

A Blueprint for Interoperable Blockchains

[Vision Paper]

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ABSTRACT

Research in blockchain systems has mainly focused on improving security and bridging the performance gaps between blockchains and databases. Despite many promising results, we observe a worrying trend that the blockchain landscape is fragmented in which many systems exist in silos. Apart from a handful of general-purpose blockchains, such as Ethereum or Hyperledger Fabric, there are hundreds of others designed for specific applications and typically do not talk to each other.

In this paper, we describe our vision of interoperable blockchains. We argue that supporting interaction among different blockchains requires overcoming challenges that go beyond data standardization. The underlying problem is to allow smart contracts running in different blockchains to communicate. We discuss three open problems: access control, general cross-chain transactions, and cross-chain communication. We describe partial solutions to some of these problems in the literature. Finally, we propose a novel design to overcome these challenges.

Keywords

Blockchains; Interoperability, Access control, Transactions

1. INTRODUCTION

A blockchain is a replicated, tamper-evident database designed for hostile environments. It consists of a number of nodes some of which may be malicious (or Byzantine), and exposes an append-only log (or ledger) abstraction. The ledger stores *transactions* that modify some global states. In the canonical example, that is cryptocurrencies [38, 17], the global states are user accounts and native currencies, and the ledger contains transactions transferring currencies from one account to another. Most blockchains support smart contracts which let users define their own states and codes that modify the states. Smart contracts are stored in the ledger, which means they are replicated and kept consistent by all the blockchain nodes.

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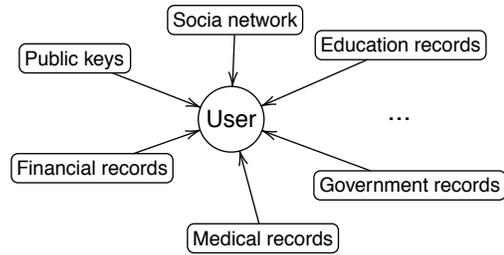


Figure 1: Example of a fragmented blockchain landscape. There is one blockchain per aspect of user identity. But these systems do not talk to each other.

Early blockchains have poor performance and scalability [22] compared to distributed databases, and many smart contracts contain security flaws [4, 31]. Much research effort has thus been spent on improving performance [19, 29] and hardening smart contracts [44, 28], resulting in a new generation of systems that achieve comparable performance to some databases, and smart contracts that are much more secure.

However, we observe that the blockchain ecosystem has a long tail. On the one hand, there are a small number of hugely popular, general-purpose blockchains. One example is Ethereum [17], a public (or permissionless) blockchain in which anyone can join. Another is Hyperledger Fabric [5], a private (or permissioned) blockchain in which nodes' identities are known to each other. On the other hand, there are thousands of other blockchains designed for specific applications, most of which are only in early stages of development. In particular, there are over 2500 blockchains for cryptocurrencies¹, 40 for healthcare², 100 for identities management³, 25 for IoT⁴. More importantly, these blockchains do not interoperate, i.e., they exist in silos. Figure 1 shows an example of many blockchains storing different aspects of a user's identity (fragmentation across verticals), including public key [10], financial records [17], medical records [7], education certificates [1] and government records [2]. In-

¹https://www.coinlore.com/all_coins

²<https://www.disruptordaily.com/blockchain-market-map-healthcare/>

³<https://github.com/peacekeeper/blockchain-identity>

⁴<https://www.disruptordaily.com/blockchain-market-map-iot/>

side each vertical, there are multiple isolated systems, compounding further fragmentation. The user is overburdened with managing numerous credentials to access different systems. Furthermore, the user is responsible for keeping data between different systems consistent, for example, to update his financial records when a new government record is issued that certifies his tax exemptions.

Like in a database, data fragmentation is a major source of inefficiency because it incurs management overheads. A typical database defragmentation algorithm would move data around so that they are in the same place. This solution, however, does not translate directly to blockchains, which would involve adding another blockchain that aggregates all data in one place, which is unwieldy and goes against the very idea of decentralization. Instead, we argue that a practical direction is to make existing blockchains interoperable. Interoperability entails more than standardizing message format across different blockchains. It requires carefully designed protocols allowing one blockchain to *access* data of another. Blockchain interoperability has received little attention from the research community. Interledger [6] and Cosmo network [3] are the only two notable examples that aim at *connecting* blockchains.⁵ The former focuses on connecting payment networks, whereas the latter focuses on low-level message exchanges.

