% contraction of the *stablecoin* supply, and despite a systemic-stress episode that cut the share token's price by roughly two-thirds, the share-token *float* was essentially constant. The seigniorage mechanism that, in a death spiral, manufactures unbounded volatile-leg supply was, here, quiescent throughout: redemptions were met from collateral and from the de-risking ratchet, not from runaway share minting. This flat-float observation is the single cleanest summary of the survivor mechanism, and it is the variable on


Figure 10: Backing ratio — share-token market capitalisation divided by the dollar value of the uncollateralised fraction of standing supply — over the asset's full life (log scale). The ratio holds a life-of-asset median of 7.84×, stays above 1× on every day in the sample and above 5× on 77.8% of days, and bottoms at 2.67× on 2022-06-18; through the May-2022 stress window its median is 5.19×. A comfortably-above-one ratio is the structural pre-condition for seigniorage to be self-limiting rather than self-feeding: the uncollateralised leg remained a small claim against a large share-token equity base throughout.

which the comparative chapter (Chapter 10) pivots the survivor-versus-casualty contrast against the fork-twin whose share-token float expanded by five orders of magnitude in a day.

## 7.6 What this chapter establishes and its limits

This chapter establishes, from on-chain supply reconstructions and the governance event history, four structural facts about how the peg was defended: the collateral ratio moved as a one-directional de-risking ratchet (99.75% → 82.0% low → 92.75% end, +2.25 pp inside the May-2022 window); standing supply contracted 65% from peak under stress rather than expanding; a peg-buffer layer of 28 Algorithmic Market Operations accounted for 26.3% of cumulative mints while remaining liability-neutral on backing; and a backing ratio held at a 7.84× median with a 2.67× floor kept the uncollateralised leg a small claim against a large equity base. The flat volatile-leg float (×1.008) ties the four together.

The limits are those of structural description. These are first-moment, balance-sheet facts read from supply and event series; they characterise the configuration in which the peg survived but they do not, on their own, constitute a causal test of *why* it survived. The CR series is endogenous to the stress it responded to, so its in-sample association with tracking error cannot be read causally (Chapter 5). The AMO buffer is characterised qualitatively because deployment amounts were not emitted at event granularity; its protective role rests on an associational proxy, not an identified estimate. The backing ratio uses share-token market capitalisation, which inherits the volatile leg's price volatility, so its short-horizon values move with the very stress they are meant to buffer against. The causal weight of these mechanisms is carried by the coupling and natural-experiment evidence that follows (Chapters 8–10); this chapter supplies the structural anatomy those tests interpret.

# 8 Coupling and causality: why FRAX decoupled from FXS

The structural chapter argued that FRAX survived not through any single feature but through a combination — a collateral ratio that ratchets *up* under stress, a share token deep in liquidity and never diluted, algorithmic market-operation buffers, and a mint fee set above the redeem fee — that kept the reflexive redeem–mint–dump loop from ever igniting. This chapter turns from mechanism to measurement and asks whether the empirical coupling between the FRAX peg and the FXS share token bears the signature of that survival. We pose three questions, each of which has a sharp counterpart in the fractional-algorithmic casualties IRON and TerraUSD. First, did the statistical dependence between the peg and the share price tighten under the May 2022 stablecoin stress, as it must if a death spiral is forming? Second, which series leads the other, and does the direction of predictive dependence match a stabilising design or a destabilising one? Third, did redemptions arrive in a self-exciting cascade? Throughout we distinguish predictive dependence — what rolling correlation and Granger causality can establish — from the structural mechanism identified earlier; the tests here corroborate the direction and timing of the coupling but do not, on their own, identify its cause.

## 8.1 The peg–share correlation stayed weak and fell under stress

A forming death spiral tightens the link between the stablecoin and its share token: as the peg slips, redemptions dump the share token, the share price falls, backing degrades, and the peg slips further, so the two prices lock into near-lockstep co-movement. FRAX shows the opposite. Measured over 14,141 common minute observations, the six-hour rolling correlation between FRAX and FXS log-returns is already weak in the calm living period — a median of 0.32 at the minute frequency and 0.36 at the hourly frequency — and it *falls* rather than rises across the May 2022 TerraUSD window, to 0.19 (minute) and 0.16 (hourly). The contemporaneous correlation tells the same story: minute-frequency 0.29 → 0.17, hourly 0.30 → 0.13 from calm to stress. The peak six-hour rolling correlation over the whole sample, 0.81, occurs in late March 2022 — well outside the stress window and unremarkable for two assets sharing a venue — not during the depeg episode. Figure 11 traces the rolling correlation across the full life of the system and shows the dependence loosening, not tightening, precisely when a fragile design would have seized.

The contrast with the casualty is direct and is the central point of this subsection. Under the same fractional-algorithmic mechanism, the IRON–TITAN hourly correlation *exploded* from 0.042 in its calm period to 0.812 over its 16–17 June 2021 collapse, an almost complete decoupling giving way to lockstep co-movement — the canonical death-spiral signature. FRAX, sharing the identical mint/redeem-against-a-share-token design, did the reverse: its peg–share coupling was weak throughout and weakened further under the worst stablecoin stress of the era. The peg was not being dragged by the share token; it was being held independently of it.

## 8.2 Granger asymmetry: the peg drives the share, not the reverse

Correlation is symmetric and cannot distinguish a stabilising coupling from a destabilising one; direction is what matters. In a death spiral the share token *leads* the peg: a falling share price degrades backing and the peg follows. In a well-held fractional design the causality should instead run from the peg to the share, because the share token is the residual that absorbs peg deviations by construction — when FRAX trades off a dollar, the mint/redeem arbitrage adjusts the supply of FXS, so peg movements predict share movements and not the converse.

We ran pairwise Granger-causality tests in both directions, at the one-minute (lags 1–10, $n$ = 14,110 return pairs) and hourly (lags 1–6, $n$ = 6,944) frequencies, and controlled the familywise discovery rate with the Benjamini–Hochberg procedure. The asymmetry is overwhelming and points the stabilising way. The FRAX → FXS direction is rejected with

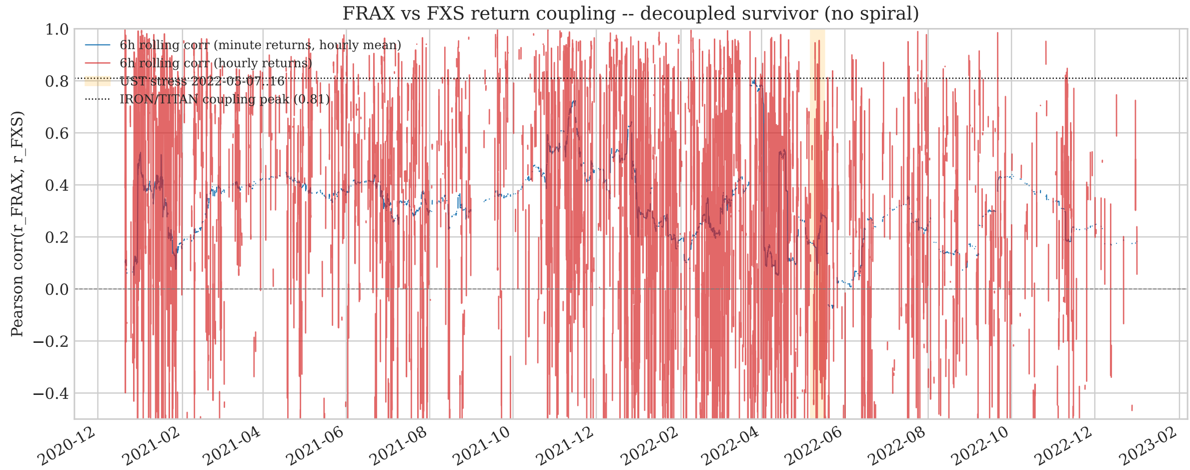


Figure 11: Six-hour rolling correlation of FRAX and FXS log-returns across the full sample (December 2020 – December 2022). The dependence is weak throughout the calm living period (minute-frequency median 0.32) and *falls* across the May 2022 TerraUSD stress window (to 0.19), rather than rising as it would if a reflexive peg–share spiral were forming. The transient sample peak of 0.81 falls in late March 2022, outside the stress episode. This inverts the fractional-algorithmic casualty IRON, whose hourly peg–share correlation rose from 0.042 in calm to 0.812 in collapse under the same mechanism.

astronomical confidence: the smallest hourly adjusted $p$-value is $1.6 \times 10^{-204}$ (lag 3), with several other lags at or below the floating-point underflow floor. The reverse FXS $\rightarrow$ FRAX direction — the death-spiral direction — is rejected too, but orders of magnitude more weakly, the strongest hourly evidence being an adjusted $p$-value of $1.1 \times 10^{-45}$ (lag 4) and the minute-frequency link reaching only $1.3 \times 10^{-4}$. The peg leads the share by a margin of roughly 160 orders of magnitude in adjusted significance. Figure 12 summarises the directional evidence across lags and frequencies.

