# t1 Litepaper

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## Abstract

t1 is the first interop rollup designed to fix fragmentation and composability challenges in scaling Ethereum. By leveraging AVS-secured Trusted Execution Environments (TEE), t1 introduces real-time proofs (RTP) that prove the integrity of t1 execution to Ethereum in less time than it takes to create a block on Ethereum (less than 12 seconds). By running partner rollup nodes in its node infrastructure, t1 aggregates and proves its state to Ethereum in real-time. As a result, t1 enables instant settlement between any combination of partner rollups and Ethereum, providing composability. All execution in t1 is cryptographically verified via zk-compressed Remote Attestation coming from Intel TDX Trusted Execution Environment (TEE), ensuring that state transitions are provably correct, tamper-proof, and bound to the current protocol version. In addition to real-time proving, t1 supports general-purpose smart contract programmability and enables writes to partner rollups, in addition to reading their state. This architecture offers a foundation for building new and enhancing existing cross-chain applications—such as yield aggregators, lending protocols, and decentralized exchanges—that require fast, programmable interoperability without reliance on third-party bridges or message-passing systems. Our mission is to unify Ethereum and its rollup ecosystem by creating a real-time proof-powered liquidity layer that enables the best user experience on cross-chain applications.

# 1. Problem

The current rollup-centric scaling strategy has delivered lower fees and higher throughput, at the cost of fragmentation. Liquidity and user activity are now spread across hundreds of rollups, forcing developers to bring their applications multichain, leveraging third-party bridges and messaging protocols. Despite widespread efforts to improve interoperability, the current landscape remains siloed:

- **Most L2 interoperability efforts focus on specific rollup stacks** rather than the entire ecosystem. These efforts reduce the number of siloes yet solidify existing siloes rather than eliminating them.
- **Interoperability protocols enable message passing and proof generation, but forego the benefits of programmability.** As a result, each chain remains a siloed execution environment. Users must take separate actions on each chain, adding friction, cost, and fragmentation.

- **Real-time Zero Knowledge Proving** is far from reality, both because of proving times, but also the complexity and bug potential of zkVMs. We expect real-time ZKP to be at least 2 years out.

As a result, no existing application can offer a seamless, cross-chain user experience today without the complexities of introducing third-party bridges or messaging protocols. Without a fundamental shift in how interoperability is achieved, Ethereum risks scaling into a fragmented network where composability remains trapped within silos.

# 2. Solution

t1 introduces a Trusted Execution Environment (TEE) enabled real-time proving (RTP) rollup to solve fragmentation in the Ethereum ecosystem today.

***Real Time Proving***

Real-time proving allows `t1` to prove its state to Ethereum every block. This means;

- Users can enjoy the low cost and high speed of rollups while their assets ***effectively*** remain on Ethereum. Funds on `t1` can be withdrawn to an L1 wallet in the same block, making interacting with `t1` feel similar to interacting with a smart contract on L1.
- Applications on Ethereum or rollups can access `t1` state (liquidity) because both are proven to Ethereum every block
- Applications on `t1` can verify state changes in Ethereum and partner rollups and create cross-chain proofs. This is achieved by running multiple partner rollup full-nodes in the `t1` node infrastructure.

***Programmability***

Programmability enables `t1` to do more than just Real-Time Proving. Smart contracts create a programmable hub for liquidity and cross-chain interactions. Programmability enables currently off-chain components, such as relayer/solver networks for ERC-7683 protocols, to be brought on-chain. Programmability also enables `t1` to become a cross-chain liquidity hub in addition to just being a bridge or a proving system that just passes proofs across blockchains. This means we can build cross-chain collateral accounts, lending/borrowing primitives, and orderbooks on `t1`, while other proving systems can only pass messages.

Furthermore, `t1`'s architecture is designed to create cross-chain application experiences without needing buy-in from any rollup or application. In that sense, `t1` is the only truly permissionless cross-chain application interface.

# 3. What are TEEs and how do they help?

Trusted Execution Environments (TEEs) are specialized hardware-based environments that isolate sensitive computations and data from the rest of the system, ensuring that data is processed correctly and

privately. In particular, TEEs provide verifiable computation guarantees through a process called "Remote Attestation," which proves to external parties that the TEE is running a specific, unmodified piece of software (bytecode) without any tampering. Verifiers can then use this attestation to confirm that a TEE's output is trustworthy. Additionally, TEEs can preserve privacy by keeping sensitive data and execution logic concealed from the system operator and external observers. In other words, TEEs are secure hardware areas that protect sensitive data and computations from tampering or unauthorized access.

