

Blockchain Layers

Blockchain technology has been around for more than a decade and is the backbone of the cryptocurrencies we have in existence today, with the most popular and valuable being Bitcoin. It is made up of an unbreakable chain which consists of blocks of data, each containing an array of transactions and securely linked to the previous block using cryptographic techniques. At its core, the blockchain consists of layers (components and subcomponents) that form a complete blockchain system. Each of these layers has a unique role, such as storing data, maintaining network connectivity, and, among others, ensuring consensus across the system. This article aims to simplify the complexity of the blockchain architecture and protocol by breaking down its layers and their corresponding functionalities.

Understanding the Blockchain Layers

There are two distinct ways to understand the layers of blockchain technology. The first way is to understand the blockchain architecture with its different layers and how they work. This architecture is made up of five layers, which are: the hardware (or infrastructure) layer, the data layer, the network layer, the consensus layer, and the application layer.

The second way lies in understanding the categorization of the blockchain network based on protocol, which defines the set of rules that govern the network. The blockchain protocol consists of four layers, namely: Layer 0, Layer 1, Layer 2, and Layer 3. We'll take a look at each of these separate layers in detail.

The Blockchain Architecture Layers

1. The Hardware (infrastructure) Layer

This is the most fundamental layer of a blockchain architecture. It consists of hardware or physical components, such as computers, network and data servers, and network connections, that process and store ledger transactions. Blockchain platforms operate based on peer-to-peer networks or peer-to-peer sharing of data. This means nodes (a computer or network of computers) on the blockchain network can interconnect to exchange and share data. This results

in the creation of a P2P network, that is, a blockchain where individual node computes, validate, and record transactions in a systematic manner in a shared ledger. Also, each node is authorised to randomly monitor data during transactions.

The infrastructure layer is responsible for facilitating a system where each node on a blockchain network can act as both a server and a client that validates and updates freshly mined blocks. This system provides a shield for the blockchain crypto ledger against unauthorised access by ensuring that verified blockchain transactions are stored in a decentralized way. Also, the hardware layer includes virtual machines, which function like operating systems and are necessary for hosting smart contracts.

2. The Data Layer

This a secure and stable blockchain layer that is primarily concerned with storing transaction information. It accommodates the blockchain, a linear succession of hashed blocks that carry transactional records. Once a certain number of transactions have been validated by the nodes, they are added to the first block known as the Genesis block. Thereafter, every new block added to the chain is iteratively linked to the Genesis block. Every block carries essential details such as the previous block's hash, the Merkle tree's root hash, timestamp, and other relevant data. This ensures the integrity and immutability of the blockchain system. Contingent on the specific blockchain, the data structure can vary from a simple transaction list, which is used by Bitcoin, to a more complicated structure, such as Ethereum State Trie, which stores account and contract state information.

The data layer is where the majority of cryptographic primitives used in the protocol – public-private key pairs, signature algorithms, and cryptographic libraries – are specified and are to be tied to stringent security standards. To secure the data in a blockchain, every transaction is “digitally signed” using a private key created and held in the sender's wallet. A public key is tied to a wallet address, and the private key is used to sign transactions and grants control over assets associated with that wallet. Since the private key is only accessible to the sender, it guarantees that data cannot be seen or modified by any other person.

One of the major importance of the digital signature is that it detects information manipulation, and the presence of any manipulation will make the signature invalid. Also, digital signature protects the owner or sender's identity because they have been encrypted for utmost security, which in blockchain jargon is referred to as "finality." Cryptographic signatures are generated using two of the most popular cryptographic algorithms: Rivest–Shamir–Adleman (RSA) and Elliptic Curve Digital Signature Algorithm (ECDSA).

3. The Network Layer

This is the third layer of the blockchain architecture which handles inter-node communication within the blockchain network. It is also known as the P2P layer or the propagation layer because it facilitates node detection and connection and generation and addition of blocks to the blockchain. The network layer is tasked with managing and maintaining the blockchain's network and distributing data throughout the network. It is also involved in transaction validation by ensuring that each node communicates and reaches an agreement on the legitimacy of the transactions.

With blockchain being an open system, the network layer ensures that every node on the P2P network can discover each other and establish quick communication and data synchronisation.

