Tracking Error and the Anatomy of a 24-Hour Death Spiral: Iron Finance (IRON/TITAN) on Polygon

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Abstract

We reconstruct, at block and 30-second granularity, the complete life and death of Iron Finance's partial-collateral ("fractional-algorithmic") stablecoin IRON and its endogenous share token TITAN on Polygon, from launch on 17 May 2021 to 15 July 2021 (59 days, 18.38M on-chain observations, zero imputation). IRON held its dollar peg tightly during its life: median price \$1.0034 and a pre-crash tracking error of +27.08 bp mean (standard deviation 57.71 bp), a regime that broke cleanly into a −2171.93 bp mean during the collapse. The asset was then destroyed in a roughly 24-hour reflexive bank run on 16–17 June 2021. We isolate the two mechanical drivers: a redeem-and-dump arbitrage opened by the lagging ten-minute TITAN price oracle (the oracle-to-spot premium exceeded the redemption fee on 53.2% of collapse intervals, mean premium-while-open 134%), and an *uncapped* reflexive minting of TITAN through the redemption leg (share supply rose from a pre-crash float of 104.7M to about 35.0T tokens, a factor near 335,000; in one minute the protocol minted more TITAN than the entire pre-crash float — the exact inversion of a binding daily mint cap). TITAN realised volatility is the only statistically significant level-1 driver of the absolute tracking error (+14.75 bp per standard deviation, $t = 2.47$), and a GARCH(1,1) fit on the calm period is exactly integrated ($\alpha + \beta = 1.0000$, IGARCH), evidence of a measurable structural fragility present before the run. Partial USDC collateral set a loss floor near \$0.76 (the effective collateral ratio) but did *not* slow the spiral — the uncollateralised UST in fact broke \$0.75 faster. Seven of eight on-chain early-warning signals were silent in the 30-day pre-crash window: the collapse was an intraday bank run, not a slowly telegraphed degradation, and this largely negative early-warning result is itself the report's central contribution. All causal language is anchored to the named test (Granger causality, Hawkes self-excitation, HAC regression); single-event analyses are flagged as without statistical power, and the cross-asset comparison is a structured analogy, not a controlled experiment.

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1 Executive summary

Iron Finance deployed a partial-collateral stablecoin, IRON, on Polygon on 17 May 2021. IRON targeted a $1 peg and was backed by a mixture of exogenous hard collateral (USDC) and an endogenous, protocol-issued share token, TITAN, in proportions governed by a slowly moving collateral ratio. It was a near-verbatim fork of the partial-collateral Frax V1 design, and as such it occupies the analytically interesting middle of the stablecoin design spectrum: more robust in principle than the pure-algorithmic UST (which held zero exogenous collateral and died), but structurally distinct from a fully collateralised stablecoin. On 16–17 June 2021 IRON was destroyed in a reflexive bank run that wiped out roughly $2 billion of value in about twenty-four hours. This report reconstructs that life and death from the on-chain record at block granularity and asks the question that motivates the whole study: could the run have been seen coming from the public ledger?

IRON was a well-pegged stablecoin while it lived. Over the pre-crash living period the median IRON price was $1.0034 and the tracking error (price minus $1) averaged +27.08 bp with a standard deviation of 57.71 bp, after flagging five thin-launch single-print artefact bars. This is the behaviour of a functioning peg. The collapse is a clean regime break: during the run the tracking error averaged −2171.93 bp with a standard deviation of 610.29 bp. IRON supply grew to a peak of 176M tokens at peak total value locked, then collapsed to 1.36M as holders redeemed.

Two mechanical features turned a price shock into a spiral. First, TITAN was priced for redemption off a ten-minute time-weighted average (TWAP) of a single thin decentralised-exchange pair. When TITAN's spot price fell faster than a ten-minute average could track, the redemption oracle remained stale and high, so a redeemer received more TITAN than the contemporaneous market value of the IRON surrendered and could immediately dump it. We measure this redeem-and-dump premium directly: the oracle-to-spot premium exceeded the 0.40% redemption fee on 53.2% of the 30-second collapse intervals, with a mean premium-while-open of 134%. Second — and decisively — the TITAN paid out on redemption was *freshly minted with no supply cap.* As redemptions accelerated, TITAN supply rose from a pre-crash float of 104.7M to about 35.0T tokens, a factor near 335,000. In a single minute the protocol minted 127.7M TITAN, more than the entire pre-crash float — the exact inversion of the binding daily mint cap that constrained UST. This is the single design choice the report identifies as fatal.

The fragility was partly measurable before the run. A level-1 regression with heteroskedasticity- and autocorrelation-consistent (Newey–West, lag 5) standard errors finds that TITAN realised volatility is the only significant driver of the absolute tracking error, adding 14.75 bp per one-standard-deviation increase ($t = 2.47$, $p = 0.0137$). The volatile leg, not the collateral leg, governed peg quality. More strikingly, a GARCH(1,1) fit on hourly tracking-error changes during the *calm* period is exactly integrated: $\alpha + \beta = 1.0000$ (an IGARCH process), meaning volatility shocks never decay. Infinite shock persistence is a structural-fragility precursor that was present and estimable while IRON still traded at peg.

The collapse was an intraday bank run, hour by hour. TITAN peaked intraday at \$64.53 at 05:08 UTC on 16 June. A first wave took it down 51.7% to \$31.17 by 10:14, with a dead-cat bounce of +67.3% to \$52.13 by 13:47; a second, fatal wave then free-fell 100% to near zero by 01:39 on 17 June. IRON broke below \$0.99 at 05:46 UTC, below \$0.95 by 09:53, and reached an intraday minimum of \$0.582 at 00:17 on 17 June during the unbacked panic — temporarily below its own collateral floor. Redemptions then froze entirely: the contract reverts every redemption once the share price rounds to zero, and the redemption record goes dark from 01:00 to 16:00 UTC before resuming with TITAN re-priced at a tiny fixed value.

Coupling was hourly and self-exciting, not instantaneous. The hourly return correlation between IRON and TITAN rose from 0.042 in the calm regime to 0.812 during the run; at one-minute frequency the correlation stays near zero (asynchronous microstructure noise, not a data gap). TITAN led IRON, with a cross-correlation peak at a lag of +27 minutes, and Granger tests (with Benjamini–Hochberg false-discovery control) confirm a dominant TITAN→IRON direction. A Hawkes self-excitation model fitted to 9,231 redemption events returns a branching ratio of 0.968 — sub-critical but near-critical: each redemption triggered on average 0.97 further redemptions, a cascade arrested only by the contract's freeze and the collateral floor, not by any equilibrating force.

On-chain signals would not have cleanly foreseen it. Seven of eight pre-registered early-warning signals were silent in the 30-day window before the crash. Liquidity-provider inflows were *accelerating* into the collapse (chasing a roughly 50,000% yield), holder concentration was *falling*, and TITAN was at its all-time high on the morning it died. Only one signal carried information — the backing-cover ratio decayed monotonically from 38.5× to 32.5× — but it never crossed its alarm level; the warning, if any, was in the slope, not the level. This negative result, framed descriptively on a single event with no claim to statistical predictive power, is the report's honest central finding.

Partial collateral bounded the loss, but did not prevent the run. Against the pure-algorithmic UST, the partial USDC backing did not slow the spiral — UST broke \$0.75 in 8 hours versus IRON's 18 — but it set a loss floor: after a transient intraday trough of \$0.582 IRON settled near \$0.76 (its effective collateral ratio, 1.024× the floor), while UST free-fell below one cent without recovering. The surviving Frax V1, by contrast, raised its collateral ratio toward 100% under stress and never let its share token hyperinflate. The lesson is that collateral fraction governs how deep a run can go, not whether it starts; the BNB-chain IRON twin's survival of the same event (Adams and Ibert, 2022) shows the failure was venue-conditioned, not mechanism-inevitable.

2 Protocol mechanics and parameters

This chapter establishes the ground-truth design of the Iron Finance Polygon deployment (the IRON stablecoin and its volatile share token TITAN) as it operated in the days surrounding the

June 2021 collapse. Every parameter and formula below is taken from the deployed contract bytecode and its administrative transaction history; the figures stated here are the constants against which the empirical tracking-error, collapse-reconstruction and death-spiral analyses of the following chapters are measured. The chapter is deliberately descriptive: it asserts what the protocol *was*, not what it *did*, and it sets up the two structural features — redemption at the *effective* collateral ratio and the freshly minted, supply-uncapped volatile leg — that the rest of the report identifies as the locus of fragility.

2.1 Architecture: a Frax-V1 fork

IRON is a partial-collateral ("fractional-algorithmic") stablecoin descended directly from the Frax V1 design. It targets a $1 peg and is backed by a mixture of an exogenous hard collateral (USDC) and an endogenous, protocol-issued share token (TITAN). The split between the two is governed by a collateral ratio that moves over time. Architecturally the system reproduces the Frax V1 contract decomposition almost verbatim — a stablecoin token, a share token, a mint/redeem pool, a treasury holding the collateral, and a collateral-ratio policy — using identical 32-bit-style fixed-point arithmetic with a price precision of 10^6 and the same genesis defaults (a collateral ratio step of 0.25%, an hourly refresh cooldown of 3600 s and a peg band of $\pm$$0.005).

Three deltas from Frax V1 are material to the failure analysis and are flagged here so that the comparative chapter can build on them:

1. **Effective- versus target-CR asymmetry.** Minting uses the *target* collateral ratio (TCR), a policy variable; redemption uses the *effective* collateral ratio (ECR), the realised ratio of collateral value to outstanding supply. Frax V1 redeemed at the single global ratio. Under stress these two ratios diverge, and redeemers are paid the larger volatile-token fraction implied by the (lower) ECR.
2. **No buyback / recollateralisation arbitrage.** The Frax V1 mechanisms that let arbitrageurs buy back or recapitalise the share token when the protocol is over- or under-collateralised are *absent* from the pool. In their place the treasury auto-invests up to 75% of idle USDC collateral in an external lending market and skims excess collateral as profit. There is no on-chain counter-cyclical buyer of the share token.
3. **Volatile-token oracle.** TITAN is priced off a fixed-window time-weighted average price (TWAP) of a single decentralised-exchange pair (TITAN against wrapped MATIC) multiplied by an external MATIC/USD reference, rather than off a deep, broadly arbitraged market.

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. The IRON design instantiates each of these dependencies explicitly: the seigniorage value of TITAN, the redeem-and-mint arbitrage path, and the TWAP oracle. 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 IRON parameters documented below are precisely the quantities that govern the speed of that response.

2.2 Fractional minting at the target collateral ratio

A user mints IRON by depositing USDC for the collateral fraction and burning TITAN for the remaining fraction, in proportions set by the target collateral ratio TCR $\in [0, 1]$. Let c be the USDC deposited (in token units), p_c the USDC/USD price from the external collateral reference, and p_s the TITAN/USD price returned by the share oracle (the TITAN/wMATIC TWAP scaled by MATIC/USD). Writing all prices in the 10^6 fixed-point convention and folding the USDC decimal rescaling into p_c, the collateral leg contributes a dollar value

$$V_c \;=\; c\,p_c, \tag{1}$$

and the total dollar value of IRON to be issued is the collateral value grossed up by the target ratio,

$$V \;=\; \frac{V_c}{\mathrm{TCR}}. \tag{2}$$

When TCR < 1 the user must additionally burn TITAN worth the non-collateralised remainder, i.e. a TITAN amount

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

Equivalently, and as stated in the protocol documentation, the two legs satisfy $V_c/\mathrm{TCR} = s_{\mathrm{burn}}\,p_s/(1-\mathrm{TCR})$, so that every \$1 of deposited value mints exactly one IRON. The IRON delivered to the caller is net of a minting fee ϕ_m applied as a dilution (fewer IRON are minted; no separate fee transfer occurs),

$$\mathrm{IRON}_{\mathrm{out}} \;=\; V\,(1-\phi_m). \tag{4}$$

On execution the protocol burns s_{burn} TITAN from the caller, transfers the USDC into the collateral reserve, and mints the IRON. A wrapper contract additionally offered a one-sided "zap" mint that accepted 100% USDC, market-swapped the $(1-\mathrm{TCR})$ portion into TITAN through a router (capped at 10% slippage, with a ten-minute swap deadline) and burned it, charging its fee on the collateral value rather than the grossed-up total. The mint path is unremarkable for the failure: it removes TITAN from circulation and requires hard collateral, and it is the redeem path that inverts both of these properties.

2.3 Redemption at the effective collateral ratio: the fatal leg

Redemption is the structurally dangerous operation. A user burns IRON and receives a USDC fraction governed by the *effective* collateral ratio $\mathrm{ECR} \in [0,1]$ plus a TITAN fraction. Critically, the TITAN paid out is *freshly minted* — it is created on demand, valued at the lagging TWAP oracle price, and is subject to *no supply cap whatsoever.*

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

$$c_{\mathrm{out}} \;=\; \frac{d'\,\mathrm{ECR}}{p_c}, \tag{5}$$

and, whenever ECR < 1, the share leg *mints* TITAN

$$s_{\mathrm{out}} \;=\; \frac{d'\,(1-\mathrm{ECR})}{p_s}. \tag{6}$$

Two properties of Equation (6) are central to every subsequent chapter. First, s_{out} is divided by the oracle price p_s: when p_s is held high by a lagging TWAP while the spot price has already fallen, the redeemer receives *more* TITAN than the contemporaneous market value of the IRON surrendered, and can sell it for a profit — the redeem-and-dump arbitrage quantified later in this report. Second, this TITAN is newly issued each time, with no ceiling on cumulative issuance; the redemption leg is therefore an unbounded money pump on the share token. This is the structural opposite of a hard daily mint cap, and the absence of any such cap is the single design choice the death-spiral chapter identifies as permitting share supply to inflate by several orders of magnitude.

Redemption executes in two steps. The redeem call immediately burns the user's IRON, mints the share leg into the collateral reserve, and credits the USDC and TITAN outputs to per-user balances; the user then calls a separate collection function after a one-block delay to receive the tokens as plain transfers from the reserve. Three guards bound the operation: the collateral payout may not exceed the reserve's global collateral balance; explicit slippage minimums protect the user; and, decisively, the redeem reverts unless $p_s > 0$. Because the oracle price is held in 10^6 fixed point, once the TITAN spot (and hence its TWAP) fell below the smallest representable unit the share price floored to zero and the $p_s > 0$ guard *reverted every redemption*, freezing the exit entirely until a fixed-price oracle was deployed. This freeze condition, not a governance pause, is what bricked redemptions during the terminal hours of the run.

