Lecture #16: Optimistic Rollups

COMS 4995-001: The Science of Blockchains

URL: https://timroughgarden.org/s25/

Tim Roughgarden

Goals for Lecture #16

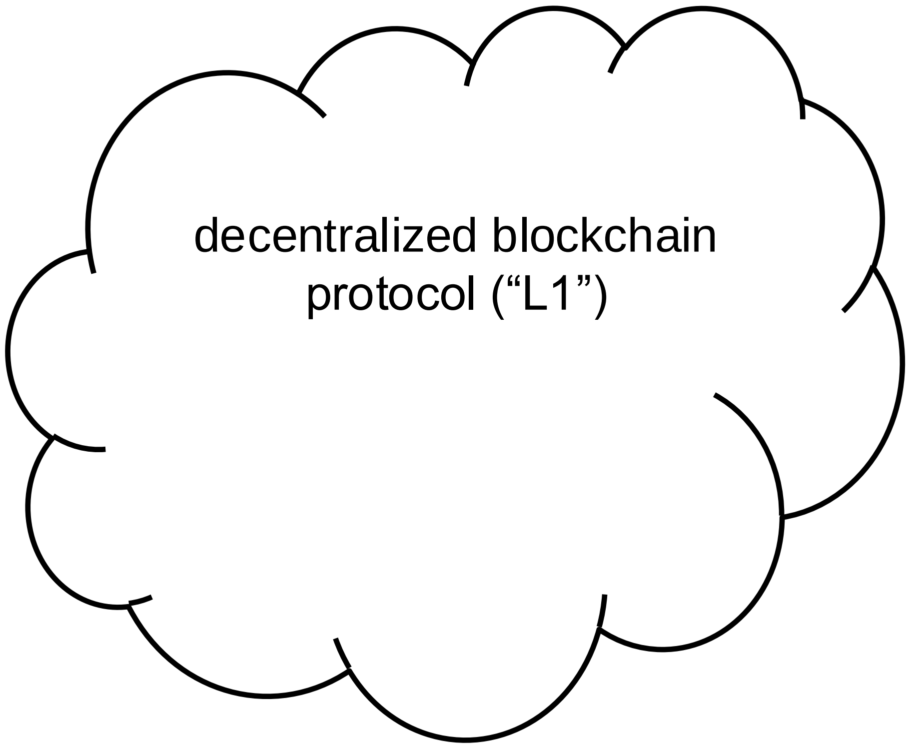
1. Rollups review.
   – an approach to sharding blockchain state and execution
   – piggyback on an “L1” for data availability, liveness, etc.
   – central to the Ethereum ecosystem

2. Optimistic rollups. (e.g., Arbitrum, Base, Optimism)
   – rollup state commitments verified via “bisection game”
   – “cryptoeconomic” security: derived from economic penalties (confiscation of staked collateral)

Recall: “Classic” Rollups

Assume: a decentralized “layer-one” blockchain (“L1”) with strong consistency and liveness guarantees. (e.g., Ethereum)

L1 ⬄ Rollup Architecture



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- not necessarily decentralized, subject to crash or Byzantine failure
- performs its own consensus (i.e., tx sequencing) and execution

L1 ⇔ Rollup Architecture

(possibly centralized) rollup

decentralized blockchain
protocol (“L1”)

