

Layer 2 blockchains for videogames

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Part I

Blockchain concepts and their limitations

In the last 3 decades internet has become a service used by virtually everyone. The framework which allowed the spread of the internet has been the *client-server* paradigm. Its success must be attributed to some important properties it guarantees, first and foremost the relative ease of implementation and maintainability of such solutions compared to others, such as peer-to-peer architectures. Moreover, client-server solutions can achieve high performance and efficiency, by handling a lot of requests thanks to the power of ad-hoc hardware and replication. Another key characteristic of client-server is the fact that the owner of the service can fully control it, and change it based on his needs, as long as he follows the laws of the region he operates in and possible commitments he made with the users.

Despite all the positive properties of the client-server paradigm, there are some situations for which it is not suitable. What if we cannot trust the service provider? What if we want a service that is fully transparent for the users? What if we want a strong guarantee that data won't be modified?

In all these cases, and more, blockchain technologies are more suitable.

In the next sections we will briefly describe how a blockchain works, why it can be useful in videogames, and what are the main limitations which have prevented its use in the video gaming industry so far.

1 What is a blockchain

A blockchain, as the name suggests, is a chain of blocks. Each block contains transactions, which, in the simplest form, are exchanges of tokens between 2 users.

What actually creates the bond between 2 contiguous blocks of the chain, is the fact that each block also contains the hash of the previous one in the chain.

Blockchains are decentralized and distributed because the record of all the existing blocks (and therefore their relative *position* in the chain) are not stored in a single, central server owned by some company. Indeed they are stored by the participants of the blockchain itself.

Since all the existing blocks are stored somewhere¹, it is possible to reconstruct the tokens owned by each user.

¹Not every node stores the full history of blocks, only full nodes do [Zohar, 2015].

In order for such a distributed ledger to work in a useful way, there is the need for a method to ensure 3 basic properties:

- The transactions in a block must be valid.
- There must be an agreement among all the participants to the blockchain about the content (and therefore the order) of the blocks in the chain.
- Once a block has been added to the chain, it cannot be modified.

1.1 Transactions

Each user of the blockchain is identified only by a pair of private and public keys $\langle p_k, P_k \rangle$.

A transaction is a *packet* of data like this²:

Sender P_k	Receiver P_k	Amount	Sender signature
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For example, if the user with public key `0x1234` and private key `0x5678` wants to send 3 tokens to the user with public key `0xabcd`, the transaction will look like this:

0x1234	0xabcd	3	sign(0x1234, 0xabcd, 3, 0x5678)
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Where `sign` is a function to sign the transaction with the private key of the sender.

The signature is crucial since it guarantees authentication, integrity and non-repudiation of the transaction.

Once a user creates a transaction, it sends it to the miners network.

1.2 Miners

The role of the miners is to guarantee the validity of the transactions, create blocks and agree on the content of each block in the chain.

When a miner receives a transaction, he propagates it to the other miners. Each miner keeps the transaction it receives in a pool, then he chooses³ a number of transactions to include in the next block.

All the transactions in a block must be valid, therefore the miner must check that:

- The signature of the transaction is valid.

²In Bitcoins things are more complex than this. A user can spend an old transaction if he has a script to *redeem* it. To spend a transaction he must provide the script to *redeem* it and a script to re-lock it. Moreover, a user can merge many old transactions into a single one and can split the output by locking portions of it with different scripts. [Nicola Atzei, 2013]

³Fees [David Easley, 2018] play a key role in the way transactions get chosen.

- The transaction is not already present in a previous block of the blockchain.
- The sender actually owns enough tokens to complete the transaction.

When a block of transactions is created, the miner adds the hash of the previous block of the chain to it.

Now the miner must solve a computationally complex puzzle and then send the block to the other miners.

If the solution to the puzzle is correct, and all the transactions in the block are valid, all the other miners will accept the block as the last block of the chain.

1.3 Proof of work

If miners could add any block they create to the blockchain, it would be impossible to obtain a consensus between the miners on what blocks are actually part of the chain.

For example, it would be impossible to have a consistent state of the blockchain among all the participants, due to the CAP theorem [Seth Gilbert, 2012].