4. The Consensus Layer

The consensus layer is critical to the existence of the blockchain. It sets the consensus rule necessary for transaction authentication between nodes and is responsible for the critical functionality of the blockchain. Without this layer, transaction validation cannot occur, leading to system failure. The consensus layer implements the protocol for block mining and processing and outlines the requirements for validators, which vary across proof-of-stake (PoS), proof-of-work (PoW), and other consensus mechanisms. This layer also features a propagation protocol for broadcasting decisions and protocol audits which protects against threats such as the 51 % attack.

In this layer, consensus is achieved in a decentralized way, meaning no central authority is needed. Numerous nodes control transaction data, making it impossible for a single node to add a transaction to the blockchain. These nodes must all agree or come to a consensus on the legitimacy of a transaction before it can be processed and recorded. This level of verification lowers, to the barest minimum, the risk of adding fraudulent transactions to the blockchain. However, if the consensus layer fails, it also means the entire blockchain system fails.

5. The Application Layer

The application layer serves as the front end of the blockchain and comprises programs that end-users take advantage of to communicate with the blockchain network. It is the layer in the blockchain on which apps and services are built and which consumer devices easily interact with. The application layer allows developers to develop new applications and services that leverage the secure, transparent, and decentralized nature of the blockchain.

This layer is further subdivided into the application layer, the execution layer, and the semantic layer. While the application layer initiates transactions, the execution layer conducts the verification process, and the semantic layer finally executes them. Decentralized applications (dApps), smart contracts, wallets, chaincode, frameworks, NFT (non-fungible token) platforms, user interfaces (UIs), APIs (application programming interfaces), and scripts all make up the programs and services in the first two layers.

The blockchain network functions as the back end technology for these applications and they communicate with it through the help of APIs. In other words, the blockchain network serves as a database or data storage these applications can access and fetch data from using APIs.

The Blockchain Protocol Layers

Layer 0

Layer zero (L0) is the blockchain itself. This layer contains the digital technologies (the hardware, network protocols, connections, and other components) that are required to implement blockchain technology. It is the foundation upon which all the other layers are built. L0 is the

initial blockchain layer that enables Bitcoin, Ethereum, and other blockchain networks to function. In addition to this, this layer makes blockchain networks accessible and interoperable. This means networks created using the same Layer 0 protocol can establish automatic communication with each other without using special bridges.

L0 also handles cross-chain interoperability and communication from the top layer to the other different layers. It allows blockchains to communicate with one another and build on the functions and use cases of each other by using diverse transfer protocols between chains and L0s, which often leads to faster transaction times and enhanced efficiency. It is at Layer 0 that cross-chain interoperability protocols (CCIPs) are implemented. This makes it possible for interoperable blockchains to seamlessly transfer information and tokens that are, to some extent, incompatible. Examples of CCIP projects that make off-chain data available to applications and blockchains include Chainlink, Polkadot, and Cosmos.

Layer 1

Layer one (L1) consists of foundational and self-sustaining blockchains. It is also known as the implementation layer and is made up of mostly public or permissionless blockchains that are designed to easily read or add financial transaction data and prevent changes to the existing ones. L1 is in charge of a blockchain network's basic functionality and fundamental operations such as programming languages, consensus mechanisms, dispute resolution, block time, and rules and parameters that govern a blockchain. Bitcoin and Ethereum are the two dominant blockchains in Layer 1. Others include Solana, Cardano, Litecoin, Binance Chain etc.

Each blockchain employs a different consensus model to establish an agreement on the kind of data to add, together with smart contracts to automate transactions without the interference of a third party. Smart contracts, unlike decentralized applications, are autonomous programs that users can't interact with directly. Some smart contracts, like that of Bitcoin, only support basic payments, while others, like that of Ethereum, enable developers to create sophisticated applications.

The numerous tasks that Layer 1 must handle and manage frequently cause scalability issues. As more users enter a blockchain, it increases the workload and the amount of computational power

required to solve certain cryptographic problems and add new blocks to the chain. This leads to higher gas fees and longer processing times. The quest to somewhat mitigate these scalability concerns has led to the development of improved consensus techniques, such as proof-of-stake (PoS), and the advent of sharding (computing and database operations partitioning used with distributed registries on blockchains). These methods, however, have been historically proven to be insufficient.