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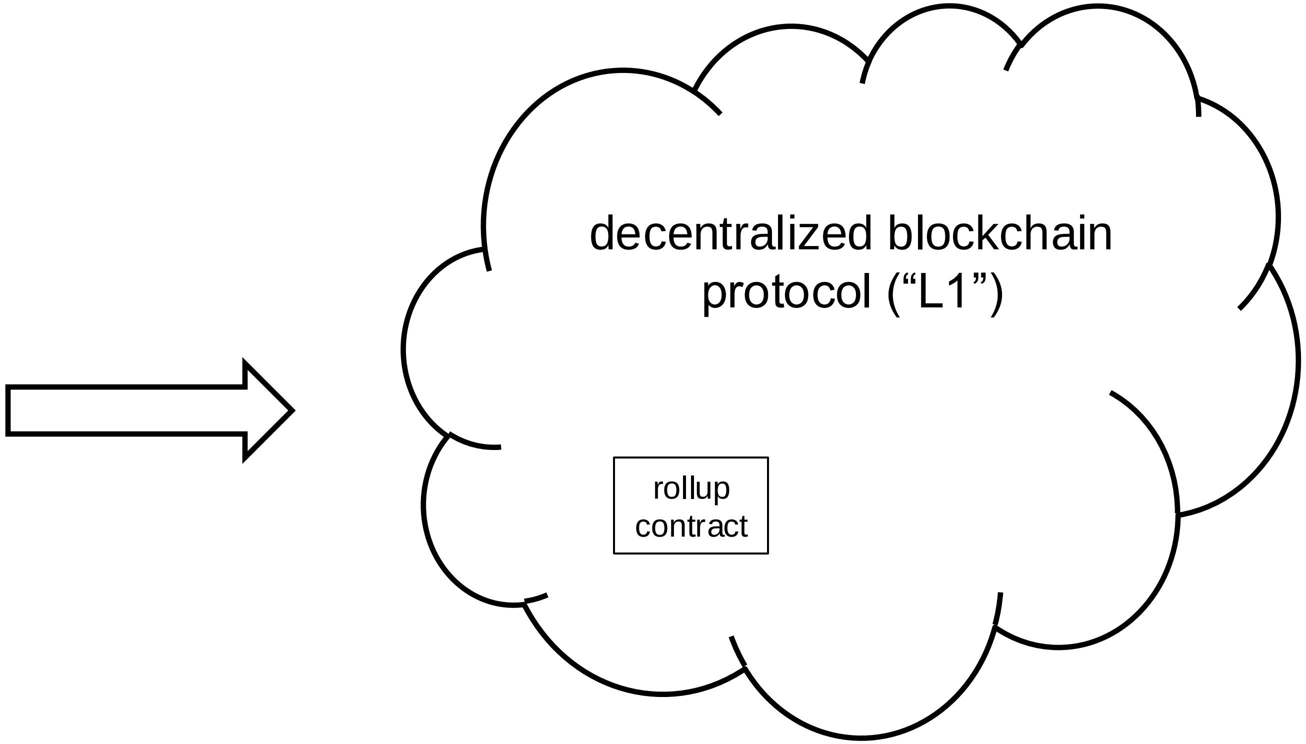

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  - pre-EIP-4844: via call data
  - post-EIP-4844: via blobs

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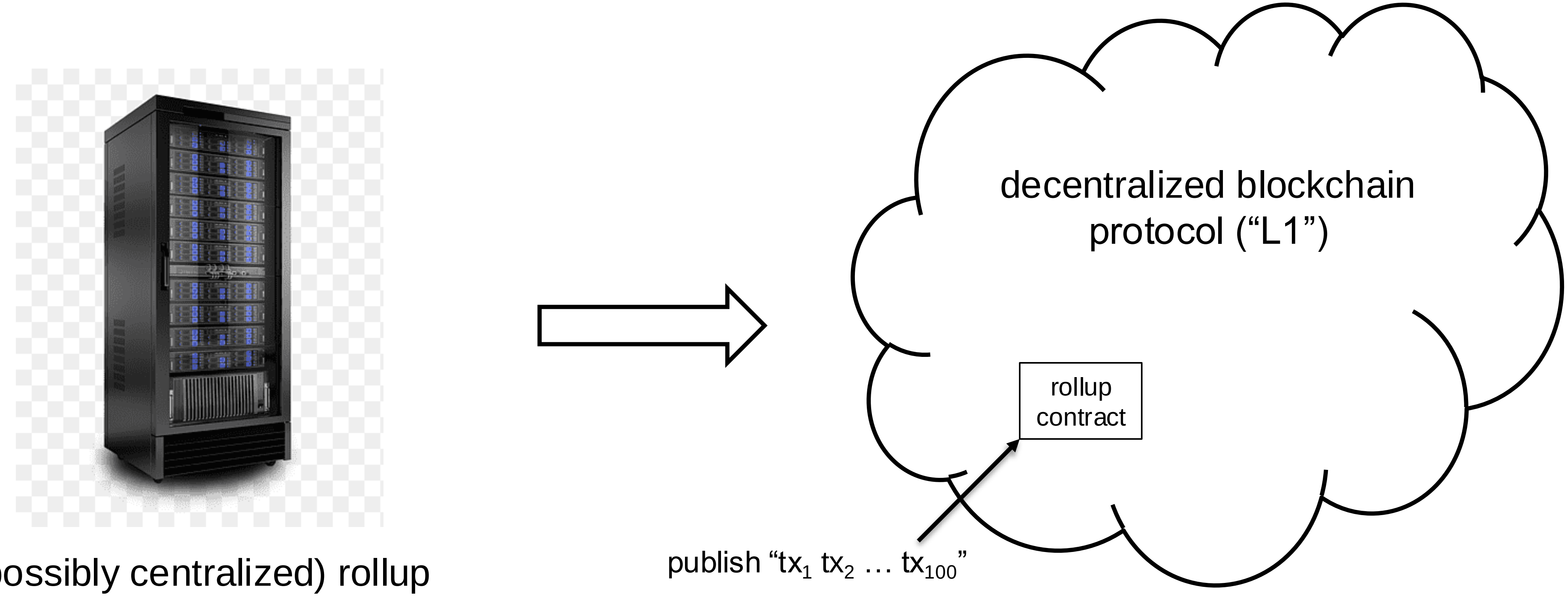