Two key requirements for achieving full unification of Ethereum and the rollup ecosystem, without reorg risks and asynchrony, are shared sequencing across all chains and real-time proving (RTP). At `t1`, we are working on RTP by employing TEEs. However, TEEs also help with cross-chain composability by enabling follower nodes in `t1` to reliably read data from and write data to partner rollups. This setup allows `t1` to aggregate the state of Ethereum and partner rollups effectively. Our design, which does not rely on shared sequencing, enables `t1` to have as low as a single-block asynchrony window (12 seconds) with Ethereum—a substantial improvement over the current seven-day window in Optimistic Rollups and hours-long window in Zero-Knowledge Rollups.

In addition to RTP and cross-chain communication, TEEs allow `t1` to offer an encrypted mempool. An encrypted mempool prevents adversarial reordering, such as sandwich attacks, where an attacker observes a pending user transaction and places trades before (front-running) and after (back-running) it, profiting at the expense of regular users. Sandwich attacks cost Ethereum users over $100mn every year. An encrypted mempool or ephemerally private blockspace also facilitates use cases like sealed-bid auctions and information incomplete games.

# 4. Architecture

## 4.1. Protocol design

`t1` is an EVM-based rollup that generates real-time proofs to provide cross-chain application infrastructure. `t1` combines the verifiable computation guarantees of Trusted Execution Environments (TEE) with additional defense layers such as economic security (AVS) and bespoke zero-knowledge proofs (ZKP) to enable fast and secure proof generation. `t1` has two network stakeholders:

- *Sequencers* are a highly decentralized set of nodes tasked with blindly finalizing the ordering of encrypted transactions in a `t1` bundle before it becomes a block. Since *Sequencers* only order transactions rather than execute them, we can achieve high decentralization and censorship resistance. *Sequencers* create *Sequencing Consensus*
- *Executors* are TEE-enabled nodes tasked with executing state changes given the finalized sequences of transactions determined by the *Sequencers* (i.e., turning bundles into blocks and a new state). *Executors* provide proof of *Execution Consensus*.

`t1` produces blocks every second. Each block involves two sequential steps:

- Tx data broadcast and bundle finalization by *Sequencers* (*Sequencing Consensus* proof)

- Execution into a block and agreement about the new state, reached by TEE-enabled *Executors* (*Execution Consensus* proof).

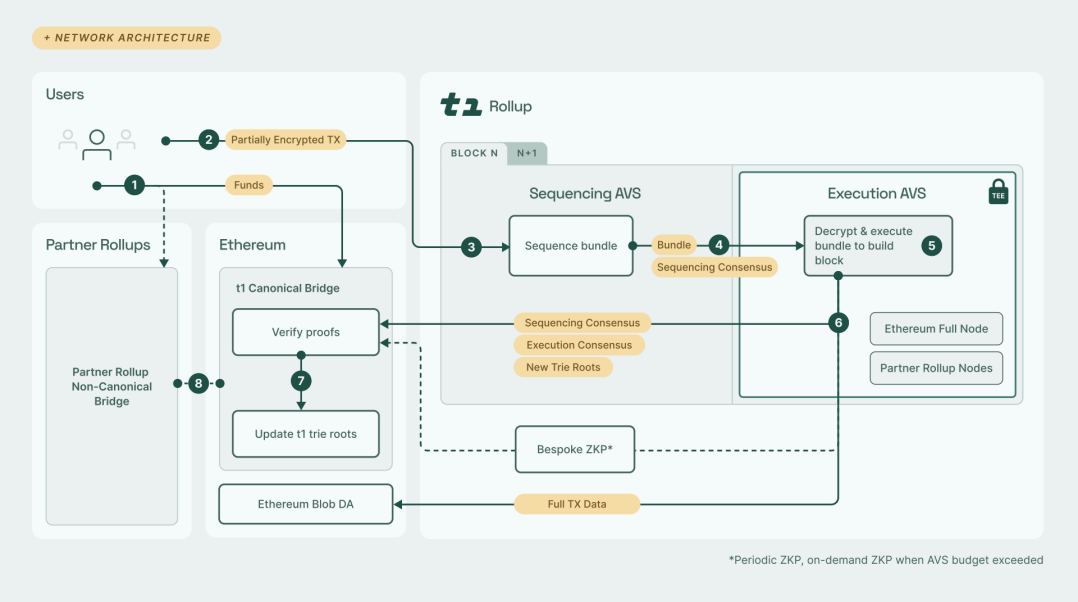
Both *Sequencing Consensus* and *Execution Consensus* are required to update the state of `t1` (aka trie root tuple) on Ethereum, only then enabling "convincing" `t1` bridge contracts on Ethereum and partner rollups to, e.g., release their funds to withdrawing users.

As `t1` gradually becomes a fully permissionless network, it's essential to implement mitigations against potential TEE exploits and develop defense-in-depth strategies. To this end, `t1` leverages two sets of EigenLayer Autonomous Verifiable Services (AVS) validators to derive its crypto-economic security from restaked assets, providing a programmatic insurance budget on top of TEE guarantees.

