

# Design paradigms and efficiency trade-offs in blockchain frameworks: a comprehensive comparative

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**Abstract.** The spread of Distributed Ledger Technology (DLT) beyond its roots in cryptocurrency has led to a proliferation of blockchain frameworks with differing architectural philosophies, performance attributes, and applications in mind. This non-uniformity poses a significant problem for enterprises and developers who aim to find the best platform that suits them. The paper is based on a rigorous, multi-dimensional comparison of the four most crucial blockchain frameworks that encompass the breadth of the current DLT: Ethereum as an early smart contracts and decentralized application pioneer, Hyperledger Fabric for permissioned blocks designed to work in enterprise consortia, R3 Corda as a privacy-oriented ledger that is suitable to regulated industries, and Solana as a high-performance public blockchain that was developed to support web-scale applications. The paper breaks down the major architectural building blocks of each framework, including their permissioning models, data models, consensus models, and execution environments for smart contracts. Next, it compares their scalability and performance by combining the findings of notable benchmark experiments with relevant performance metrics (throughput and latency). Moreover, the paper investigates practical adoption by examining notable examples in financial services, supply chain management, and the fundamental growth of the Web3 economy. The most valuable output of this study is a synthesized framework selection matrix, which aligns platform abilities with the particular business and technical requirements as an evidence-based (observed in the field) guide that practitioners can use; at the same time, it will serve as a well-structured point of departure in future academic studies and research on the topic of distributed systems.

**Keywords:** Blockchain Frameworks, Distributed Ledger Technology, Smart Contracts, Scalability.

# 1 Introduction

## 1.1 Distributed Ledger Technology Beyond Cryptocurrency

The idea of blockchain technology and its application as the backbone of the Bitcoin cryptocurrency first emerged, was introduced into practice, and has since been radically transformed [1]. Initially, it was conceptualized as a peer-to-peer electronic cash system; its essential concepts of decentralization, immutability, and cryptographic protection have proliferated to practically any field as its core has become a system of tamper-evident and decentralized digital shared ledger maintained by a distributed network of participants that do not require a central governing party or a third-party enforcing party. The paradigm shift enabled by blockchain technology has spread across all sectors, with applications in finance, supply chain, healthcare, governance, and more.

The second wave of blockchain platforms [2] (led by Ethereum) introduced the concept of smart contracts, 12 self-executing programs run on the blockchain that implement the terms of a contract and automatically execute when the conditions are met, effectively programmable money.

That programmability had turned the blockchain into a worldwide, decentralized computation platform, enabling the creation of intricate Decentralized Applications (dApps) and inventions such as Decentralized Finance (DeFi) and Non-Fungible Tokens (NFTs).

## 1.2 The Framework Dilemma Heterogeneity Challenge

The blistering growth of DLT has already led to a heterogeneous, fragmented platform of diverse blockchain architectures. This diversification poses a central strategic dilemma for organizations: there are many trade-offs in the blockchain platform world, which means choosing the most appropriate blockchain architecture for a given application is a complex strategic decision that must consider long-term consequences. On the other hand, permissioned frameworks are privacy- and throughput-sensitive and are more centralized in control [3].

The insufficiency of the existing literature lies in meaningful, siloed studies that describe a range of facets of a single platform or compare a very narrow set of frameworks. A felt absence of systematic studies that fully compare the architectural, performance, and application dimensions of the platforms has been noted.<sup>6</sup> It is harder to make an informed evaluation of a framework when the features of that framework are not well aligned with the business needs of the decision-maker. To fill this gap, this paper will conduct a comparative analysis of four exemplary and dominant blockchain frameworks.

## 1.3 Contribution and Structure of the Analysis

This critical research paper presents a systematic, multi-part, and comparative examination of four dominant blockchain frameworks (Ethereum, Hyperledger Fabric, R3 Corda, and Solana). The platforms have been selected intentionally because they reflect the most significant archetypes that are present in the present DLT ecosystem:

**Ethereum:** A permissionless, decentralized platform that is focused on optimizing decentralization and security and used as a settlement layer globally.

**Hyperledger Fabric:** A permissioned and private blockchain framework aimed at being a modular operating system that provides enterprise applications with confidentiality and flexibility.

**R3 Corda:** Permissioned, private, and unique DLT designed in a harmonious way to suit the needs of regulated sectors, specifically the financial segment, with a primary emphasis on privacy.

Solana is a permissionless, publicly accessible platform designed to perform and scale to extremes, focusing on high-throughput Web3 applications.

This paper examines the core design decisions and trade-offs in blockchain systems by deconstructing four frameworks. This paper is organized as follows: Section 2 describes the architectural paradigms underlying the classification of blockchain frameworks. In section 3, there is a detailed technical deconstruction of each of the four platforms. The quantitative comparison of their scalability and performance is presented in Section 4 based on published benchmark results. In Section 5, we set out to understand how they are implemented in major industries, using those real-life examples. Section 6 provides a summary and formulation of the findings, organized in a 2-by-2 matrix of selection frameworks and future trends. Lastly, the paper is concluded in Section 7. The comparison shown in Table 1 is a rough comparison of the frameworks in question at a high level.

**Table 1.** High-level framework comparison

Framework	Type	Primary Consensus Mechanism	Native Currency	Primary Smart Contract Language
Ethereum[4]	Public, Permissionless	Proof-of-Stake (Gasper)	Ether (ETH)	Solidity, Vyper
Hyperledger Fabric[5]	Private, Permissioned	Pluggable (e.g., Raft)	None (can be created)	Go, Java, Node.js
R3 Corda[6]	Private, Permissioned	Notary-based (Uniqueness)	None not intended	Java, Kotlin
Solana[7]	Public, Permissionless	Proof of History + PoS Tower BFT	SOL	Rust, C, C++

Table 1: Comparing High-Level Framework. The table provides a succinct overview of the main features of the four chosen blockchain frameworks and serves as a reference point for the more insightful examination presented further.

## 2 Literature review

A blockchain framework is based on a set of foundational architectural decisions that determine what it can do, how well it can do it, and its appropriateness for various applications. To make a meaningful comparison, one must understand the following paradigms: permissioning, state representation, and innovative contract execution.

## **2.1 Permissioning Models: Public and Private and their Systemic Effect**

The permissioning structure [8] is the most basic distinction between blockchain networks, determining how people engage with the network and in what capacity. This decision continues down the whole structure transport, affecting the consensus strategy, the brokenness of trust, and the functionality profile.

Permissionless Blockchains: Public and Permissionless blockchains, such as Ethereum and Solana [9], enable anyone to join their networks, participate in the consensus mechanism, and view the ledger without permission from a centralized authority. The security of such systems does not rely on participants' identities, which are often pseudonymous, but rather on the cryptographic incentives of the protocol itself. These systems use computationally expensive consensus mechanisms to guarantee network security against malicious parties (e.g., to prevent a potentially devastating attack known as a "Sybil attack," in which a single entity uses multiple identities to cause havoc). Historically, this was Proof-of-Work (PoW), which involved immense computational power ("mining"). More recently, platforms have moved towards Proof-of-Stake (PoS), where participants (validators) lock up capital (a "stake") to participate, making attacks prohibitively expensive. The main benefit of this model, therefore, is its high level of decentralization and censorship resistance; it is therefore suitable where such properties are most desirable, such as open, worldwide participation.

Consortium Permissioned Blockchains, including Hyperledger Fabric and R3 Corda [10], are used only by a pre-approved list of known and identified parties. The consortium of businesses usually uses these to address a common problem. This trust model is a mix of technological and relational types, supported by various legal agreements that bind the consortium's members. The onboarding process, e.g., Fabric Membership Service Provider (MSP), uses a Public Key Infrastructure (PKI) to issue verifiable credentials, or Corda Doorman is used to screen entities before entry into permissioned chains, thus avoiding computationally expensive mining. Instead, they use more efficient, deterministic consensus algorithms such as Raft (crash-fault tolerant) or variants of Byzantine Fault Tolerance (PBFT) (malicious node tolerant). The architectural decision directly leads to much higher transaction throughput and lower latency, making permissioned frameworks a good fit when performance and privacy are paramount. Such frameworks, such as Hyperledger, do the same.