The blockchain wouldn't even be immutable, since it would be easy to replace an old block with another one.

For these and many other reasons, there must be a consensus mechanism among miners, in order to agree on what blocks are part of the chain.

The chronologically first consensus mechanism that has been used in a blockchain is proof of work (PoW) [Nakamoto, 2009]: after a miner creates a block of transactions, it has to add a *number* to it, such that the hash of the whole block starts with a predefined amount of zeroes. Since the hash is a non-invertible function, the only way to find a number with the property described above is brute force.

This simple mechanism solves the problems we discussed before. Indeed, now, it requires a lot of resources to modify an old block of the chain: not only a malicious miner should re-compute the hash of the block he wants to change, but also the hashes of all the blocks after it (since each block contains the hash of the previous one, which has changed).

Moreover, PoW reduces the number of blocks that can be created in a given interval of time, making it possible to reach a consistent state among the majority of miners⁴.

In order to make PoW work with faster hardware, it is possible to collectively choose the amount of required leading zeroes in the hash of the new proposed block.

⁴It is still possible that 2 miners solve different blocks at roughly the same time. In this case, the blockchain will have a branch. After some time one of the 2 branches will be longer than the other, because it is unlikely that the 2 branches evolve at the same speed. At this point, the longer branch will be the one chosen by the miners, and the other one will be discarded.

Moreover, miners can add their address in a field of the block, so that they get rewarded for their work if they are able to create a new block.

1.4 Journey of a transaction

Here we make a summary of the steps that a transaction must follow to be included in the blockchain:

1. User **A** creates a transaction **T**, signs it and sends it to the miners network.
2. A miner **M** receives **T** and forwards it to the other neighboring miners.
3. **M** receives many other transactions, then creates a block **B** with only valid transactions, among which **T**.
4. **M** adds the hash of the last block of the chain and his address for the reward to **B**.
5. **M** starts trying different numbers until it finds a number that satisfies the PoW requirements.
6. **M** forwards the new block **B** to the other miners.
7. The other miners check the validity of **B**, if it is valid they will consider it the last block of the chain, else they will simply ignore it.

1.5 Blockchain programmability

Until now we have seen a blockchain where simple users can exchange some currency with plain transactions. Bitcoin is an example of a blockchain with these characteristics.

More recently a new kind of programmable blockchains has arisen, whose main exponent is Ethereum.

The core concepts of a programmable blockchain like Ethereum are similar to the ones of a *plain* one, with 2 main additions⁵:

Smart contracts Blockchain wallets controlled by an immutable script.

Account-based model Nodes keep the blockchain state in a *table* like the one in Table 1.

A transaction can now be defined as an argument in a state transition function:

$$\mathcal{N}(state_{old}, transaction) = state_{new}$$

A smart contract is deployed via a transaction, where its source code is specified.

Other users of the blockchain can interact with a smart contract by sending transactions where they specify the interface function to call and the necessary arguments.

⁵Another evident difference of Ethereum is that it now uses proof of stake, but it is not important in this context.

Address	Balance	Nonce	Code	Storage
0x1234	3	149		
0xabcd	101	74	<code>if(bal > 0) then sendMoney(...)</code>	<code>bal = 23</code>

Table 1: Simplified example of the account-based state

When such a transaction is included in a block, the validator must also execute the code specified by the smart contract, whose execution, being deterministic, can be checked by the other validators. All validators should reach the same state.

Each smart contract has associated storage, which is part of the state of the blockchain and can be read and written during execution.

Smart contracts are immutable, which means it is not possible to change, or even delete, the code of the smart contract after it is deployed. This property is particularly relevant because it means that a user can be sure of what will happen if he interacts with a smart contract, by simply reading the smart contract code.

Another important aspect of smart contracts are execution fees. A smart contract will be executed by a validator, and the more complex the smart contract is, the more resources and time the validator will have to use.

For this reason, when a transaction is created, it is necessary to specify a maximum fee that the validator will earn by including the transaction in the block. Each instruction in a smart contract has an associated fee. If during the execution the total fee exceeds the maximum fee specified in the transaction, the execution will be aborted.