However, an attacker controlling more than the crypto-economic security of the Execution AVS stake and also the necessary TEEs (that they managed to compromise) could produce an integrity proof for a fraudulent new state of `t1`. For this attack to be economically viable, the value-at-risk would need to be higher than the slashable Execution AVS stake. To ensure that `t1`'s economic activity is not bound by this security budget, we introduce a *bespoke ZKP* mechanism as an additional defense layer: `t1` uses incentivized *periodic ZKP* to create *checkpoints*. When cumulative value-at-risk since the last *checkpoint* is about to exceed the crypto-economic security budget, the *Canonical Bridge* will require the provision of an *on-demand ZKP* before it accepts such a new `t1` state—halting finalization until then. However, with adequate `t1` gas price policies incentivizing proactive *checkpoint* creation, we don't expect this situation to ever happen under normal conditions, achieving a good tradeoff between finalization latency and hard-times resilience.

Note: ZKP generation will likely be outsourced to another network that can meet the latency and cost requirements.

## Figure 1: Architecture diagram



## 4.2. Flow

1. A user, Alice, deposits funds to a `t1` bridge contract on Ethereum or on a *Partner Rollup*. Once the deposit is confirmed on the source chain, it gets processed by `t1`, and Alice gets her funds credited towards her aggregate `t1` balance.
2. Alice changes her wallet's network to `t1`, creates a `t1`-native transaction (with some fields encrypted to the shared rotating TEE pubkey), uses her wallet to sign it, and submits it to the network (i.e. the `t1` mempool); this may or may not be a specially-treated withdrawal transaction (to Ethereum or a *Partner Rollup*).
3. A `t1` *Sequencer* receives and gossips such a partially-blind transaction to other *Sequencers* in the `t1` *Sequencing AVS* network.
4. After collecting transactions for one `t1` slot (currently set to one second), the slot-leading *Sequencer* proposes an ordering (a blind non-executed bundle). The rest of the *Sequencers* vote on it using Espresso HotShot to form a Sequencing *Consensus*. This bundle and a proof of *Sequencing Consensus* is then passed on to the *Execution AVS*network.
5. `t1` *Executors* validate the proof of *Sequencing Consensus*, decrypt the encrypted parts of the received bundle (if needed and due) using their TEE-derived shared rotating private key, and execute its now fully plaintext ordered transactions against the current state of the `t1` blockchain. The slot-leading *Executor* proposes a new trie root tuple *r* of state trie root, withdrawals trie root, and proof-of-read trie root—and the rest of the *Executors* vote on such new trie tuple *r* to form *Execution Consensus*.
    - Note: *Executors* use follower nodes also running in TEEs to read from and write to *Partner Rollups*(whenever required by a `t1` tx).
6. The *Execution* AVS posts `t1`'s new trie roots *r* and all the corresponding consensus proofs to the Ethereum `t1` *Canonical Bridge* contract and the full compressed transactions to Ethereum blob DA.
    - In addition, `t1` progressively incentivizes the generation and posting of *periodic ZKPs* to the *Canonical Bridge* on Ethereum to create *ZKP checkpoints,* resetting the value-at-risk counters and also speeding up the potential *on-demand ZKP* creation when required. `t1` dynamic gas pricing considers how much AVS security budget is still available to reach an equilibrium.
    - In the rare event that new `t1` transactions' (as per all new trie root tuples) cumulative value since the last *ZKP checkpoint,* despite the mechanisms above, would exceed the crypto-economic security budget provided by *Execution AVS*, also an *on-demand ZKP* is required by the *Canonical Bridge*, pausing finalization until then; this would increase the withdrawal delay to hours under such extreme conditions.
7. `t1`'s *Canonical Bridge* contract on Ethereum checks the new submitted `t1` trie root tuple *r*, *Sequencing Consensus,Execution Consensus,* and transaction data availability for consistency. If successful, such *r* is accepted. This then generally facilitates withdrawals from `t1` to Ethereum with a single-Ethereum-block delay only (i.e. 6 seconds on average).
    - Suppose Alice had desired to withdraw funds in step 2. She may now submit to the *Canonical Bridge* an Ethereum claim transaction with an inclusion proof of her withdrawal transaction in `t1` (as contained within the withdrawal trie committed to in *r*). The contract then releases the funds to Alice on Ethereum.

8. If Alice wishes to withdraw funds to her account on a *Partner Rollup* rather than on Ethereum, the same trie root tuple *r* update in the *Canonical Bridge* (i.e., on Ethereum) is required as in 7. However, she submits the claim transaction with an inclusion proof of the withdrawal to the (non-canonical) `t1` bridge contract on *Partner Rollup*instead. The *Partner Rollup* bridge contract verifies the inclusion proof with respect to *r* as accepted by the *Canonical Bridge* on Ethereum (using *Partner Rollup*'s Ethereum read abilities, usually via *Partner Rollup*'s own L1 canonical bridge) and then releases the funds to Alice on *Partner Rollup*.