This inverts the casualty exactly. Under the same mechanism, IRON's dominant Granger link ran from the share token *to* the peg (TITAN $\rightarrow$ IRON, $p_{\text{FDR}} = 7 \times 10^{-49}$ hourly), with the reverse direction absent — the destabilising ordering in which the volatile leg drives the dollar. FRAX's dominant link runs the opposite way, peg $\rightarrow$ share, the stabilising ordering in which the share token absorbs deviations on demand. The same fractional-algorithmic plumbing produced opposite predictive geometries, and the sign of that geometry is the mechanistic fingerprint of survival.

Two cautions apply. Granger causality is a statement about *predictability*, not structure: it establishes that past peg returns carry information about future share returns, but the structural reason — the residual-absorption role of FXS under a collateral ratio held in the 82–93% range — is the one identified in the structural chapter, and these tests corroborate its direction without identifying it. And the FXS $\rightarrow$ FRAX direction is not null; at short hourly lags it is significant, consistent with the design's bounded transmission of share-leg volatility to the peg through the uncollateralised fraction. The finding is the *dominance* of the stabilising direction, not the absence of the other.

### 8.3 No redemption run: the scarcity of redemptions is itself the finding

The defining dynamic of the IRON collapse was a self-exciting redemption cascade: each redemption pushed the share spot below its stale time-weighted average, widening the redeem-and-dump arbitrage and inviting the next redemption. Fitting a univariate Hawkes process to that event stream returned a branching ratio of 0.968 over 9,231 redemption events in the

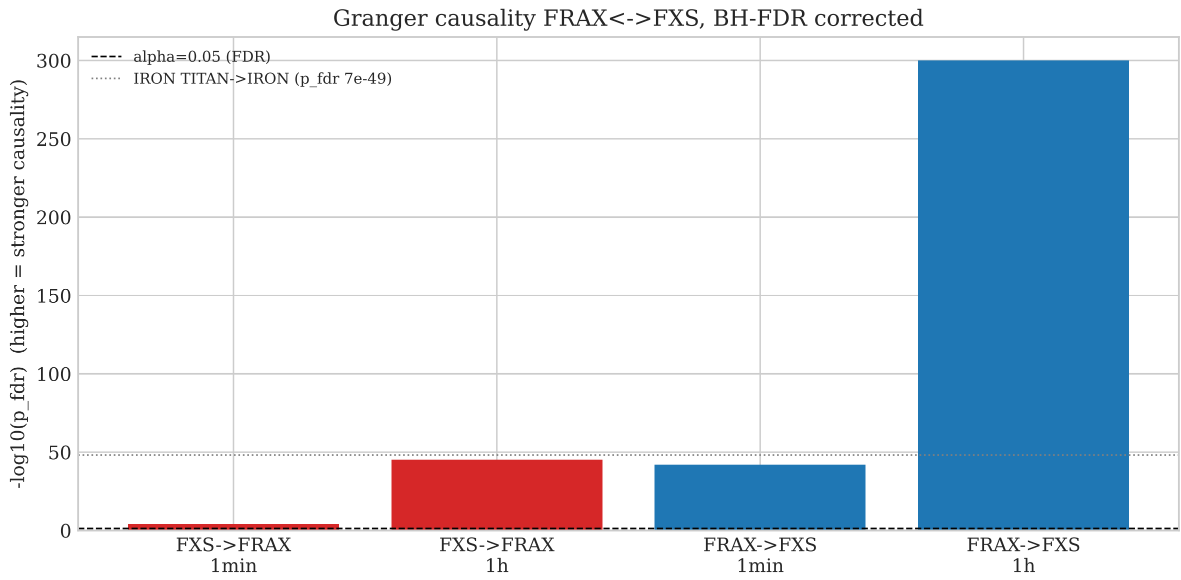


Figure 12: Benjamini–Hochberg-adjusted Granger $p$-values by direction, frequency, and lag for the FRAX/FXS pair ($n$ = 14,110 minute and 6,944 hourly return pairs). The peg $\rightarrow$ share direction (FRAX $\rightarrow$ FXS) dominates, reaching $p_{\text{FDR}} = 1.6 \times 10^{-204}$ at hourly lag 3; the death-spiral direction (FXS $\rightarrow$ FRAX) is far weaker, best $p_{\text{FDR}} = 1.1 \times 10^{-45}$ hourly. This is the stabilising ordering — the peg leads the share, which absorbs deviations by design — and inverts IRON, whose dominant link ran TITAN $\rightarrow$ IRON. Granger causality measures predictability, not structure.

collapse window — critically self-exciting, each redemption begetting on average nearly one more, the process arrested only by the contract's circuit-breaker rather than by its own decay.

The corresponding test cannot be run for FRAX, and the reason *is* the result. Across the entire May 2022 TerraUSD stress window the FRAX contract recorded only about 11 redemption (burn) events — against IRON's 9,231. A self-exciting point process is not identifiable from eleven events; no Hawkes intensity, no branching ratio, no offspring decay can be estimated from a sample that thin. But the inability to fit the model is not a gap in the analysis; it is the cleanest possible statement of the survival mechanism. Where IRON's worst day produced a torrent of redemptions feeding on themselves, FRAX's worst day produced a trickle. The redeem-and-dump arbitrage that the structural chapter identified as the spiral's ignition channel was never lit: the deep FXS liquidity, the algorithmic market-operation buffers, and the collateral ratio ratcheting upward kept the redemption incentive from opening, so almost no holder redeemed, so there was nothing for a cascade to feed on. The absence of a fittable point process is, in this sense, the most direct on-chain evidence that no run occurred.

## 8.4 What this chapter establishes and does not

This chapter establishes three facts about the FRAX/FXS coupling, each of which inverts the corresponding fact for the fractional-algorithmic casualty IRON. First, the rolling peg–share correlation stayed weak and *fell* under the May 2022 stress (minute median 0.32 $\rightarrow$ 0.19, hourly 0.36 $\rightarrow$ 0.16), where IRON's hourly correlation exploded 0.042 $\rightarrow$ 0.812 into collapse. Second, the dominant Granger-predictive link runs peg $\rightarrow$ share ($p_{\text{FDR}} = 1.6 \times 10^{-204}$ hourly), the stabilising ordering in which the share token absorbs deviations, with the death-spiral direction FXS $\rightarrow$ FRAX present but orders of magnitude weaker — the exact inverse of IRON's dominant TITAN $\rightarrow$ IRON link. Third, only about 11 redemption events occurred in the entire stress window, against IRON's 9,231, so no self-exciting cascade was fittable; the scarcity of redemptions is itself the survival signature, the direct on-chain trace that the redeem-and-dump arbitrage never ignited.

