Layer 2 Scaling Solutions

A Standalone Overview

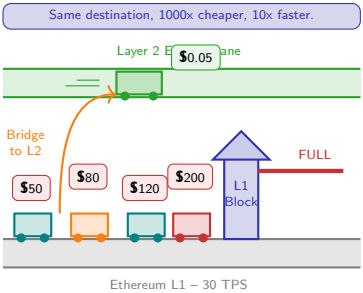
BSc Blockchain Course

Why Can't Ethereum Handle All Its Transactions?

Ethereum processes roughly 15–30 transactions per second. That was sufficient in 2020, but the explosion of DeFi, NFTs, and on-chain gaming pushed demand far beyond capacity. When blocks are full, users compete for inclusion by bidding up gas fees – transforming a $2 swap into a $50 or $100 ordeal during peak congestion. **Three symptoms of the throughput bottleneck:**

- **Hard TPS ceiling:** ∼30 TPS regardless of demand – every node must re-execute every transaction
- **Gas fee auctions:** Users bid against each other for block space; during NFT mints, gas can exceed $200 per transaction
- **Exclusion by cost:** Small-value users and developing-world applications are priced out entirely

Layer 2 solutions move execution off the main chain while keeping Ethereum as the trust anchor – like building express lanes above a congested highway.



Layer 2 solutions execute transactions off Ethereum's main chain but post proofs back to L1, inheriting its security while achieving higher throughput and dramatically lower fees.

Source: Ethereum.org (2024). "Scaling." ethereum.org/en/developers/docs/scaling; L2Beat (2024). l2beat.com/scaling/summary

Think About Your Last On-Chain Transaction – How Much Did You Pay in Fees?

If you have ever used Ethereum directly, you have experienced the fee problem. You signed a transaction, saw the gas estimate, and had to decide: is this swap, this mint, this transfer worth the fee? For many users, the answer increasingly became "no." Small transactions became uneconomical, and entire categories of applications – micropayments, gaming, social media – became impossible on L1.

Reflection – Before We Continue

1. **Recall the last time you sent a transaction on Ethereum L1 (or any blockchain).** How much was the fee relative to the value you were transferring? If you sent $20 worth of tokens and paid $8 in gas, that is a 40% overhead. Would you pay a 40% surcharge at a physical store? At what fee-to-value ratio does a transaction stop making sense?

2. **Think about applications that require many small transactions:** a game where every move is on-chain, a social network where every post is a transaction, or a micropayment system that tips creators fractions of a cent. How many of these applications are viable at $5 per transaction? At $0.01 per transaction? What changes when fees drop by a factor of 1,000?

3. **Consider the tradeoff:** to make transactions cheaper, the L2 introduces a new operator (the sequencer) and a new trust assumption (the proof system). Are you comfortable trusting a company to batch your transactions honestly? What guarantees would you need before depositing significant funds?

Keep your answers in mind – we will revisit them when we examine L2 trust assumptions.

Gas fees are the price of security: every validator re-executes your transaction. L2s ask: can we get the same security without paying that price?

What Makes Layer 2 Different from Layer 1?

Three execution models compared across six dimensions:

Property	L1 (Ethereum)	Optimistic Rollup	ZK Rollup
Security model	Full consensus	Fraud proofs	Validity proofs
TPS	∼30	∼2,000–4,000	∼2,000–10,000
Avg. tx cost	$1–$50+	$0.01–$0.10	$0.01–$0.20
Finality	∼12 min	7 days (challenge)	Minutes (proof)
EVM compatible?	Native	Yes (OP Stack, Arbitrum)	Partial (growing)
Data posted	Full state	Compressed tx data	State diffs + proof

The fundamental insight:

Ethereum L1 requires every validator to re-execute every transaction. That is why it is secure – and why it is slow. Rollups batch hundreds of transactions, execute them off-chain, and post only a compressed summary (plus a proof of correctness) back to L1. The result: the same security at a fraction of the cost.