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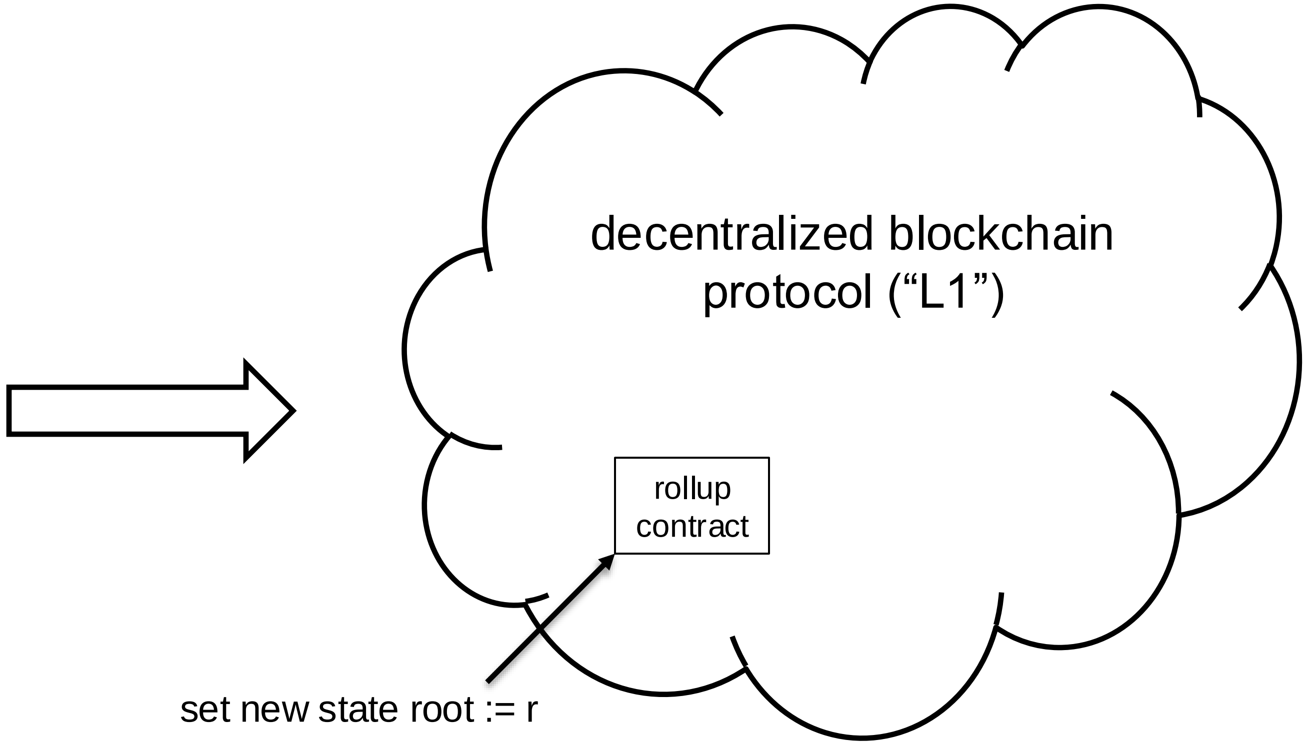

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- (hard part) state commitment correctness verified by L1
  - question: how can L1 do this without re-executing rollup txs itself?