2.4 The collateral-ratio policy

The TCR and ECR are held in a dedicated collateral-ratio policy contract, separate from the pool and treasury, in 10^6 fixed point. The genesis configuration set TCR = ECR = 100%, a ratio step of 0.25%, a refresh cooldown of 3600 s, a peg target of \$1 and a peg band of ±\$0.005, with effective-CR redemption enabled. A permissionless refresh, callable at most once per cooldown, reads the IRON oracle price and adjusts the target ratio by one step: if IRON trades above \$1.005 the TCR is decremented (less collateral required, more reliance on TITAN); if below \$0.995 it is incremented (more collateral required). The effective ratio is then recomputed mechanically as

$$\mathrm{ECR} \;=\; \min\!\left(\frac{V_{\mathrm{collateral}}}{\mathrm{IRON}_{\mathrm{supply}}},\,1\right), \tag{7}$$

where $V_{\mathrm{collateral}}$ is the global collateral value (reserve USDC plus the external lending-vault balance, net of unclaimed redemptions). The documented schedule moves the target ratio by at most 0.25% per hour, i.e. no more than 6% per day. This bounded adjustment speed is exactly the response-rate constraint of the Klages-Mundt and Minca (2019) deleveraging model: the policy can re-collateralise only gradually, while the market value of the endogenous backing can collapse within a single block.

The administrative history of the ratio step in the days before the collapse is itself informative and is summarised in Table 1: the step was reduced from 0.25% to 0.10% on 13 June, further to 0.05% on 15 June, then restored to 0.25% at 09:47 UTC on 16 June — hours before the death spiral. Slowing the step damps the policy's reaction speed precisely when the protocol was already under strain. Independent third-party reconstructions place the operative ratios on 16 June at roughly TCR ≈ 70% and ECR ≈ 74–75% (so redeemers received approximately three-quarters USDC and one-quarter TITAN); the exact per-block series is recovered in this report's collapse chapter from the replayed refresh and admin transactions, since the policy emits no events on refresh.

2.5 Fees

Fees live in a separate policy contract, in 10^6 fixed point, with hard maxima of 0.5% on minting and 0.9% on redemption. The operative fees during 16 June were a 0.30% minting fee and a 0.40% redemption fee, both set on 29 May. As the run accelerated the redemption fee was raised to its 0.9% maximum at 22:22 UTC on 16 June, then cut to 0% at 09:23 UTC on 17 June. Because the redeem-and-dump arbitrage profit reached multiples of the underlying value once the oracle lag opened up, even the maximum 0.9% fee was far too small to deter redemption; the death-spiral chapter shows the arbitrage premium exceeded the redemption fee on a majority of the collapse interval. Fees are charged implicitly — minting issues fewer IRON, redemption reduces the redeemable value — so no fee-transfer log exists and fee revenue must be computed rather than observed.

2.6 The volatile-token TWAP oracle and the freeze condition

TITAN is valued for both mint and redeem through a fixed-window TWAP oracle reading the deepest TITAN venue (the TITAN/wMATIC pair), scaled to USD by an external MATIC/USD reference. The oracle is a standard Uniswap-V2-style fixed-window construction: it stores a cumulative-price accumulator and a timestamp; a permissionless update is only accepted once at least one window period has elapsed, at which point the reported average price is the change in the accumulator divided by the elapsed time. The reported price therefore spans *at least* one period and lags spot by up to roughly twice the period.

The TITAN oracle's window was set to 600 s (ten minutes) on 21 May and was still in force at the 16 June collapse. Under a per-block crash a ten-minute average cannot keep pace with spot, so the redemption price p_s in Equation (6) remained well above the contemporaneous market price — the precise mechanism the protocol's own post-mortem identifies, namely that "because of how the ten-minute TWAP oracle works, TITAN spot price drops even further in comparison to the TWAP redemption price" (Iron Finance, 2021). During the run the team cut the window to 300 s (17:58 UTC, 16 June) and 60 s (22:26 UTC) in an attempt to let the oracle catch up, then restored 600 s (00:09 UTC, 17 June); none of these changes arrested the feedback loop. By contrast the IRON-side oracle — which feeds only the collateral-ratio policy, since mint and redeem hard-code IRON at $1 — used a 3600 s window and was supplemented on 9 June with a second venue and averaged across the two. The asymmetry is structural: the *stable* leg is priced at a hard-coded $1 for execution and read from a deep market only for policy, whereas the *volatile* leg, whose mispricing transfers value to redeemers, is read from a single thin pair through a lagging average.

As the TITAN spot approached zero, its scaled USD price fell below the smallest value representable in 10^6 fixed point and the oracle returned exactly zero. The redeem guard $p_s > 0$ then reverted, freezing all redemptions until a fixed-price oracle was substituted; redemptions resumed on 17 June with TITAN re-priced at a tiny fixed level. This freeze is examined empirically in the collapse chapter as a gap in the redemption record during the terminal hours.

2.7 Parameter timeline

Table 1 consolidates the administrative parameter changes in the extraction window that bear on the failure analysis. The collateral-ratio step, fees and TWAP window are the three operative knobs; the table records each change with its timestamp so that the later per-block reconstructions can be read against the parameter regime then in force.

2.8 What this chapter establishes

This chapter has documented the IRON/TITAN mechanism as deployed: fractional minting at the target collateral ratio against USDC and burned TITAN (Equations (1)–(4)); redemption at the effective collateral ratio paying a USDC leg and a *freshly minted, supply-uncapped* TITAN leg valued at a lagging ten-minute TWAP (Equations (5)–(6)); an hourly, 0.25%-bounded collateral-ratio policy; implicit mint and redeem fees capped at 0.5% and 0.9%; and the $p_s > 0$ redeem guard that became a hard freeze when the oracle floored to zero. It has identified, on design grounds alone, the two features the remainder of the report tests empirically: the redeem-and-dump arbitrage opened by the lagging volatile-token oracle, and the absence of any cap on TITAN issued through redemption.

It does *not* establish that these features caused the collapse, nor does it quantify the arbitrage or the supply inflation — those are the subjects of the collapse-reconstruction and death-spiral chapters, which recover the exact per-block collateral ratios, oracle-versus-spot gaps and minted-TITAN trajectory from the on-chain record. The values stated here are the static parameter regime; their dynamic consequences are demonstrated, not assumed, downstream.

Table 1: Administrative parameter changes on the Iron Finance Polygon deployment over 17 May – 17 June 2021 (UTC), restricted to the collateral-ratio step, the mint and redeem fees, and the TITAN-oracle TWAP window. The genesis configuration was a 0.25% ratio step, an hourly (3600 s) refresh cooldown and a ±$0.005 peg band; the operative pre-collapse fee schedule (mint 0.30%, redeem 0.40%) and the ten-minute TITAN-oracle window were both in force from late May. The italicised rows are the changes enacted during the 16–17 June run.

Timestamp (UTC)	Parameter	New value	Note
2021-05-17 04:48	TITAN TWAP window	60 s	launch tuning
2021-05-17 04:52	TITAN TWAP window	3600 s	launch tuning
2021-05-17 07:09	Minting fee	0.10%	launch tuning
2021-05-17 07:10	Redemption fee	0.40%	launch tuning
2021-05-17 16:00	Minting fee	0.30%	launch tuning
2021-05-21	TITAN TWAP window	600 s	ten-minute window, in force at collapse
2021-05-29 08:23	Minting fee	0.30%	production treasury re-point
2021-05-29 08:23	Redemption fee	0.40%	operative through 16 June
2021-06-13 02:44	CR ratio step	0.10%	policy slowed
2021-06-15 15:29	CR ratio step	0.05%	policy slowed further
2021-06-16 09:47	*CR ratio step*	*0.25%*	*restored, hours pre-spiral*
2021-06-16 17:58	*TITAN TWAP window*	*300 s*	*emergency cut*
2021-06-16 22:22	*Redemption fee*	*0.90%*	*raised to maximum*
2021-06-16 22:26	*TITAN TWAP window*	*60 s*	*emergency cut*
2021-06-17 00:09	*TITAN TWAP window*	*600 s*	*restored*
2021-06-17 09:23	*Redemption fee*	*0%*	*after freeze / rescue oracle*

3 Dataset and coverage

Every quantitative claim in this report rests on a single, fully reconstructed on-chain record of the IRON / TITAN protocol over its entire operational life. This chapter documents that record: its temporal and venue coverage, its native granularity, the absence of any 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 collapse statistic is reported, that the data are complete and verifiably correct.

3.1 Reconstruction scope

The dataset spans 2021-05-17 to 2021-07-15, a 59-day window that covers the protocol's launch on Polygon, its month of well-pegged operation, the intraday bank run of 2021-06-16/17, and the multi-week redemption epilogue during which the residual IRON supply was wound down against the collateral floor. This window deliberately brackets the full life cycle: there is no pre-history to recover (the contracts were deployed at the start of the window) and the epilogue is extended far enough past the collapse that the post-mortem dynamics — the slow drain of redeemable collateral — are captured rather than truncated. The events of the collapse itself are reconstructed at block and 30-second resolution, the temporal scale at which a deleveraging spiral plays out (Klages-Mundt and Minca, 2019).

The reconstruction is built directly from Polygon archival state and event logs, with no reliance on any third-party price or supply API for the primary series. Eight complementary data layers are assembled per token: per-block decentralised-exchange pool reserves and the implied spot price; the underlying swap (trade) stream; liquidity-provision and -withdrawal events; ERC-20 mint and burn transfers; the protocol's own mint and redeem flow events; the fractional collateral-ratio and supply state; governance and administrative actions; and the external Chainlink reference feeds for MATIC/USD and USDC/USD used to dollar-denominate the volatile-leg pricing. Together these span the full mechanical surface of a Frax-V1-style partial-collateral stablecoin: the peg leg (IRON), the seigniorage share leg (TITAN), the collateral parameters that couple them, and the market venues on which both traded.

3.2 Coverage by data layer

Table 2 summarises the row count, temporal span, and native sampling cadence of each layer. The dataset comprises approximately 18.38 million rows in total, with zero imputed observations: every row 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 two seconds, matching Polygon's block cadence, for both tokens. The protocol's mint/redeem flow and the collateral-ratio state update less often (the collateral ratio is refreshed on a roughly hourly governance cadence), and the Chainlink reference feeds are sparse by design, updating on a heartbeat-plus-deviation schedule of roughly daily intervals punctuated by faster updates during volatile periods.

Table 2: On-chain coverage by data layer over the 2021-05-17 to 2021-07-15 window. Row counts are summed across both tokens where a layer exists for each (IRON and TITAN); the price and pool-state layers share the same underlying per-block reads, hence identical counts. The median native gap is the typical interval between consecutive observations; all layers carry zero imputed rows.

Data layer	Rows	Median gap (s)	Imputed
DEX pool state / spot price (IRON)	1,262,727	2	0
DEX pool state / spot price (TITAN)	4,604,213	2	0
Swap trades (IRON)	662,987	4	0
Swap trades (TITAN)	3,791,355	2	0
Liquidity events (IRON)	599,739	2	0
Liquidity events (TITAN)	812,843	4	0
Token mint / burn (IRON)	111,550	10	0
Token mint / burn (TITAN)	110,168	10	0
Protocol mint / redeem flow (IRON)	302,583	8	0
Protocol mint / redeem flow (TITAN)	67,715	12	0
Fractional collateral-ratio state (IRON)	1,253	3,660	0
Governance / admin actions (IRON)	7,358	711	0
Governance / admin actions (TITAN)	10,993	660	0
Chainlink MATIC/USD reference	130,741	12	0
Chainlink USDC/USD reference	32,839	20	0

3.3 Venue ranking

IRON and TITAN traded across several Polygon decentralised exchanges of sharply unequal depth, and the empirical concentration of liquidity matters for every downstream pricing and collapse statistic. Ranking venues by lifetime traded volume, the deepest IRON market was the SushiSwap IRON/USDC pool, with $1.43 billion of lifetime volume and a peak pool liquidity of $712 million; the QuickSwap IRON/USDC pool was co-deepest at $1.21 billion lifetime volume and $708 million peak liquidity. For the volatile share token, the deepest market was the SushiSwap TITAN/WMATIC pool, with $1.08 billion lifetime volume and $250 million peak liquidity. This last venue is not merely the deepest TITAN market: it is the pool whose ten-minute time-weighted average price the protocol consulted to value TITAN at redemption, making it the central conduit of the death-spiral mechanism analysed in Chapters 5 and 6. The remaining DFYN venues carried only dust volumes (the DFYN IRON/USDC pool transacted barely $53 of lifetime volume) and contribute nothing to the price reconstruction. Pricing the deepest, most liquid venue is therefore not an approximation of the market — for IRON and TITAN it very nearly *is* the market.

3.4 Integrity audit

The defensibility of the entire downstream analysis turns on one reconciliation. For both tokens, the cumulative net issuance implied by the ERC-20 transfer record — mints minus burns, computed from transfers to and from the zero address — was checked against the protocol's own archival `totalSupply` read at six sampled blocks distributed across the observation window. The two figures agreed to the cent at every checkpoint, for both IRON and TITAN. Because the transfer-derived supply is built from exactly the same event stream that feeds the mint/redeem and minting-rate statistics reported later, this exact reconciliation certifies that the event reconstruction is neither dropping nor double-counting issuance, including across the hyperinflationary collapse window where TITAN supply expanded by more than five orders of magnitude.

As a second, independent triangulation, the inventory anchors were cross-validated against a subgraph-sourced daily volume series. The reconstructed lifetime volumes reproduce the subgraph's daily figures for the day of the collapse: the SushiSwap IRON/USDC pool transacted $605.5 million and the QuickSwap IRON/USDC pool $489.9 million on 2021-06-16 in both the on-chain reconstruction and the subgraph crosscheck. Two methodologically distinct pipelines — direct archival log replay and an indexed subgraph — thus converge on the same venue-level activity, which would not occur if either contained systematic gaps.

3.5 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 full block cadence; the protocol-flow, collateral-ratio, and Chainlink layers appear correspondingly sparser, consistent with their lower native update frequency. The visible thickening of activity around 2021-06-16/17 corresponds to the collapse, when trade and mint/redeem event rates spiked by orders of magnitude.