## 4.3. Bridge Contracts

`t1` leverages its contracts on Ethereum and rollups to accept deposits into `t1` and allow users to withdraw funds from `t1` back to their blockchain of choice.

Ethereum's contract acts as the *Canonical Bridge* where `t1` trie root updates are posted. Their validity is ensured by verifying *Sequencing Consensus, Execution Consensus,* and the data availability commitment to a blob posted on Ethereum (DA). Therefore, **this contract is the source of truth for `t1` state.**

Withdrawals to Ethereum can be enabled immediately after a transaction updates this contract, by a further "claim" transaction carrying a Merkle proof, on L1 or *Partner Rollup* itself. Withdrawals on *Partner Rollups* require the local `t1` bridge contract to check the state of the *Canonical Bridge* on Ethereum before the funds can be released to the user on *Partner Rollup*. The state of the `t1` Canonical Bridge can be relayed to the Partner Rollup via the arbitrary message passing capability of the Partner Rollup's own Canonical Bridge. This approach prevents attacks that could otherwise result in double-spend due to reorgs.

## 4.4. Sequencers

In `t1`, Sequencers sequence and broadcast partially-encrypted transactions, forming a consensus on a blind block order ("bundles"), which is then passed to Executors for execution. Most of the rollups nowadays utilize single-sequencer designs, compromising security for speed; also, usually both sequencing and execution are performed by a single entity, leading to little censorship resistance. We want to separate sequencing (broadly accessible) and execution (higher hardware requirements, esp. a TEE) to allow for fast, decentralized consensus, offering strong resistance to censorship and bribery, while minimizing MEV from transaction ordering.

`t1`'s long-term design employs Espresso Systems' HotShot Consensus, a BFT protocol adapted for PoS, enhancing decentralization. Sequencers, part of `t1`'s AVS, use restaked stake with slashing conditions to maintain security and integrity in transaction sequencing.

## 4.5. Executors

TEE-enabled Executors oversee the current state of `t1` by running transactions from Sequencer-ordered blind bundles and establishing consensus on the new state. They utilize t1VM, a TEE-optimized and

interop-enriched version of Reth, which ensures full backwards compatibility with Ethereum while adding cross-chain-composability-specific capabilities such as reading a chain's contract method or requesting a write call to it. An Ethereum full node is maintained within the Executor for streamlined interaction with the canonical bridge, while follower nodes (clients) for other rollups run by the Executor allow for real-time state monitoring and interactions with them, without the delays usually required for fraud or zero-knowledge proofs. t1VM includes unique capabilities powered by Reth's ExEx, enabling Executors to interact with both Ethereum and other (partner) rollups from within `t1`'s Solidity smart contracts.

Executors operate under a leader-based, instant-finality PoS Byzantine Fault Tolerant consensus system, representing the second category of `t1`'s AVS, and they are liable to slashing to enforce system integrity.

All execution happens inside Intel TDX-based TEEs, which cryptographically isolate the runtime logic and protect it from tampering, even by the host OS. Before processing transactions or joining Execution Consensus, each Executor must successfully complete a hardware-backed Remote Attestation, as detailed in the Remote Attestation Design and Enforcement.

## 4.6. Special Opcodes for Cross-Chain Composability

The *t1VM*, based on Reth and optimized to run within Intel TDX enclaves, introduces several custom precompiles and execution extensions (ExEx) to support seamless cross-chain programmability. These opcodes are enclave-executed thanks to co-located Partner Rollup follower nodes.

These special instructions allow `t1` smart contracts to:

- **xchain.readState(uint64 chain, bytes calldata data)**
  Query the state of a remote Ethereum or Partner Rollup contract in near-time, using enclave-hosted follower nodes. Reads are cached and committed via proof-of-read trees in block headers.
- **xchain.sendTx(uint64 chain, bytes calldata data)**
  Submit transactions to Ethereum or Partner Rollup mempools from inside a `t1` VM contract, enabling best-effort multi-chain coordination.
  While the transaction submission is initiated synchronously from within `t1` VM, its inclusion and execution on the target chain are asynchronous processes. Smart contracts must be designed to handle potential failure, delayed inclusion, or rollback by relying on callback patterns, event monitoring, and appropriate timeout handling.
- **xchain.sendTxAs(address user, uint64 chain, bytes calldata data)**
  Relay transactions to other chains *on behalf of a user*, enabling use cases like delegated execution, paymasters, or cross-chain proxy control.
- **xfeed.queryPrice(string feedId, uint64 timestamp)**
  Access a signed price feed snapshot (e.g., from a partner CEX or L1 oracle) as of a specific timestamp, as observed by the enclave. This enforces deterministic read behavior, allowing values to be committed into the proof-of-read trie and enabling reproducibility across replays. Suitable for use in collateral valuation, liquidation triggers, or TWAP rebalancing.