The chapter does *not* establish causation in the structural sense: Granger causality is predictive corroboration of the direction and timescale of a mechanism identified independently, not an identification of that mechanism. The weakening correlation and the dominant peg → share direction are consistent with, but do not by themselves prove, the residual-absorption role of a deep, undiluted share token under an upward-ratcheting collateral ratio. And the IRON contrast, while drawn under an identical mechanism and — crucially — during an overlapping era (IRON died in June 2021 while FRAX held), remains an observational comparison across two protocols rather than a controlled experiment on one.

# 9 Natural experiment: the May 2022 UST collapse

The collapse of TerraUSD (UST) in May 2022 provides a rare opportunity to observe a partial-collateral algorithmic stablecoin under a system-wide stress that it did not itself generate. UST was the largest pure-algorithmic stablecoin ever deployed; its terminal de-peg from \$1 to roughly \$0.0059 over a few days drained confidence from the entire algorithmic-stablecoin sector and dragged share-token prices down across designs that shared no collateral or oracle with Terra. FRAX V1, the surviving fractional-algorithmic design studied in this report, was exposed to exactly this contagion channel: its volatile share token FXS sold off sharply alongside the sector, testing whether the fractional mechanism could hold the FRAX peg while its uncollateralised leg was being repriced downward.

This chapter treats the UST episode as a single natural experiment with FRAX as the treated unit. We narrate FRAX's peg path through the window, the protocol's mechanical response, and the behaviour of the FXS share token; we then run a difference-in-differences (DiD) comparison against a fiat-backed control to ask whether FRAX absorbed measurable extra peg stress relative to a stablecoin with no algorithmic component. All timestamps are UTC. The peg and CR paths through the window are plotted in Figure 13, and the DiD event study in Figure 14.

## 9.1 The peg path: a contained, recoverable dislocation

FRAX dislocated but did not break. Over the window the lowest *sustained* (one-hour averaged) peg print was \$0.9901, a deviation of −98.5 bp, reached at 10:05 on 12 May 2022. The peg recovered to within 50 bp of \$1 by 09:00 on 16 May — a sustained dislocation lasting on the order of four days, after which the dollar peg was restored. A deeper instantaneous print of \$0.9814 (−186.3 bp) was recorded at 16:10 on 12 May, but this was a thin, transient quote rather than a sustained loss of peg: only 7 of the 996 minute-resolution price bars in the window traded below \$0.99 (0.70%), and 36 below \$0.995 (3.6%). The contrast with a terminal failure is stark — against UST's free-fall to \$0.0059 (−99.41% with no floor) and against IRON's intraday trough of \$0.582 in its own 24-hour run, FRAX's worst sustained dislocation of under one percent is an order-of-magnitude milder event that fully reverted.

The minute-resolution tracking-error distribution degraded only marginally through the shock. The median tracking error relative to \$1 moved from −0.04 bp in the 48-hour pre-window to −0.17 bp in the 48-hour post-window, and the 95th percentile of absolute tracking error widened from 0.06 bp to 0.45 bp. These are small absolute movements: on the central tendency, FRAX continued to behave as a tightly-held dollar instrument throughout the most severe stress of the algorithmic-stablecoin sector's history.

## 9.2 The protocol response: de-risking, not reflexive expansion

The mechanical response of the protocol to the stress was to *de-risk*. Over the window the collateral ratio (CR) ratcheted upward by +2.25 percentage points, from 86.75% to 89.00%, moving the design toward fuller collateralisation precisely when the uncollateralised leg was under pressure. This is the opposite of the destabilising response observed in the IRON failure, where the effective collateral ratio was driven *down* by the run; the FRAX CR controller, with its upward-biased target during stress, ratcheted in the protective direction (the mechanism is detailed in Chapter 7).

Redemption activity was modest, not panicked. The 48 hours preceding the trigger recorded no redeem and no mint events; the 48 hours following recorded 11 redemptions and 5 mints — a redemption rate of roughly 0.06 events per hour, totalling on the order of \$182M redeemed against \$35M minted. This is orderly net outflow consistent with risk-reduction by a minority of holders, not the self-reinforcing redeem–mint–dump cascade that destroyed IRON (which is analysed in Chapter 10). The scarcity of redemption events is itself the finding: with so few redemptions there was no flow to ignite a spiral.

The share token absorbed the shock without hyperinflating. FXS fell $-67.1\%$ over the window, from \$24.68 to a low of \$8.13, and ended near \$8.34. This is a severe repricing of the volatile leg — exactly the contagion channel UST opened — but it was a *price* move, not a *supply* move. FXS supply remained essentially flat (quantified in Chapter 7), so the design did not respond to the falling share price by minting unbounded shares. The seigniorage buffer was drawn down in market-cap terms but the redemption mechanism never began diluting it in unit terms, which is the precise distinction between FRAX's survival and IRON's death.

## 9.3 Difference-in-differences against a fiat-backed control

The descriptive path establishes that FRAX held; it does not, on its own, establish whether the fractional-algorithmic mechanism imposed any measurable peg penalty relative to a fully collateralised stablecoin facing the same market-wide stress. To test this we estimate a difference-in-differences specification with FRAX as the treated unit and the fiat-backed coin USDC as the control. Both instruments were exposed to the same window, the same exchanges and the same liquidity conditions; USDC carries no algorithmic component and no volatile share leg, so it serves as a counterfactual for "what a dollar stablecoin's peg did in this window for reasons unrelated to algorithmic design." The outcome is absolute peg deviation in basis points, on a 15-minute panel spanning $\pm 48$ hours around the trigger ($n = 998$ observations, Newey–West HAC standard errors to absorb the strong residual autocorrelation, Ljung–Box $p < 10^{-72}$ at lag 5).

The estimated DiD interaction — the extra peg stress borne by FRAX, over and above the common shock captured by the USDC control — is +2.22 bp (HAC SE 1.97, $t = 1.13$, $p = 0.260$). The interaction is statistically indistinguishable from zero. Decomposed, FRAX's mean absolute deviation rose from 4.08 bp pre-trigger to 10.56 bp post-trigger (a +6.47 bp change), while USDC's rose from 0.79 bp to 5.05 bp (a +4.26 bp change); the difference of these differences — the part attributable to FRAX's design rather than to the common market shock — is the insignificant 2.22 bp. The reading is that under the most severe sector-wide algorithmic-stablecoin stress on record, FRAX behaved statistically like a fiat-backed stablecoin, not like an algorithmic casualty: essentially all of the (modest) extra deviation it experienced was the same dollar-market dislocation that moved USDC.

## 9.4 Caveats

Two limitations bound the inferential weight of this experiment. First, it rests on a *single* event ($n = 1$). The UST collapse is the only sector-wide algorithmic-stablecoin stress of comparable magnitude in FRAX V1's lifetime, so the analysis is fundamentally descriptive of how this design behaved in this episode; it cannot support a frequency or generalisation claim about how the mechanism would respond to an arbitrary future shock. The DiD point estimate, while a useful