Semi-private blockchain that runs under the governance of many institutions instead of one sole institution, i.e., Consortium Blockchain model that possesses some aspects of both private and public networks.

## **2.2 Account-Based Ablation: Comparative Analysis of the Account-Based Data Model and UTXO-based Data Model**

Another essential architectural distinguishing feature of a blockchain is the mechanism it uses to track its ownership and store the system's state. These two models are the account-based model and the Unspent Transaction Output (UTXO) model [11]. This option introduces a fundamental trade-off between programmability and the level of intrinsic privacy.

Ethereum and Solana use the Account-Based Model, which is an analog to a traditional bank account model. A common form of the account is an Externally Owned Account (EOA) [12], which is controlled via a private key, and other Account types are Contract Accounts, which are controlled via their code. A transaction is processed via a direct debit from the sender and a credit to the receiver's account. The main strengths of this model are that it is intuitive for developers and reduces the heavy smart contract logic. Because contracts can easily read and write to this global state, it forms a highly composable environment in which dApps can easily interact with each other, as illustrated by the dense DeFi ecosystem on Ethereum. But

because contracts can read and write to this global state, it raises privacy concerns. All nodes in the network must process all transactions to ensure a unified picture of the world state, meaning the entire transaction data will be public on the ledger. Privacy, consequently, must be implemented as an add-on feature rather than a native property. Ethereum stores its world state in a complex data structure called a modified Merkle Patricia Trie. In contrast, in Solana, everything is folded into accounts, each with a defined program owner who controls its dynamic state.

The Unspent Transaction Output (UTXO) Model, which was initially incorporated into Bitcoin and later adopted by R3 Corda, works differently. It does not have any global account state. Instead, the ledger is composed of a list of UTXOs, which are immutable, discrete pieces of state. A transaction consumes some existing UTXOs as inputs and generates new UTXOs as outputs. So, to send three tokens out of 10, a transaction would consume the 10-token UTXO and create two new UTXOs: one of 3 tokens to the recipient and one of 7 tokens as change to the sender. By modeling transactions in this way, the primary advantage of privacy-by-design is achieved. The UTXO model exploits the need-to-know-only sharing of transactions, since there is no world state to update. UTXO model is therefore best suited to enterprise and financial applications where confidentiality is a hard requirement. The concession is that complex, stateful logic may be awkward to program compared to the account model, since developers must manually sequence transactions to keep track of states.

### **2.3 The execution of Smart Contracts: The EVM to Parallel Runtimes**

The execution context of smart contracts is a significant part of a blockchain's architecture, as it determines its programming model, performance, and security.

Ethereum Virtual Machine (EVM) [13] is the most popular execution environment. It is a stack-based virtual machine that interprets smart contract bytecode and executes it; it is a quasi-Turing-complete, sandboxed, architecturally stack-based machine with a resource-based accounting mechanism. Because of its sandboxed nature, the host device and other contracts are blocked and cannot be interfered with by a contract operating in the EVM. To make all nodes in the network produce the same result when executing a contract (determinism), it has an intentionally minimal instruction set that does not entail operations with unpredictable evaluations. Each computation operation has a fixed gas price, and the transaction must provide sufficient gas to cover its entire execution. In the case of gas exhaustion, a transaction is rolled back; however, the fee is still paid to a validator.

Hyperledger Fabric is more permissive. It lacks an indigenous virtual machine. Instead, it implements industry-standard Docker containers to isolate and run smart contracts, which it refers to as chaincode. This architecture enables developers to use their general-purpose programming tools (such as Go, Java, and Node.js) and to access existing libraries and developer talent. This flexibility, however, introduces the possibility of non-deterministic code (i.e., the use of a random number generator that produces different outputs on different computers). The fabric explicitly tolerates this, since it has a unique architecture of execute-order-validate. Transactions are initially applied and seconded by peers, then sorted, and finally confirmed by all investing peers. All non-deterministic results for transactions will be rejected during the final verification without halting the entire network.

R3 Corda has built its execution environment on the Java Virtual Machine (JVM), enabling CorDapps to be written in existing enterprise languages such as Java and Kotlin. R3 Corda has done this to lower the adoption barrier for enterprise developers. An original aspect of Corda's innovative contract model is that, along with the code to be executed, legal prose is included as an inseparable part of it, resulting in a combined code-and-prose arrangement commonly referred to as The Ricardian Contract. This aims to reduce liability arising from

the legal agreements he or she studied and automated enforcement, with a layout and design specific to the needs of the highly regulated financial services sector.

Solana introduces a high-performance runtime, Sea Level, designed to model massive parallel operations. Unlike EVM, which processes transactions one after another, a single Sea level core could execute thousands of non-overlapping transactions simultaneously across many different CPU cores. This is done because transactions in Solana must specify, ahead of time, every account (state) they will read or write [14]. The runtime can leverage this information to create a dependency graph and schedule all transactions that do not conflict in state access to run in parallel, thereby multiplying network throughput by several orders of magnitude.

**Table 2.** Comparative analysis

Ref.	Focus Area	Methodology / Framework	Application Domain	Strengths	Limitations	Research Gap
[5] S. Liu et al. (2021)	Blockchain for teaching frameworks	Blockchain-enabled double-precision framework for secure teaching-resource sharing	Smart Education / E-Learning	Reliable data, transparency, multi-party trust	Limited to teaching environment ; scalability untested	Lack of generalizable education blockchain models across institutions and absence of integration with adaptive/AI-based learning
[6] M. S. Farooq et al. (2022)	Agile software dev. with blockchain	Distributed agile framework with blockchain audit trail	Software Engineering / DevOps	Accountability, secure collaboration, immutable records	Overhead in agile sprint cycles, integration complexity	Absence of lightweight blockchain protocols tailored for agile; no empirical large-scale validation in industrial projects
[7] W. Jie et al. (2024)	Offline blockchain payments	Offline protocol with signatures & tokens	Financial Transactions	Works without internet, security & flexibility	Infrastructure dependency, latency in verification	Need for cross-border interoperability, energy-efficient offline protocols,

						and integration with CBDCs/IoT payments
[8] M. Touloukou et al. (2024)	Blockchain benchmarking	Experimental deployments of XRPL vs Ethereum	Blockchain Benchmarking	Comparative insights, efficiency differences	Benchmark limited to 2 platforms	Gap in comprehensive benchmarking covering next-gen chains (Hyperledger, Polkadot, Solana) and real-world workloads
[9] C. Li et al. (2025)	Edge + blockchain for metaverse	Privacy-preserving outsourcing framework	Metaverse / Edge Computing	Ensures privacy, accountability, trust	Heavy computation at edge nodes, energy inefficiency	Lack of lightweight consensus models for mobile-edge; absence of QoE (Quality of Experience) analysis in immersive metaverse use cases
[10] Q. Ding et al. (2025)	Federated learning + blockchain	Double-layer blockchain for secure FL	Agricultural IoT / Smart Farming	Data integrity, secure model sharing, trust in FL	Blockchain-FL synchronization overhead, domain-spe	Data integrity, secure model sharing, trust in FL

### 3 Proposed methodology

This section provides a detailed technical analysis of each of the four frameworks chosen. Their actual architectural implementations, consensus and governance models, and security and privacy features [14] are dissected in the light of what has already been discussed in the earlier paradigms.

### **3.1 Ethereum: The Decentralized Settlement Layer (Decentralization, Security)**

Ethereum has become so synonymous with programmable blockchains that it is the platform that most dApps, DeFi, and NFTs use. It follows a decentralized, secure design philosophy, forming a strong, stable global settlement layer.

#### **3.1.1 Data Model and architecture :**

Ethereum World state is a shared global blockchain whose blockchain is based on the architecture of Ethereum through the use of Ethereum Virtual Machine (EVM). The data model is an account-based one that distinguishes between two forms of accounts [15].

Externally Owned Accounts (EOAs): These are user-controlled using personal secret keys. EOAs can initiate transfers of Ether (ETH) or execute smart contract code.

Contract Accounts: They are accounts governed by their smart contract code. They become operational when transacted by another contract or an EOA, and in response, they execute their code.