Three trust models compared:

- **Ethereum L1:** "Every validator re-executes your transaction."
  Maximum security, maximum cost. You trust the consensus of thousands of independent validators.
- **Optimistic Rollup:** "Assume valid unless challenged within 7 days."
  One honest watcher can revert a fraudulent batch. Cheap execution, delayed withdrawal finality.
- **ZK Rollup:** "A mathematical proof guarantees correctness."
  The L1 verifier contract checks a succinct proof. Fast finality, expensive proof generation.

All three models terminate their chain of trust at Ethereum L1. The difference is what you prove and when you prove it.

Rollups do not weaken Ethereum's security – they outsource execution while posting compressed data and proofs back to L1. The security guarantee is inherited, not replaced.

Source: Vitalik Buterin (2021). "An Incomplete Guide to Rollups." vitalik.eth.limo; L2Beat (2024). l2beat.com

Follow One Swap from Your Wallet Through an L2 and Back

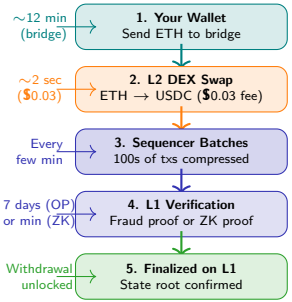
A token swap on Arbitrum – every step traced: Step 1 – Bridge: You send ETH from your L1 wallet to the Arbitrum bridge contract on Ethereum. The contract locks your ETH on L1 and credits an equivalent amount on Arbitrum. This takes one L1 confirmation (∼12 minutes).

Step 2 – Swap on L2: You use a DEX on Arbitrum (e.g. Uniswap deployed on Arbitrum) to swap ETH for USDC. The sequencer includes your transaction in the next L2 block – typically within 1–2 seconds. You pay ∼$0.03 in fees.

Step 3 – Batch to L1: The sequencer collects hundreds of L2 transactions into a batch and posts the compressed data to Ethereum L1 as calldata. One L1 transaction settles an entire batch.

Step 4 – Verification: For Arbitrum (optimistic), the batch enters a 7-day challenge window. Any watcher can submit a fraud proof if the batch is invalid. For a ZK rollup, a validity proof is posted and verified on-chain within minutes.

Step 5 – Finalize: After verification, the state root is finalized on L1. You can now withdraw your USDC back to L1 through the bridge (or keep it on L2 for further use).

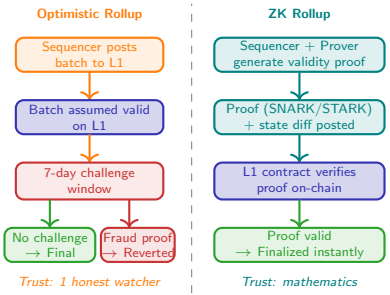


Your swap was $0.03 on L2; settlement was shared across hundreds of transactions on L1.

The user experiences a fast, cheap swap on L2. Behind the scenes, the sequencer batches transactions and the L1 provides the final security guarantee – the best of both worlds.

Source: Arbitrum Docs (2024). docs.arbitrum.io; Ethereum Foundation (2024). "How Rollups Work." ethereum.org

Who Checks the Work – A Challenger or a Prover?



Two philosophies of verification:

- **Optimistic (fraud proofs):**
  Post the batch, assume it is correct. A 7-day window lets anyone challenge. If fraud is proven, the batch is reverted and the sequencer is slashed. Security requires *at least one honest* observer watching at all times.

- **ZK (validity proofs):**
  Generate a cryptographic proof that every transaction in the batch was executed correctly. The L1 verifier checks the proof in $O(1)$ time – regardless of batch size. No challenge window needed; finality is immediate.

Current landscape:

- **Optimistic:** Arbitrum, Optimism, Base – fully EVM-compatible today, dominant in TVL
- **ZK:** zkSync Era, StarkNet, Polygon zkEVM – faster finality, rapidly improving EVM support

Optimistic rollups rely on game theory (someone will challenge); ZK rollups rely on mathematics (the proof is valid or it is not). Both derive final security from Ethereum L1.