All read-based opcodes, such as xchain.readState and xfeed.queryPrice, are executed inside the TEE, and their outcomes are committed into a proof-of-read trie, which is included in the block header and committed to Ethereum. Remote reads are deterministically committed to Ethereum L1 via a proof-of-read trie, ensuring verifiability and auditability of all external dependencies in `t1` state transitions.

In contrast, transaction submission opcodes, such as xchain.sendTx and xchain.sendTxAs, initiate asynchronous best-effort actions toward external chains. These are not committed to the proof-of-read trie. Instead, applications using these opcodes must be designed to handle external success or failure events explicitly, through callback patterns, confirmation monitoring, or timeout strategies.

## 4.7. Further rollup node subnetworks

Additional subnetworks may appear in the broader `t1` ecosystem where some TEE-enabled *Executor*-style nodes, probably running as an AVS, provide light-client-like "oracle" services to e.g. `t1` *Executors* who wish to act upon the latest (low-latency) state in some other (possibly arcane/insecure) rollup/L2. These could come with an insurance fund or marketplace for reorgs and other rollbacks, e.g., caused by a technical issue, security council breach, etc.

Such a subnetwork may or may not be operated by the same physical node operator and on the same hardware as a `t1` *Executor*. `t1` is being built in a modular way such as to facilitate tangential applications of this sort via a robust shared infrastructure layer. It is conceivable that different smaller subnetworks may emerge to account for the different, possibly fine-granular security, latency, liveness, etc., requirements per Partner Rollup.

## 4.8. Mempool encryption

`t1` has an encrypted mempool that is designed to eliminate ordering-related MEV. The system uses a rotating private key shared among `t1` *Executors* that remains sealed within the TEE. As a result, transactions partially encrypted to the corresponding shared public key, which *Sequencers* order into partially encrypted bundles, can only be decrypted inside *Executors*, for execution, allowing the creation of the block with its new state. Once transactions are executed, their full plaintext content is made public, and anyone is able to reproduce the computed state.

## 4.9. Remote Attestation Design and Enforcement

`t1` leverages Intel TDX-based Trusted Execution Environments (TEEs) to ensure that state transitions are executed within secure, hardware-isolated environments. However, enclave security alone is insufficient without a mechanism to prove—publicly and succinctly—that these nodes are indeed running unmodified, audited software.

To that end, `t1` runs the full DCAP quote-verification logic *inside* a Risc0 zkVM and compresses the trace into a Groth16 proof ≈ 200 bytes. A single proof is emitted only when a validator (i) first joins, (ii)

upgrades to a new image hash, or (iii) refreshes its TCB after Intel raises the minimum SVN. **NodeRegistry** verifies that proof once, stores the validator's pubkey + measurement as *active*, and thereafter needs only an ordinary ECDSA signature on each block.

## Binding attestation to protocol state and mempool key

`t1` leverages Intel TDX-based Trusted Execution Environments (TEEs) to ensure that state transitions are executed within secure, hardware-isolated environments. These enclaves expose hardware-backed remote attestation capabilities that allow the network to verify—cryptographically and succinctly—that every node runs a known, trusted configuration.

Each attestation report includes multiple fields:

- **report_data** — A 64-byte custom field set by the enclave at launch, it commits to
  - **validatorPubKey** – the enclave's long-lived signing key;
  - **currentProtoVersion** – governance-set tag bumped on every allowed-measurement change;
  - **HashPubHPKE** – the hash of the epoch mempool-encryption public key;
  - **nonce** – 256-bit challenge issued by **NodeRegistry** to prevent replay.
- **RTMR3** — A cryptographic measurement (SHA-384) of the enclave's runtime configuration, such as the Docker Compose manifest, root filesystem hash, and other application-specific initialization data.
- **imageId** — A unique identifier for the expected software binary or container image (e.g., a hash of the enclave codebase).

The zkVM verifies that the Quote's signature chain is intact, the **TCB SVN** ≥ **minTCB, REPORT_DATA** matches the supplied nonce and protocol parameters, and that the TD measurement appears in the on-chain allow-list Merkle root. The proof's public outputs (**validatorPubKey, measurementHash, HashPubHPKE**) are recorded in **NodeRegistry**; any later block signed by a key absent from this *active set* is rejected.

## zkVM Proof Compression

Once the TD Quote is generated by the Executor enclave, it is passed into a dedicated **zero-knowledge virtual machine (zkVM)**, such as **RISC Zero**, which serves as an off-chain attestation verifier. The zkVM performs a full cryptographic validation of the TDX quote, including all relevant fields, and outputs a succinct proof that can be efficiently verified on-chain.

The zkVM verifier performs the following steps:

1. **Quote Parsing**
   It deserializes the TD Quote structure and extracts key fields, including:
   - **report_data** – the verifier-defined 64-byte binding value,
   - **RTMR3** – the measured runtime hash,
   - **imageId** – the identity of the runtime image,

- TDX report metadata and signature.