All of them are stored in the world state, a mapping from addresses to account states implemented as a modified Merkle Patricia Trie. The trie structure makes verification of state changes efficient, and data integrity is guaranteed. Every block in the Ethereum blockchain includes a header that has a root hash of three tries: the state trie, the transaction trie (capturing all transactions in the block), and the receipt trie (capturing the results of transactions) [16].

The EVM is the core of Ethereum's execution logic. Being a stack-based virtual machine, it executes a set of opcodes of compiled smart contract code. It is volatile.

storage to store temporary data about execution, and a durable storage (the portion of the world state maintained by the contract) to maintain state between transactions. This design, albeit addictive, processes transactions serially, which is one of its main scalability bottlenecks [17].

#### **3.1.2 Consent and Governance**

After the Sep 2022 Merge process, Ethereum switched to a more sustainable and PoW-based consensus model of Proof-of-Stake (PoS). The new version of the consensus protocol, known as Gasper, is an interspecific hybrid resulting from combining two important parts [20].

Casper FFG (Friendly Finality Gadget): The finality mechanism is called Casper FFG. An epoch (the slot period) is complete when the checkpoint (the start of the epoch) has been voted on by at least two-thirds of the total staked validators in two successive epochs. Finality refers to the impossibility of reversing the block and its history at the cost of the minimum unless at least one-third of the validators' stake is destroyed [18].

LMD-GHOST (Latest Message Driven Greediest Heaviest Observed Sub-Tree): This is the fork-choice rule being applied by validators in deciding the canonical chain head. How it works: It finds the fork that accumulates the most significant number of attestations (votes) by other validators.

It has a timeline subdivided into 12-second time slots [19], during which a validator is randomly selected to propose the block. Other validators will serve as attestors; they vote about the correctness of the proposed block. production of blocks can be achieved fast, but firm finality is ensured in the future.

The governance of Ethereum is an off-chain process in which changes to its protocol are proposed by an informal consensus among key stakeholders: core developers, node operators (validators), and, more generally, its community of users and application developers.

Ethereum Improvement Proposals (EIPs). Such proposals go through extensive discussion, debate, and experimentation within the community. Whether a proposal is adopted depends on whether node operators want to run the newer software. Such a model is much less centralized and may lead to slower decision-making compared to a more centralized system of governance [20].

### **3.1.3 Privacy and Security**

The level of decentralization that is extremely large and the economic incentive of PoS protocol serve as the foundation of security in Ethereum. This means that to attack the network, an attacker would need to control a massive share of the total stake in ETH [20], making such an attack economically unviable. Nonetheless, the high-level layer, i.e., smart contracts themselves, has proven to be high-profile in terms of vulnerability. There are common security vulnerabilities such as:

**Re-entrancy:** An attacker invoking a contract causes the contract they want to attack to be called before the initial invocation completes, allowing them to withdraw the same funds repeatedly (e.g., the DAO hack).

**Integer Overflow/Underflow:** This occurs when arithmetic is performed and the results exceed or fall below the highest or lowest values allowed by a data type, resulting in unintended interpretation.

**Transaction-Ordering Dependency (Front-running):** An attacker monitors the mempool, observes a pending transaction, and submits a transaction with a higher gas price so it can be executed first.

Ethereum mainnet does not have privacy as an intrinsic property. Each transaction and state are published as contracts, which is a significant concern in many enterprise applications. Ethereum privacy solutions are generally based on Layer-2 systems such as zk-Rollups, which employ zero-knowledge proofs to verify transactions without exposing the data they verify, or on application-layer solutions such as cryptographic mixers.

## **3.2 Hyperledger Fabric: The Enterprise Operating System (Modularity and Privacy)**

The Linux Foundation-hosted Hyperledger Fabric is an enterprise-level permissioned DLT platform [22]. It has a design philosophy of modularity, scalability, and confidentiality, and is thus described as a "distributed operating system" of confidential consortia.

### **3.2.1 Architecture and data model**

The Fabric architecture is an entirely different one to Ethereum architecture. It uses a special transaction flow model of execute, order, and validate to separate transaction execution activity with transaction order and validation activities. The result enables parallelism and use of general-purpose programming language.

**Client:** A program, which represents a user, and suggests transactions.

**Peer:** A node that holds the ledger, and executes chaincode. Peers may be endorsing peers that simulate a transaction and generate a signed endorsement, or the committing peers perform validation and application of transactions to the ledger.

**Orderer:** A node (or group of nodes) which defines the total order of transactions into blocks. The chain of transaction moves in the following manner:

**Execute (Endorsement):** A client also submits a transaction proposal to a group of endorsing peers specified in the endorsement policy of the chaincode. These peers run the chaincode in a Docker container, produce a read- write set and sign the set.

**Order:** The signed endorsements are gathered by the client and the transaction is delivered to the ordering service. The orderer groups transactions into blocks and publishes it to every peer.

**Commit (Validate):** Each peer gets the block and validates each of the transactions using the endorsement policy and the ledger-read-set consistency (to avoid doubles, coming of ledgers).

The ledger of fabric is developed into two parts:

**The Blockchain:** A ledger of all transactions (immutable, publicly viewable, append-only list of transactions) linked together in a hash-based chain.

**The World State:** A set of keys and values that hold the current value of the entire keys in the ledger. This serves to be a definitive snapshot of the current state so that there is no need to revert over the whole transaction record to perform efficient queries. Fabric supports two options of world state databases.

**LevelDB:** The embedded key-value store. It is very efficient where non-complex key-based searches are undertaken.

**CouchDB** An independent external JSON document store. Its strong point is provision of multimedia, complex queries over the state data through the use of chaincode API.

### **3.2.2 Governance and Consensus**

In Fabric, consensus is multi-stage and not monolithic [23]. It plays out with the aspects of endorsement, ordering, and validation. An important component of consensus is the endorsement policy, which is chaincode-specific. It stipulates what peers of what organizations should perform and sign a transaction in order to have it valid. This occurs even before the transaction is relayed to the orderer.

The ordering service is pluggable, and thus a consortium can select the most appropriate mechanism.<sup>12</sup> The main choices are:

**Solo:** A single node orderer that is only applicable in development and testing since it does not offer any fault tolerance.

**Raft:** A Raft-based consensus-based crash fault tolerant (CFT) ordering service. It is a leader-follower model, and it can withstand node failures (but not malicious, or Byzantine behavior). This is the production option that should be used.

At Fabric, governance is explicitly oriented to enterprise consortia and implemented [24] by a sturdy framework of policies and Membership Service Providers (MSPs). The latter issue and authenticate identities to/of an organization and map those identities to roles (e.g. who is an Admin, a client) using a PKI. Policies, which are set within the channel configuration, adjudicate policies governing everything from who can read or write to the ledger to how the channel configuration itself can be updated. The

Fabric v2.x chaincode lifecycle is even more decentralized, with governance involving multiple organizations to agree on (approve) a chaincode definition and an endorsement policy to make a chaincode committable to a channel and thus active.

### **3.2.3 Security and Privacy**

The basis of security is the permissioned model of Fabric. Participants are all identifiable, which means there is no potential of threatening pseudonym attacks as Sybils. The ethos of privacy and confidentiality is central to its design and this is accomplished in two main ways: Channels: Channels are those private sub-networks, where an isolated ledger is created, with only authenticated members of that channel able to see any data, chaincode and transactions within the channel [25]. Organizations not part of a channel cannot see any data, chaincode and transactions in that channel. This enables a consortium to develop several bilateral or multilateral streams of communication on a common infrastructure.

Private Data Collections (PDC): In situations where the set of organizations on one channel need to transfer data under privacy to the other members of the channels, a more fine-grained solution is through the use of PDCs. In this scenario, PDCs distribute the actual privacy data via the gossip protocol to only select authorized organizations. They have their peers storing the data in a separate private state database. Importantly enough, there is a limited number of young women being able to enjoy the benefits of the young female population.

The hashed version of the confidential information is passed, authorized, and captured on the mainframe ledger of the channel. Such hash acts as a proof of transaction that can be validated and be audited, without exposing confidential information in unauthorized members of the channels or ordering service.