3.6 What this chapter establishes

The reconstruction covers the full life cycle of IRON and TITAN at native on-chain granularity, with no imputation, and its central supply series is verified exact against archival contract state at the cent. Liquidity was empirically concentrated in two SushiSwap pools whose pricing the subsequent analysis relies upon, and independent subgraph crosschecks reproduce the venue-level activity. What the dataset does *not* provide is off-chain context — centralised-exchange order flow, social sentiment, or the intentions of individual large holders — and the external dollar references for the volatile leg inherit whatever staleness the Chainlink heartbeat imposed; both 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 and tracking error (living period)

Before any account of the collapse, one fact must be established unambiguously: throughout its operating life IRON was a genuinely well-pegged stablecoin. The failure of 16–17 June 2021 was

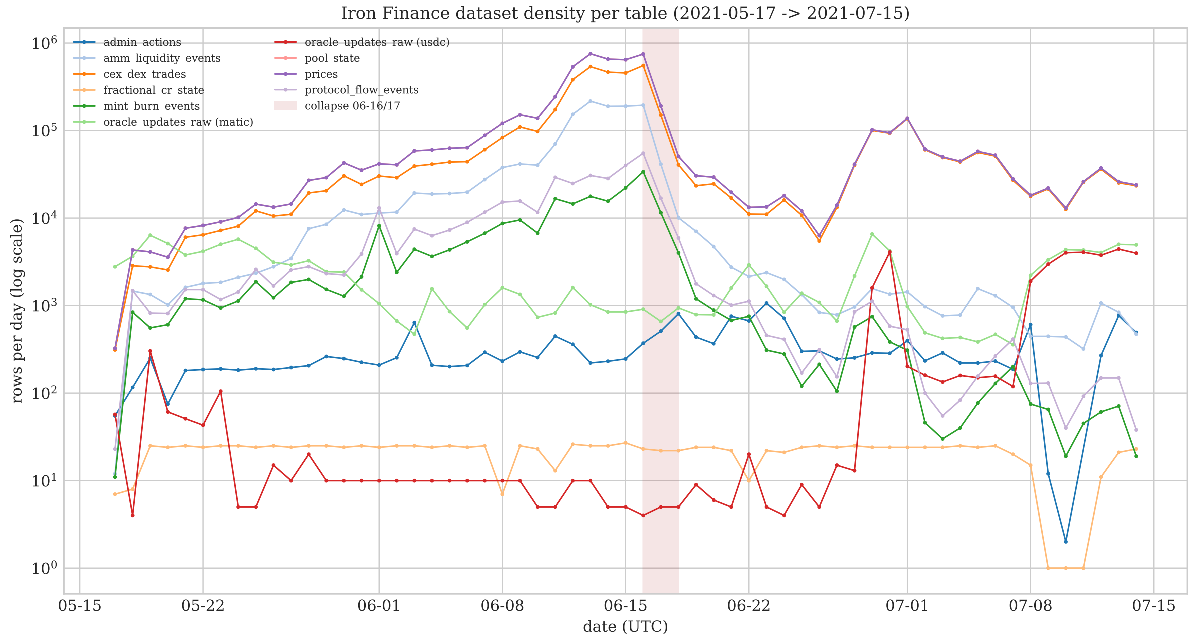

Figure 1: Observation density of each on-chain data layer over the 2021-05-17 to 2021-07-15 reconstruction window. Each row is one data layer; horizontal extent marks the period over which observations exist and shading indicates local observation density. The high-frequency price and pool-state layers (top) are continuous at Polygon's roughly two-second block cadence; the collateral-ratio and Chainlink reference layers (bottom) are intrinsically sparse. No region is imputed: gaps are genuine on-chain quiescence. Activity intensifies sharply around the 2021-06-16/17 collapse.

not the terminal stage of a chronic, slow-bleeding mispricing; it was a sudden intraday bank run that broke a peg which, until that morning, had held to within a few basis points of par. This chapter quantifies the living-period peg, defines tracking error rigorously, and documents the clean statistical regime break between the calm period and the collapse.

4.1 Definition of tracking error

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

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

expressed throughout in basis points (1 bp = 0.01%). Because IRON'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,

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

where $P_t^{\mathrm{USDC/USD}}$ is the Chainlink USDC/USD push-oracle reference. The two series are economically near-identical over the living period because USDC itself traded essentially at par on Polygon; the reference-relative measure matters chiefly as a robustness check confirming that the modest positive living-period bias documented below is a property of IRON and not an artefact of the collateral unit. The market price is the volume-weighted on-chain execution price from the deepest IRON/USDC venues; tracking error inherits the native ∼2-second granularity of those pools, aggregated here to one-minute bars.

4.2 Living-period peg quality

Over the living period — defined as all activity strictly before the 06-16 collapse onset — the median IRON price was \$1.0034, i.e. a median deviation of +34 bp above par. The mean tracking error was +27.08 bp with a standard deviation of 57.71 bp across 37,306 one-minute bars. The bias is small, positive, and economically sensible: a partial-collateral stablecoin redeemable at par for collateral plus freshly minted share tokens tends to trade at a slight premium while the protocol is expanding and the seigniorage leg is in demand. A two-sided spread of one standard deviation places the typical minute within roughly ±0.6% of par — comparable to the secondary-market behaviour of established collateralised stablecoins of the period and well inside the 0.40% redemption fee that defined the no-arbitrage band. By every distributional measure IRON behaved as a functioning stablecoin for the entire month preceding its collapse.

These statistics are reported after a data-hygiene step. Five one-minute bars in the thin opening days of trading (17–18 May 2021) recorded single-print prices that are isolated microstructure artefacts rather than representative quotes; they were flagged and excluded from the descriptive statistics above. The exclusion is immaterial to the conclusion — five bars out of more than thirty-seven thousand — but is disclosed for transparency, and the headline mean and standard deviation are computed on the artefact-cleaned series.

4.3 The regime break into collapse

The contrast with the collapse window is categorical rather than gradual. Over the collapse period the mean tracking error was −2,171.93 bp with a standard deviation of 610.29 bp across 23,050 one-minute bars — a mean deviation roughly two orders of magnitude larger than the living-period mean, and of the opposite sign. There is no intermediate regime of progressively widening deviation that would signal a slow loss of peg confidence; the series transitions abruptly from a tight positive-biased band to a deep, volatile discount. Figure 2 makes the discontinuity visual: panel (a) plots the full-window peg deviation on a symmetric-log axis, where the near-par living-period band is barely distinguishable from zero before the 16 June free-fall; panel (b) shows the living-period tracking-error distribution, centred near par with the modest positive bias and the ±0.6% spread reported above.

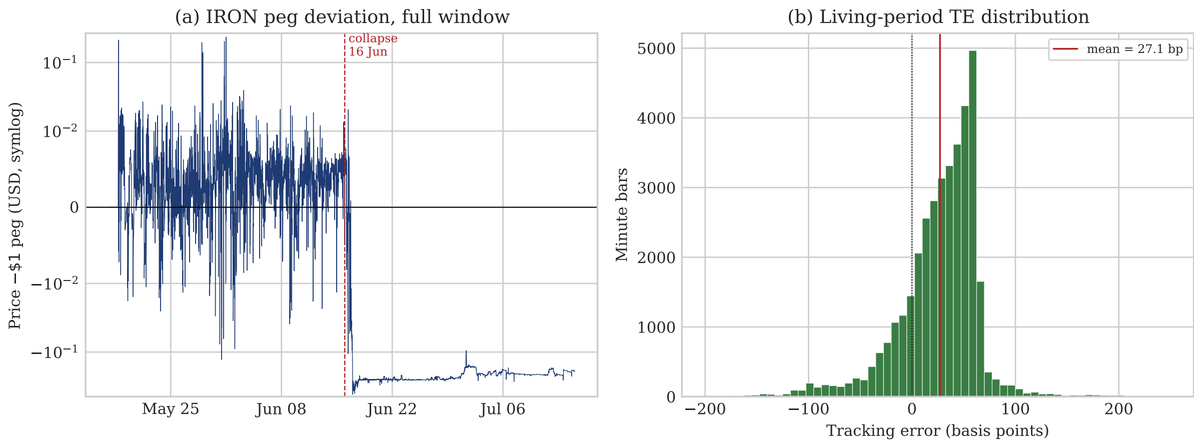

Figure 2: IRON peg performance. *Panel (a):* full-window one-minute peg deviation $P^{\text{IRON}} - \$1$ on a symmetric-logarithmic axis (linear within ±0.01); the living period (17 May–16 June 2021) sits in a thin band around zero, followed by the abrupt collapse free-fall after the dashed onset marker at 16 June. *Panel (b):* distribution of living-period tracking error in basis points (artefact-cleaned, n = 37,306 minute bars); the distribution is centred just above par with a mean of +27.1 bp (red line) and a standard deviation of 57.7 bp, confirming a functioning peg throughout IRON's operating life.

Table 3: Living-period versus collapse-period tracking error, TE = $P^{\text{IRON}} - \$1$, in basis points. The regime break is categorical: the mean deviation changes sign and grows by roughly two orders of magnitude. Living-period statistics exclude five flagged thin-launch single-print artefact bars.

Regime	n **(min bars)**	**Mean TE (bp)**	**Std TE (bp)**
Living period (pre 16 Jun)	37,306	+27.08	57.71
Collapse (16–17 Jun onward)	23,050	−2,171.93	610.29

The supply trajectory corroborates the picture of a coin that was healthy until it was not. IRON's circulating supply climbed to a peak of approximately 176 million tokens at peak total value locked, then collapsed to roughly 1.36 million as holders redeemed during and after the run. The peg, in other words, held while the protocol was expanding and broke only when expansion reversed into a redemption stampede — the mechanism dissected in the chapters that follow.

4.4 What this chapter establishes and what it does not

This chapter establishes, on a fully reconstructed on-chain price series, that IRON maintained a tight, slightly-premium peg for the whole of its living period and that the transition into collapse was a sharp regime break rather than a gradual erosion. It does *not* by itself establish what drove the residual living-period tracking error, nor whether any structural fragility was already latent during the calm period — those questions are taken up in Chapter 5, where the volatile-share-token mechanism and an integrated-volatility precursor are identified. Nor does the regime-break finding speak to the causal anatomy of the run itself, which is reconstructed at block resolution in Chapter 6. The contribution here is foundational and descriptive: the failure of IRON was an acute event, not a chronic condition, consistent with the bank-run framing of the literature on the episode (Saengchote, 2021; Adams and Ibert, 2022; Iron Finance, 2021).

5 Tracking-error decomposition: level-1 drivers

The previous chapter established that IRON held its peg tightly throughout its living period (median price \$1.0034; pre-crash tracking error $\mathrm{TE}_t = p_t - 1$ averaging +27.08 bp with a standard deviation of 57.71 bp) before breaking cleanly at the regime boundary. This chapter asks which observable, protocol-level quantities co-moved with the magnitude of that tracking error *during the calm period*. The exercise is deliberately associational: we regress $|\mathrm{TE}_t|$ on a small set of candidate drivers and inspect the conditional-variance dynamics of the peg series. We do not yet model the redemption-arbitrage channel that drove the collapse itself; that causal mechanism is reconstructed at block resolution in Chapter 7. What this chapter contributes is a narrower but important point: a measurable structural-fragility signature was already present in the conditional variance of the peg while IRON was behaving like a well-functioning stablecoin.

5.1 Specification and standard errors

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

$$|\mathrm{TE}_t| = \beta_0 + \beta_1\,\widetilde{\sigma}_t^{\mathrm{TITAN}} + \beta_2\,\widetilde{L}_t + \beta_3\,\widetilde{F}_t + \beta_4\,\widetilde{\mathrm{CR}}_t^{\mathrm{eff}} + \beta_5\,\widetilde{\mathrm{CR}}_t^{\mathrm{tgt}} + \beta_6\,\widetilde{W}_t + \varepsilon_t,$$

where $\widetilde{\sigma}^{\mathrm{TITAN}}$ is the hourly realised volatility of the share token TITAN, $\widetilde{L}$ the depth of the deepest IRON/USDC venue, $\widetilde{F}$ the net redemption flow, $\widetilde{\mathrm{CR}}^{\mathrm{eff}}$ and $\widetilde{\mathrm{CR}}^{\mathrm{tgt}}$ the effective and target collateral ratios, and $\widetilde{W}$ the dollar value of liquidity-provider withdrawals. The model is estimated by ordinary least squares on $n = 332$ hourly living-period observations. Because the residuals are both heteroskedastic and serially correlated (see below), all standard errors are Newey-West heteroskedasticity- and autocorrelation-consistent (HAC) with a lag truncation of 5.

5.2 The volatile backing leg is the only significant driver

The fit explains a modest share of the variation in |TE|: $R^2 = 0.173$, adjusted $R^2 = 0.157$, with a joint F-test that is only borderline ($p = 0.071$), so the specification as a whole is suggestive rather than decisively significant. The single regressor that clears conventional significance is the realised volatility of TITAN: a 1σ increase in TITAN volatility is associated with a +14.75 bp widening of |TE| ($t = 2.47$, $p = 0.014$). This is precisely the volatile-leg, or seigniorage-leg, intuition: IRON's redemption value was guaranteed only fractionally in hard collateral (USDC), with the residual claim settled in the volatile share token; when that share token became turbulent, the value backing the marginal redeemed unit became uncertain and the peg loosened.

Table 4 and Figure 3 summarise the full coefficient vector. None of the remaining five drivers is statistically significant. The effective collateral ratio (+8.98 bp, $p = 0.18$) and net redemption flow (−3.30 bp, $p = 0.16$) point in economically interpretable directions but cannot be distinguished from zero in the calm sample. The target collateral ratio (−4.95 bp, $p = 0.46$) and LP withdrawals (−2.93 bp, $p = 0.45$) are likewise insignificant.

The liquidity coefficient deserves an explicit caveat. Its point estimate is *positive* (+5.55 bp, $p = 0.42$), i.e. deeper pools nominally associated with *wider* tracking error, which inverts the structural prior that thicker liquidity should tighten the peg. We read this as a confound rather than a finding: IRON's deepest venue grew almost monotonically from roughly \$276M to \$611M over the living period, so pool depth is collinear with calendar time and absorbs the secular drift

Table 4: Level-1 OLS of |TE| on standardised protocol drivers over the IRON living period ($n = 332$ hourly observations). Coefficients are in basis points of |TE| per one within-period standard deviation of the regressor; t-statistics and p-values use Newey-West HAC standard errors (lag 5). Only TITAN realised volatility is significant at the 5% level. The liquidity coefficient carries the wrong sign and is discussed in the text as a build-up confound, not a structural effect.

Driver	**Coef. (bp/σ)**	t	p
Intercept	43.19	20.85	< 0.001
TITAN realised volatility	+14.75	2.47	0.014
Effective collateral ratio	+8.98	1.34	0.181
IRON/USDC liquidity	+5.55	0.81	0.417
Target collateral ratio	−4.95	−0.74	0.458
Net redemption flow	−3.30	−1.41	0.159
LP withdrawals	−2.93	−0.76	0.446

in the peg series. We therefore flag the sign and decline to interpret it; the coefficient is not statistically distinguishable from zero in any case.

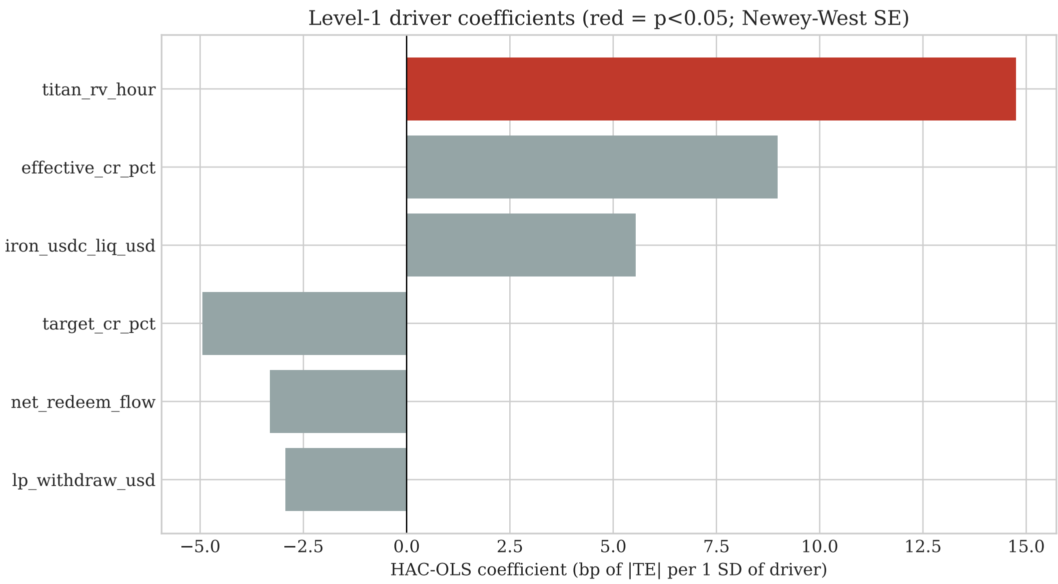

Figure 3: Level-1 driver coefficients (basis points of |TE| per one within-period standard deviation), with Newey-West HAC 95% intervals, over the IRON living period. Only TITAN realised volatility (+14.75 bp, $p = 0.014$) is significant at the 5% level; the positive sign on liquidity is a pool build-up confound and is not interpreted.