2. **Signature and Certificate Validation**
   It validates the **Intel DCAP certificate chain**, confirming the quote was generated by a genuine Intel TDX-capable CPU using a valid Provisioning Certification Key (PCK) signed by Intel. This ensures the enclave is rooted in hardware trust.
3. **Attestation Field Checking**
   The zkVM enforces that:
   - **report_data** matches the expected constants
   - **RTMR3** equals the known good runtime measurement corresponding to the declared **imageId**,
   - The claimed **imageId** is part of the protocol's published set of approved executor images.
4. **Public Output Commitment**
   After verifying the quote and all integrity constraints, the zkVM outputs the attested values—**imageId, RTMR3, report_data**, and an *attestation passed* flag—as public data in the proof's journal. These values are included as public inputs to the zkSNARK, allowing any on-chain verifier contract to enforce attestation rules based on them.
5. **Proof Generation**
   The zkVM emits a succinct zero-knowledge proof (e.g., a STARK or SNARK) that confirms:
   *"A valid TDX quote signed by Intel proves the enclave with* **imageId** *ran a trusted runtime matching* **RTMR3***, and correctly reported* **report_data** *= X."*
   This proof is submitted alongside:
   - Node registration requests, i.e., in *NodeRegistry*,
   - Claims of protocol version compliance, e.g, in smart contract upgrades.

On-chain verifier contracts, such as the *Canonical Bridge* or *Node Registry,* do not inspect the raw quote but instead validate the zkSNARK. These contracts check that:

- The zk-proof is cryptographically valid and corresponds to the expected zkVM circuit
- The attested **report_data** matches the expected constants
- The **RTMR3** is one of the currently whitelisted runtime hashes for the declared **imageId**
- The **imageId** is recognized and not revoked
- The node is not already slashed or removed from the active set

By relying on zk-compressed attestation, `t1` achieves a **trust-minimized, gas-efficient enforcement** of enclave integrity, with all sensitive quote validation logic occurring off-chain in a reproducible zkVM program.

## Enclave-Keyed Access and Upgrade Safety

To decrypt and process encrypted user transactions, Execution AVS nodes require access to a shared mempool decryption key. This key is **sealed to the enclave** and is **only provisioned to nodes** that have passed **remote attestation**, verified via zk-compressed TD Quotes.

The attestation proof must confirm that the enclave:

- Runs a permitted executor **imageId**,
- Measures the expected runtime configuration (**RTMR3**),
- Reports a fresh **nonce** bound into **report_data**,
- Declares **validatorPubKey** and **HashPubHPKE** that match the on-chain epoch constants,
- Reveals a CPU/TDX **SVN** not lower than **minTCB**,
- Embeds the current protocol tag **currentProtoVersion** in **report_data**.

Only then can the node receive the decryption key from existing peers in the network. Key transfer is performed through an in-enclave, mutually-attested ECDH handshake:

- Both TDs verify that the counterparty's Quote hash and **validatorPubKey** are marked as *active* in **NodeRegistry**.
- They derive a session key from ECDH entirely inside their respective enclaves.
- The live node re-wraps the sealed **root_secret** under that session key and transmits it; the newcomer unseals it and deterministically derives its HPKE keys.
  *Unverified or inactive nodes cannot complete this handshake and therefore never obtain the decryption key.*

Whenever the protocol is upgraded—such as a new Canonical Bridge version, runtime logic revision, or dependency patch—`t1` Security Council simultaneously (i) bumps **currentProtoVersion**, (ii) publishes an updated Merkle root of **allowedMeasurements**, (iii) may raise **minTCB**, and (iv) schedules an epoch-wide HPKE key rotation by emitting **HashPubHPKE′**. These values define the next valid executor configuration.

Execution AVS validators enforce this policy by accepting only nodes that submit zk-compressed attestation proofs verifying these exact values. Executors must re-attest using the new configuration in order to regain access to the sealed mempool key and resume consensus participation. Until they do, the attested-ECDH channel refuses to deliver **root_secret**, instantly disabling their ability to decrypt new transactions or sign blocks. This mechanism ensures that outdated or forked nodes are cryptographically excluded from transaction execution and state transition, providing strong upgrade enforcement at both the enclave and consensus levels.

By binding sealed key access to a multi-factor enclave attestation—checked off-chain in a zkVM and enforced on-chain by verifier contracts—`t1` achieves robust upgrade safety and execution integrity without relying on manual trust or off-chain coordination.

A complete formal specification of the attestation pipeline can be found in the companion document **[Draft] TEE Architecture and Remote Attestation in `t1`**.

## 4.10. Data availability

In addition to the new trie roots and *Sequencing Consensus* and *Execution Consensus* proofs going to L1, the full (yet compressed) transactions (inputs to the state transition function) are posted on Ethereum as blobs by the *Executors,* and their availability is checked by the *Canonical Bridge* when validating a new proposed trie root tuple. This enables anyone to recreate the state of `t1` (but for what happened since the last Ethereum block, so on average for a maximum of 12 seconds) from trusting Ethereum and Ethereum alone. This also supports forced transaction inclusion.