Source: Buterin, V. (2021). "An Incomplete Guide to Rollups"; Ethereum Foundation (2024). "Optimistic vs ZK Rollups." ethereum.org

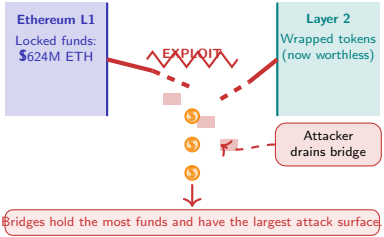
What Happens When the Bridge Gets Hacked?

Bridge Exploits – Over $2B Lost Since 2021 Bridges are the connective tissue between L1 and L2 – and they are the single most attacked component in the entire blockchain ecosystem. Between 2021 and 2024, bridge hacks accounted for more stolen funds than all DeFi protocol exploits combined.

Three major bridge disasters:

- **Ronin Bridge (Mar 2022):** $624M stolen. Attackers compromised 5 of 9 validator keys. The hack went undetected for 6 days because no one was monitoring the multisig.
- **Wormhole (Feb 2022):** $320M lost. A bug in the Solana-side verification logic let the attacker mint wrapped ETH without depositing real ETH on the other chain.
- **Nomad (Aug 2022):** $190M drained. A configuration error made every message valid, allowing anyone to drain funds by copying a successful transaction.

Bridges concentrate risk: they hold locked funds on one side and issue IOUs on the other. A single vulnerability drains both sides.

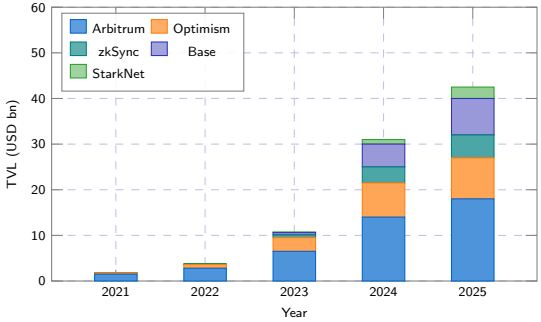


Bridges are the weakest link in the L2 ecosystem: they concentrate billions in locked funds behind smart contract logic that must be flawless. A single bug can drain everything.

Source: Rekt News (2024). rekt.news/leaderboard; Chainalysis Bridge Exploit Report (2023).

How Much Value Has Already Moved to Layer 2?

Layer 2 Total Value Locked – illustrative growth (USD billions):



Illustrative values based on L2Beat and DefiLlama data. Not investment advice.

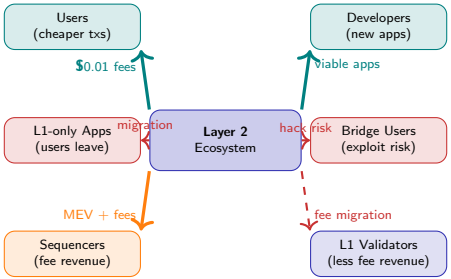
What the data reveals:

- **Arbitrum dominates:**
  First mover among optimistic rollups. Full EVM compatibility made migration easy for existing DeFi protocols. Holds the largest share of L2 TVL.
- **Optimism and Base:**
  OP Stack (Optimism's open-source framework) powers Base (Coinbase's L2) and dozens of other chains. The "superchain" thesis: a shared standard multiplies adoption.
- **ZK rollups accelerating:**
  zkSync Era and StarkNet launched mainnet in 2023. TVL growing rapidly as EVM compatibility improves and proof costs decrease.
- **EIP-4844 catalyst:**
  Proto-danksharding (March 2024) reduced L2 data posting costs by 10–100x, making sub-cent transactions routine and unlocking new application categories.

More transactions now occur on Ethereum L2s than on L1 itself. The trend is structural: Ethereum is becoming a settlement layer, not an execution layer.

Source: L2Beat (2024). l2beat.com/scaling/tvl; DefiLlama (2024). defillama.com/chains; EIP-4844 specification.