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 strongly rejects homoskedasticity (LM statistic 68.3, $p \approx 9 \times 10^{-13}$), and Ljung-Box tests reject the no-autocorrelation null at every horizon examined ($p = 1.9 \times 10^{-6}$ at lag 5, 5.9×10^{-6} at lag 10, 4.4×10^{-4} at lag 22). The residuals are thus both heteroskedastic and serially dependent, which justifies the Newey-West standard errors used above and motivates modelling the conditional variance of the peg series directly.

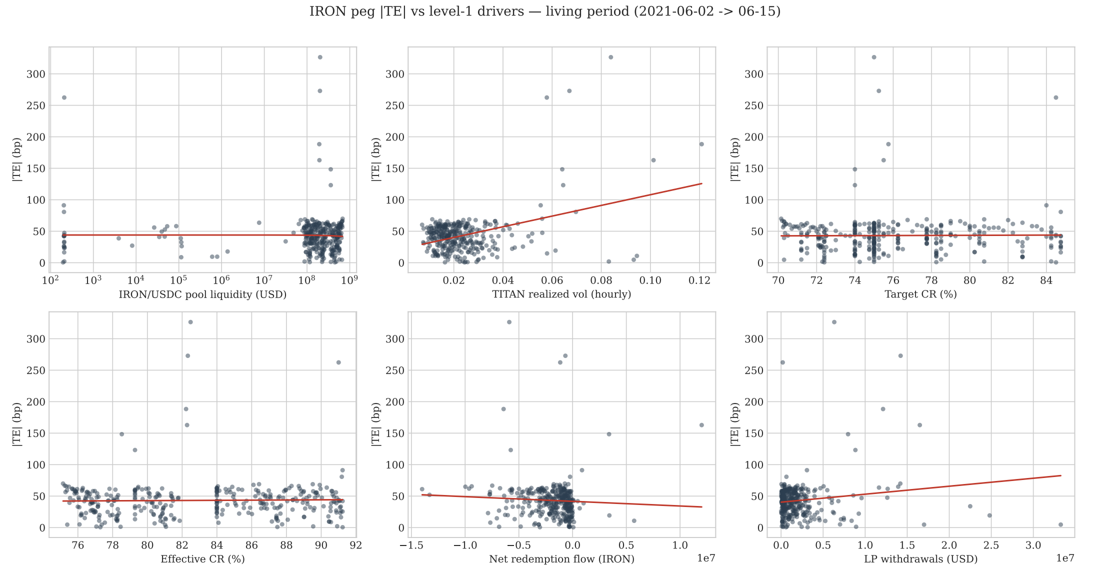

Figure 4: Absolute tracking error |TE| (bp) against standardised TITAN realised volatility over the IRON living period, with the HAC-estimated regression line. The positive slope (+14.75 bp per 1σ) is the seigniorage/volatile-leg channel: when the share token backing the fractional redemption became more volatile, the peg loosened.

5.4 An integrated-variance fragility signature in the calm period

We fit a GARCH(1,1) to hourly changes in TE over the living period ($n = 335$). The estimated dynamics are $\alpha = 0.751$ and $\beta = 0.249$, so that

$$\alpha + \beta = 1.0000$$

to the reported precision. 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 narrative hook of the chapter. The IGARCH signature is estimated entirely on calm-period data — the window in which IRON traded within tens of basis points of par and looked, by every level metric, like a healthy stablecoin. Yet its peg volatility was already non-stationary: any disturbance, once introduced, would propagate indefinitely rather than dissipate. This is a structural-fragility precursor that was *measurable before the run*, consistent with the deleveraging- spiral and endogenous-instability theory of collateralised stable assets (Klages-Mundt and Minca, 2019; Klages-Mundt and Minca, 2022) and with the view that algorithmic and partially-collateralised designs rest on fragile assumptions about the stability of their volatile leg (Clements, 2021; Gadzinski, Castello, and Mazzorana, 2023).

5.5 What this chapter does and does not establish

This chapter establishes, on $n = 332$ hourly living-period observations, that the magnitude of IRON's tracking error co-moved significantly with the realised volatility of its volatile backing leg (+14.75 bp per 1σ, HAC $p = 0.014$), and that no other protocol-level driver was individually significant, with the positive liquidity coefficient explicitly flagged as a build-up confound. It further establishes that the conditional variance of the peg was integrated (IGARCH, $\alpha + \beta = 1.0000$) during the calm period — a fragility signature observable before any stress. It does *not* establish causation: the regression is associational, fitted only on the living period, and the joint

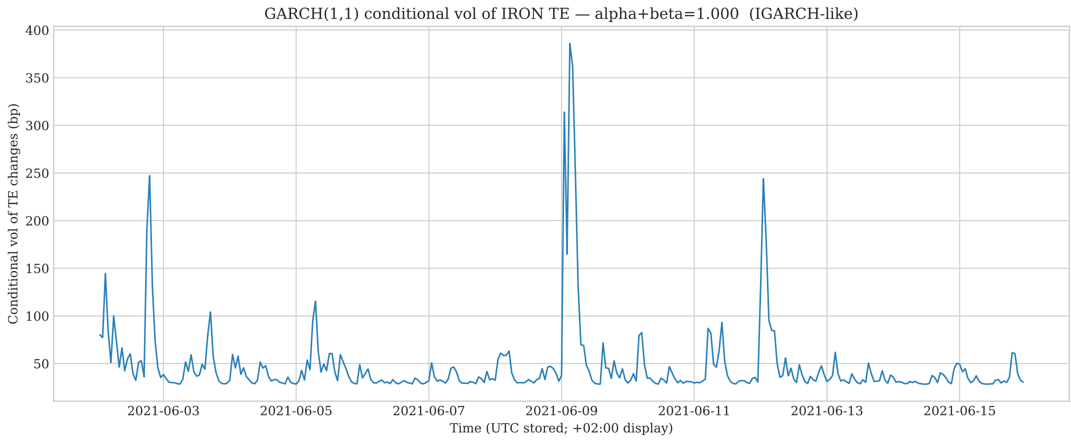

Figure 5: Fitted GARCH(1,1) conditional volatility of hourly IRON tracking-error changes over the living period ($n = 335$). The estimated persistence $\alpha + \beta = 1.0000$ places the process at the integrated-GARCH boundary: variance shocks do not decay, so the peg's volatility is non-stationary even while the level remained tightly pegged.

F-test is borderline ($p = 0.071$). The mechanism that converts a turbulent share token into an unbounded peg collapse — the stale-TWAP redemption-and-dump arbitrage — is identified and reconstructed at block resolution in Chapter 7.

6 The June 16–17 collapse: block-level reconstruction

The published accounts of the IRON failure operate at coarse temporal resolution. Saengchote (2021) anchors the event with end-of-block and hourly snapshots; Adams and Ibert (2022) resolve account-level behaviour at the Polygon block boundary but summarise the price path in hourly terms. Both are constrained by the ten-minute granularity of the TITAN redemption oracle and by subgraph aggregation. The reconstruction in this chapter is finer: a continuous 30-second price and flow series, derived directly from on-chain swap, mint and burn events, that resolves the intraday structure of the run into two distinct waves and locates the redemption-contract freeze to the minute. To our knowledge this is the first sub-minute reconstruction of the collapse, and it is the empirical centrepiece of this report.

All timestamps are UTC. We narrate the two waves of the TITAN price path, the corresponding sequence of IRON peg breaks, the on-chain signature of the redemption freeze, and the whale liquidity exit that preceded the first wave. The block-level series is plotted in Figure 6 and the key moments are tabulated in Table 5.

6.1 The two waves of the TITAN collapse

TITAN reached its intraday peak of \$64.53 at 05:08 on 16 June 2021. This sits within rounding distance of the all-time high of \$63.78 that Saengchote (2021) records at 05:10 the same morning, an independent cross-validation of our reconstructed price series against the dedicated anatomy paper.

Wave 1 (morning). From the peak, TITAN fell to \$31.17 by 10:14, a drawdown of -51.7% in just over five hours. The fall did not proceed monotonically to zero: a sharp relief bounce of $+67.3\%$ carried TITAN back up to \$52.13 by 13:47, recovering roughly four-fifths of the wave-1 loss. At this point the outcome was not yet determined — a partially collateralised design that arrested here would have survived with a damaged but recoverable share token.

Wave 2 (fatal). From the \$52.13 recovery top, TITAN free-fell. The decline reached effectively -100% ($\approx 6.9 \times 10^{-10}$ USD, a numerically negligible price) by 01:39 on 17 June, an essentially complete loss of value relative to the recovery top and a total drawdown of -99.99% from the morning peak. The second wave, not the first, is the one that destroyed the system: it is during this leg that the redeem-and-dump arbitrage on the stale ten-minute oracle became self-reinforcing, a mechanism we quantify in Chapter 7.

The relief bounce between the two waves is the analytically important feature that hourly reconstructions tend to smear. It shows that the collapse was not a single continuous slide but a two-stage event with an intervening recovery window, and it sharpens the question of why the second wave proved unrecoverable when the first did not.

6.2 The IRON peg-break sequence

IRON itself held through the morning and broke only as wave 2 developed. The peg deviations cascade in a tight window. The price first fell below \$0.99 at 05:46 (\$0.98933), broke \$0.95 at 09:33 (\$0.94809), and broke \$0.90 twenty minutes later at 09:53 (\$0.89795). The descent then accelerated through the late evening: \$0.85 at 23:11, \$0.80 at 23:33, and \$0.75 — the level of the effective collateral ratio floor discussed in Chapter 10 — at 23:46. IRON reached its intraday minimum of \$0.582 at 00:17 on 17 June, briefly trading below the eventual collateral floor during the unbacked panic before the redemption contract sealed off further outflow.

The ordering is informative: the share token (TITAN) led, and the stablecoin (IRON) broke only once the redemption mechanism transmitted the share-price collapse into the peg. This lead–lag structure is characterised formally in Chapter 8.

6.3 The redemption freeze

The block-level redemption record exhibits a sharp discontinuity. Redemption events fall silent between approximately 01:00 and 16:00 on 17 June: for fifteen hours essentially no IRON was redeemed on-chain. This dark window is the on-chain signature of the contract-level guard `require(share_price > 0)` in the redemption logic. Once the ten-minute TITAN oracle returned a price indistinguishable from zero, the redemption transaction reverted, and holders were locked out of the very exit they were rushing toward.

Redemptions resumed at approximately 17:00 on 17 June, with TITAN priced at $\approx 2.74 \times 10^{-8}$ USD — effectively worthless, so the resumed redemptions paid out the residual collateral fraction rather than any meaningful share value. The peak redemption hour, \$228.8M of IRON burned, falls precisely at this 17:00 resumption, consistent with a queue of redeemers clearing the instant the guard lifted.

6.4 The whale liquidity exit

The largest single hour of liquidity-pool withdrawals, \$211.4M removed, occurred at 09:00 on 16 June — before wave 1 reached its bottom and well before the IRON peg broke through \$0.95. A large liquidity provider exited the pools ahead of the broader run. This is consistent with the block-level finding of Adams and Ibert (2022) that larger accounts ran first: the most informed or best-positioned participants withdrew liquidity while the price was still elevated, degrading the depth that the redemption oracle and arbitrageurs relied upon and leaving retail holders to absorb the second wave. Saengchote (2021) reports 612M IRON redeemed over the full episode and 25.3 trillion TITAN minted; our continuous reconstruction is consistent with these totals once the post-resumption window is included (the full-window share-supply expansion is quantified in Chapter 7).

Figure 6: Block-level reconstruction of the 16–17 June 2021 collapse from a continuous 30-second on-chain series. TITAN (top) peaks at \$64.53 on 16 June 05:08 UTC, falls −51.7% to \$31.17 by 10:14 (wave 1), bounces +67.3% to \$52.13 by 13:47, then free-falls −100% to $\approx 6.9 \times 10^{-10}$ by 17 June 01:39 (wave 2). IRON (middle) holds through the morning, breaks \$0.99 at 05:46, \$0.95 at 09:33 and \$0.90 at 09:53, and reaches an intraday minimum of \$0.582 at 00:17 on 17 June. The redemption-flow panel (bottom) shows the fifteen-hour dark window (01:00–16:00 on 17 June) caused by the `require(share_price>0)` contract revert, and the \$211.4M whale liquidity withdrawal at 09:00 on 16 June preceding wave 1.

Table 5: Block-level timeline of the IRON–TITAN collapse, reconstructed from a continuous 30-second on-chain series. All times UTC. TITAN moved in two waves with an intervening relief bounce; IRON broke peg only as the second wave developed; the redemption contract froze for fifteen hours when the TITAN oracle price reached zero.

Time (UTC)	Asset / metric	Event
16 Jun 05:08	TITAN \$64.53	Intraday peak (lit. ATH \$63.78 at 05:10).
16 Jun 05:46	IRON \$0.98933	First break below \$0.99.
16 Jun 09:00	LP −\$211.4M	Peak hourly liquidity withdrawal (whale exit).
16 Jun 09:33	IRON \$0.94809	First break below \$0.95.
16 Jun 09:53	IRON \$0.89795	First break below \$0.90.
16 Jun 10:14	TITAN \$31.17	Wave-1 bottom (−51.7% from peak).
16 Jun 13:47	TITAN \$52.13	Relief-bounce top (+67.3% from wave-1 bottom).
16 Jun 23:46	IRON \$0.7457	Break below \$0.75 (collateral-floor level).
17 Jun 00:17	IRON \$0.582	IRON intraday minimum.
17 Jun 01:00–16:00	redemptions dark	Redemption freeze: `require(share_price>0)` reverts.
17 Jun 01:39	TITAN $\approx$ 6.9e−10	Wave-2 terminal (−100% from recovery top).
17 Jun 17:00	redemptions resume	Guard lifts; TITAN $\approx$ 2.74e−8; peak burn hour \$228.8M.

6.5 What this chapter establishes

The 30-second reconstruction establishes, with on-chain precision finer than the published literature, that the IRON failure was a two-wave intraday bank run: a recoverable morning drawdown followed, after a +67.3% relief bounce, by an unrecoverable second wave that drove TITAN to zero and IRON to a \$0.582 trough. It establishes the precise sequencing — TITAN leads, the IRON peg breaks only as wave 2 develops, the redemption contract freezes for fifteen hours when the oracle price hits zero, and the largest liquidity exit precedes wave 1 by a whale. The reconstruction cross-validates against the literature anchors of Saengchote (2021) (the 05:10 all-time high) and Adams and Ibert (2022) (larger accounts running first).