## 4.11. Forced tx inclusion (incl. exit)

If the `t1` rollup is down, any user can submit their "self-sequenced" `t1` transactions (that may include, e.g., liquidating a position and then withdrawing to Ethereum) to the *Canonical Bridge* contract on Ethereum.

# 5. Infrastructure partners

## Automata DCAP

Automata provides an open-source implementation of Intel's DCAP remote attestation framework, enabling trusted enclave verification without relying on Intel's centralized services. `t1` leverages Automata's DCAP tools inside Executor nodes to generate and validate TD Quotes, forming the basis for zk-compressed Remote Attestation proofs. This ensures that only nodes running verified enclave software participate in Execution Consensus, anchoring hardware trust into Ethereum via zk verification. Automata's work allows `t1` to decentralize TEE validation, maintaining security even as the network grows permissionless.

## EigenLayer AVS

EigenLayer's Autonomous Verifiable Services (AVS) system allows new protocols to inherit Ethereum's economic security through re-staking. Stakers from Ethereum can re-stake their assets, like ETH, into an AVS, which secures another service, beyond Ethereum, like *Sequencer* and *Execution Consensus* for `t1`. This model gives new chains like `t1` the ability to bootstrap security without building independent validator sets (leading to inefficiently locked-up capital). EigenLayer includes strict slashing mechanisms to align validator incentives across networks, ensuring that re-staked validators are punished for misbehavior, maintaining strong decentralized security.

## Espresso Hotshot Consensus

Espresso's Hotshot consensus enables finalizing block contents with low latency by utilizing a leader-based protocol that minimizes coordination overhead. HotShot employs a highly decentralized set

of nodes, where blocks are proposed by a leader and validated through multiple rounds of voting to ensure consensus. The protocol is designed for scalability and achieving finality within a second, even under high network load conditions, all while maintaining decentralization and security by involving many participating nodes in the consensus process.

## RFQ bridges

As `t1` targets to solve cross-chain composability and UX challenges, it must provide a world-class experience for users wanting to withdraw tokens from `t1` to partner chains. The `t1` bridge contract on the destination chain first facilitates such a withdrawal. However, there's no guarantee that the `t1` contract has enough assets for the withdrawal. If it doesn't, `t1` will tap into RFQ bridge protocols, quickly moving funds between the different `t1` bridge contracts in the background, all to ensure users can seamlessly withdraw tokens to their address on any destination chain.

# 6. Security

## Reorgs

`t1` is building a real-time proving rollup that enables near-instant cross-chain settlement without waiting for long confirmation delays. This significantly enhances user experience and application composability across Ethereum and partner rollups. However, this design introduces finality risk — the chance that a transaction could be rendered void due to a reorg in one of the chains involved. To address this, `t1` employs multiple tactics outlined below.

Firstly, `t1` reorgs together with the L1. When this happens, the user experience on `t1` is identical to the user experience on the reorged L1. Basically, the transaction never takes place. It's also worth noting, reorgs on Ethereum are rare: Since the Merge to Proof-of-Stake, ~0.059% of Ethereum blocks have been reorged (almost always one-block deep, with only 4 instances of 2-block reorgs). Moreover, rollups that use centralized sequencers have even lower reorg risk.

The main practical reorg risk arises when the source chain (from which a deposit was made to t1) reorgs after relevant funds were already withdrawn out of t1 to the third chain. In this rare scenario, `t1` would be out of funds. There are some approaches we are considering to alleviate this problem:

- Inclusion preconfirmations: An inclusion preconfirmation is an optimistic crypto-economic guarantee that the deposit transaction will be included in the source chain. Since inclusion pre-confirmations are independent of both ordering and execution success, they are rather cheap. An inclusion pre-confirmation would guarantee that even in the event of a reorg on the source chain (e.g. a late block on Ethereum), a `t1`-depositing transaction will eventually make it to the source chain. However, its success is not guaranteed as a malicious user could e.g. have their funds spent before the block is created for which the preconf had been given. This would result in the `t1`-depositing tx to be correctly included, albeit as a reverting tx.

- Execution-success preconfirmations: These optimistic crypto-economic guarantees also bind the sequencing entity to ensuring that a given tx succeeds (i.e., not revert), not just that it be included. They are expected to be more expensive, but would allow for fast deposits secured up to the crypto-economic threshold of the slashable stake of the sequencing entity.
- Insurance pools: `t1` can introduce an insurance pool for fast deposit-and-withdrawals and keep track of which portion of all deposits is final and which is still prone to reorgs, thus also capping the maximum loss. This is effectively the purpose that solvers serve today in intent-based bridging and cross-chain swaps. Such instant deposit-and-withdrawal actions can require a certain premium fee that would go to an insurance pool so that potential source-chain-reorg-related losses can be covered by the insurance pool. In the absence of preconfirmations, the size of instant deposit and withdrawals would be limited by the size of the insurance pool.