There are 3 main types of resources that require fees during the execution of a smart contract:

Computation The instructions executed.

Calldata The arguments passed in the transaction.

Storage The cost of writing to the smart contract storage.

1.6 Tokens

Smart contracts can be used to implement tokens, which are virtual assets that can be owned by the accounts.

Tokens differ from the currency of the blockchain (e.g. Bitcoin or Ether) because they are generally used in a closed environment and serve a specific purpose (for example a certain token could signify membership to a certain organization).

There exist 2 kinds of tokens:

Fungible tokens A token is indistinguishable from another one, and it can be fractioned.

Non-fungible tokens A token has a unique identifier and value, it cannot be fractioned.

2 Why blockchain can be used in videogames

In the previous sections, we have briefly seen how a blockchain work. Now we will see why it can be used for videogames.

Ownership of digital assets A videogame could reward the player with NFTs. This would be different than rewarding a player with a game-specific item, because the player would own the NFT independently from the game, and would even be free to sell it for fiat money.

Cross compatibility If players are rewarded with tokens, it would be easier for other games to integrate them. In this way, players could easily import and use items earned in one game in another one.

Transparency One of the key characteristics of blockchains is transparency. All transactions are public, therefore it can potentially be easier to detect cheaters in a competitive environment. Blockchain would also make it impossible for software houses to censor some players.

Fairness Smart contracts could be used to create a fair ground between the software house and the player base, for example by using smart contracts to implement loot boxes.

3 Why blockchain cannot be used in videogames

Blockchain can be used in videogames at different stages.

Most blockchain-powered videogames today are using blockchain as a storage for in-game rewards. This means that the execution of the game happens off-chain (generally on a server), but the server can decide to reward a player with on-chain tokens.

This paradigm is useful to implement the ownership of digital assets, and, to some extent, cross-compatibility, but it doesn't help with transparency and fairness.

To achieve transparency and fairness the game itself should be executed inside a smart contract on the blockchain.

There are 2 main issues with doing so:

Costs Usually the main loop of a videogame is quite complex. This means that the fees for executing the smart contract will be high.

Scalability and performance Blockchains have a much lower throughput than client-server solutions. This is an inherent characteristic of blockchain as we know it nowadays, and, as we have seen, a core principle of their functioning.

In recent years a new framework that can help with both issues has emerged: blockchain layer 2 [[corwintines, 2023](#)].

Part II

Blockchain layer 2

As we have seen in [Why blockchain cannot be used in videogames](#) layer 1 blockchains suffer from high fees and poor scalability.

This is a direct consequence of the blockchain trilemma [[Musharraf, 2021](#)], which states that we can have only 2 out of distribution, security and scalability. To try to tackle these issues layer 2 blockchains have been invented.

The core idea behind layer 2 is to transfer as much load as possible outside of the blockchain, and use the layer 1 properties only to finalize the operations that happened off-chain.

They try to do so by starting from a predefined state, usually stored in a smart contract, bundling up many transactions off-chain, and eventually reporting to the smart contract what happened off-chain [[EthereumCommunity, 2022](#)]. The smart contract can verify that some predetermined rules have been followed during the off-chain operation.

The off-chain transactions can be faster because they don't have to involve all the nodes of the blockchain to be verified, and can resort to simpler verification protocols that scale better and are more suited for certain applications.

In the next sections we will explore some of the most used layer 2 approaches, and we will find out why ZK rollups are arguably the best solution for videogames.

4 Off-chain state channels

The core idea behind state channels is to let channel participants perform transactions off-chain, and only submit 2 on-chain transactions to open and close the channel.

The lifecycle of a channel is made up of 3 phases [[minimalism, 2023](#)]:

Opening To open a channel all the participants must add funds to a smart contract and agree to the initial state by signing it.

Usage Once a state channel is open, participants can start exchanging transactions off-chain. A transaction looks like this:

Old state	New state	Transaction to go from old state to new state	Nonce
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A transaction to be considered final must be valid (i.e. following the rules stated in the smart contract, such as not spending more than what you own) and signed by all parties in the channel. If a transaction is valid, it cannot be reverted.