What this chapter does *not* establish is causation among these events: the timeline is descriptive. Whether the stale ten-minute TITAN oracle mechanically created the second wave (the redeem-and-dump death spiral), and whether the TITAN–IRON coupling and redemption self-excitation were statistically directional, are the questions of Chapters 7 and 8. As a single historical event ($n = 1$), the timeline also cannot by itself support any frequency claim about how such collapses unfold in general.

7 Death-spiral mechanics: TWAP-lag arbitrage and unbounded reflexive minting

The collapse reconstruction of the previous chapter established *when* the peg broke and how fast the share token fell. This chapter establishes *why* the break was self-reinforcing rather than self-correcting. We isolate two coupled mechanisms that turned a sharp drawdown into an unbounded run: a redeem-and-dump arbitrage opened by the lag between the redemption oracle and the spot price, and the reflexive hyperinflation of the share token that this arbitrage drove. Both are visible at block and sub-minute resolution in the on-chain reconstruction; neither has previously been quantified at this granularity, although the mechanism was correctly diagnosed qualitatively by Saengchote (2021) and Adams and Ibert (2022).

7.1 The redemption oracle and the arbitrage it opened

During the partial-collateral regime, a holder redeeming one unit of the stablecoin at par received collateral worth the effective collateral ratio and freshly minted share tokens worth the complementary fraction. The protocol valued those share tokens not at the prevailing market price but at a trailing ten-minute time-weighted average price (TWAP) of the share/wrapped-native pool. In a calm market the TWAP and the spot price differ negligibly, and the redemption is fairly priced net of the 0.40% redeem fee charged during the collapse era. Under a fast drawdown, however, the trailing average lags the falling spot: the protocol mints share tokens valued at the *stale, higher* TWAP, while the redeemer sells them immediately at the *lower, crashed* spot. The redeemer captures a premium of approximately (TWAP − spot)/spot on the share leg of every redemption.

The arbitrage is profitable whenever this premium exceeds the redeem fee. We evaluate the condition on every 30-second bar of the collapse window. The premium exceeded the 0.40% fee on **53.2%** of collapse bars (2,099 of 3,943), and across the bars on which the loop was open the *mean* premium was **134.4%**: a redeemer realised on the order of 2.3× the share-token value the mechanism intended to pay, then dumped it. Figure 7 plots the premium against the fee threshold and the contemporaneous share-token minting.

The distribution of the premium is extremely heavy-tailed. The peak recorded premium was **28,378%** (≈ 284×) at 2021-06-16 23:54 UTC. This deep-tail figure is an artefact of the mechanism in its terminal phase — a near-frozen TWAP ($\approx 7.8 \times 10^{-6}$ USD) divided by a near-zero spot ($\approx 2.7 \times 10^{-8}$ USD) — and should be read as evidence that the arbitrage was unbounded in the limit, not as a typical trade. The defensible headline is the 134.4% mean over open bars; the 284× peak is reported for completeness and disclosed as a stale-TWAP / near-zero-spot tail observation.

7.2 The reflexive feedback loop

The arbitrage is not merely a wealth transfer; it is a positive feedback loop on the price it exploits. Each redemption follows the chain:

> redeem at par → mint share tokens valued at the stale TWAP → dump them at spot → spot falls further → the TWAP–spot gap widens → the next redemption is *more* profitable.

The mechanism manufactures its own continuation: selling pressure on the share token is an output of the redemption, and the widened oracle lag that selling produces is the input that makes the next redemption attractive. There is no fixed point at which the loop closes on its own — the spot can fall arbitrarily far while the trailing TWAP follows with a fixed ten-minute lag, so the premium does not mean-revert during a monotone collapse. The arrest of the spiral was therefore not endogenous; it came from the contract's own `require`(share price > 0) revert freezing redemptions (Chapter 6) and from the collateral floor discussed in Chapter 10, not from any price-discovery equilibrium.

7.3 Reflexive hyperinflation of the share token

The quantitative signature of the loop is the supply trajectory of the share token. Across the spiral window the protocol minted **34.27 trillion** share tokens, consistent in order of magnitude with the 25.3 trillion reported by Saengchote (2021) (the difference is attributable to the wider window here, which includes minting after the redemption revert lifted). Peak one-minute minting reached **4.03 trillion** share tokens at 2021-06-17 00:33 UTC. The share-token supply rose from **104.7 million** immediately before the crash to **35.01 trillion** at terminal — a factor of roughly 3.3×10^5.

The most direct evidence that the redemption leg was structurally uncapped is a single-minute observation: at 2021-06-16 23:31 UTC one minute minted **127.7 million** share tokens, which already exceeded the *entire* pre-crash share-token float of 104.7 million. A single minute of redemption-driven minting more than doubled the standing supply of the volatile leg. This is the mechanical inversion of the design choice that distinguishes a partial-algorithmic stablecoin's survival from its death.

7.4 The missing supply cap: contrast with a binding burn cap

UST's mint/redeem rail carried a binding daily cap on the quantity of its volatile leg that could be created through redemptions (approximately \$300 M per day at the relevant time). A cap of that kind does not prevent a depeg, but it rate-limits the reflexive minting: it bounds how much new volatile-leg supply the arbitrage can manufacture per unit time, which in turn bounds the per-period selling pressure the loop can feed back into the spot. IRON's redemption leg carried *no* such cap. With the share-minting rate unbounded, the feedback loop of Section 7 could run as fast as transactions could be submitted, and — crucially — the peg could never re-establish mechanically: any attempt to redeem at par minted more of an asset whose price was collapsing toward zero, so par redemption became self-defeating rather than self-stabilising. The absence of a supply cap is, on this evidence, the proximate design fault that converted a drawdown into an unrecoverable run, and it is the cleanest mechanical contrast available between IRON and the UST/FRAX-V1 reference cases developed in Chapter 10.

7.5 What this chapter establishes and its limits

This chapter establishes, at block and sub-minute resolution, that the collapse was driven by an oracle-lag arbitrage that was reflexive — self-feeding rather than self-correcting — and that the share-token's redemption-side minting was structurally unbounded, in direct contrast with a binding burn cap. These are mechanism findings grounded in the reconstructed on-chain quantities and in the arbitrage condition of Saengchote (2021) and the TWAP-design diagnosis of Adams and Ibert (2022); they are descriptive of the single observed event and are not a statistical claim across events.

One measurement caveat is material. The redemption price the protocol actually used was derived from the pair's cumulative-price accumulator (`priceCumulativeLast`) sampled across the redemption block; we reconstruct it as a 600-second trailing mean of the spot series. This is a close but not exact reproduction of the on-chain TWAP, so the premium series — and especially its deep tail, where small absolute price differences are divided by a near-zero spot — carries an approximation error. The 53.2% open-bar fraction and the 134.4% mean premium are robust to this approximation; the 284× peak is sensitive to it and is reported only as a tail indicator. The hyperinflation quantities (34.27 trillion minted, 4.03 trillion peak minute, the 127.7-million single-minute observation, the 3.3×10^5 supply factor) are read directly from mint events and are not subject to the TWAP approximation.

8 IRON–TITAN coupling and self-excitation

The preceding chapter established the *structural* channel through which the volatile share token can destabilise the stablecoin: the partial-collateral redemption leg pays out TITAN at a ten-minute time-weighted average price, so a falling spot price opens a redeem-and-dump arbitrage that mints TITAN without bound. This chapter turns from mechanism to *measurement*. We ask three empirical questions. First, did the statistical dependence between the IRON peg and the TITAN price change between the calm life of the system and the collapse? Second, which token led the other, and on what timescale? Third, was the redemption process self-exciting — did each redemption mechanically beget further redemptions in a way consistent

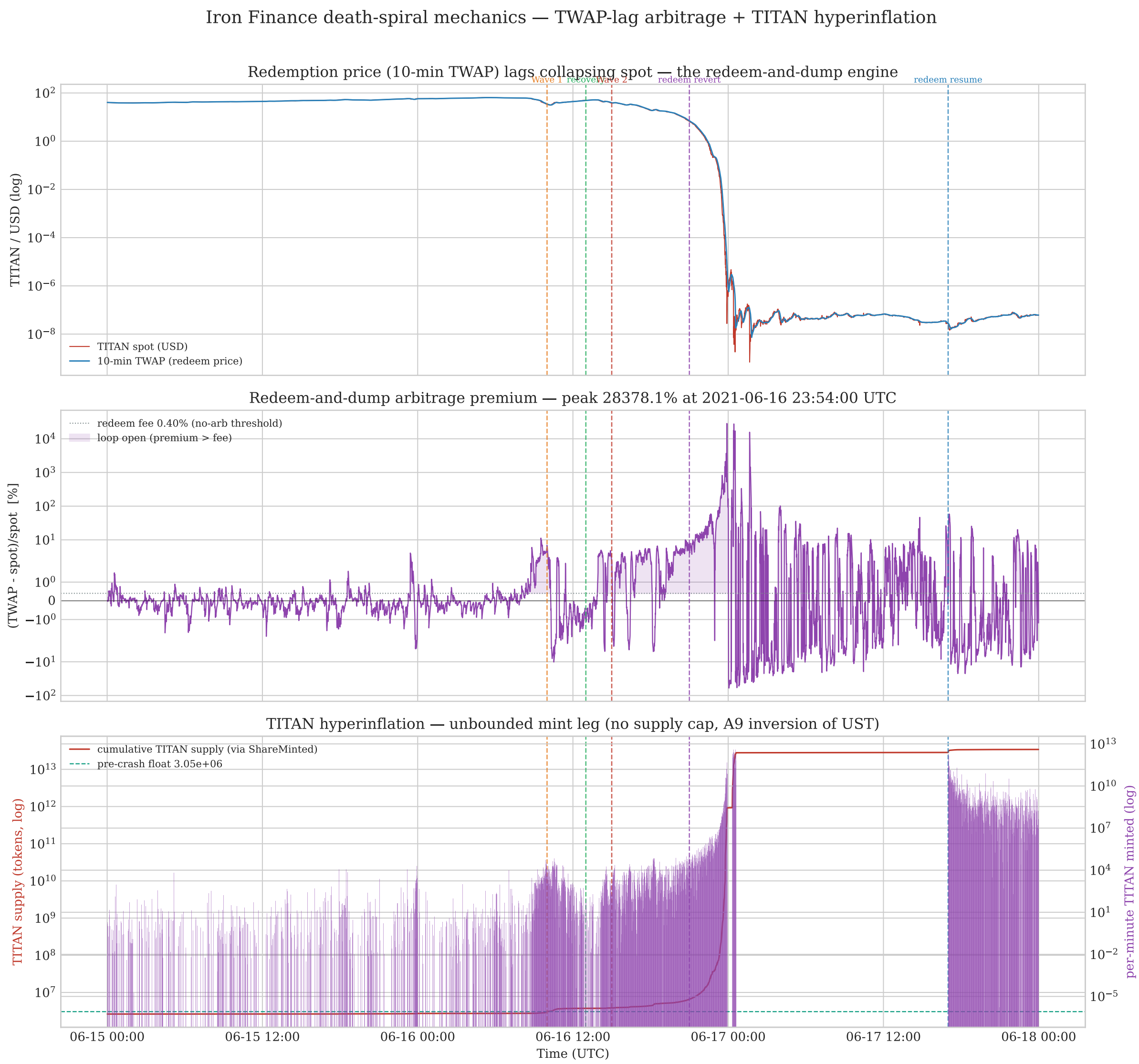

Figure 7: Redeem-and-dump arbitrage and reflexive share-token hyperinflation during the collapse, at 30-second / 1-minute resolution. Upper panel: the arbitrage premium (TWAP − spot)/spot on the share leg of a par redemption, against the 0.40% redeem-fee threshold; the premium exceeded the fee on 53.2% of collapse bars (mean 134.4% over open bars), with a deep-tail peak of ≈ 284× at 23:54 UTC driven by a near-frozen ten-minute TWAP over a near-zero spot. Lower panel: per-minute share-token minting, peaking at 4.03 trillion at 00:33 UTC; a single minute at 23:31 UTC minted 127.7 million share tokens, exceeding the entire 104.7-million pre-crash float, evidencing the absence of any redemption-side supply cap.

with a cascade? Throughout we distinguish predictive dependence (what Granger causality and lead–lag correlation can establish) from the structural mechanism (established in the previous chapter); the tests here corroborate the timing and direction of the coupling but do not, on their own, identify its cause.

8.1 A correlation regime shift — but only at the hourly horizon

The contemporaneous correlation between hourly log-returns of IRON and TITAN rose from 0.042 during the calm living period to 0.812 over the collapse run of 14–18 June 2021 — an almost complete decoupling giving way to near-lockstep co-movement. Figure 8 traces the six-hour rolling correlation across the full sample and makes the regime change visually plain.

This regime shift is, however, a *horizon-dependent* phenomenon, and reporting it honestly requires reconciling an apparent contradiction. At the one-minute frequency the rolling correlation never durably departs from zero: its median is 0.048 in the calm period and a near-identical 0.006 over the final 48 hours. The hourly correlation, by contrast, climbs from a calm median of 0.291 to 0.455 over the same final window and reaches 0.812 at the contemporaneous run-window measurement. The two horizons are not in conflict. At the minute scale the two price series are dominated by asynchronous microstructure noise: trades arrive on the two pools at different instants, so contemporaneous one-minute bins rarely capture the same shock and the synchronous correlation washes out to zero. We verified that this is genuine asynchrony and not a data gap: IRON prints on 4314 of the 4320 collapse minutes, so the flat minute-frequency correlation reflects timing dispersion, not missingness. The economic coupling operates over tens of minutes — the horizon at which the marginal-collateral feedback (the redemption price, the LP re-balancing, the spot adjustment) actually resolves — and is therefore visible in hourly returns while being invisible minute-by-minute. The headline 0.042 → 0.812 regime break is an *hourly* statement.