Layer 2

Layer two or L2 are the overlapping networks that sit directly on the base Layer (L1) of the blockchain ecosystem and continually exchange information with it. Because they rely on infrastructure from Layer 1 blockchains, they are usually more scalable and efficient. Also, they can handle high transaction volumes and lessen the load on the underlying blockchain network. Layer 2 solutions have several options for their implementation: sidechains, state channels, ZK rollups, and nested blockchains. Many developers find ease working with L2 solutions because they are designed to bypass the limitations of scalability, isolation, and low flexibility.

For example, Bitcoin Layer 2 blockchains include Bitcoin Lightning Network and Stack, while Ethereum's Layer 2 blockchains include Polygon, Arbitrum, and Optimism. All of these L2 blockchains are faster and cheaper compared to their L1 blockchains. However, L2s are more centralized due to their smaller size. This dependence on their underlying blockchains means that L2s can't run when L1s are down. On the flip side, the majority of L2s are experimental networks that are just being implemented with no guarantee that they will be as secure as L1 blockchains.

Layer 3

Layer three is the last layer and the application layer of the blockchain protocol. It hosts decentralized applications (dApps) and many other protocols that facilitate other blockchain-based applications and services that users interact with. DApps are software applications that are designed to run on a blockchain network, offering a secure, transparent, and autonomous user experience. They range from applications as simple as cryptocurrency wallets

to complex financial applications such as decentralized exchanges (DEXs), money markets, prediction markets, lending protocols etc.

DApps are typically built on top of different blockchains, with each blockchain employing a different consensus technique and having different smart contract capabilities. While Bitcoin is not suitable for Layer 3 applications, Ethereum remains the most popular blockchain for decentralized applications as it has over 2700 dApps with more still being developed.

Layer 3 applications act as the user interface or front end while masking the technical aspects of their communication with their underlying blockchains and other protocols. It is still further divided into two significant sub-layers: application and execution. Just as explained in the layered structure of blockchain architecture above, L3 applications and services are what give blockchains their real-world applicability and usability.

Cross-chain Interoperability

In the context of blockchains, cross-chain interoperability refers to the ability of disparate blockchain networks to communicate, exchange data, and execute transactions with each other. It enables the seamless transfer of data and assets between different blockchain networks, eliminating the need for intermediaries and centralized exchanges. Blockchain interoperability is founded on cross-chain messaging protocols, which enable read/write operations between multiple different blockchains.

In 2022, the blockchain interoperability market was valued at USD 275 million. As of 2024, this market is experiencing robust growth and has been projected to soar to around USD 2.88 billion by 2032. Factors responsible for fueling this growth and expansion include advancements in decentralized applications (dApps), the growth of decentralized finance (DeFi), and increasing demands for cross-chain asset transfer. Based on the emphasis of various industry leaders and sources, blockchain interoperability is crucial for: improved scalability and efficiency, enhanced accessibility and liquidity, and among others, innovation and collaboration in financial services.

The use of Layer 2 protocols is one of the pivotal and notable solutions for facilitating cross-chain interoperability in blockchain networks. These protocols constitute a secondary layer

blockchain that processes transactions and logs them unto the underlying blockchain. By processing transactions on a secondary layer blockchain, these protocols alleviate the load on a primary blockchain, enhancing its scalability and throughput and boosting its overall network performance. Also, Layer 2 solutions, such as sidechains and other interoperability protocols, can enable cross-chain transactions and asset transfers between different blockchains.

Conclusion

Understanding what blockchain layers entail involves understanding them in two distinct ways: blockchain architecture layers and blockchain protocol layers. The former is made up of five layers while the latter consists of four layers, all of which has been explained in detail. Collectively, these layers define the functionality and operations of blockchain networks, such as Bitcoin and Ethereum. Cross-chain interoperability enables blockchain networks to seamlessly interact, exchange data, and conduct transactions with each other. Layer 2 protocols constitute one of the most pivotal and broadly recognized solutions to facilitate blockchain interoperability, as they enhance the scalability and overall performance of the different blockchains.