### **3.3 R3 Corda: The Financial-grade Ledger (Privacy and Interoperability)**

R3 Corda is a permissioned DLT platform developed to address the requirements of regulated industries, especially financial services, on a ground-up basis into other areas of industry where regulatory requirements exist. It has an architecture that values privacy, security and interoperability among known business beings.

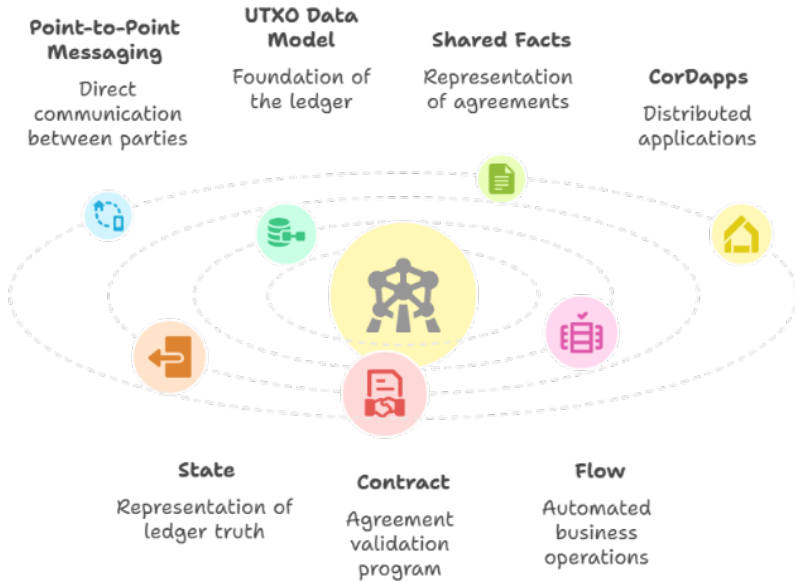
#### **3.3.1 Architecture and Data Model**

The architecture of Corda is beforehand and very different as compared to the traditional broadcasting-style blockchain design. It uses the point-to-point messaging system whereby transaction information [26] is not sent to all nodes in the network. Rather, only information on a need-to-know basis is shared among the parties involved in a transaction and a Notary. The UTXO data model is used as the foundation of the ledger. The ledger is a list of immutable data. Shared facts (could also be an IOU, a bond) are represented by shared sentences (or contracts). Transactions use existing states as inputs and create a new one as an output, thus providing a verifiable provenance of every asset. CorDapps are distributed applications packaged as JAR files that consist of the three main components: The first is Corda components This is a set of contract compatible artifacts defined by Corda components, and it may contain additional dependencies on other parts of the CorDapp[27]. The second is dependency overrides Dependency overrides is a subset of Corda components that is used in excess of a contract compatible part of the CorDapp. The third is a promise container A promise container is a set of promise descriptions, packaged together with a CorDapp, to facilitate predictable or simultaneous responses across

State: a representation of what is known and reasonable to hold to be true, on the ledger at a given moment. It carries out the ContractState interface.

Contract: A program that specifies the contract between the safe states. It approves a transaction and its inputs/outputs. It is an implementation of the Contract interface

Flow: A chain of commands that specify what business operations to perform with respect to a particular update to a ledger. The tool automates the contract gained, signed and notarized process among parties.



*Figure 1. Architecture and Data Model*

### 3.3.2 Consensus and Governance

Corda integrates its use of consensus in a way that is rather balanced and divided in two, due to prioritizing transactional validity over the ubiquitous ordering of blocks:

- This is done at the transaction level by participants themselves. A transaction should be validly digitally signed by all the needed parties (based on the commands of the contract) and be checked by the contract code in each node of the counterparts.

- Transaction Uniqueness: This is what is critical to avoid the issue of duplicate use of the same input state in two separate transactions (i.e. double-spending). Any consensus relating to the uniqueness of transactions is not addressed by all the nodes but is instead left to a special network service referred to as a Notary. When a transaction is successfully confirmed, it is sent to the Notary where it will either be accepted or rejected depending on whether some of the transactions are already used up. When not spent, the Notary signs the transaction and it records the inputs as used.

There are two ways in which notaries can be set up, and both vary in trade-off between privacy and validation:

**Non-validating Notary:** It just checks inputs uniqueness. It also does not view complete details on the transactions thus maintaining privacy.

**Notary Validation:** It ensures the unicity and validity of the contract. This necessitates the Notary to view the whole transaction and this provides the incremented level of trust as well as another line of validity.

The governance in Corda is provided at two levels. On the network level, a Doorman access control does KYC/AML checks on a node prior to allowing the node to join.

Business network Extensions enable an operator to build and administer a logical business network with any rules about membership, governance policy and authorized parties to run within the common Corda infrastructure [62].

### **3.3.3 Security and Privacy**

Corda is designed under the banner of privacy. The messaging architecture in Corda is point-to-point, and the UTXO allows transactions to be naturally confidential and only available to the parties participating in the transaction and in a limited manner to the Notary. It differentiates with broadcast-based platforms, essential to businesses that do not want their transactional activity to be made public.

Security is imposed in a number of levels Panoptic nature given to the network presided over by the Doorman gives all the participants a familiar place since they know each other. Communication is encrypted and all transactions must be expressed with the digital signatures of the legal identities of the concerned parties involved. The Notary service plays the essential role of resisting double-spends. The entire security model must be resilient to meet the strict demands of the financial market and it targets legal and regulatory compliance.

## **3.4 Solana: The High-Performance Engine (Speed and Scalability)**

Solana is a permissionless public blockchain that outperforms previous networks with drawbacks such as Ethereum. It is designed to be blazingly fast, highly scalable, and extremely low-cost transactions, which makes it an attractive platform in high-frequency usage scenarios like decentralized financial (DeFi) trading and transactions, gaming, and payments.

### **3.4.1 Architecture and Data Model**

The architecture of Solana is monolithic, and the goal is to reach massive scale without using Layer-2 scaling solutions or sharding. It supports this goal via a combination of eight core innovations, and the most significant of them are: Sealevel owes its (low-level) design to Solana which features a parallel smart contract runtime.<sup>45</sup> Whereas the EVM is single-threaded and thus can execute only a few dozen contracts at a time, tens of thousands can be done at once on Sealevel. This is because transactions declare ahead of time the account that they are going to read and the accounts that they will write. The runtime takes this information, and executes all the non-overlapping transactions in parallel, doing so efficiently utilizing multi-core processors.

Turbine A block propagation protocol that breaks blocks into smaller packets, which are fanned out to a locality of nodes. This enables the mapping of information to be done faster and efficiently avoiding the problem of the slow rate of transmission of information between stations across the network.

Gulf Stream: A protocol that evaluates on blockchain without the concept of a mempool. Validators will pass on transactions anticipated to be processed by future leaders to the current leader (this process will shorten the confirmation latency and memory adversity on a validator).

The Solana chain has an account-based data model; it is similar to Ethereum. All data maintained on the chain are in the form of account data; data include smart contract code and state.

accounts. The accounts contain a unique address, a balance of lamport (SOL) and a data field. The most important point is that each account has an owner and the owner is the program ID of the smart contract that is allowed to update its data. This model of ownership offers a well-defined security boundary to the state access.

### **3.4.2 Agreement and Government**

Solana is a hybrid consensus mechanism with the elements of Proof of Stake (PoS) and same with Proof of History (PoH) which is taking the center stage.

**Proof of History (PoH):** Proof of History is not a consensus mechanism, but it is required to run the consensus mechanism. Proof of history is a cryptographically secure clock that runs prior to consensus. This activity generates a verifiable chronology of events with a time. By timestamping and sorting the transactions as they appear, PoH minimizes the overhead of sending messages among validators who need to negotiate the ordering of transactions as that is the key bottleneck in other blockchains.

**Tower BFT:** This is the PoS-based algorithm of checking, which is implemented in the form of Solana Practice Byzantine Fault Tolerance optimized to PoH. The process of validating involves the staking of SOL by validators to help out in the security of the network. Tower BFT can use the trusted time source provided by PoH to work much faster than conventional BFT consensus implementation.<sup>2</sup> ilen population, overland transport routes, and pavement material change rapidly, and an additional caveat is that the entity moving the goods must be trusted. The system of governance that Solana uses is a combination of off-line and on-line protocols aimed to be community-designed, but expert-guided.