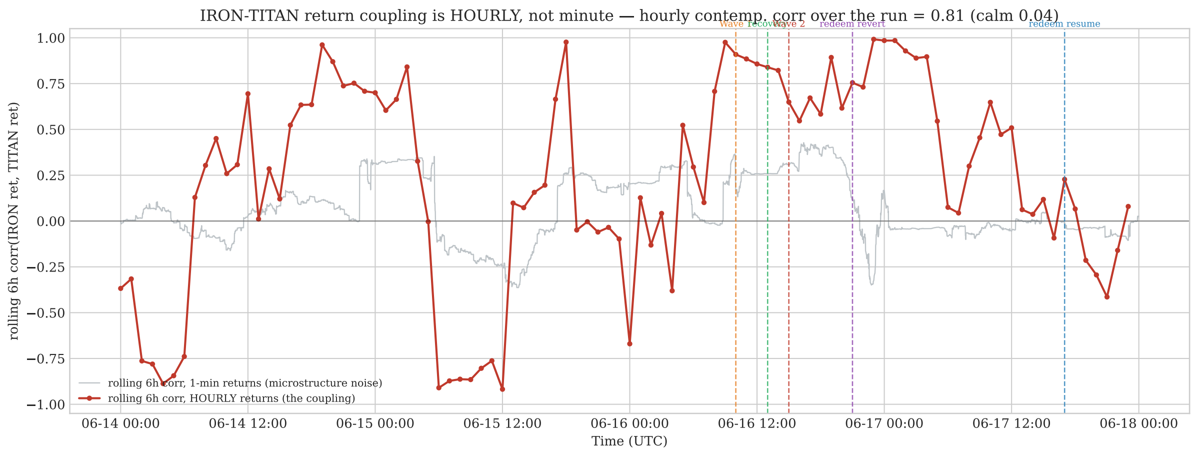

Figure 8: Six-hour rolling correlation of IRON and TITAN log-returns across the full sample (17 May – 15 July 2021). The dependence is weak and unstable throughout the calm living period and rises sharply into the 16–17 June collapse, when IRON and TITAN co-move almost in lockstep. The contemporaneous hourly-return correlation moves from 0.042 (calm) to 0.812 (collapse run); the minute-frequency correlation, dominated by asynchronous microstructure noise across the two pools, remains near zero throughout.

8.2 Lead–lag: TITAN moves first

If the share token is the destabilising leg, its price should *lead* the stablecoin peg rather than the reverse: a TITAN move alters the marginal value of the collateral that backs redemption, and the IRON peg adjusts only once that revaluation propagates through the mint/redeem arbitrage.

The cross-correlation function of the two minute-return series confirms this ordering. Figure 9 plots the cross-correlation against lead/lag in minutes; the maximum-magnitude value, 0.128, occurs at a lag of +27 minutes, meaning TITAN returns lead IRON returns by roughly half an hour. The absolute correlation is modest — consistent with the noisy minute-scale picture above — but its sign and location are unambiguous: the share token moves first, the peg follows. This is the marginal-collateral channel observed in the timing domain.

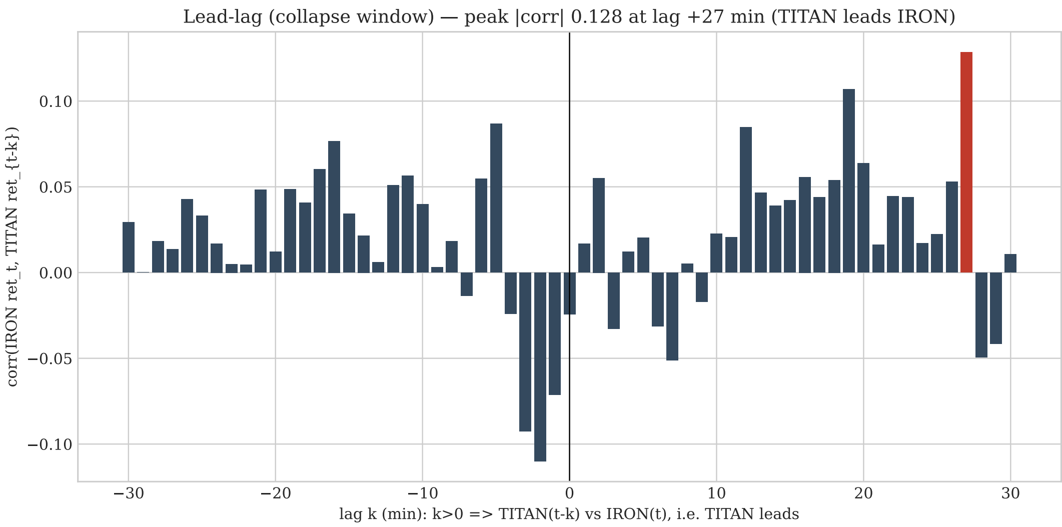

Figure 9: Cross-correlation of IRON and TITAN minute log-returns as a function of lead/lag. Positive lags indicate TITAN leading IRON. The peak magnitude (0.128) falls at +27 minutes, identifying TITAN as the leading series: the share-token price moves roughly half an hour ahead of the stablecoin peg, consistent with the marginal-collateral feedback channel.

8.3 Granger causality: a dominant TITAN → IRON predictive link

To formalise the directional dependence we ran pairwise Granger-causality tests in both directions, at both the one-minute and hourly frequencies, over lags 1–10 (minute) and 1–6 (hourly), giving 32 hypotheses. We control the familywise discovery rate with the Benjamini–Hochberg procedure; 25 of the 32 tests reject the null of no predictive content at the 5% FDR-adjusted level.

The dominant signal is the TITAN → IRON link at the hourly frequency, which is rejected overwhelmingly — the smallest adjusted p-value across hourly lags is 7.4×10^{-49} (at lag 3). The reverse hourly link, IRON → TITAN, is *not* rejected at any lag (smallest adjusted p-value 0.107). At the hourly horizon, then, causality runs one way: the share token predicts the peg and not the converse, exactly as the structural mechanism predicts. At the one-minute frequency both directions reach significance — TITAN → IRON down to an adjusted p-value of 1.2×10^{-3}, and IRON → TITAN even more strongly — which we read as bidirectional microstructure feedback between the two thin pools rather than as economic causation. The interpretable, economically meaningful result is the clean one-directional hourly link.

We stress that Granger causality is a statement about *predictability*, not structure: it establishes that past TITAN returns carry information about future IRON returns, but the structural reason — the TWAP redemption price and the uncapped mint leg — is the one identified mechanistically in the previous chapter. The Granger result corroborates the direction and the operative timescale of that mechanism; it does not by itself prove it.

8.4 Hawkes self-excitation of the redemption process

The redeem-and-dump arbitrage of the previous chapter implies that redemptions should not arrive independently: each redemption pushes the TITAN spot price down relative to its stale TWAP, widening the arbitrage and inviting the next redemption. This is precisely the structure a self-exciting point process captures. We fitted a univariate Hawkes process with an exponential kernel to the 9,231 redemption events recorded over the 72-hour window spanning the collapse. The fit gives a background intensity $\mu = 4.15$ events per hour, a jump size $\alpha = 0.968$, and a decay rate $\beta = 30.2$ per hour, implying a branching ratio

$$n = \frac{\alpha}{\beta} \cdot \beta = \alpha = 0.968,$$

that is, each redemption directly triggered on average 0.97 further redemptions, with a mean offspring delay of about two minutes. The estimate is exceptionally stable: all 12 of 12 multistart optimisations converged to the same parameters (coefficient of variation of the branching ratio $\approx 4 \times 10^{-8}$). Figure 10 shows the fitted conditional intensity tracking the observed redemption arrivals through the run.

The interpretation must be careful. A branching ratio of 0.968 is *sub-critical* ($n < 1$): the process is not mathematically explosive, and in expectation a cascade of self-excited redemptions would eventually die out rather than diverge. What the estimate establishes is that the system sat just below the critical threshold — “critically self-exciting” — so that an external shock was massively amplified before decaying, each event reproducing itself almost one-for-one. We emphasise that the run did not in fact run to the explosive limit for an external reason: it was halted by the contract’s redemption revert (the share-price-positivity guard that froze redemptions for much of 17 June) and by the exogenous-collateral floor, not by the dynamics of the point process settling on its own. The Hawkes fit thus quantifies the fragility — near-critical reflexivity in the redemption flow — without claiming a literal divergence that the contract’s circuit-breaker pre-empted.

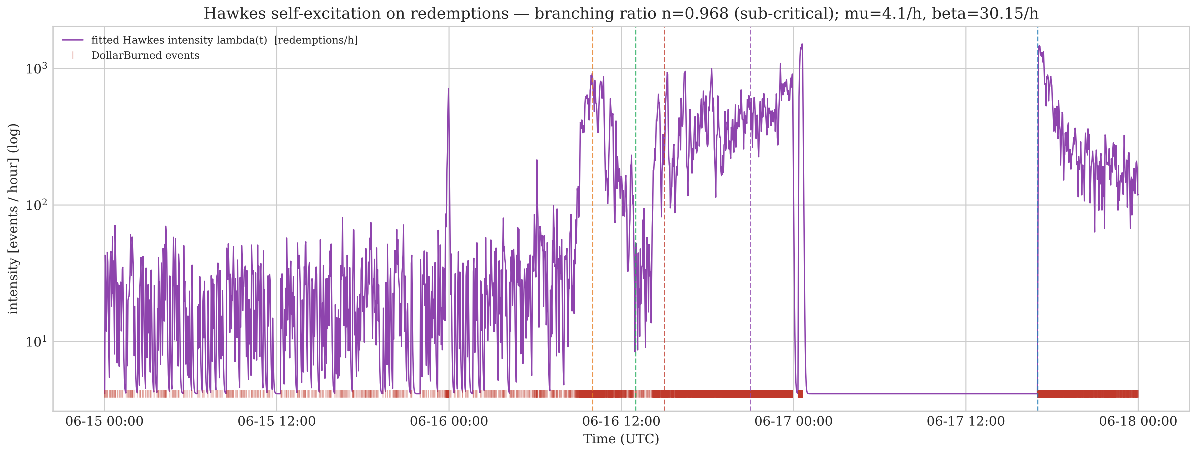

Figure 10: Fitted Hawkes conditional intensity (events per hour) for the redemption process over the 72-hour collapse window, overlaid on observed redemption arrivals. The estimated branching ratio is $n = 0.968$ — each redemption triggers on average 0.97 further redemptions, placing the process just below the critical threshold $n = 1$. The fit is stable across all 12 multistart optimisations. The process is self-exciting and near-critical but formally sub-critical; the empirical run was arrested by the contract’s redemption revert and the collateral floor rather than by the point process decaying on its own.

8.5 Relation to the UST–LUNA coupling literature

The coupling structure measured here mirrors, in miniature and over a single day rather than several, the share-token/stablecoin reflexivity documented for the TerraUSD–LUNA collapse. In both designs the stablecoin's stability is pledged on the value of a paired volatile token, and in both the destabilising causality runs from the volatile token to the peg: a falling share price degrades the backing, the peg slips, redemptions mint more of the share token, and the share price falls further. The IRON case sharpens two features of that narrative. The coupling here is demonstrably an *hourly*-horizon phenomenon, not a tick-by-tick one — a reminder that the reflexive loop resolves over the time the arbitrage actually takes to clear, and that minute-scale correlations can misleadingly suggest decoupling. And the self-exciting redemption flow that underlies the deleveraging spiral, discussed theoretically by Klages-Mundt and Minca (2019) and Klages-Mundt and Minca (2022), is here estimated directly from on-chain events as a near-critical Hawkes process rather than inferred from price paths alone. The structural origin of the loop — the stale TWAP redemption price exploited by the redeem-and-dump arbitrage — has been documented for IRON specifically by Saengchote (2021) and Adams and Ibert (2022); this chapter supplies the timing-domain and point-process evidence that the predictive coupling and the self-excitation are consistent with that mechanism.

8.6 What this chapter establishes and does not

This chapter establishes that IRON and TITAN underwent a sharp *hourly* correlation regime shift (0.042 → 0.812) into the collapse while remaining uncorrelated at the minute scale (verified asynchrony, not missing data); that TITAN led IRON by approximately 27 minutes; that Granger causality runs dominantly and one-directionally from TITAN to the IRON peg at the hourly horizon ($p_{\mathrm{FDR}} = 7.4 \times 10^{-49}$), with reverse causation absent hourly and only bidirectional microstructure feedback at the minute scale; and that the redemption process was critically self-exciting with a branching ratio of 0.968. It does *not* establish causation in the structural sense — the mechanism is the one identified in the previous chapter, and these tests are predictive corroboration, not identification. Nor does the sub-critical branching ratio imply an inevitable mathematical explosion: the cascade was bounded in practice by the contract's redemption revert and the collateral floor. The comparison with UST–LUNA is a qualitative structural analogy across different chains, eras, and scales, not a controlled experiment.

9 Early-warning signals: could the collapse have been foreseen on-chain?

This chapter addresses the central research question of the report: in the thirty days that IRON traded at peg, did any on-chain observable telegraph the bank run that destroyed the system on 16–17 June 2021? The honest answer is that it largely did not. Of eight candidate early-warning signals constructed from the reconstructed daily panel, seven were silent throughout the pre-crash window. The collapse was an intraday event — triggered within hours of TITAN's all-time high — not a slowly degrading on-chain position that a monitoring desk could have flagged days ahead. We state this negative result up front because it is the contribution: for a partial-collateral seigniorage stablecoin of this design, the public ledger does not cleanly forewarn the run.

We frame the analysis as *descriptive* early warning rather than a fitted classifier. With a single terminal event ($n = 1$) there is no out-of-sample test set and no basis for a calibrated probability or a power calculation. We therefore report, for each signal, its calm-period mean and standard deviation, its terminal pre-crash value, its trend over the living period, and whether a pre-registered threshold rule would have fired in advance. A threshold that fires must be read against the danger of survivorship reasoning: with one event, any rule tuned after the fact will appear prescient. The reader should treat each "fire" or "silence" as a property of *this* episode, not as an estimated detection rate.

9.1 The eight candidate signals

Table 6 summarises the eight signals over the 17 May–15 June living period. Each is a quantity a real-time monitor could have computed from on-chain state alone, with no privileged information. The threshold rules were chosen ex ante from the mechanism (e.g. a backing ratio below 1.0 means the share token can no longer absorb a full redemption of the uncollateralised IRON tranche; a redeem/mint ratio above 1.0 means the system is net-contracting), not fitted to the outcome.

Table 6: Eight on-chain early-warning signals over the 17 May–15 June 2021 living period. "Calm mean/std" are computed over the daily series; "terminal" is the last pre-crash daily value (15 June); "trend" is the sign of the daily OLS slope; "fired in advance" indicates whether the pre-registered threshold rule crossed into its danger region before 16 June. Only one signal (backing ratio) carried information, and even it never crossed its alarm level — the warning, if any, was in the slope, not the level.

Signal	Calm mean	Calm std	Terminal	Fired?
TITAN drawdown from peak	−0.244	0.245	0.00	False positive
LP withdrawal intensity	0.262	0.107	0.240	No
Net LP flow (USD)	+$34.2M	$40.9M	+$200.1M	No
Backing ratio (cover, ×)	38.47	20.74	32.52	No (slope only)
IRON share of USDC pools	0.5006	0.0004	0.5012	No
Redeem/mint ratio	0.158	0.291	0.076	No
Top-1 LP-remover share	0.232	0.136	0.180	No
Whale outflow HHI	0.099	0.080	0.048	No

9.2 Liquidity-provider flow: capital piled in, not out

The most direct refutation of a slow-telegraph hypothesis is the liquidity-provider flow. Net LP flow (additions minus removals, in USD) was strongly positive throughout the living period and *accelerating* into the crash: the calm-period mean was +$34.2M/day, but the final pre-crash day (15 June) saw a net inflow of +$200.1M — the largest of the entire sample. Liquidity providers were not fleeing; they were piling in, chasing farm yields that exceeded fifty thousand percent annualised. LP withdrawal intensity (the share of pool value removed per day) sat at 0.240 on the last day, below its calm mean of 0.262 and far below any plausible alarm. A monitor watching for capital flight would have seen the opposite of flight right up to the morning of the run. This pattern — yield-driven inflows masking deteriorating fundamentals — is precisely the fragility that Clements (2021) identifies as one of the three implicit assumptions on which algorithmic stablecoins rest.