Who Wins and Who Loses from Cheaper Transactions?



The same technology – very different outcomes:

Users: Transaction fees drop from dollars to fractions of a cent. Applications previously impossible on L1 – gaming, social, micropayments – become viable. The user base expands from crypto-natives to mainstream.

Developers: New application categories open up. A game with 10,000 on-chain moves per second is feasible on L2, impossible on L1.

Sequencers: The new power brokers. They order transactions, capture MEV, and earn fees. Currently centralized for most L2s – a concentration of power that mirrors the exchanges L1 was meant to displace.

L1 validators: Revenue shifts from execution fees to data-availability fees. The "ultrasound money" thesis depends on whether L2 demand for L1 block space compensates.

Bridge users: Every bridge crossing is a risk event. $2B+ lost in bridge exploits since 2021.

Layer 2 redistributes value: users and developers benefit from cheaper execution, but sequencers gain new power and bridge users bear new risks.

Source: Flashbots (2024). "MEV on L2s"; L2Beat Risk Framework (2024). l2beat.com/scaling/risk

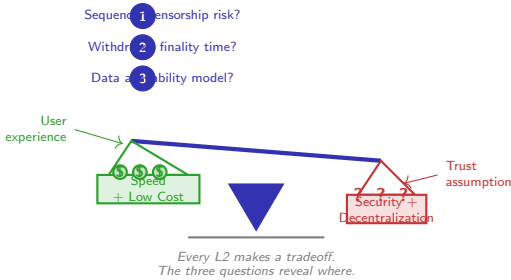
Three Questions That Reveal Any L2's True Design

Before trusting any Layer 2 with your assets, apply these three questions:
Question 1: Can the sequencer censor or reorder your transactions?

Most L2s today run a single centralized sequencer. If it censors your transaction, can you force inclusion through L1? Look for: forced inclusion mechanisms, decentralized sequencer roadmaps, and L1 escape hatches. If none exist, you are trusting the operator not to censor you. **Question 2: How long until your withdrawal is final on L1?**

Optimistic rollups: 7 days. ZK rollups: minutes to hours. Fast bridges offer instant withdrawals but introduce additional trust assumptions and counterparty risk. Know the finality model before depositing large amounts. **Question 3: Where is the transaction data stored?**

If the L2 posts full data to Ethereum (a "rollup"), anyone can reconstruct the state and exit. If it stores data off-chain (a "validium"), a separate committee must stay honest. Data availability determines whether you can always prove your balance – even if every L2 operator disappears. *An L2 that passes all three inherits Ethereum's security. Each failure adds a trust assumption.*



The three questions are a checklist, not a guarantee: even well-designed L2s can have bugs, centralized upgrade keys, or untested escape hatches. Layer 2 shifts risk – it does not eliminate it.

Source: L2Beat Risk Analysis (2024). l2beat.com/scaling/risk; Ethereum Foundation (2024). "Layer 2 Security." ethereum.org

Your Challenge: Evaluate a Real L2 Protocol

Pick one Layer 2 from the list below and evaluate it using the three questions from the previous slide.

Case: Compare Two Real L2 Protocols

Choose one protocol from each column:

Optimistic Rollups	ZK Rollups
Arbitrum One (arbitrum.io)	zkSync Era (zksync.io)
Optimism (optimism.io)	StarkNet (starknet.io)
Base (base.org)	Polygon zkEVM (polygon.technology)

For each chosen protocol, fill in the evaluation framework:

Question	Your Finding	Evidence (cite source)
Q1: Can the sequencer censor you?	.....	.....
Q2: How long until withdrawal is final?	.....	.....
Q3: Where is transaction data stored?	.....	.....

Discuss (5 minutes): Compare your optimistic rollup with your ZK rollup. Which offers stronger security guarantees today? Which has a more credible decentralization roadmap? Where do you disagree with your partner? Use **l2beat.com/scaling/risk** as your primary data source.