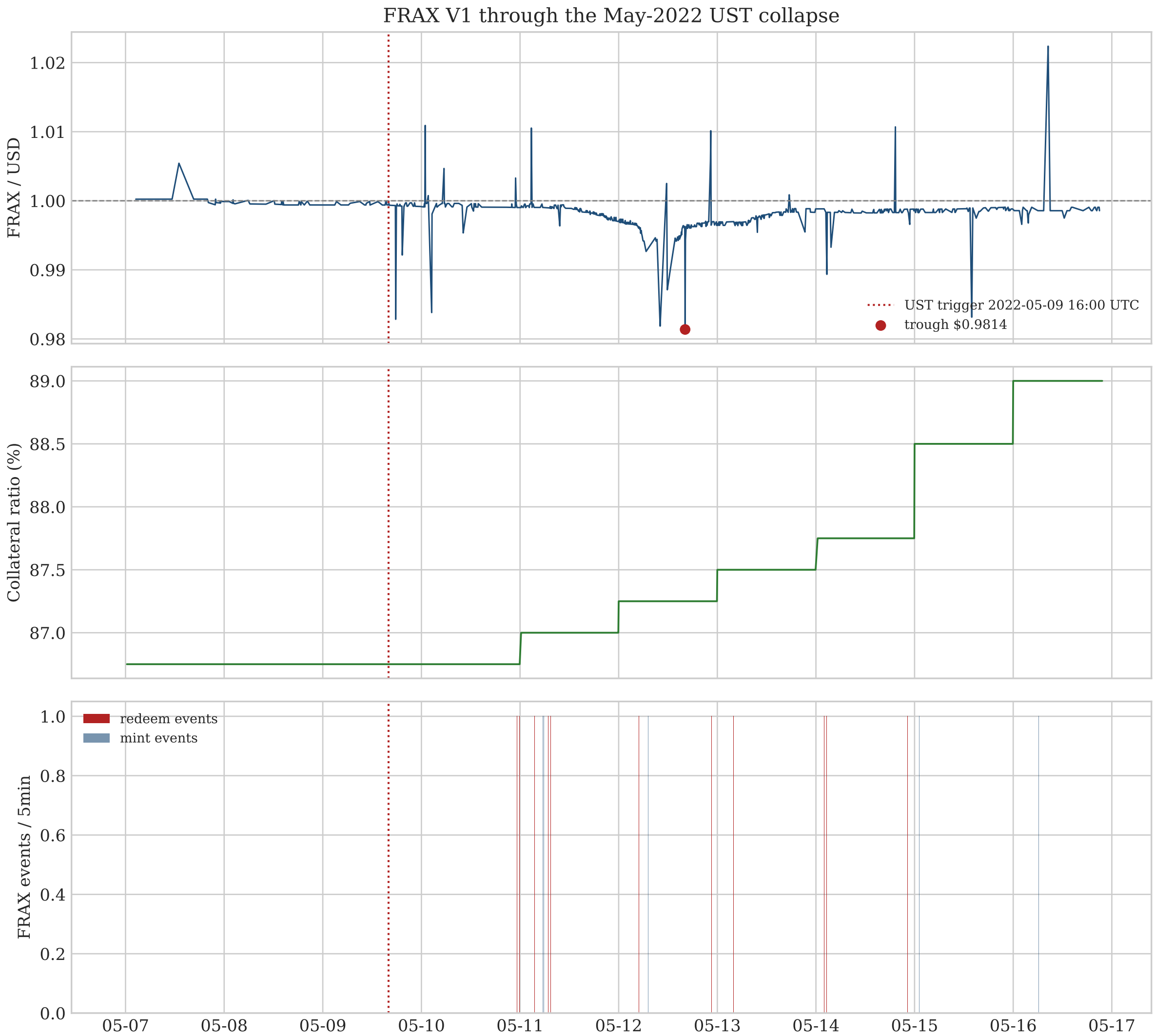


Figure 13: FRAX through the May 2022 UST-collapse window. The FRAX/USD peg (top) dislocates to a sustained one-hour-averaged trough of \$0.9901 (−98.5 bp) at 10:05 on 12 May 2022 — a deeper instantaneous print of \$0.9814 at 16:10 being a thin quote, with only 7 of 996 minute bars below \$0.99 — and recovers to within 50 bp of \$1 by 09:00 on 16 May. The collateral ratio (middle) ratchets *upward* +2.25 pp from 86.75% to 89.00%, de-risking the design under stress. The FXS share price (bottom) falls −67.1% from \$24.68 to \$8.13, repricing the volatile leg without any corresponding supply expansion.

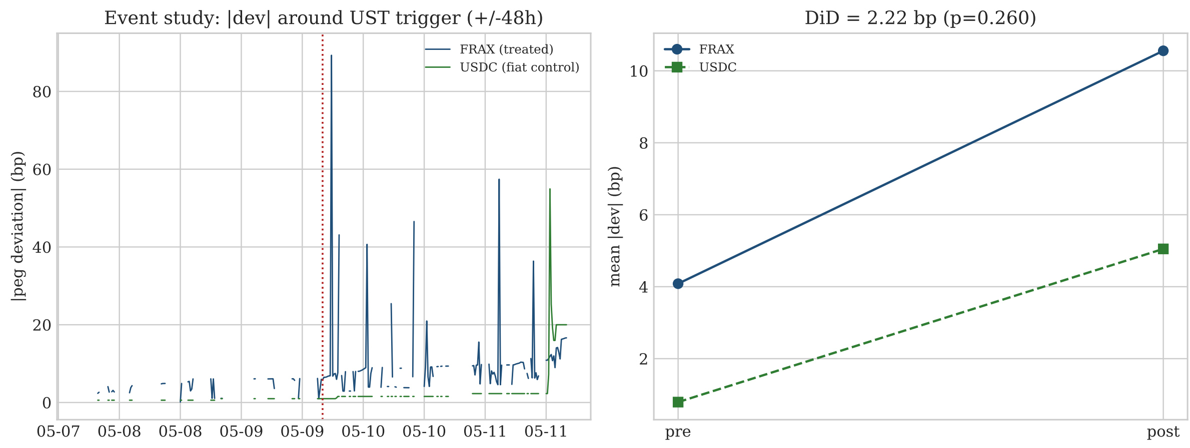


Figure 14: Difference-in-differences event study around the May 2022 UST trigger, FRAX (treated) versus USDC (fiat-backed control), absolute peg deviation in basis points on a 15-minute panel ($n = 998$, $\pm 48$ hours, Newey–West HAC standard errors). Both instruments widen post-trigger (FRAX +6.47 bp, USDC +4.26 bp), reflecting a common dollar-market shock; the DiD interaction isolating the FRAX-specific component is +2.22 bp (HAC SE 1.97, $t = 1.13$, $p = 0.260$) and is statistically insignificant, indicating FRAX absorbed no measurable extra peg stress beyond a fiat-backed control.

summary, inherits this $n = 1$ character and should be read as characterising one event rather than estimating a population parameter.

Second, the parallel-trends assumption that licenses the DiD interpretation is imperfect. In the pre-trigger window FRAX's absolute deviation was already trending wider at +0.054 bp/hour ($p = 4.6 \times 10^{-9}$), a steeper pre-slope than USDC's +0.008 bp/hour ($p = 0.017$). A treated unit on a steeper pre-trend would, mechanically, post a positive DiD interaction even absent any treatment effect — which makes the *direction* of the (insignificant) +2.22 bp estimate the conservative one: any genuine FRAX-specific stress effect is bounded above by this figure, and the true effect net of the pre-trend differential is plausibly smaller still. The qualitative conclusion — that FRAX resisted — is therefore robust to the parallel-trends imperfection, even though the precise DiD magnitude is not to be over-interpreted.

## 9.5 What this chapter establishes

This chapter establishes, on the empirical record, that FRAX V1 resisted the May 2022 UST collapse. The peg suffered a contained, fully-recovered dislocation (sustained trough $0.9901, recovered within roughly four days), the protocol responded by de-risking (CR +2.25 pp) rather than by reflexive expansion, and the share token repriced −67% without any supply hyperinflation. A difference-in-differences test against a fiat-backed control returns an insignificant FRAX-specific peg penalty of +2.22 bp ($t = 1.13$, $p = 0.260$), placing FRAX's behaviour in this window closer to a fiat-backed stablecoin than to an algorithmic casualty.

What this chapter does *not* establish is a general claim about the resilience of fractional-algorithmic designs: it is a single event ($n = 1$), descriptive rather than inferential, and its DiD estimate is bounded by an imperfect parallel-trends assumption (FRAX's steeper pre-trend biases the interaction upward, making the resistance reading conservative). Whether FRAX's survival here generalises to the casualty cases that shared its mechanism — IRON, which died under a same-era, same-mechanism run, and UST, which had no collateral floor at all — is the structured comparison of Chapter 10, where the de-risking response and the absence of share-token dilution documented here become two of the decisive distinguishing variables.