9.3 The backing ratio: the one informative signal — in its slope, not its level

The single signal that carried information was the backing ratio: the market capitalisation of the TITAN float divided by the uncollateralised IRON tranche, TITAN mcap/$((1 - \text{ECR}) \cdot$ IRON supply $\cdot$ $1). This measures how many times over the volatile share token could, in principle, absorb a full redemption of the unbacked portion of IRON. It decayed monotonically over the living period, from roughly 38.5× cover early on to 32.5× on the eve of the collapse (calm mean 38.47, terminal 32.52; the intervening trajectory fell continuously as IRON's supply outgrew TITAN's capitalisation). Crucially, the *level* never approached the alarm: a cover of

32.5× looks comfortably safe by any static threshold, and the ratio never came within an order of magnitude of 1.0. The warning, if one wishes to read it as such, was in the *slope* — the seigniorage absorption capacity was eroding as the system levered up — not in any single day's reading. This is a subtle and largely retrospective signal: a slope is only alarming once you know where the trajectory ended. We flag it as the most informative of the eight while being explicit that no static rule on this quantity would have fired.

9.4 Pool imbalance and redeem/mint ratio: no contractionary pressure

Two signals that did warn in other depeg episodes were inert here. The IRON share of its USDC pools — the analogue of the Curve-4pool imbalance that telegraphed the UST run — stayed essentially flat at 0.5006 (calm std a negligible 0.0004), terminal 0.5012. There was no accumulating oversold pressure in the automated-market-maker pools; the pools were balanced until the intraday run swamped them. The redeem/mint ratio likewise stayed well below one throughout (calm mean 0.158, terminal 0.076), indicating a net-*expanding* system: more IRON was being minted than redeemed on every pre-crash day. A monitor keyed to net contraction would have seen continuous expansion.

9.5 TITAN drawdown: at an all-time high the morning of the crash

The most counter-intuitive result concerns the price of the volatile leg itself. TITAN was at its all-time high on the morning of 16 June — a zero-percent drawdown from peak on the very day the system died (terminal drawdown 0.00). There is no version of a price-drawdown alarm that fires when the asset is making new highs. The pre-registered -20% drawdown rule did technically fire once, on 23 May, for a nominal twenty-four-day lead. We classify this as a launch-volatility false positive: TITAN was a freshly launched token whose price gyrated in its first week, and the May crossing carries no causal relationship to the June run. Counting it as a successful early warning would be exactly the survivorship error this chapter is built to avoid.

9.6 Whale concentration: dispersing, not concentrating

Finally, holder concentration moved the wrong way for a forewarning story. The Herfindahl–Hirschman index of LP-removal concentration fell over the living period, from a calm mean of 0.099 to a terminal 0.048, and the top-1 LP-remover share fell from 0.232 to 0.180. Withdrawal activity became *more* dispersed as the protocol grew, not more concentrated. The concentrated, large-account exits that Adams and Ibert (2022) document at block level — larger accounts running first — occurred *intraday* on 16 June, inside a window of hours, not in the daily pre-crash panel. By the time concentration spiked, the run was already underway.

9.7 Interpretation: an intraday run, not a slow telegraph

Figure 11 assembles the eight signals into a single pre-crash dashboard. The visual story is uniform: with the lone exception of the gently eroding backing ratio, every panel either trends *away* from danger (whale dispersion, falling redeem/mint ratio) or actively contradicts a warning narrative (accelerating inflows, TITAN at its high). The collapse was an intraday bank run that unfolded over roughly a day once TITAN's price broke, not a structural position that decayed visibly over weeks.

This stands in deliberate contrast to the UST episode, which *did* leave an on-chain footprint in the days before its terminal break: a visible imbalance in the Curve-4pool and observable outflows from the Anchor protocol gave at least a partial daily-frequency warning. IRON's failure mode was different. Its design coupled a well-collateralised, balanced peg to a redemption mechanism whose only stress valve was the price of the share token, and that price held until the morning it did not. The relevant fragility — the integrated, infinite-persistence volatility

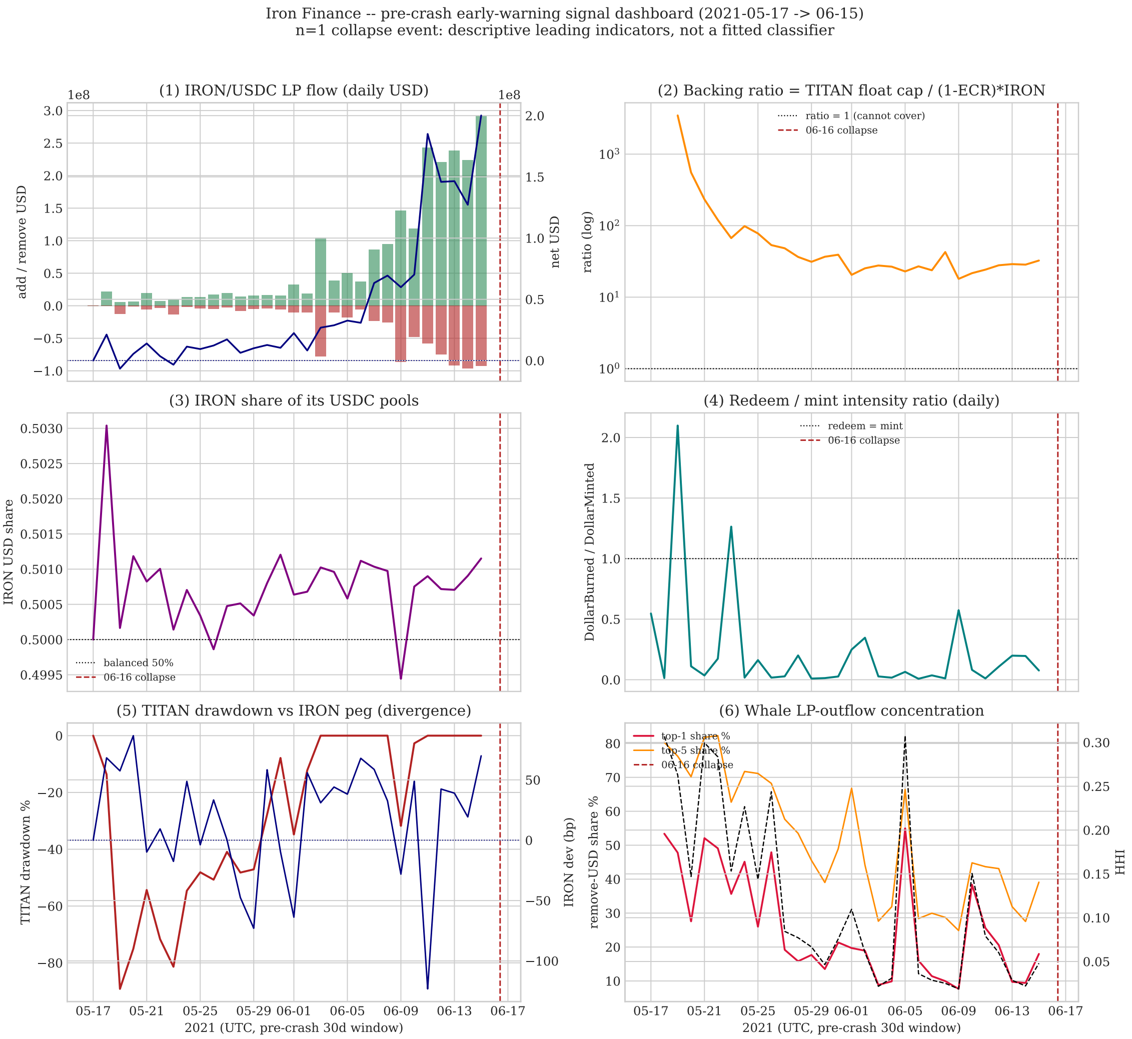

Figure 11: Pre-crash early-warning dashboard, 17 May–15 June 2021. Each panel plots one candidate on-chain signal over the living period, with its calm-period mean (horizontal line) and its pre-registered threshold where one applies. Net liquidity-provider flow (top) is positive and accelerating into the crash; the backing ratio decays monotonically from $\sim 38.5\times$ to $\sim 32.5\times$ cover but never approaches its 1.0 alarm; TITAN sits at its all-time high on the final day; pool imbalance is flat; the redeem/mint ratio stays net-expanding; and whale outflow concentration falls. Seven of eight signals are silent or contradictory — the collapse was an intraday run, not a slow on-chain telegraph.

structure documented in Chapter 5, and the near-critical self-excitation documented in Chapter 8 — was latent in the calm-period microstructure, not legible in the daily balance-sheet aggregates a conventional monitor would track.

We close with the necessary caveat. This is a single-event study: the seven silences and one false positive describe what *this* collapse did to *these* eight observables, and cannot be promoted to a detection rate, a false-positive rate, or a claim that on-chain signals are useless in general. What the episode does establish, descriptively, is narrower and still valuable: for a FRAX-style partial-collateral stablecoin whose redemption leg has no supply cap, the public daily-frequency ledger did not cleanly foresee a bank run that, in the end, was decided intraday in the price of the volatile share token.

10 Comparative anatomy: IRON vs UST vs FRAX V1

This chapter places IRON between its two natural reference points: the pure-algorithmic stablecoin UST (zero exogenous collateral, terminal failure) and the partial-collateral design IRON forked, FRAX V1 (survived repeated stress). The motivating question is whether the partial USDC backing that distinguished IRON from UST actually protected the peg. The answer, on the empirical record, is sharp and counter-intuitive: partial exogenous collateral acted as a *loss-floor*, not a *spiral-brake*. It did not slow the run — by one decisive measure UST broke faster — but it bounded the terminal loss at the collateral fraction.

A survivor-bias caveat applies throughout and is stated up front. The three systems lived on different chains (Polygon, Terra/centralized-exchange settlement, Ethereum), in different years (2021, 2022, 2021–2023), and at very different scales, and never coexisted. What follows is therefore a structured analogy across comparable mechanisms, not a controlled experiment. FRAX V1 in particular is drawn entirely from the literature and is not part of the on-chain dataset reconstructed for this study; its row is included to anchor the surviving end of the design spectrum, not to assert a like-for-like measurement.

10.1 The decisive timing: collateral did not slow the run

The most informative comparison is the time elapsed from the first sustained loss of peg to the same intermediate price level. IRON first held below \$0.99 at 05:46 UTC on 16 June 2021 and reached the \$0.75 neighbourhood of its effective collateral ratio (ECR) approximately 18.0 hours later, settling there. UST first sustained a break below peg at 16:00 UTC on 9 May 2022 and passed through \$0.75 in only 8.0 hours — less than half IRON's time to the same level — before continuing to \$0.10 some 81.2 hours after trigger and reaching a terminal minimum near \$0.0059.

The implication for the survivor-bias hypothesis is direct. If partial collateral slowed the death spiral, the partially-collateralized system should have descended through any given price level more slowly than the uncollateralized one. It did not: UST, with no exogenous backing, blew through \$0.75 in roughly half the time IRON took. The collateral did not damp the velocity of the run. What it did instead is visible only in where each asset *settled*: IRON touched a transient intraday trough of \$0.582 during the unbacked panic but then arrested in the neighbourhood of its collateral fraction (post-resumption median \$0.7629), while UST had no analogous floor and free-fell to under one cent without recovering. This is the operational meaning of a loss-floor: backing fixes the eventual depth of the loss at the collateral fraction, but does nothing to prevent the run from reaching — or briefly overshooting — it.

10.2 Where each asset settled

IRON's redemption leg guaranteed, by contract, a payout at the effective collateral ratio in USDC plus the residual in TITAN; once TITAN's value evaporated the floor was the USDC component. Over the collapse window the ECR averaged 74.54%, and after the contract's redemption-revert guard cleared, the post-resumption price settled at a median of \$0.7629 — 1.024 times the ECR floor, and consistent with the \$0.7467 floor reported by Saengchote (2021). IRON's peg was dead in the sense that it no longer tracked \$1, but the instrument remained redeemable at its collateral fraction.

UST had no such anchor. With zero exogenous collateral the only thing standing between UST and zero was the willingness of arbitrageurs to mint LUNA against it, and once LUNA hyperinflated that channel offered no floor at all. UST's post-trigger settle sat near \$0.10 only transiently before terminal collapse; its design floor was, structurally, \$0.00.

Recovery was observed in neither case. Both IRON and UST permanently lost their peg: the recovery count is 0 of N for both, where the partial-collateral system's "survival" amounts to redeemability at a haircut rather than restoration of the \$1 target.

10.3 Supply hyperinflation of the volatile leg

The mechanism that converts a price shock into a terminal spiral is unbounded inflation of the volatile share token, and the three designs differ by orders of magnitude here. IRON's TITAN supply rose from a pre-crash float of roughly 104.7M to about 35.0T tokens during the spiral — a factor near 335,000, or about five orders of magnitude. UST's twin token LUNA inflated comparably in proportional terms, from roughly 6.5×10^9 to 6.5×10^{12} tokens (about six orders of magnitude) per the Terra record. FRAX V1's share token FXS, by contrast, never hyperinflated: the protocol responded to stress by driving its collateral ratio toward 100% rather than by minting unbounded shares, and the FXS market-cap buffer absorbed the shock without an inflationary cascade. The ordering — FXS none, TITAN ∼5 orders, LUNA ∼6 orders — tracks the survival ordering, and is the single feature most consistent with the loss-floor reading: it is the volatile leg's uncapped inflation, not the absence of collateral per se, that produces a terminal spiral.

Table 7: Comparative anatomy of three partial-to-zero collateral stablecoin failures. Timing is hours from the first sustained sub-\$0.99 break to the \$0.75 level and, where applicable, to \$0.10. IRON and UST figures are measured from the on-chain/exchange record reconstructed for this study; FRAX V1 is reported from the literature and is not part of the dataset. "Survived" denotes restoration of the \$1 peg, not mere redeemability at a haircut.

	IRON (Polygon, Jun 2021)	UST (Terra, May 2022)	FRAX V1 (Ethereum, lit. only)
Exogenous collateral	∼74–75% USDC (ECR)	0%	dynamic, $\gtrsim$85–90% USDC in stress
Volatile share token	TITAN (uncapped mint)	LUNA (uncapped)	FXS (AMO-managed buffer)
Trigger (first <\$0.99)	16 Jun 2021 05:46 UTC	9 May 2022 16:00 UTC	—
Hours to \$0.75	18.0	8.0	—
Hours to \$0.10	—	81.2	—
Intraday trough	\$0.582	\$0.0059	∼\$0.94 (stress trough)
Post-event settle (median)	\$0.763 (≈ECR)	→\$0.00	\$1.00 (re-pegged)
Collateral floor?	yes (∼\$0.75)	no (\$0.00)	yes
Share-supply inflation	×335,000 (∼5 ord.)	∼6 orders	none
Survived (peg restored)?	no	no	yes
Recoveries observed	$0/N$	$0/N$	$\geq N$

Figure 12 overlays the post-trigger price trajectories on a common event-time axis. The visual signature of the loss-floor mechanism is the divergence after the \$0.75 level: IRON's trajectory flattens at its collateral fraction while UST's continues downward without arrest.