Closing Any participant can decide to send a transaction to the smart contract on layer 1. At this point, a challenge period starts, where the other parties can send a transaction to challenge the one proposed by the first participant.

For example, if user A wants to finalize the state channel with an old transaction, and user B has a newer transaction signed by all the parties, he can use the newer transaction to prove that user A is malicious. In this case user A would lose all the funds he added to the smart contract of the state channel.

The presence of the challenge period enhances the security of honest users: they can challenge malicious parties and they can withdraw their funds if other parties stop responding.

In any case, at the end of the challenge period, funds in the state channel are distributed based on the last valid transaction sent to the smart contract.

It is important to note that the state of a channel doesn't only hold currencies, but also any other possible variable. For this reason, state channels can be used to run computation off-chain.

4.1 State channels and videogames

As we have seen state channels rely on layer 1 blockchain to guarantee liveness (the smart contract for the channel is always available), security and finality (as soon as a transaction is signed by everyone, it is not revertible).

Moreover, since they allow off-chain computation, state channels don't suffer from the scalability and performance issues typical of blockchains.

On the other hand, in a video gaming context, state channels do not guarantee the transparency and fairness properties we are looking for.

For example, let's imagine we have a state channel to play a game of chess against a computer, where you get a reward if you win. The state channel would be initialized and signed by the player and the server where the chess engine runs. Then the player and the server could start exchanging transactions to move pieces. Let's now say that the player is one move away from checkmate, and the server refuses to acknowledge the transaction that delivered checkmate. The player cannot send the checkmating transaction to the layer 1 smart contract, because the server could challenge it with the last co-signed transaction. And in this framework it would be impossible to prove that the server did it intentionally, maybe it simply didn't receive the transaction.

Therefore this solution wouldn't be much different than a simpler client-server solution with on-chain storage.

5 Sidechains

Sidechains are independent blockchains that can interoperate with the layer 1 blockchain.

Being separate, sidechains can use different consensus mechanisms than the main blockchain. On the one hand, this can help with performance, scalability and fees cost, but, on the other hand, the sidechain may lose some important guarantees of the layer 1 blockchain. For example, a sidechain could trade distribution for scalability to satisfy the blockchain trilemma and be scalable.

Sidechains can communicate with the blockchain via bridges.

Bridges are mechanisms that allow to connect different blockchains, allowing users to transfer assets between them [alemanaa, 2022].

There are many types of bridges, one of the most used kind locks or burns items in one blockchain and mints the same item in the other one, in order to simulate the transfer.

6 Rollups

Rollups are mechanisms where multiple transactions are performed off-chain and aggregated in a single batch transaction which is submitted to a smart contract on the layer 1 blockchain.

Off-chain transactions are executed in a layer 2 blockchain, where the validators (also called sequencers) also have the task to send batches of layer 2 transactions to the layer 1 smart contract.

Based on the mechanism that is used to determine the validity of the transactions in the batch, it is possible to categorize rollups into optimistic and zero-knowledge.

6.1 Optimistic rollups

The main assumption of optimistic rollups is that the majority of the transactions inside a batch are valid, therefore sequencers can send the new state of the layer 2 blockchain to the layer 1 smart contract, without any validity proof.

The caveat is that the layer 1 smart contract will wait a challenge period (usually 7 days) before accepting the new state. During this period other participants to the layer 2 blockchain can send fraud proofs to challenge the new state sent by the sequencer.

This mechanism enables better scalability and cost efficiency than in layer 1 blockchains, since smart contracts can be executed on layer 2, and the layer 1 fees are split among all the transactions in a batch.

6.1.1 Entering an optimistic rollup

To enter a rollup a user must deposit some assets (generally tokens) in the layer 1 rollup smart contract. These assets are then transferred to the layer 2 blockchain via a bridge to a specified address.

At this point, the user must wait until the transaction made by the bridge to the specified address gets processed by the sequencer and sent in a batch to the layer 1 smart contract.

6.1.2 Exiting an optimistic rollup

To exit a rollup a user must send an exit transaction to the layer 2 sequencer. The sequencer will execute the transaction by burning all the assets of the user (that should be included in the exit transaction), and then include this transaction in a batch.