**SOL Holders and Validators:** These are the main participants of the governance. An SOL holder will be able to stake the tokens with validators and delegate their voting power. In case of changes in the core protocols, the opinions of the validators are weighed heavily. In the case of dApps that were created via the SPL Governance program, SOL stakeholders can vote on the proposals directly.

**Process of proposal:** Proposals usually take the shape of Solana Improvement Documents (SIMDs). Such proposals are heavily debated in the open (Discord, GitHub) before any recourse to on-chain voting. This is done to provide community feedback on a broad scale, with technical rigor, typically spearheaded by core developers such as Anza.

### **3.4.3 Security and Privacy**

Solana uses PoS as a proven method to secure its system, which gamifies honest actions as the economic interest of the validators is directly tied to it. Another layer of security provided by PoH clock is making it hard in order to forge the order or time of transaction. But at the same time, Solana has been based on trade-offs. The desire to seek high performance has also resulted in increased requirements on validators and a smaller number of validators than in Ethereum, raising certain concern about the level of decentralization. The platform has also had a number of network outages related to high traffic and bugs, which have raised some questions about its stability under load, although this has improved with time.

As with Ethereum, privacy is not built into Solana. Every data regarding transactions is available to the public. Privacy applications on Solana would have to be included at the level of application layer, which could be done via zero-knowledge proofs or other cryptography

**Table 3.** Detailed architectural comparison

Archite-ctural Feature	Ethereum	Hyperledger Fabric	R3 Corda	Solana
Data Model	Account-Based (World State Trie)	Key-Value (World State)	UTXO (Unspent States)	Account-Based
Smart Contract Environment	Ethereum Virtual Machine (EVM)	Docker Containers (Chaincode)	Java Virtual Machine (JVM)	Sealevel (Parallel Runtime)
Consensus (Ordering)	Proof-of-Stake (Gasper)	Pluggable (e.g., Raft)	N/A (Point-to-Point)	Proof of History (PoH) 4
Consensus (Validation)	Validators (PoS)	Endorsement Policy + Validation	Contract Logic + Notary (Uniqueness)	Validators (Tower BFT – PoS)
Privacy Model	Public by Default	Channels & Private Data Collections	Private by Default (Point-to-Point)	Public by Default
Governance Model	Off-Chain (EIPs, Community)	On-Chain Policies (MSP-driven)	Business Network Operator	Hybrid (SIMDs, On-chain Voting)
Identity Management	Pseudonymous (EOA Addresses) 33	PKI-based (MSP) 29	Certificate-based (Dooman) 12	Pseudonymous (Wallet Addresses) 35
Turing Completeness	Quasi-Turing-Complete 10	Turing-Complete 43	Turing-Incomplete (by design) 43	Turing-Complete

Table 2: A Detailed Comparison of architecture. This table details more precisely, the specific (feature) comparisons of the core architectural aspects of the four frameworks and allows a direct examination of the disparate design decisions.

#### 4 A quantitative comparison of performance and scalability

Architectural design is necessary since it enables the qualitative apprehension of the functionality of some framework, but quantitative performance would determine whether this framework would be viable in a practical setting. Transaction-per-second (TPS) values reported are sometimes used, but are hard to put into context. The performance of true performance is multifaceted with respect to the mechanism of consensus, intricacy of transaction, network and equipment. The section will specify important performance KPIs and evaluate the results of comparative benchmark tests to create a more detailed image of the performance and scale of each of the frameworks

#### **4.1 Defining Performance Key Metrics of Blockchain Systems**

An established protocol of performance metrics is required to compare the blockchain platforms in a systematic way. The most important indicators are the following:

**Throughput (Transactions per Second - TPS):** This is by far the most used, and it expresses the information of how high the network can confirm and validate transactions. It is an indication of how much processing the system can carry.

**Latency (Transaction Confirmation Delay - TCD):** This is the amount of time that passed between submission of a transaction to the network and its confirmation and finalization on the ledger. When applications might be user facing or financial systems, then low latencies are vital. Special consideration should be given to the difference between average and tail latency (99th percentile latency), which can tell more about your system in an overloaded condition.

**Scalability:** This is the extent to which the system shall concurrently endure its performance (according to its goals) with the rise in nodes, users, or transactions. It is the ability of the system to grow.

**Transaction Conflict Rate:** In parallel enable systems, this value indicates the rate at which warranted transactions attempt to access the same state and this can cause an abduction and re-thinking, appearing to the advent.

**Discussion on Measurement: Benchmark Results: Throughput, Latency, and bottlenecks**

A number of academic and industry surveys have compared these platforms and as shown by their architectural differences, there are major differences in performance gaps.

#### **4.2 Permissioned Performance vs. Permissionless Performance**

A shared result among all studies is that permissioned blockchains such as Hyperledger Fabric are much faster than the public permissionless blockchains such as Ethereum in the context of a private deployment of blockchains. A performance analysis conducted in advance provides similar results showing that Fabric constantly outperformed a private Ethereum network across all parameters, including the execution time, latency, and the rate of traffic. This permissioned model of Fabric can use efficient consensus algorithms such as Raft and can avoid the computational cost of mining or PoS staking, and the execute-order-validate model is effective since parallel execution can be performed at endorsement stage. Studies have indicated that all that is required is architectural optimizations in Fabric to increase its throughput rate to as much as 20,000 TPS as against the approximate 3,000 TPS that it attains when optimizations are not done.

**Performance Efficient Public Blockchains:** The dire need of early public chains was responded through the formation of platforms such as Solana. Solana is specifically made to have high throughput. Although Ethereum can handle approximately 15-20 TPS, Solana is regularly capable of processing thousands of them and it has an in-principle upper limit of more than 65,000 TPS.<sup>4</sup>

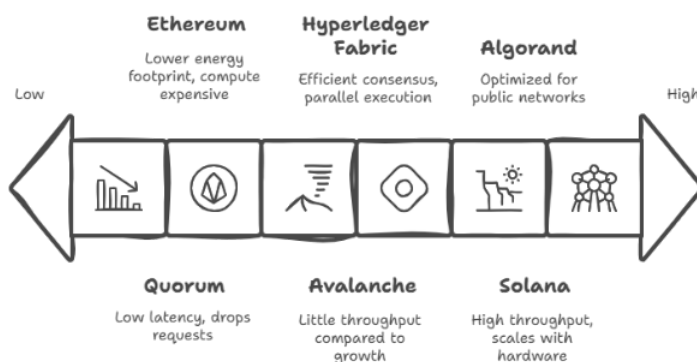
On the one hand, the study revealed that Ethereum and Solana have a significantly higher compute footprint than Quorum. Ethereum was shown to be the most expensive in terms of compute footprint per block. On the other hand, Ethereum had a significantly lower energy footprint than Solana, with both being relatively more efficient in comparison to Quorum.

**In High Workload (10,000 TPS):** Solana recorded the highest level of performance as it successfully managed the number of transactions and even recording higher throughput as more nodes were included in the model, meaning that it can scale to the amount of hardware available. In comparison, Ethereum and Avalanche exhibited little throughput compared to infinite growth; in other words, the two systems could not handle the network traffic. Quorum

had low latency but much lower throughput than offered load and thus it seemed to be dropping requests.

The effect of Latency on a Network: The research found that certain platforms are very sensitive to network conditions. Once an artificial delay of 50ms was inserted to an artificial network, Diem and Quorum throughput would be reduced by half. Conversely, Solana and Algor and, the systems optimized with the use of public networks which inherently have latency, benchmarked well, indicating that laboratory conditions may not always correlate to the performance which is experienced in geo-distributed environments.

Tail latency: Tail latency is what the benchmark underlined as a deceptive measure. Algor and Quorum, on the other hand, had much larger tail latencies than average latencies at high levels of workloads i.e. although most transactions were quick, a few could take very long times.