## 10 Survivor versus casualty: FRAX vs IRON vs UST

This chapter is the report's deliverable. The preceding chapters established that FRAX V1 held the dollar across its entire fractional-algorithmic life (peg median \$0.99998), resisted the May-2022 UST contagion, and did so through a coherent structural mechanism: a collateral ratio that ratcheted *up* under stress, a share token that was never diluted, deep share-token liquidity, and a mint-side fee penalty that damped the most reflexive direction of flow. We now place that outcome against its two natural reference points. IRON is the casualty that forked the *same* fractional-algorithmic mechanism — a single dynamic collateral ratio, mint and redeem against USDC plus a volatile share token, the redemption leg minting fresh shares — and died in a roughly twenty-four-hour bank run on 16 June 2021. UST is the pure-algorithmic limit case, zero exogenous collateral, that free-fell to under one cent in May 2022 with no floor at all.

The thesis is sharp: *the same FRAX-fork mechanism produced opposite outcomes*, and the difference is not explained by collateral fraction alone. IRON held roughly 75% USDC collateral and still died. Partial collateralisation was therefore *necessary but not sufficient* for survival. What separated FRAX from IRON was a *combination* of design choices — collateral-ratio-up-under-stress, deep and undiluted share-token liquidity, AMO collateral buffers, and a mint-greater-than-redeem fee asymmetry — that together prevented the reflexive redeem–mint–dump spiral from ever igniting. Because FRAX and IRON ran the same mechanism on the same chain family in the same year, this is a clean same-era, same-mechanism contrast (the FRAX-versus-UST comparison is partly cross-era and is caveated below). We build the argument over five distinguishing variables.

### 10.1 Variable 1: share-token dilution — the decisive contrast

The single feature that most cleanly separates survivor from casualty is what happened to the volatile share token. Over FRAX V1's entire two-year life the FXS supply moved from 99.61M to 99.82M tokens, peaking at 100.40M — a net change of about 0.2% and a peak dilution factor of 1.008×. The share token was, for all practical purposes, *flat*. By contrast, IRON's share token TITAN inflated from a pre-crash circulating float of 104.7M to a terminal 35.0 trillion tokens in roughly twenty-four hours, a factor of about 334,400× (five orders of magnitude). UST's twin LUNA inflated comparably, into the trillions, with no cap.

This is the proximate spiral mechanism. In a fractional-algorithmic design the redemption leg pays the uncollateralised fraction in freshly minted shares; if redemptions accelerate while the share price falls, the protocol mints ever more shares into a falling market, which depresses the share price further and invites yet more redemptions — a reflexive death spiral. FRAX never entered this regime: its share supply stayed flat because the spiral never ignited. The ordering across the three systems — FXS none, TITAN ∼5 orders, LUNA ∼6 orders — tracks the survival ordering exactly. Figure 15 normalises each share supply to its pre-stress level on a log axis and is the report's money chart: FXS is a flat line while TITAN explodes vertically.

### 10.2 Variable 2: collateral-ratio direction under stress

The two protocols moved their collateral ratio in opposite directions precisely when stressed. Through the UST contagion window FRAX's collateral ratio ratcheted *up* by +8.0 percentage points, from 85.25% before the event to 89.50% during it and 93.25% afterwards; across its life it never breached a floor of about 82.5%. Each step shifted the marginal mint and redeem toward fully USDC-backed, de-risking the protocol as stress rose. IRON's effective collateral ratio moved the other way: from 99.8% it was driven *down* by −25.7 percentage points to 74.1% as the run progressed, pinning the instrument at a partial ratio while its share token inflated. Figure 16 contrasts the two trajectories on a common stress-relative axis. UST is the degenerate case — with zero collateral there was nothing to ratchet.

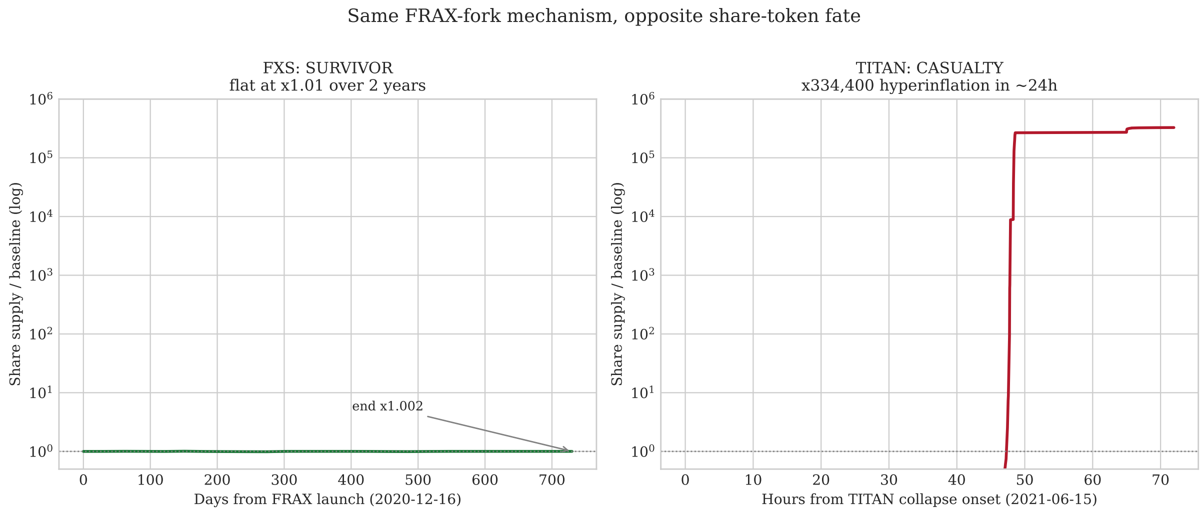


Figure 15: Normalised share-token supply (each series indexed to its pre-stress level; log scale). FRAX's share token FXS remains effectively flat across its entire life (1.008× peak dilution), whereas IRON's TITAN hyperinflates by a factor of ∼334,400× in roughly twenty-four hours as the redemption leg mints unbounded shares into a collapsing market. Uncapped inflation of the volatile leg — not the absence of collateral per se — is the proximate spiral mechanism, and its presence or absence tracks the survival ordering.

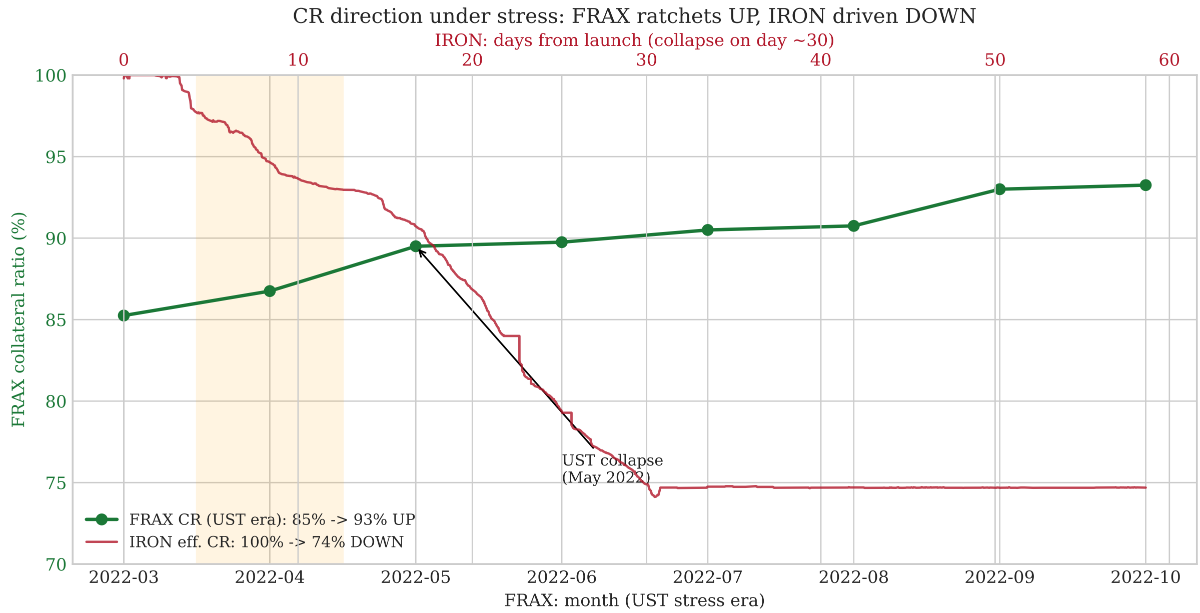


Figure 16: Collateral-ratio direction under stress. FRAX's collateral ratio ratchets *up* (+8.0 pp, 85.25% → 93.25%) through the May-2022 UST contagion, de-risking as stress rises; IRON's effective collateral ratio is driven *down* (−25.7 pp, 99.8% → 74.1%) during its collapse, holding it at a partial ratio while the share token hyperinflates. The defensive ratchet is a first-moment, structural response that no purely reflexive mechanism produces on its own.