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  - intuitively, a specific line of code that was executed incorrectly
- L1 verifies proof of incorrectness directly
  - L1 performs minimal re-execution necessary to resolve dispute
  - details quite complex, hard to get right

Sequencers vs. Challengers

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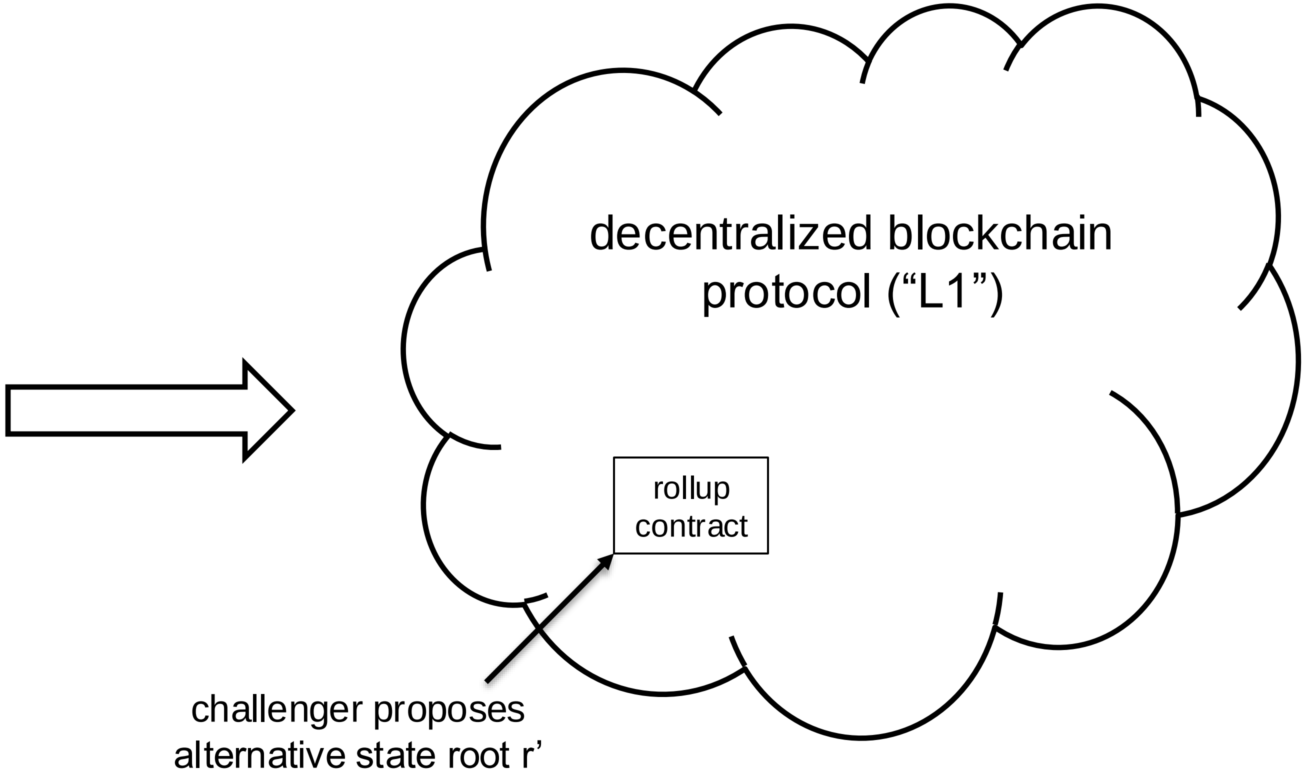

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Question: how can L1 know which state commitment is correct?

Dispute Resolution

Idea: L1 performs minimal amount of re-execution necessary to determine winner (sequencer vs. challenger).

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Canonical scenario: initial state commitment σ_0, assumed correct.

- ordered batch L = $t_1, t_2, \ldots, t_k$ of rollup txs
- sequencer alleges that σ_1 is correct state commitment after executing L
- challenger disagrees, posts alternative commitment $\sigma'_1 \neq \sigma_1$
- for simplicity, suppose both L1 + rollup execution layers are EVM-based