At this point, the user must to generate a cryptographic proof (generally a Merkle proof) to show that the exit transaction was inside the last batch, and that the layer 2 account that submitted such transaction belongs to the user.

Now it is possible to send the proof to the layer 1 smart contract, along with an address where to send the withdrawn assets.

6.1.3 L2 - L1 interaction

The sequencers store the state of the rollup as a Merkle tree (see section [Merkle trees](#)). The root of such tree is also stored in the layer 1 smart contract. [\[EthereumCommunity, 2023\]](#).

When a sequencer wants to send a batch to the layer 1 smart contract, it must send a transaction containing:

- The Merkle root of the old state.
- The Merkle root of the new state.
- An highly compressed summary of all the transactions in the batch (containing also the input data of the transactions).
- The Merkle root of the transactions in the batch.

The layer 1 smart contract receives the transaction and compares the Merkle root of the old state with the one in its storage. If they match, the Merkle root in the storage is updated to the Merkle root of the new state.

The highly compressed list of all the transactions and their inputs won't be part of the layer 1 state, but it will simply be stored as calldata, for cost reasons.

The Merkle root of the transactions in the batch is necessary in order to let other participants prove that their transaction is part of the batch (for example when a user wants to withdraw assets from the rollup).

At this point, the challenging period begins, and other users can send fraud proofs. 2 main proving schemes can be adopted:

Single round In this scheme all the transactions' inputs being part of a batch must be stored (as calldata) in the layer 1 smart contract. Since the smart contract has all the transactions and their inputs, it can replay them and verify whether the new state Merkle root matches with the one sent by the sequencer.

Multi round This proving mechanism is more complex but also more efficient. In this case, only the Merkle root of the summary of transactions is required be stored as calldata.

The process to prove fraud consists of a dialogue between the sequencer (asserter) and the challenger, supervised by a layer 1 smart contract. At each step the asserter must split computation performed in a batch into 2 equal halves and state the output⁶ of each one of the 2 halves. The challenger can decide which half he wants to challenge. This process goes on until only a single instruction remains in the asserter computation. At this point, both the asserter and the challenger must send their prediction for the outcome of that instruction, which is executed by the layer 1 smart contract, which can easily find out who is lying. This process can be visualized in Figure 1.

Since we have the Merkle root of the batch and all the transactions in the layer 2 blockchain are available to other users, the challenger can prove whether a specific part of the computation shouldn't be there by hashing all the transactions that were actually included in the block. And in case the sequencer and the challenger agree on the computation, the proof we described above is enough to understand who is lying about the new state.

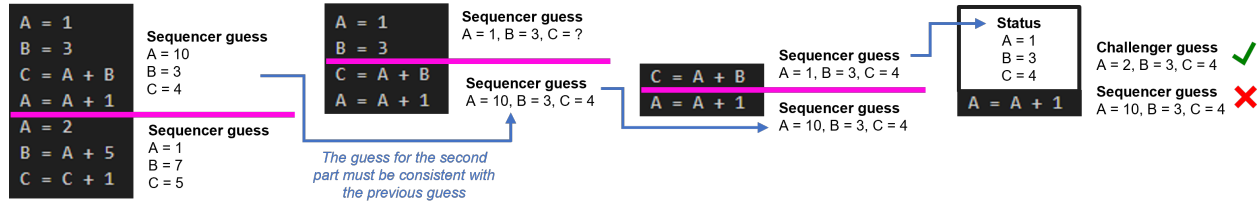


Figure 1: The multi round fraud proof mechanism visualized.

It is interesting to note that even a single honest participant to an optimistic rollup has the power to stop malicious activities by any number of other nodes.

6.1.4 Optimistic rollups and videogames

Optimistic rollups are a step in the right direction towards the use of the blockchain in videogames.

⁶With output here it is intended the hash of the full state of the computation till this point

Indeed they do not suffer from the transparency and fairness problems we discussed in section [State channels and videogames](#), and, at the same time, they maintain more security and decentralization guarantees than sidechains, since they maintain a strict bound with the layer 1 blockchain.