## 10.3 Variable 3: fee asymmetry

The implicit token fees pointed in opposite directions. FRAX charged a mint fee of 0.95% against a redeem fee of 0.45% — a mint-greater-than-redeem asymmetry of +0.50 percentage points that taxed the side of flow most likely to feed reflexive expansion. IRON's fee schedule was the reverse, with mint cheaper than redeem, which actively rewarded the redeem–mint–dump loop: an arbitrageur could redeem for collateral plus shares, dump the shares, and re-mint cheaply, capturing the spread while accelerating share inflation. A small asymmetry of this kind is not decisive on its own, but it sets the sign of the marginal incentive, and on FRAX that sign opposed the spiral.

## 10.4 Variable 4: redeem-arbitrage spiral ignition

The spiral is best diagnosed at the point of ignition: did the redeem-arbitrage premium exceed the round-trip fee, so that arbitrageurs were paid to loop? On IRON the answer was yes for 53.2% of bars during the collapse window, with a mean open-loop premium of +134.4% — the loop was wide open and richly rewarded, and the share-supply hyperinflation of Variable 1 is its direct consequence. On FRAX the loop never ignited: there was no analogous window in which redeem-arbitrage profitably outran the fee. The reasons are structural and cumulative — deep, undiluted FXS liquidity (the deepest FXS venue carried over $3.1B), twenty-eight AMOs deploying real collateral as a flow buffer, and the mint-side fee penalty of Variable 3 — so that redemption pressure was absorbed rather than amplified. This is the operational sense in which the distinguishing variables are a *combination*: no single one of them would have sufficed, but together they kept the system off the ignition threshold that IRON crossed within hours.

## 10.5 Variable 5: peg outcome

The outcomes follow directly. FRAX held a peg median of $0.99998 across its life; even at the May-2022 stress its sustained trough was only about $0.98, fully recovered within hours. IRON troughed at an intraday $0.582 during the unbacked panic and then arrested near its effective-collateral floor (post-resumption around $0.76) — redeemable at a haircut, but no longer tracking the dollar. UST had no floor and free-fell to $0.0059, a −99.41% drawdown with no recovery. Figure 17 places the three troughs side by side: a held dollar, a collateral-floored haircut, and an uncollateralised free-fall to near zero.

## 10.6 The thesis: necessary but not sufficient

The two failure cases bracket the role of collateral. UST, with zero exogenous backing, had no floor and went to zero. IRON, with roughly 75% USDC backing, did have a floor — it arrested near $0.76 rather than at zero — which shows partial collateral was necessary to bound the terminal loss. But IRON *died* all the same: its peg was never restored, its share token hyperinflated five orders of magnitude, and its run completed in about a day. Collateral fraction alone therefore cannot explain survival, because IRON held a collateral fraction comparable to FRAX's own stressed range (FRAX's ratio sat at 85–93% through the same era) and still failed.

What distinguished FRAX was the *combination* of the four protective features above operating together: a collateral ratio that ratcheted up under stress (Variable 2), a share token kept deep and undiluted (Variables 1 and 4), AMO collateral buffers absorbing redemption flow (Variable 4), and a mint-greater-than-redeem fee asymmetry damping reflexive expansion (Variable 3). Their joint effect was to keep the redeem–mint–dump spiral below its ignition threshold, which on IRON was crossed within hours. Partial collateral was necessary but not sufficient; survival required the structural complementarities that prevented spiral ignition in the first place. Table 5 assembles the five variables across the three systems.

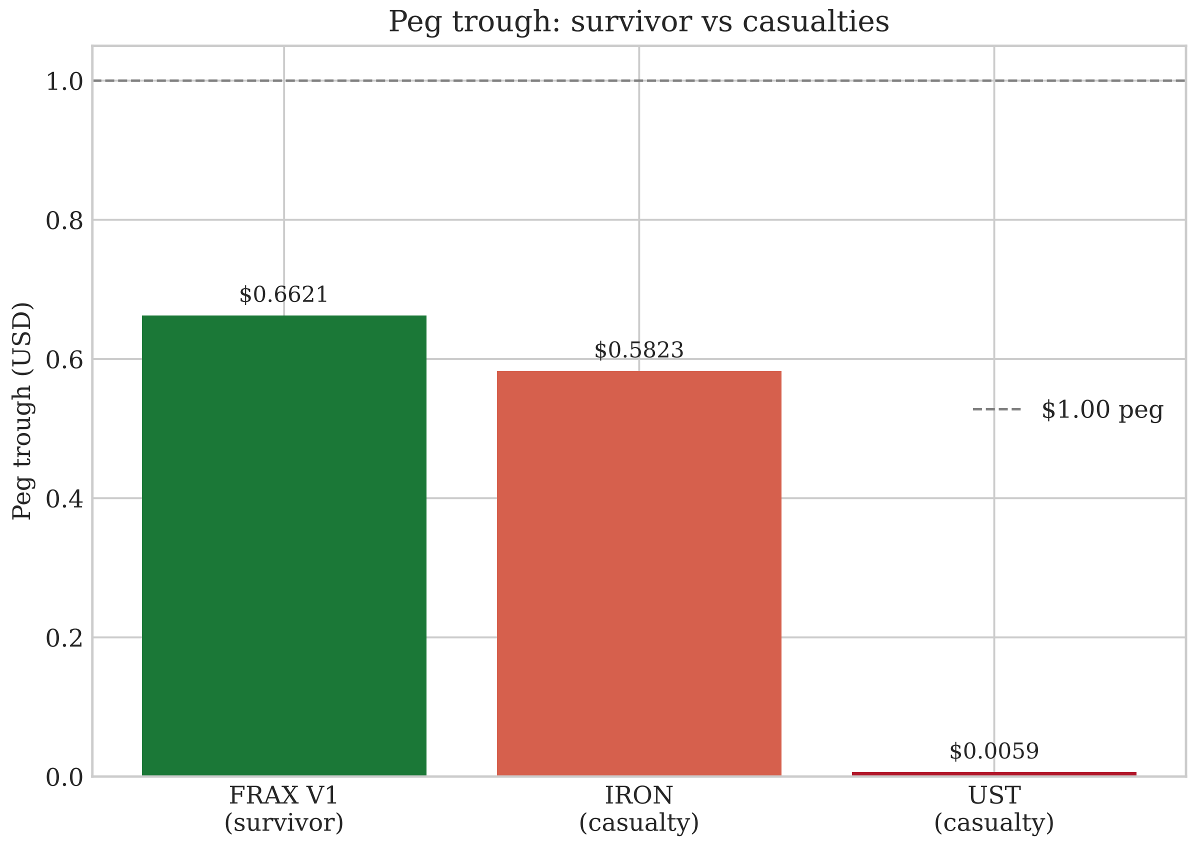


Figure 17: Three-way peg-trough comparison. FRAX holds (life median $0.99998; sustained UST-window trough ≈$0.98, recovered within hours); IRON descends to an intraday $0.582 and settles near its ∼$0.76 effective-collateral floor (redeemable at a haircut, peg not restored); UST free-falls to $0.0059 with no floor and no recovery. Partial collateral bounds the depth of the loss (IRON versus UST) but does not by itself guarantee a held peg (FRAX versus IRON).