Reorgs are a risk that needs to be accounted for in any on-chain architecture; although they are rare, they can happen. t1's approach to reorgs is risk-based and strikes a balance between enabling a good user experience, providing the right functionality, and accounting for the worst-case scenario.

# 7. Native `t1` applications

Applications built natively on `t1` leverage real-time proving and are designed to provide a better user experience with seamless cross-chain coordination. We're still early in uncovering all of the possibilities real-time proving enables, but have identified a few primitives that are uniquely enabled by `t1`:

- Cross-chain vaults, non-custodial cross-chain yield optimization that automates yield discovery and rebalancing across rollups. Using `t1`'s real-time proving (RTP) interoperability infrastructure, funds move between lending protocols and yield sources.
- Cross-chain loans enable users to deposit collateral into lending contracts on any partner rollup, while market makers borrow against these deposits through `t1`'s cross-chain collateral accounts to fill intents. Loans can be settled and returned to the origin chain within one minute, with a share of bridging fees passed back to depositors as yield. This design reduces capital requirements for borrowers while delivering competitive, real-demand-driven returns to lenders.

These use-cases build TVL on t1 and empower the network to become a programmable liquidity layer that any connected chain can tap into. Thanks to RTP, `t1` eliminates the fragmentation of liquidity across isolated ecosystems and enables applications to operate as if liquidity were unified.

`t1` is also designed to enhance the functionality of existing applications. For Ethereum L1 applications, `t1` offers an execution environment with significantly lower costs while maintaining composability with Ethereum, enabling applications to scale. Appchains and rollups can leverage `t1`'s infrastructure to access cross-chain liquidity without the need for custom integrations or shared sequencer agreements. By being as a permissionless interop layer, `t1` allows partner applications to improve capital efficiency and offer better UX.

**Today, applications need to deploy on multiple rollups to meet user demand. In the future, applications built on `t1` will be able to serve users across multiple rollups by deploying on `t1` alone.**

# Glossary

## TEE

Trusted Execution Environments (TEEs) are specialized hardware-based environments that isolate sensitive computations and data from the rest of the system, ensuring that data is processed correctly and privately. In particular, TEEs provide verifiable computation guarantees through a process called "Remote Attestation" which proves to external parties that the TEE is running a specific, unmodified piece of software (bytecode) without any tampering. Verifiers can then use this attestation to confirm that a TEE's output is trustworthy. Additionally, TEEs can preserve privacy by keeping sensitive data and execution logic concealed from the system operator and external observers. In other words, TEEs are secure hardware areas that protect sensitive data and computations from tampering or unauthorized access.

## ZKP

A zero-knowledge (ZK) proof is a cryptographic protocol that enables one entity (the prover) to convince another one (the verifier) that a particular claim is true without disclosing any details about the claim itself. ZKPs used in blockchains are additionally succinct, meaning that the work required by the verifier to check the proof is substantially smaller than the work of re-running the computation required to reach the claim independently.

## AVS

AVS is a term coined by EigenLayer that refers to services or applications built on top of the Ethereum blockchain and used for security and validation mechanisms. These services could include rollups, DA layers, interoperability protocols, etc. It allows Ethereum validators to use their staked assets to provide security to other applications built on EigenLayer.

## Reth

Reth (Rust Ethereum) is an Ethereum execution node implementation focused on being user-friendly, modular, and efficient. Reth is an execution client compatible with all Ethereum consensus client implementations that support the Engine API. As a full Ethereum node, Reth will allow users to sync the complete Ethereum blockchain from genesis and interact with it (and its historical state, if in archive mode) once synced.

## Reth ExEx

Execution Extensions aka ExEx is a feature of Reth that allows developers to receive comprehensive data about a newly “mined” block in an observer-listener pattern. Thanks to this, developers can perform actions based on certain changes on the blockchain in an efficient and seamless way.

## Real-Time Proving (RTP)

RTP is the ability to prove state transitions in a rollup within one base layer block, which is 12 seconds for Ethereum L1. Real-time proving, for example, allows rollup deposits to be withdrawn immediately (real-time settlement).

## Sequencer

Sequencers are a highly decentralized set of nodes tasked with blindly finalizing the ordering of encrypted transactions in a `t1` block. Since Sequencers only order transactions rather than executing them, we can achieve high decentralization and censorship resistance. Sequencers create Sequencing Consensus. More: Sequencers.

## Executor

Executors are a network of TEE-enabled nodes tasked with executing state changes given the ordered sequences of transactions (i.e. bundles) determined by the Sequencers. Executors provide proofs of Execution Consensus. More: Executors.

# Figure 2: Roadmap

Now, how do we get there? Voila! 🙂