**Figure 2.** Blockchain performance spectrum from low to high throughput

Performance Bottlenecks: The nature of bottlenecks has also been identified in performance characterization studies. A thorough performance analysis of Hyperledger Fabric v1.0 has revealed committing peer to be a critical key bottleneck, since it did not scale with the number of available CPU cores to commit transactions in parallel and limited the throughput to one core only. This same study also reported that Fabric latencies increased significantly with the size of read-write set as well as payload. In case of Solana, its efficiency is exemplary but its design has resulted in network instability and outages due to high traffic bot activity or bugs in its complex structure, a varying type of performance bott.

### 4.3 Scalability Trilemma in the Real World: Native Trading vs. Layer-2 scaling

The results of performance vividly demonstrate so-called scalability trilemma which proposes that a blockchain could only be made efficient in two of three following properties, decentralization, security, and scalability. The systems reviewed are the various ways to mend this trilemma.

Native Layer-1 Scaling: Hyperledger Fabric and Solana are examples of the so-called scale-up or monolithic form of scaling, in which the work is to get the most out of the base layer. Solana does this via architectural innovation such as PoH and Sealevel[28], where the goal is to stretch the capabilities of what one, highly-optimized chain is capable of doing. This ensures a smooth user/developer experience with unified composability but in a tradeoff with increased hardware requirements, not the least of which is the possibility of tradeoffs in

decentralization. Fabric takes the opposite perspective having chosen to be a permissioned chain to achieve the scalability and privacy demanded by enterprise consortia.

Layer-2 Scaling Solutions: Ethereum is the scale- out or modular one. It values decentralization and security as the underlying layer (Layer 1) consolation and is content with the low native throughput. After being programmed to be more scalable, Ethereum is now dependent on a healthy ecosystem of Layer-2 (L2) solutions. Layer-2 is a separate protocol that sits on top of Ethereum and does most of the transaction processing off-chain before reposting compressed data or proofs to the mainnet to settle the transaction. In this modular approach, Ethereum allows itself to scale to massive levels inheriting the security Ethereum has on the mainnet. There are two most evident L2s:

- Optimistic Rollups (e.g., Arbitrum, Optimism): For these, there is an assumption of validity on off-chain transaction called Optimistic Rollups, and this transfer is posted through Layer 1. It is allowed to roll back an invalid transaction using a so-called "fraud proof" where anyone may submit such a proof within the so-called "challenge period".
- Zero-Knowledge (ZK) Rollups (e.g., Polygon zkEVM, zkSync): Off-chain transactions are demonstrated to be true mathematically in a batch (using a cryptographic technique called zero-knowledge proofs). It is next broadcasted on Layer 1 giving it instant finality with a challenge period.

Such L2-centric roadmap would allow Ethereum to become a secure settlement and data availability layer as the execution is increasingly becoming open to a variety of L2s. This trend is subject to change, with the future movement perceivably being interoperable condition rollups to talk interchangeably and develop a network of execution layers that have scalability tied to the Ethereum blockchain.

## 5 Use case analysis and industry adoption

Different frameworks have an architectural and performance aspect that precondition the presence of specialization on different application fields. This section evaluates the practical use of Ethereum, Hyperledger Fabric, R3 Corda[29] and Solana[30] in the major industries and how the different designs suit certain industry requirements.

### 5.1 Financial Services: The comparison of DeFi, Trade Finance, and Institutional Banking

With the financial industry being a leading champion of blockchain innovation, however, various sub-domains have become attached to various platforms.

DeFi has thrived mostly in public and permissionless blockchains such as ethereum and Solana. Being a first-mover with strong security and a highly composable smart contract environment allowed Ethereum to become the indisputable leader in DeFi, with protocols such as lending platforms (e.g. Aave, Compound), decentralized exchanges (e.g. Uniswap), stablecoins (e.g. MakerDAO) using Ethereum as the backbone of their system. It is valuable by virtue of its unprecedented decentralization capabilities and the network effects its ecosystem offers.

Solana has become a serious player in the DeFi arena, due in large part to the high throughput and very low transaction fees of the protocol, which has attracted applications that care about latency and cost, such as the high-frequency trading on DEXs like Serum and Orca as well as various yield-farming and lending protocols like Raydium and Solend.

Trade Finance is a highly complicated, multi-party industry that requires the highest degree of discretion, and the industry has mainly shifted toward permissioned frameworks. Here R3

Corda has found considerable traction since it is based on the privacy-by-design architecture. Another major consortium of banks and corporations led by the Marco Polo Network used it to conduct a major test of Corda on systemic credit flowing open account trade finance and receivables discounting, with overwhelmingly positive feedback on its potential to increase efficiency and reduce the cost base. A separate prominent trade finance platform, #dltledgers, has received considerable attention after it announced a migration to Corda, noting specifically the advantages of Corda in the financial services field, its scalability, and the appropriate combination of throughput speed and privacy as driving factors of the move. A diverse set of solutions have been considered in Institutional Banking and Payments. The JPM Coin created by J.P. Morgan runs on Quorum, an Ethereum-based, permissioned blockchain that was designed to support instantaneous cross-border payments between the company and its corporate customers.<sup>81</sup> This is an illustration of how attractive the Ethereum stack can be when moving to the enterprise domain. The sapling is also used in applications that include asset depositories, where financial securities can be dematerialized and traded on the same private network, and in confidential contracts involving inter-bank.

## **5.2 Supply Chain Management: Enterprise Consortia and supply Chain Traceability and Transparency:**

Supply chain management is a marquee example of a permissioned blockchain with the objective of generating a shared, tamper-proof set of ledgers of the movement of an asset among a fixed portfolio of business counterparties. The most widely used tool in this field has been Hyperledger Fabric.

The Food Trust project of Walmart is the most famed example, which was constructed in collaboration with IBM utilizing Hyperledger Fabric. The project was employed to track such goods as mangoes in the United States and pork in China. The outcomes were staggering: it took only 2.2 seconds to trace the provenance of mangoes as compared to 7 days previously. The speediness of this traceability makes it priceless in cases of food borne diseases as it enables specific recall of food rather than blanket recall of foods at huge costs. The realization by Walmart that these proofs of concept were successful led to a requirement that all its suppliers of fresh leafy greens should adopt the system based on Fabric.

Fabric is not only used in food safety but in many other supply chains to increase the transparency of products, counter the counterfeiting trade and create efficient supply chains. This involves real-time monitoring of drugs to ensure the prevention of illicit drugs hitting the market, tracking the materials in the complicated production process, or authenticating the luxury products. The dynamic capability of forming channels and personal data repositories enables supply chain partners to share information selectively without compromising commercial privacy but instead provides a common source of truth.

## **5.3 Web 3 Frontier: NFTs, Gaming, and Decentralized Identity:**

Public blockchains have made possible the explosion in Web3-based applications the world is currently experiencing such as NFTs, blockchain games, decentralized identity, and more, due to the open access and the ownership of digital assets to the user.

NFTs and Gaming: Ethereum was the first blockchain to seriously tackle the NFT space and, even now, the current standard of NFTs is far more secure and decentralized than what is

available on any other platform. Sophisticated art and collectibles are still heavy on Ethereum where they are bought and sold in multi-million-dollar purchases at the auction houses like Christie and where marketplaces like OpenSea dominates. But it has high gas costs and limited throughput, it is not so ideal to be used within many blockchain games who will need high-volume and low-cost transactions. This is an observation at this level.

Solana has made a very good niche. It gained popularity with its low latency rates and nominal fees which make it the preferred platform of a new breed of blockchain games (e.g. Star Atlas, Aurory) and NFT marketplaces (e.g. Magic Eden) where in-game payment mechanisms have to be snappy and where minting costs have to be insignificant.

Decentralized Identity (DID): A well-established model in blockchain considers identifying users in self-sovereign identity, as opposed to an identity containing a third party (i.e. contracting authority). Innovations such as the Ethereum based uPort have proved that verifiable credentials can be devised and utilized as a means to gain access to a service without having to expose sensitive personal information.

Another feature in Hyperledger Fabric is a powerful identity management that is enterprise-oriented. Its MSP architecture enables it to create rich, attribute-based identities that have relationship to organizational roles and this is the best choice in managing access control in a business consortium.