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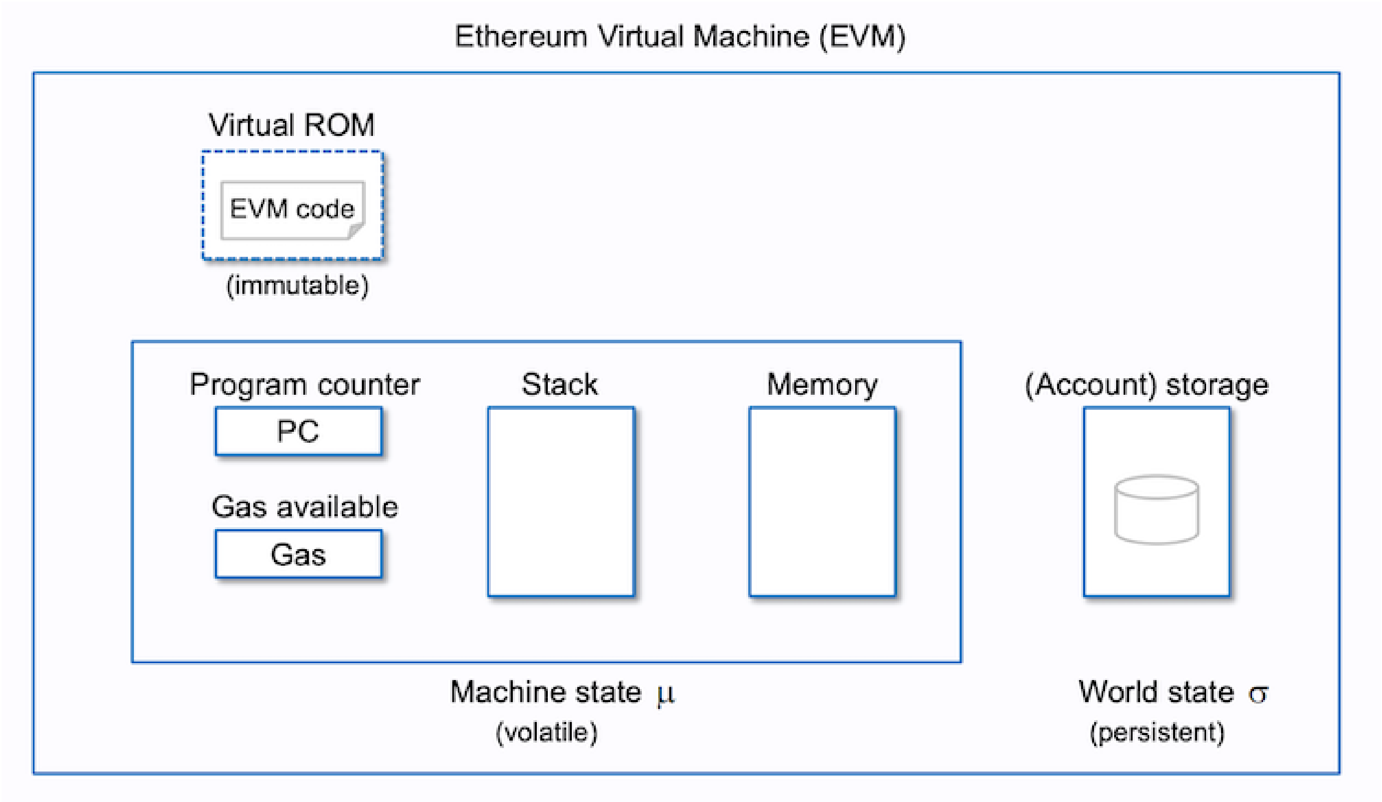
Resolving σ'_1 $vs.\sigma_1$: *execution trace* = view execution of $t_1,t_2,\ldots,t_k$ as sequence $\mu_1, \mu_2, \ldots, \mu_N$ of EVM states (≈ one per line of EVM bytecode executed, in the rollup's execution layer)

Visualizing an EVM State



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Bisection Games

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- sequencer reveals midpoint $\mu_{N/2}$ of its computation (with Merkle proof)
  - i.e., submits to rollup's L1 contract, which verifies the proof

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Throughout: if one party fails to submit expected L1 tx in a reasonable (TBA) amount of time ➔ lose dispute and its stake.