The main problem of the majority of the implementations of optimistic rollups are:

High fees Even if fees are lower than using a layer 1 blockchains, the need to send all the transactions and their inputs in a batch (although compressed) as calldata, isn't enough to lower the fees enough for adoption in the video gaming world.

Withdrawal time As we have seen in section [Exiting an optimistic rollup](#), it takes a very long time (usually 7 days) to be able to withdraw the assets from an optimistic rollup. This doesn't pair well with the cross compatibility property, since different games will most likely run on different optimistic rollups implementations.

6.2 Zero-knowledge rollups

Zero-knowledge rollups are a layer 2 scaling solution that operates similarly to optimistic rollups. Therefore, as in optimistic rollups, the layer 2 sequencers receive various transactions, execute them and only update the layer 1 smart contract when a batch of transaction has been executed.

As in optimistic rollups, this mechanism improves scalability and performance of the blockchain, and splits the layer 1 fees among all the transactions in a batch.

The core difference between optimistic rollups and ZK rollups is in the way the transaction batch update gets validated in the main blockchain.

Sequencers of ZK rollups must send a zero-knowledge proof along with the changes to the old state. The zero-knowledge proof is a cryptographic demonstration that the proposed changes to the state are actually the result of executing all the transactions in the batch.

This change makes it so that it isn't required to store a compressed summary of the transactions' inputs on the layer 1 chain as calldata, greatly lowering the fees needed. Moreover, the layer 1 smart contract can immediately verify whether the changes are valid, so the challenge period can be completely removed.

6.2.1 Entering a ZK rollup

The process to enter a ZK rollup is very similar to the one described in [Entering an optimistic rollup](#).

The user must deposit some assets in the layer 1 smart contract, a bridge will transfer the assets to the rollup. After the sequencer adds the transfer transaction to a batch, the user will be able to use his assets in the ZK rollup.

6.2.2 Exiting a ZK rollup

If the process to enter a ZK rollup is basically the same as the one to enter an optimistic rollup, the exiting process shows some differences caused by the different way in which transaction batches are verified in layer 1.

To exit a ZK rollup a user must initiate an exit transaction by sending all his assets to a specific burn address.

As soon as this transaction is added to a batch by the sequencer, the user must create a Merkle proof to prove the presence of the exit transaction in the batch.

Then he can send a withdrawal request to the layer 1 smart contract with the following information:

- The Merkle proof.
- The exit transaction input data.
- The Merkle root of the transaction batch containing the exit transaction.
- A layer 1 address where to deposit the withdrawn assets.

The layer 1 smart contract can hash the transaction data and use the Merkle proof to verify that such transaction is indeed part of the Merkle root of the batch. If this is the case the smart contract will deposit as many assets as those burned in the exit transaction to the specified layer 1 address.

This process has a way lower latency than the one used for optimistic rollups, because the challenging period doesn't exist in ZK rollups.

6.2.3 L2 - L1 interaction

Similarly to optimistic rollups, the sequencers must compute the Merkle tree of the state of the rollup, and send its root along with:

- The Merkle root old state.
- The transactions (this time without inputs).
- The validity proof.
- The Merkle root of the transactions in the batch.

to the layer 1 smart contract.

When the smart contract receives the batch, it will execute the validity proof, check the old state and, if everything matches, update the rollup Merkle tree root in its storage [dionysius, 2023].

6.2.4 Intuition on the validity proofs

Validity proofs are complex cryptographic objects that allow to demonstrate the truthfulness of a computation-based statement in way less time than executing the full computation.

In the case of ZK rollups, the statement to prove is that, given the computation deriving from the list of transactions in the batch and the old state, we get to the proposed new state.

For costs reasons, it is not possible to run the full computation of the batch (it would defeat the purpose of ZK rollups), therefore we want to translate this problem into an easier-to-compute mathematical problem, where the transactions become values to plug in a set of equations, so that these mathematical equations are satisfied.

One way to do so is to use the PLONK scheme [Buterin, 2019], or ZK-STARK [Aleksander Berentsen, 2022].