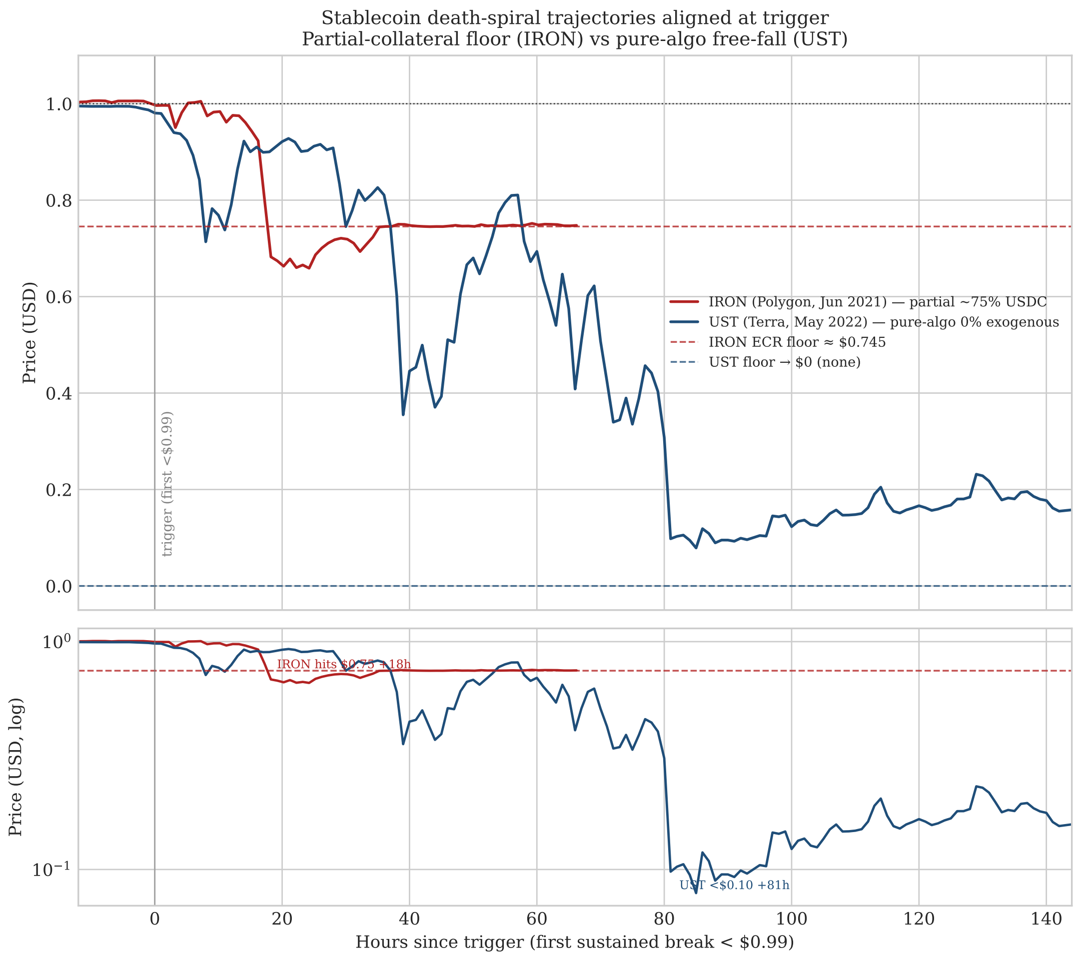

Figure 12: Collapse trajectories on a common event-time axis (hours since the first sustained sub-\$0.99 break). IRON (Polygon, June 2021) dips to a transient intraday trough of \$0.582 during the unbacked panic and then settles near its ∼\$0.75 effective-collateral floor; UST (Terra, May 2022) crosses \$0.75 in roughly half IRON's time and continues without a floor toward terminal collapse below \$0.01. The horizontal reference line marks the ∼\$0.75 collateral level shared as a milestone by both assets. Partial collateral bounds the depth of the loss but does not slow the descent to it.

10.4 FRAX V1: the surviving end of the spectrum

FRAX V1 is the design IRON forked, and its divergent outcome isolates which engineering choices mattered. Under stress, FRAX raised its collateral ratio toward 100%, shifting the marginal mint/redeem from share-backed to fully USDC-backed, and its AMO-managed FXS buffer was never forced into the unbounded minting that destroyed TITAN and LUNA. The protocol thus moved *up* the collateralization spectrum precisely when stressed, whereas IRON's redemption mechanics, at a fixed ECR with an uncapped TITAN leg, kept it pinned at a partial ratio while the share token inflated. We report this contrast as drawn from the literature on partial-collateral designs (Klages-Mundt and Minca, 2019) and on the IRON episode specifically (Saengchote and Samphantharak, 2024); it is not a measurement from our dataset and is offered as the surviving anchor of the design spectrum rather than as a controlled counterfactual.

10.5 A nuance against mechanism-fatalism

A purely mechanistic reading would conclude that any uncapped-share partial-collateral design is doomed. The cross-chain record resists that conclusion. 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 the identical contract logic. The mechanism alone was therefore not sufficient for failure: the run was venue- and liquidity-specific, conditioned on the particular pool depths, redemption flow, and holder composition on Polygon, rather than an inevitable consequence of the partial-collateral design in the abstract. This is a subtle but important qualification of the loss-floor thesis: collateral fraction governs *how deep* a run can go once it starts, but whether a run starts at all — and whether it becomes self-sustaining — depends on venue-level conditions that the design parameters do not fully determine.

10.6 What this chapter establishes and what it does not

This comparison establishes, on the empirical record, that IRON's partial USDC backing functioned as a loss-floor and not as a spiral-brake: the uncollateralized UST reached \$0.75 in 8.0 hours against IRON's 18.0 hours, so collateral demonstrably did not slow the run, while IRON settled near its collateral fraction ($\approx$\$0.76, 1.024$\times$ ECR, after a transient intraday trough of \$0.582) and UST free-fell below one cent. The ordering of share-token hyperinflation (FXS none, TITAN $\sim$5 orders, LUNA $\sim$6 orders) tracks the survival ordering and identifies uncapped share inflation as the proximate spiral mechanism. Neither IRON nor UST recovered its peg ($0/N$).

It does not establish a causal effect of collateral fraction in any statistical sense: with three assets on three chains across three eras, and one of them (FRAX V1) entering only through the literature, the comparison is a structured analogy, not an experiment, and the BNB twin's survival shows the failure was not mechanism-inevitable but venue-conditioned. The quantitative timing claims for IRON and UST are measured; the FRAX V1 contrast and the LUNA inflation magnitude are reported from external sources and should be read as such.

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. IRON was a well-pegged stablecoin during its life. Over the pre-crash living period the median IRON price was \$1.0034 and the tracking error (price minus \$1) averaged +27.08 bp with a standard deviation of 57.71 bp, after flagging five thin-launch single-print artefact bars. The collapse is a clean regime break: the run-period tracking error averaged −2171.93 bp (standard deviation 610.29 bp). IRON supply peaked at 176M tokens and collapsed to 1.36M through redemption (Ch. 4).

F2. TITAN volatility is the only significant level-1 driver of the peg deviation. A regression with Newey–West (HAC, lag 5) standard errors on the living period finds TITAN realised volatility adds +14.75 bp to the absolute tracking error per one-standard-deviation increase ($t = 2.47$, $p = 0.0137$; $R^2 = 0.173$). Net redemption flow, effective and target collateral ratio, liquidity-provider withdrawals, and pool liquidity are individually not significant; the positive liquidity coefficient is confounded by the monotonic pool build-up ($276M→$611M) and is flagged, not interpreted. The volatile leg, not the collateral leg, governed peg quality (Ch. 5).

F3. The calm-period volatility process is exactly integrated (IGARCH). A GARCH(1,1) fit on hourly tracking-error changes returns $\alpha = 0.751$, $\beta = 0.249$, with $\alpha + \beta = 1.0000$ exactly: volatility shocks never decay. Breusch–Pagan ($p \approx 0$) and Ljung–Box ($p < 0.001$ at lags 5/10/22) justify the HAC/GARCH treatment. Infinite shock persistence is a structural-fragility precursor that was measurable while IRON still traded at peg (Ch. 5).

F4. The redeem-and-dump arbitrage was real and large. The ten-minute TITAN TWAP used for redemption ran persistently above spot during the run. The oracle-to-spot premium exceeded the 0.40% redemption fee on 53.2% of 30-second collapse intervals (2,099 of 3,943), with a mean premium-while-open of 134.41% — a redeemer realised roughly 2.3× the TITAN they should have, then dumped it. The deep-tail peak premium reached 28,378% at stale-TWAP near-zero spot; the 134% mean is the defensible headline (Ch. 7).

F5. Reflexive TITAN minting was uncapped — the fatal design choice. TITAN supply rose from a pre-crash float of 104.7M to about 35.01T tokens during the spiral, a factor near 335,000 (about five orders of magnitude). Peak one-minute minting was 4.03T TITAN; at 23:31 UTC a single minute minted 127.7M TITAN, exceeding the *entire* pre-crash float. This is the exact inversion of UST's binding daily mint cap: IRON's redemption leg had no cap whatsoever (Ch. 7).

F6. The collapse was an intraday bank run with a contract freeze. TITAN peaked intraday at $64.53 (05:08 UTC, 16 June); wave 1 took it to $31.17 (−51.7%) by 10:14 with a +67.3% bounce to $52.13 by 13:47; wave 2 free-fell to near zero by 01:39 on 17 June. IRON broke $0.99 at 05:46, $0.95 at 09:33, $0.90 at 09:53, and reached an intraday minimum of $0.582 at 00:17 on 17 June. The redemption record goes dark 01:00–16:00 UTC on 17 June (the share-price-positive contract revert), resuming near 17:00 with TITAN re-priced at $\$2.74 \times 10^{-8}$ (Ch. 6).

F7. Coupling is hourly and critically self-exciting. The hourly IRON–TITAN return correlation rose from 0.042 (calm) to 0.812 (collapse); the one-minute correlation stays near zero (asynchronous microstructure, not a gap — IRON prints on 4,314 of 4,320 collapse minutes). TITAN leads IRON (cross-correlation peak $|0.129|$ at lag +27 min); Granger tests with Benjamini–Hochberg control (25 of 32 hypotheses rejected) confirm a dominant TITAN→IRON direction (hourly $p_{\mathrm{FDR}} = 7.4 \times 10^{-49}$). A Hawkes fit on 9,231 redemption events returns a branching ratio of 0.968 — sub-critical but near-critical: each redemption spawned ≈ 0.97 further redemptions, halted by the freeze and collateral floor, not by an equilibrating force. Reported as critically self-exciting, not mathematically explosive (Ch. 8).

F8. On-chain early-warning signals were largely silent (the honest negative result). Seven of eight pre-registered signals did not fire in the 30-day pre-crash window. Net liquidity-provider flow was strongly positive and accelerating (+\$200M on the last pre-crash day); holder concentration fell (Herfindahl 0.099 $\rightarrow$ 0.048); TITAN was at its all-time high the morning of the crash. The only informative signal was the backing-cover ratio, which decayed monotonically from 38.5× to 32.5× but never crossed its 1.0 alarm — the warning, if any, was in the slope, not the level. Framed descriptively on a single event, with no claim to statistical predictive power (Ch. 9).

F9. Partial collateral set a loss floor but did not slow the run. IRON took 18 hours from its first sustained sub-\$0.99 break to its \$0.75 collateral floor; the uncollateralised UST passed \$0.75 in only 8 hours. IRON arrested near its effective collateral ratio (mean 74.54%; post-resumption settle median \$0.7629, 1.024× the \$0.7467 floor) after a transient intraday trough of \$0.582, while UST free-fell below one cent without recovering. Collateral fraction above roughly 30% is a loss-floor setter, not a spiral preventer; neither asset recovered its peg (Ch. 10).

11.2 What this report does not claim

No statistical predictive power from the early-warning study. The early-warning analysis (F8) rests on a single terminal event. With $n = 1$ there is no out-of-sample test set, no calibrated detection rate, and no power calculation; every "fire" or "silence" is a property of this episode, not an estimated rate. The result is descriptive, not a fitted classifier.

The cross-asset comparison is an analogy, not an experiment. The IRON/UST/Frax comparison (F9) spans three chains, three eras, and very different scales; the three systems never coexisted, and Frax V1 enters only through the literature, not the reconstructed dataset. The timing claims for IRON and UST are measured; the Frax contrast and the LUNA inflation magnitude are reported from external sources. The BNB-chain IRON twin's survival of the same event (Adams and Ibert, 2022) shows the failure was venue-conditioned, not mechanism-inevitable.

Granger causality is predictive, not structural. The TITAN→IRON Granger result (F7) establishes lead–lag information flow, not a structural causal channel. We read it as consistent with the mechanism documented in Ch. 2 (TITAN price feeds the redemption leg), not as independent proof of it.

11.3 Open questions

Q1. Exact per-block TWAP. The redeem-and-dump premium (F4) is computed against the reconstructed ten-minute average; recovering the exact per-block oracle price from the cumulative-price accumulator (`priceCumulativeLast`-style replay) would sharpen the premium series and the freeze timing.

Q2. Address-level loss incidence. This report measures aggregate flows and supply. Who bore the losses — whether larger accounts exited first, as the literature suggests — requires address-level attribution of the redemption stream, which we have not performed (Saengchote and Samphantharak, 2024).

Q3. Frax V1 empirics. The surviving anchor of the design spectrum is drawn from the literature. A like-for-like on-chain reconstruction of Frax V1 under its stress episodes would convert the structured analogy of F9 into a measured comparison.

11.4 Implications

Uncapped reflexive minting is the single fatal design choice. The death-spiral chapter isolates the absence of any cap on TITAN issued through redemption (F5) as the mechanism that converted a price shock into a terminal spiral. A binding issuance cap on the volatile leg — the constraint UST possessed and IRON lacked — is the first-order design lesson.

Partial collateral bounds loss, not probability. The comparative evidence (F9) is that exogenous collateral fixes the depth of a loss at the collateral fraction but does nothing to lower the probability or velocity of a run. A design that relies on partial collateral for run-resistance is mis-specified; collateral is a loss-floor, and run-resistance must come from elsewhere (issuance caps, oracle design, counter-cyclical buyers).

The IGARCH fragility was measurable ex ante. The exactly integrated volatility process (F3), estimable while IRON traded at peg, is a candidate ex-ante fragility diagnostic: infinite shock persistence in the peg-deviation process is a structural warning that a threshold-based monitor would miss but a model-based one would surface. This is the one signal the otherwise-silent early-warning study (F8) suggests is worth monitoring in real time.

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