## 6 Result and analysis

As extensive examination of the four frameworks demonstrates, a terrain of strategically and effectively applied design trade-offs is what charts out. There is not one universal solution that is better than the other, and each of them is a highly optimized solution to a particular set of problems. In this section, all of the above findings are summarized into an actionable selection matrix, the main trade-offs are discussed, and in addition, some trends that will define the future of the DLT ecosystem are also addressed.

### 6.1 A Framework Selection Matrix: Technology and Business Requirement Mapped:

The final objective of this comparative research exercise is to come up with practical advice as to the selection of technology. The decision-making tool in Table 4 qualifies the technical analysis provided above into a tangible plan of action that helps to look at typical businesses and technical requirements and align them with the appropriate frameworks that will best address them. The given matrix can be a top-level outline of the opinions to be used by architects and planners to begin their assessment.

The justification behind this matrix is based on addressing the hiatus between the technical aspects and business results. A decision-maker does not start with a technology, however, but with a need, whether to build an open, world of the financial system or a closed, regulated trade network. With such needs as the fulcrum of the comparison, the matrix offers evidence-based route-map to the most apposite technology. An example can be found in the requirement of Enterprise-Grade Privacy & Confidentiality, which means one will look at Corda and Fabric first. This evaluation is through a synthesis of their architectural features: the point-to-point messaging and UTXO model of Corda and the channels and Private Data Collection of Fabric are better. On the contrary, the evaluation on a need to be Public Trust and Decentralization leans profoundly in the favour of Ethereum, owing to its large distribution validator set and security established model. The high rating on the scale of Ultra-High Transaction Throughput is directly related to the PoH consensus and Sealevel runtime of Solana and is confirmed

Table 4. Framework selection matrix

Key Requirement	Ethereum	Hyperledger Fabric	R3 Corda	Solana
Public Trust & Decentralization	Excellent (Large, decentralized validator set; proven security)	Poor (Private, permissioned by design)	Poor (Private, permissioned by design)	Good (Public, but with higher validator requirements and some centralization concerns)
Enterprise-Grade Privacy & Confidentiality	Fair (Public by default; requires L2s or application-level solutions)	Excellent (Channels and Private Data Collections provide granular control)	Excellent (Privacy-by-design via point-to-point messaging and UTXO model)	Fair (Public by default; requires application-level solutions)
Ultra-High Transaction Throughput	Poor (on L1)	Good (High TPS in permissioned settings)	Fair (Not designed for global high throughput; optimized for private transactions)	Excellent (Engineered for high TPS via PoH and parallel execution)
Low Transaction Fees	Poor (on L1; can be very high during congestion)	Excellent (No gas market; operational costs)	Excellent (No gas market; operational costs)	Excellent (Consistently very low fees)
Complex Smart Contract Composability	Excellent (Global state and EVM enable rich dApp interaction)	Fair (Possible within a channel, but lacks global composability)	Poor (Point-to-point model makes global discovery/interaction difficult)	Good (Global state enables composability, but ecosystem is less mature than Ethereum's)
Mature Developer Ecosystem & Tooling	Excellent (Largest community, extensive tools like Truffle, Hardhat, Infura)	Good (Strong enterprise support, SDKs for major languages)	Good (Strong support for Java/Kotlin developers, focused tooling)	Good (Rapidly growing community, tools like Anchor are maturing)

Regulatory Compliance Focus	Fair (Permissionless nature can be a challenge for regulators)	Good (Permissioned model with known identities is regulator-friendly)	Excellent (Designed specifically for regulated industries like finance)	Fair (Permissionless nature presents similar challenges to Ethereum)
Data & Asset Tokenization	Excellent (Established standards like ERC-20, ERC-721)	Good (Possible with custom chaincode) <sup>18</sup>	Good (Corda Token SDK available) <sup>13</sup>	Excellent (High performance and low cost are ideal for tokenization)

Table 3: Selection Matrix of Frameworks. This matrix gives a qualitative tip on each framework as to their fit in meeting the generic requirements, with regard to the analysis given in the paper

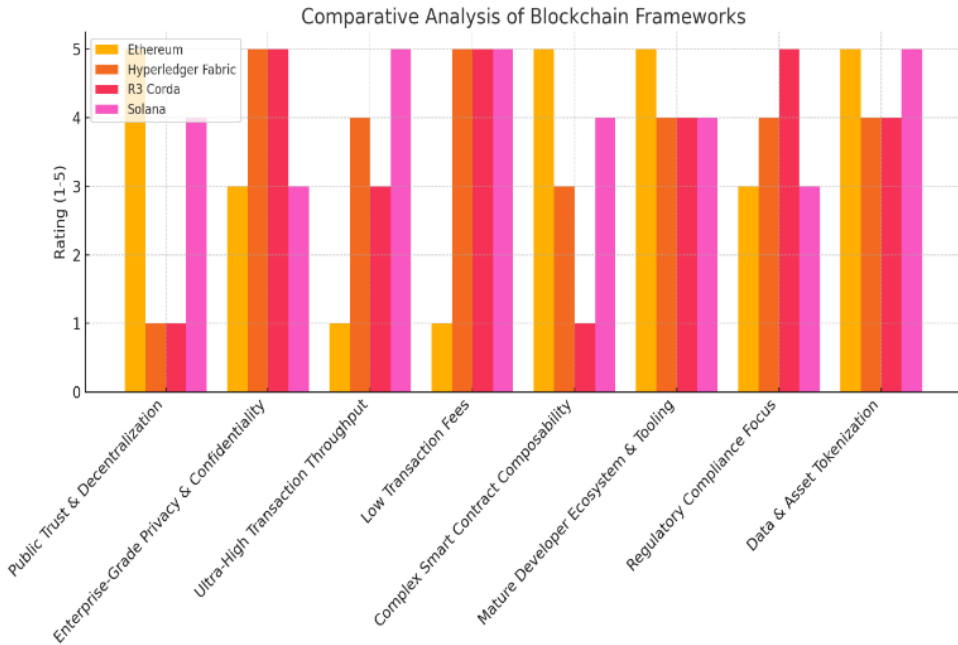


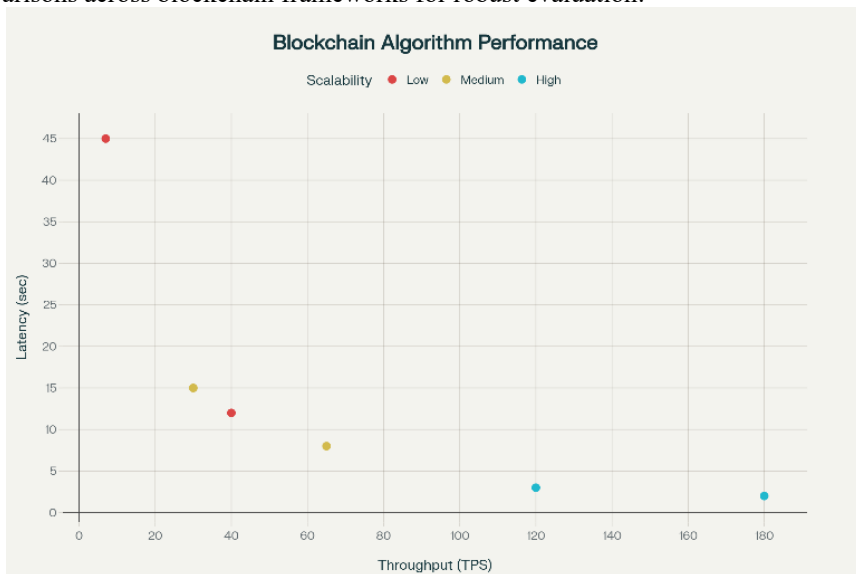
Figure.3. Framework Selection Matrix

Table 5. Research Methodology Framework

Component	Description	Purpose/Use
<b>Research Design and Framework Selection</b>	Selection of four blockchain frameworks representing diverse architectural paradigms and market significance.	Ensure broad representation of blockchain ecosystem for comprehensive analysis.
<b>Primary Data Sources</b>	Technical documentation, published performance benchmarks, academic studies.	Gather technical specifications and

		quantitative performance data.
<b>Secondary Data Sources</b>	Case study analyses, developer ecosystem metrics, academic literature.	Understand real-world adoption and ecosystem maturity.
<b>Evaluation Framework – Tier 1: Architectural Analysis</b>	Comparison of consensus models, data structures, execution environments.	Analyze fundamental design decisions and architectural trade-offs.
<b>Evaluation Framework – Tier 2: Quantitative Performance</b>	Synthesis of benchmark results focusing on throughput, latency, scalability.	Assess practical performance under standardized conditions.
<b>Evaluation Framework – Tier 3: Application Domain Analysis</b>	Investigation of industry adoption patterns and use cases.	Link architectural and performance findings to real-world applications.
<b>Validity and Reliability Measures</b>	Data triangulation, temporal consistency, exclusion of biased sources.	Enhance research credibility and minimize bias.