6.2.5 ZK rollups and videogames

ZK rollups share a lot of features with optimistic rollups:

Improved scalability ZK rollups help with blockchain scalability, by operating on a smaller blockchain and only communicating with the layer 1 blockchain in batches.

Reduced layer 1 fees ZK rollups share the fee of the layer 1 transactions among all the transactions in a batch.

Transparency and fairness In a ZK rollup context, operations still happen on a public blockchain with a consensus algorithm.

Decentralization and security These 2 are directly inherited from the layer 1 blockchain, thanks to validation proofs.

Moreover, ZK rollups do not suffer from the 2 main problems identified in [Optimistic rollups and videogames](#):

~~**High fees**~~ ZK rollups further reduce the fees compared to optimistic rollups, since layer 2 transactions inputs must not be stored as calldata.

~~**Withdrawal time**~~ ZK rollups, thanks to validity proofs, do not have a challenge period. Exiting a rollup takes as much time as waiting for the sequencer to update the layer 1 smart contract, and the smart contract transaction to be included in a block on layer 1.

For these reasons, ZK rollups are, in the majority of cases, the most suited layer 2 blockchain type to implement videogames.

Part III

Starknet

Starknet is one of the most successful implementations of ZK rollups. It uses Ethereum as layer 1.

7 Starknet actors

Starknet organizes its participants in various roles [[StarknetCommunity, 2022](#)]. Each role carries out one of the tasks needed to make ZK rollups work.

At the moment some of the roles present in Starknet are centralized for development reasons, but the core concepts of each role do not make any centralization assumption, and in the future will be decentralized.

7.1 Sequencers

Sequencers can be compared miners, since their tasks are:

Aggregation They have to collect and store in a pool transactions from users.

Batching They have to group transactions together into batches, and decide when to close a batch. This decision can be taken based on the number of transactions received, or on the time elapsed since the last batch.

Execution Once they form a batch, they have to actually execute the transactions to update the state.

At this point, sequencers have to pass the block they've created to provers.

7.2 Provers

Prover must supervise the work of sequencers and communicate with the layer 1 smart contract:

Execution check Provers execute some sampled transactions they received in a block a second time, to check sequencers work.

Proof generation Provers have the task to generate the zero-knowledge proof to demonstrate a correct handling of the execution of the transactions.

Communicating with layer 1 Finally they have to send the batch of transactions and the proof to the layer 1 smart contract.

7.3 Nodes

Nodes are the auditors of Starknet. Their tasks are:

Replaying Nodes can replay old transactions to ensure their correctness.

Storage Nodes can store the blocks produced by the sequencers and provers, to guarantee availability in the layer 2 blockchain.

Checking proofs Nodes can also check the proofs provided by the provers. This is a cheaper way compared to replaying transactions to guarantee the honesty of the provers.

Part IV

Appendix

8 Merkle trees

A Merkle tree is a binary tree data structure where [Buterin, 2014]:

Leaves A leaf is labeled with the hash of a block of data.

Internal nodes An internal node is labelled with the hash of the label of its 2 children.

This kind of structure is very useful in distributed systems, because it allows to verify data integrity very efficiently.

Indeed, to check data integrity, it is sufficient to compare the hash contained in the roots of the Merkle trees, since it is dependant on all of its children (direct and indirect). Moreover, in case the roots don't match, it is possible to rapidly identify the corrupted data, by descending in the tree and following the paths where the hashes do not correspond.

In the blockchain context Merkle trees are extensively employed, for example:

Block headers Block headers contain the root of the Merkle tree built with all the transactions inside the block.

Simple payment verification The presence of the Merkle root in the header of blocks, allow for a lightweight algorithm to verify the existence of a transaction T:

1. The lightweight node L fetches only the headers of all the blocks of the blockchain from full nodes (headers are orders of magnitude smaller than full blocks).
2. L asks the Merkle proof (see section 8.1) for the transaction T to full nodes.
3. Now L can easily verify whether the Merkle proof is valid, by simply calculating the Merkle root and searching for it in one of the headers he previously fetched.

8.1 Merkle proof

A Merkle proof is a cryptographically sound demonstration that a certain item belongs to a particular Merkle tree whose root is known.