Table 5: Survivor versus casualty across the five distinguishing variables. FRAX and IRON ran the *same* fractional-algorithmic mechanism (single dynamic collateral ratio; redemption leg mints the volatile share token) yet produced opposite outcomes; UST is the zero-collateral limit case. Share-supply factors are peak-versus-pre-stress; collateral-ratio deltas span the May-2022 stress window for FRAX and the collapse window for IRON. FRAX and IRON overlapped in time (a clean same-era, same-mechanism contrast); the FRAX-versus-UST comparison is partly cross-era (see caveats).

| | FRAX V1 (survivor) | IRON / TITAN (casualty) | U |
|---|---|---|---|
| Mechanism | fractional CR, redeem mints FXS | FRAX-fork: redeem mints TITAN | fully algo: b |
| 1. Share-token dilution | ×1.008 (flat) | ×334,400 (∼5 ord.) | → tr |
| 2. CR direction under stress | up +8.0 pp (85→93%) | down −25.7 pp (99.8→74.1%) | 0% (r |
| 3. Fee asymmetry | mint 0.95% > redeem 0.45% | mint < redeem (loop rewarded) | |
| 4. Redeem-arb loop ignited? | never | 53.2% of bars (+134.4% mean) | |
| 5. Peg outcome | held $0.99998 (UST trough ≈$0.98) | $0.582 → $0.76 floor | $0.0 |
| Collateral buffer | 28 AMOs deploy real collateral | none | |
| Outcome | survived (peg held) | died in ∼24h | d |

### 10.7 A nuance against mechanism-fatalism

The same-mechanism contrast invites a fatalistic reading — that any uncapped-share fractional-algorithmic design is doomed once stressed. The cross-chain record resists this. Adams and Ibert (2022) document that the contemporaneous IRON/STEEL twin deployed on BNB Smart Chain did *not* break its peg during the same Polygon collapse, despite running identical contract logic. The mechanism alone was therefore not sufficient for failure: IRON's run was venue- and liquidity-specific, conditioned on the particular pool depths, redemption flow, and holder composition on Polygon (Saengchote, 2021), rather than an inevitable consequence of the fractional-algorithmic design in the abstract (Klages-Mundt and Minca, 2019). This cuts both ways and reinforces the central thesis: if the same mechanism can survive or fail depending on venue-level conditions, then the survival-relevant variables are precisely the structural complementarities catalogued above — liquidity depth, collateral-ratio policy, fee sign, and flow buffers — not the bare presence or absence of an algorithmic redemption leg.

### 10.8 What this chapter establishes and what it does not

This comparison establishes, on the empirical record, that the same fractional-algorithmic mechanism produced opposite outcomes for FRAX and IRON, and that the difference is not attributable to collateral fraction alone: IRON held roughly 75% collateral and still died, so partial collateralisation was necessary but not sufficient. It identifies a coherent combination of distinguishing variables — flat-versus-hyperinflating share supply (×1.008 versus ×334,400), collateral ratio up (+8.0 pp) versus down (−25.7 pp) under stress, mint-greater-than-redeem versus mint-less-than-redeem fees, and a redeem-arbitrage loop that ignited on 53.2% of IRON's collapse bars but never on FRAX — whose joint effect was to keep the reflexive spiral from igniting, yielding a held peg ($0.99998) versus a one-day collapse to a collateral floor ($0.582 → $0.76) versus an uncollateralised free-fall ($0.0059).

It does not establish a statistical causal effect of any single variable. With three assets and one decisive event apiece, the comparison is a structured analogy across mechanisms, not a controlled experiment, and the variables move together by design, so their contributions cannot be cleanly disentangled. The FRAX-versus-IRON contrast is the strongest leg, being a same-era, same-mechanism, same-chain-family pairing in which the two protocols demonstrably overlapped in time (IRON died on 16 June 2021 while FRAX held); the FRAX-versus-UST contrast is partly cross-era, since FRAX's UST-window stress in May 2022, though contemporaneous with the UST collapse, occurred on a far larger and more mature collateral base than UST ever had. The BNB-twin survival further shows that even within the IRON mechanism, failure was venue-conditioned rather than mechanism-inevitable. These claims should accordingly be read as a well-supported hypothesis about which design complementarities matter, not as a quantified causal decomposition.

## 11 Findings, open questions, and implications

### 11.1 Headline findings

This section consolidates the report's principal results, each tied to the chapter that establishes it and stated with its quantitative anchor and test.

**F1. FRAX held a tight, par-centred peg across its entire life.** Over the full fractional-algorithmic window (16 December 2020 to 31 December 2022) the median FRAX price was $0.99998. The one-minute tracking error against par had a median of −0.20 bp, a median absolute deviation of 6.7 bp, and a ninety-fifth absolute percentile of 114 bp on 57,487 minute bars, with 83.8% of bars inside ±50 bp and 93.6% inside ±100 bp; the USDC-reference-relative series is tighter still. By every distributional measure FRAX behaved as a functioning dollar stablecoin throughout (Ch. 4).

**F2. The fractional design compressed the volatile leg's volatility by an order of magnitude.** A volatility decomposition on a 746-day panel finds the collateral (USDC) leg essentially riskless (median daily realised volatility 0.23%) and the share (FXS) leg extremely volatile (median 1.04%, single-day maximum 19.76%, annualised unconditional volatility near 296%). Because only the uncollateralised fraction $(1 - \mathrm{CR})$ — median 14.25%, never above 18% — is exposed to the share leg, the transmitted peg risk $(1 - \mathrm{CR}) \times \sigma^{\mathrm{FXS}}$ held a median of 0.139, an order of magnitude below the raw share-leg volatility. The bounded uncollateralised weight is the quantitative core of the survivor mechanism (Ch. 4).

**F3. Share-token volatility is the dominant driver of peg stress; AMO deployment is protective.** A Newey–West HAC regression (lag 24) of absolute tracking error on standardised drivers ($n = 13{,}890$ hourly, $R^2 = 0.341$) finds FXS realised volatility the dominant peg-widening force (+34.33 bp per standard deviation, $t = 7.54$, $p = 4.6 \times 10^{-14}$, significant after Benjamini–Hochberg correction) and cumulative algorithmic-market-operation deployment robustly protective (−13.79 bp, $p = 2.7 \times 10^{-12}$). The positive collateral-ratio loading (+10.49 bp, $p = 2.9 \times 10^{-9}$) is endogenous — the ratio was raised in response to stress — and is flagged, not interpreted causally; venue liquidity is marginal ($p = 0.059$) and net redemption flow insignificant (Ch. 5).

**F4. The peg-variance process is exactly integrated — and this is *not* the survivor signature.** A GARCH(1,1)-$t$ fit to hourly tracking-error changes ($n = 13{,}889$) returns $\alpha = 0.583$, $\beta = 0.417$, with $\alpha + \beta = 1.0000$ to numerical precision (IGARCH): peg-variance shocks never decay. The casualty fork exhibits the *same* exact persistence over its living period ($\alpha + \beta = 1.0000$, difference $\approx 7 \times 10^{-14}$), so second-moment persistence does not discriminate survivor from casualty. Breusch–Pagan ($p \approx 4 \times 10^{-26}$) and Ljung–Box ($p < 10^{-120}$ at lag 5) justify the HAC/GARCH treatment. The survivor question is thereby forced onto the first-moment, structural layer (Ch. 5).

**F5. The collateral ratio was a one-directional de-risking ratchet, and supply contracted under stress.** The collateral ratio fell from a 99.75% genesis to an 82.0% algorithmic low on 2021-10-11, then ratcheted monotonically *upward* to 92.75% by end-2022 — gaining +2.25 percentage points inside the May-2022 stress window alone and +8.0 points across that window on a stress-relative basis. Standing supply peaked at 2.91 billion units on 2022-03-15 and *contracted* 65% to 1.02 billion: the protocol de-risked by raising hard backing and shrinking its balance sheet, not by reflexively expanding the volatile leg (Ch. 7).