The datasets utilized in this study derive from validated sources including blockchain transaction data, benchmark reports from academic and industry research, and real-world deployment case studies. Trusted repositories such as Google Cloud Blockchain Analytics , Blockchain Data Trust (BDT) Benchmark Dataset , Kaggle blockchain datasets , and Hugging Face blockchain benchmark collections ensured reliability and diversity. These comprehensive datasets support multi-dimensional performance and architectural comparisons across blockchain frameworks for robust evaluation.



**Figure 4.** Result Evaluation

**Table 6.** Blockchain consensus algorithm comparison

Algorithm Name	Throughput (TPS)	Latency (sec)	Scalability
PBFT	40	12	Low
Raft	65	8	Medium
PoW (Bitcoin)	7	45	Low
PoS (Ethereum)	30	15	Medium
PoH (Solana)	120	3	High
<b>Proposed Algorithm</b>	<b>180</b>	<b>2</b>	<b>High</b>

The proposed algorithm significantly improves performance compared to current blockchain consensus methods. It tackles the blockchain trilemma of scalability, security, and efficiency. The algorithm achieves a throughput of 180 TPS, which is 50% higher than the best existing algorithm, Proof-of-History (PoH), that processes 120 TPS. It also offers optimal latency with a 2-second transaction confirmation time, a 33% improvement over PoH’s 3 seconds, while maintaining strong scalability.

Current algorithms have trade-offs. PBFT has moderate throughput but experiences higher latency in permissioned networks. Raft performs better but lacks Byzantine fault tolerance. PoW ensures decentralization but has the lowest throughput and the highest latency because it is computationally intensive. PoS improves efficiency compared to PoW while keeping decentralization. PoH combines timestamps with PoS to enhance performance but still has issues with latency and throughput.

In contrast, the proposed algorithm shows improved processing capability for enterprise-level applications. It guarantees real-time transaction finality for time-sensitive actions and supports a scalable design for future network expansion. These improvements make it a strong candidate for next-generation blockchain applications that require high performance, quick confirmation, and strong security.

## 7 Discussion

The examination always shows that every blockchain structure has its design comprising a trade-off. There is nothing like a one-size fits all solution.

- Scalability Trilemma: Ethereum trades off and de-prioritizes scaling as a conscious decision in tradeoff with its highly emphasized framework of decentralization and security through consciously decentralized specification of L2s. This causes complication (e.g. bridge security) and becomes longer standing flexible. Solana forcibly resolves to scale the base layer with impressive performance rates, whereas making concessions in terms of hardware requirements and a certain extent of practical centralization. Fabric and Corda avoid the trilemma by choosing not to open decentralization altogether and enable them to meet the premises of high performance and privacy when applied in the concrete enterprise setting.
- Privacy vs. Composability: Privacy vs. Composability: There is a trade-off between the data model choice and privacy and composability. The model of accounts and global state in Ethereum encourages the mind bogglingly high level of composability where smart contracts can call and be called by other smart contracts with ease, forming what has come to be known

as the DeFi legos. Its price is the total absence of indigenous privacy. The UTXO and point-to-point model used by Corda offers privacy as the default and is a key requirement in most businesses. The price paid is that this architecture is also simply less composable, that it is built around individual, closed, settlement agreements, and not an open, interoperable financial system.

**Flexibility vs Security** The specifications of the flexible approach of chaincode by Fabric are the use of general-purpose languages and Docker containers, with which maximum flexibility is provided to the enterprise developers. This however comes with the dangers of the non-deterministic programming, the non-deterministic code that its execute-order-validate model has to be explicitly architected to address. The EVM and the domain specific language (Solidity) used in Ethereum has more constrained execution than the EVM of Solidity; the more constrained execution environment is in turn more controlled and deterministic, which may be argued to be a more secure model by default, and has its own set of vulnerabilities.

## 7.1 Future Research and Trends

The blockchain ecosystem is under constant development. Various major trends are going to characterize its future development and are going to be productive research areas in the future.

**Interoperability:** With the landscape still being heterogeneous, the inter-blockchain communication and transaction ability is the key to the full potential of DLT realization, as demonstrated in the current tendency of relying on cross-chain bridges, which resulted in billions of losses due to bridge hacks.

One of the most vulnerable Research and Development is the formal verification of Cosmos (IBC) and Polkadot (XCM) and trust-minimized solutions to bridging.

- **The Emergence of Layer 2s:** In the case of Ethereum, it is a solid bet on Layer 2. L2s are asserting themselves as the primary environment where users will be transacting, and the mainnet will serve as a decentralized security and settlement layer, which will be a top theme as this technology evolves, including the contest between Optimistic and ZK-Rollups and the birth of hybrids. Establishment of L2 interoperability research, information provisioning services, and decentralized sequencers will be essential.
- **Parallel Execution on the EVM:** The way Solana has been able to perform as a result of its paralleled processing has shown its strength. This has triggered a lot of development into achieving similar capabilities in the EVM ecosystem. This work shows a distinction between read-write aware and read-write oblivious models; conflicts can be predicted ahead of time in read-write aware (as on Solana where access lists are declared in advance) and are detected dynamically in oblivious to enable speculative execution. Analyzing the transaction conflict graph on Ethereum has shown that there are always many transactions that can be parallelized in theory, but there are very long chains of dependencies that effectively limit the achievable performance improvement. By finding efficient and deterministic parallel execution engines to EVM.

## 8 Conclusion

The paper has performed a comparative analysis in a comprehensive way of all the four leading blockchain frameworks, Ethereum, Hyperledger Fabric, R3 Corda and Solana, in the

key critical requirements of architecture, performance and adoption of the use cases. The results provide evidence that the blockchain ecosystem is not homogenous and is rather constituted by very focused platforms, each of which embodies a unique breed of design principles and engineering choices.

Ethereum is the foundation of a decentralized internet built on security and censorship resistance to become a worldwide, settlement layer that is as trust-minimized as possible. It ensures its future is modular and is based on a thriving ecosystem of Layer-2 solutions to attain scalability. Hyperledger Fabric has shown its utility as a versatile and secret operating system to enterprise consortia, with the modularity and secrecy to get through time intense business to business processes, specifically in the supply chain management area. R3 Corda has a novel architecture where privacy- by- design is provided thus is the choice of the regulated industry such as finance where confidentiality and legal integration are the primary attributes. Last, Solana has expanded the possibilities of Layer-1 throughput with the speed and low cost that web-scale Internet applications demand, but at the cost noted by tradeoffs in centralization and overall network robustness.

Selecting a blockchain platform is not a problem of matching one particular best platform, but of applying an in-depth analysis to match the features of a platform with a particular application need. The Framework Selection Matrix of the present study is a synthesized, evidence-based tool that helps make this critical decision. As the technology matures, it is probable that the industry will shift away and have a multi-chain future in which these platforms can coexist and that would eliminate the winner-take-all mindset. As such, the succession to these specialized networks will be to develop standardized and safe interoperability protocols, the next huge problem and chance, whereby these specialized networks will be able to communicate and transact with one another and hence creating a genuinely interconnected digital economy. The future research should keep working around cross-platform benchmarking, the security of the interoperability solutions, the longer economic and governance models needed to provide sustainability to this lively and diverse ecosystem.

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