If a verifier V wants proof from W that item C is part of the Merkle tree M whose root is known, it can ask W to send, for each level of M, the *missing children*.

Let's take the example of Figure 2:

1. W sent to V: $\langle D, H_{A-B}, H_{E-H} \rangle$.

2. Now V has all the information compute $H_{C-D} = \text{hash}(C \cdot D)$.
3. Now V has all the information compute $H_{A-D} = \text{hash}(H_{A-B} \cdot H_{C-D})$.
4. Finally V has all the information compute the Merkle root $H_{A-H} = \text{hash}(H_{A-D} \cdot H_{E-H})$.
5. At this point V can verify if the known Merkle root matches with H_{A-H} .

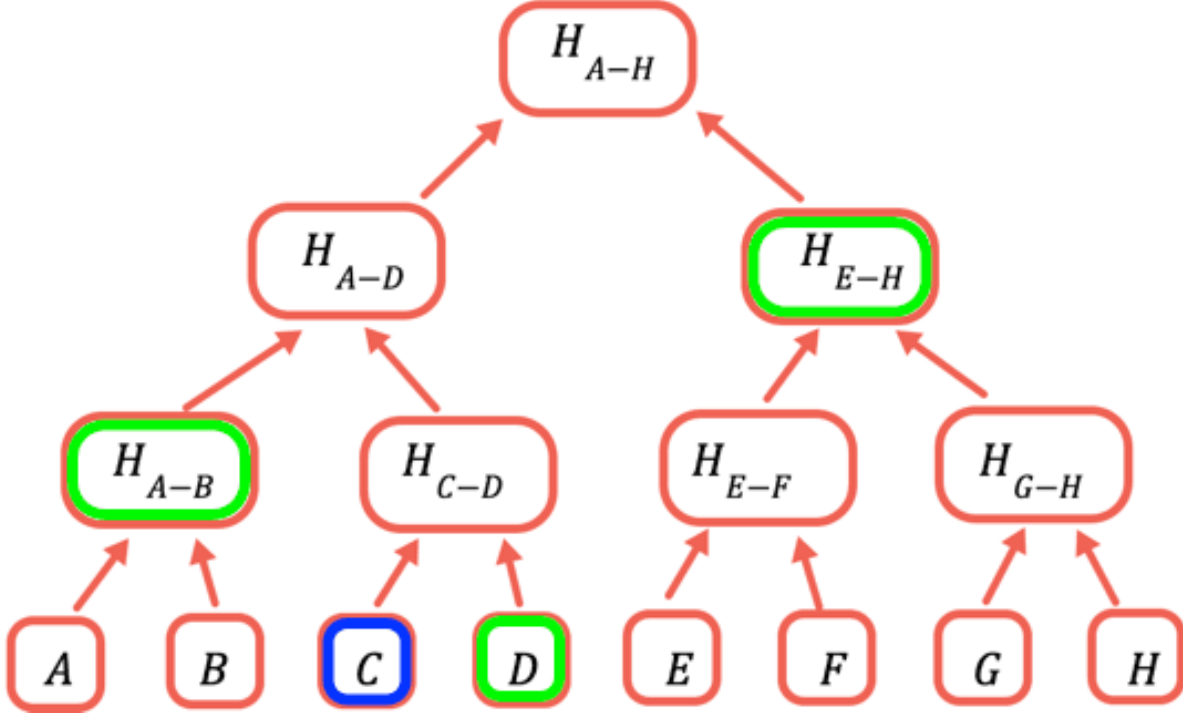


Figure 2: An example of a Merkle proof from [Pomerantz, 2021].

This works because W cannot produce fake *missing children* in order to obtain a desired root, since the hash function is non-invertible.

The usefulness of Merkle proofs lies in the fact that it is sufficient to exchange an amount of information that is logarithmic compared to the number of items in the set.

In the previous example, only 3 items were exchanged: $\langle D, H_{A-B}, H_{E-H} \rangle$. If data wasn't organized in a Merkle tree, all the items $\langle A, B, D, E, F, G, H \rangle$ should have been exchanged to compute the final hash.

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