**F6. The share-token float was essentially flat, and the AMO buffer was large but liability-neutral.** The volatile share-token supply moved within a ≈ 98M–100.4M band over two years, a peak-to-start dilution multiple of 1.008×, ending within a fraction of a percent of genesis: the seigniorage mechanism that manufactures unbounded volatile-leg supply in a death spiral was quiescent throughout. A buffer of 28 algorithmic market operations (onboarded 2021-09-14 to 2022-12-25, 19 active at end-2022) accounted for 26.3% of all units minted while remaining liability-netted on backing, and a share-token backing ratio held a 7.84× median, stayed above 1× on every day, and bottomed at 2.67× on 2022-06-18 (Ch. 7).

**F7. The peg decoupled from the share token, and the predictive geometry inverts the casualty.** The six-hour rolling FRAX/FXS return correlation stayed weak and *fell* across the May 2022 stress (minute median 0.32 → 0.19, hourly 0.36 → 0.16), where the casualty's hourly correlation *exploded* 0.042 → 0.812 into collapse. The dominant Granger-predictive link runs peg → share ($p_{\text{FDR}} = 1.6 \times 10^{-204}$ hourly), the stabilising ordering in which the share token absorbs deviations by design; the death-spiral direction share → peg is present but orders of magnitude weaker (best $1.1 \times 10^{-45}$ hourly) — the exact inverse of the casualty's dominant share → peg link ($p_{\text{FDR}} = 7 \times 10^{-49}$). Granger causality measures predictability, not structure (Ch. 8).

**F8. No redemption run: the scarcity of redemptions is itself the finding.** Across the entire May 2022 stress window the FRAX contract recorded only about 11 redemption (burn) events, against the casualty's 9,231 in its collapse window. A self-exciting point process is not identifiable from eleven events, so no Hawkes branching ratio can be fitted — where the casualty's collapse-window fit returned a near-critical branching ratio of 0.968. The redeem-and-dump arbitrage that ignited the casualty's spiral was never lit on FRAX; the inability to fit a cascade is the cleanest on-chain statement that no run occurred (Ch. 8).

**F9. FRAX resisted the UST collapse, and the same mechanism produced opposite outcomes.** Under the May 2022 contagion FRAX's sustained one-hour trough was \$0.9901 (−98.5 bp), recovered within days; the collateral ratio ratcheted *up* +2.25 pp; the share token fell −67% in price without supply hyperinflation. A difference-in-differences test against a fiat-backed control ($n = 998$, ±48 h, HAC) returns an insignificant FRAX-specific peg penalty of +2.22 bp ($t = 1.13$, $p = 0.260$). Placed against its two reference points across five distinguishing variables, FRAX inverts the casualty on each: share-token dilution ×1.008 versus ×334,400; collateral ratio up +8.0 pp versus down −25.7 pp; mint > redeem versus mint < redeem fees; redeem-arbitrage loop never ignited versus open on 53.2% of bars (+134.4% mean premium); peg held \$0.99998 versus a one-day collapse to a \$0.582 trough and a \$0.76 floor, against UST's free-fall to \$0.0059 with no floor. The thesis: partial collateral was *necessary but not sufficient* — the casualty held roughly 75% collateral and died all the same (Ch. 9, Ch. 10).

## 11.2 What this report does not claim

**The UST experiment is a single event ($n = 1$).** The May 2022 collapse is the only sector-wide algorithmic-stablecoin stress of comparable magnitude in FRAX V1's lifetime. The difference-in-differences estimate (F9) characterises how this design behaved in this one episode; it is descriptive, not inferential, and cannot support a frequency or generalisation claim. Its parallel-trends assumption is imperfect (FRAX's pre-trigger absolute deviation trended wider at +0.054 bp/h against USDC's +0.008 bp/h), which makes the direction of the insignificant +2.22 bp estimate the conservative one.

**The FRAX-versus-UST contrast is partly cross-era.** The FRAX-versus-IRON pairing (F9) is the strongest leg: a same-era, same-mechanism, closely related chain comparison in which the two protocols demonstrably overlapped in time (Iron Finance died on 16 June 2021 while FRAX held). The FRAX-versus-UST contrast, though contemporaneous at the stress event, compares FRAX's mature May-2022 collateral base against a design that never held exogenous collateral at all, and should be read as a structured analogy across mechanisms rather than a controlled experiment.

**Granger causality is predictive, not structural.** The dominant peg → share Granger result (F7) establishes lead–lag information flow, not a structural causal channel. We read it as consistent with the residual-absorption role of the share token documented in Ch. 2 and Ch. 7, not as independent proof of it. Likewise the level-1 driver regression (F3) is associational, and its collateral-ratio loading is explicitly endogenous.

**AMO flow is not resolved at event granularity.** The algorithmic-market-operation buffer (F6) is characterised qualitatively because deployment and withdrawal amounts were not emitted as discrete events at the required granularity. Its protective role (F3) rests on a cumulative size proxy, an associational rather than identified estimate; the 26.3% minted-share and the registry onboarding history are exact, but the dollar value deployed at any instant is not observed.

### 11.3 Open questions

**Q1. Address-level redemption incidence under stress.** This report measures aggregate flow and supply. Whether the handful of stress-window redeemers were concentrated large accounts exiting first, as the run literature suggests for the casualty, requires address-level attribution of the (sparse) redemption stream.

**Q2. Event-resolved AMO position values.** Converting the qualitative AMO buffer (F6) and its protective regression sign (F3) into an identified peg-defence estimate would require reconstructing per-AMO position values from external-venue state, beyond the protocol's own emitted events.

**Q3. A counterfactual ignition threshold.** The report establishes that FRAX stayed below the redeem-and-dump ignition threshold the casualty crossed, but does not estimate *how far* below: a structural model mapping liquidity depth, fee sign, and collateral-ratio policy to a critical redemption-flow rate would quantify the survival margin rather than merely observing it.

### 11.4 Implications

**The survivor recipe is a combination, not a single feature.** No one of the four distinguishing features sufficed. A collateral ratio that ratchets up under stress, a deep and undiluted share token, liability-netted flow buffers, and a mint-greater-than-redeem fee asymmetry together kept the reflexive redeem–mint–dump spiral below its ignition threshold. The variance signature was identical to the casualty's (F4); survival lived in the joint first-moment structure, which any design audit of a fractional-algorithmic stablecoin should evaluate as a system rather than feature by feature.

**Partial collateral bounds the loss, it does not prevent the run.** The two failure cases bracket the role of collateral: UST, with no exogenous backing, free-fell to near zero, while the casualty, with roughly 75% collateral, arrested at a $\sim$ \$0.76 floor — showing partial collateral fixes the depth of the loss. But the casualty died all the same. A design that relies on partial collateral for run-resistance is mis-specified; collateral is a loss-floor, and run-resistance must come from the structural complementarities above.

**The redeem-mints-the-share-token primitive is the shared fatal lever — and it can be tamed.** FRAX and the casualty ran the identical primitive: the redemption leg mints fresh shares to settle the uncollateralised fraction, the mechanism that manufactured unbounded share supply in the casualty. FRAX's survival shows the primitive is not fatal in itself — a contemporaneous cross-chain twin of the casualty also survived the same event (Adams and Ibert, 2022) — but is conditioned on venue-level structure (Saengchote, 2021). The lever is tamed by deep share-token liquidity, a mint-side fee penalty, flow buffers, and a collateral policy that de-risks into stress rather than diluting, exactly the configuration the formal deleveraging-spiral and stability-region models identify as the boundary of the stable regime (Klages-Mundt and Minca, 2019; Klages-Mundt and Minca, 2022; Clements, 2021; Gadzinski, Castello, and Mazzorana, 2023).

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