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- repeat until locate position i of computation s.t. $\mu_i = \mu'_i$ and $\mu_{i+1} \neq \mu'_{i+1}$

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Bisection game:

- sequencer, challenger reveal midpoints $\mu_{N/2}, \mu'_{N/2}$ of computations
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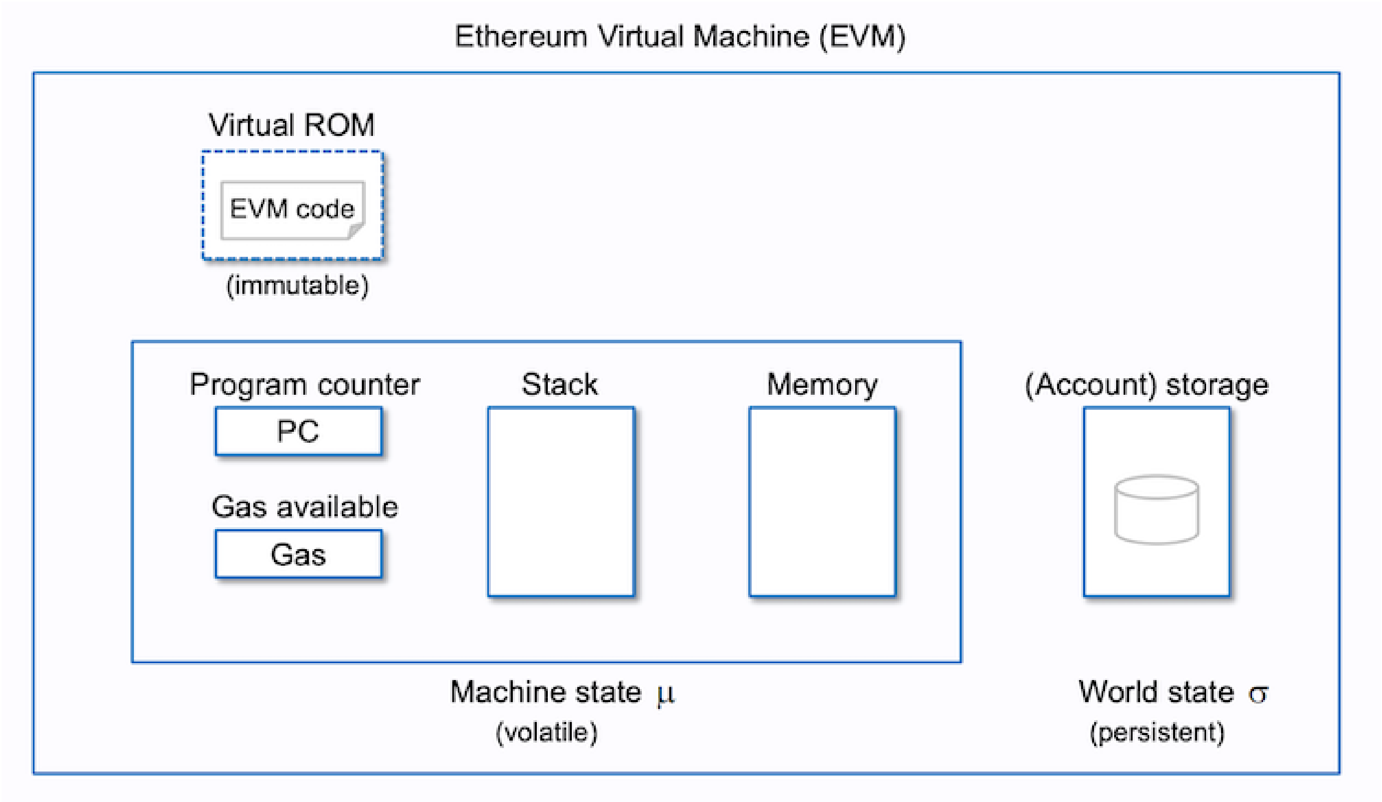

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  - ≈ simulating one step of the EVM (inside a smart contract)
  - if not, contract rejects σ_1 as invalid, confiscates sequencer's stake
  - if so, contract confiscates challenger's stake

Key Property of Optimistic Rollups

Resolving ${\sigma'}_1$ $vs.$ σ_1: view processing of txs in as a sequence of EVM states

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Key property: if sequencer posts incorrect state commitment, any honest challenger can win dispute resolution ➔ no safety violation, and big economic penalty to sequencer.

- would expect sequencer to only publish correct state commitments

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- DoS attacks (e.g., if only whitelisted challengers)
- failure of L1 (i.e., not consistent/live/censorship-resistant)
- bribery (i.e., dishonest rollup sequencer pays L1 validators to exclude challengers' L1 txs)

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- rollup users have option to treat rollups txs as finalized earlier, if desired
  - cf., security parameter k in longest-chain consensus

Example: The Cost of Censorship

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  – in practice, N ≈ 60 and T ≈ 50K (7 days), so N/T ≈ 0.12%