In this vision paper, we go deeper than connecting blockchains, and seek designs that allow smart contracts in one blockchain to access data of other smart contracts in another blockchain. To this end, we identify three challenges. The first is to support secure, fine-grained access control for smart contracts. Although any access policy can arguably be implemented and enforced inside a stand-alone smart contract, we note that good security practice requires decoupling control policy and enforcement from actual data access. The second challenge is to support general cross-chain transactions which are different to atomic swaps [25, 20] and cross-chain deals [26]. This difference is similar to that between general and one-shot transactions in distributed databases [18, 42]. The final challenge is to enable communication between smart contracts, which is currently not possible for contracts in different blockchains [8, 46].

We propose to overcome the first challenge by decoupling access control from user smart contracts. We present a framework consisting of a high-level language for specifying fine-grained policies, and a runtime environment with access to historical states. For the second challenge, we design a protocol that supports a transaction model similar to Sinfonia’s mini-transaction [15] model which captures conditional cross-chain swaps. For the third challenge, we propose a publish/subscribe framework that let smart contracts send and receive messages to and from the outside world.

In summary, our paper makes the following contributions:

- We highlight the problem of blockchain fragmentation, and propose to mitigate it by making blockchains interoperable.
- We discuss three challenges in designing interoperable blockchains: access control, general transactions, and cross-chain communication.
- We present high-level solutions to these challenges.

⁵However, there are no complete implementations of these proposals.

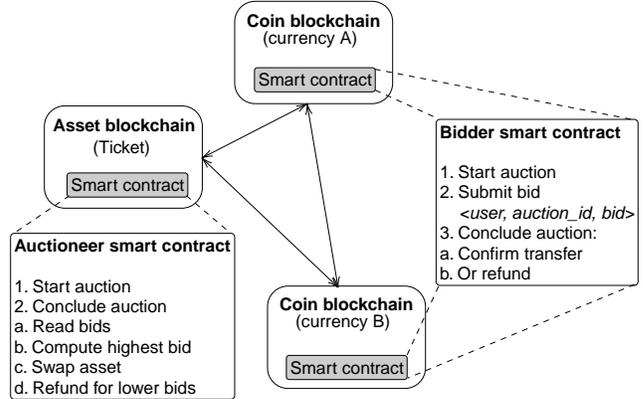


Figure 2: Example of cross-chain, general transactions spanning three blockchains. The auction transaction involves writes which are dependent on reads.

Section 2 presents the problem in detail by elaborating the three challenges. It explains why current systems fail to adequately address these. Section 3 sketches our solutions. We wrap up in Section 4 with concluding remarks.

2. CHALLENGES

We first motivate the problem of blockchain interoperability through an example of an auction application. Next, we discuss three crucial challenges that need to be addressed. We describe how state-of-the-art systems only provide partial building blocks for addressing these challenges.

2.1 Motivating Example

Alice owns a coveted football ticket stored on a ticket blockchain (many permissioned blockchains are designed for asset management, and therefore can be used to implement such ticket application). Bob and Carol are avid football fans and both want to buy the ticket. They are users of the ticket blockchain, and each of them owns currencies at other coin blockchains (for example Ethereum or XRP [12]). Alice wants to start an auction on her ticket, to which Bob and Carol submit their bids. The ticket blockchain does not support bid submissions, thus Bob and Carol have to declare their bids in their own blockchains. This auction is implemented as smart contracts running on the three blockchains realizing a distributed workflow [33].

Figure 2 shows the contracts’ logics and how they interact. In particular, Alice uses an Auctioneer contract that escrows the ticket when the auction starts. Bob and Carol specify their bids to a Bidder contract that escrows the amount of currencies submitted. Before they can submit bids, the Auctioneer contract must start the auction at the Bidder contract. When Alice decides to end the auction, the Auctioneer contract reads submissions from the Bidder contracts on the other two blockchains. It then computes the highest bid, taking into account prevailing exchange rates among different currencies. Finally, it atomically transfers ownership of the ticket to the highest bidder, deducts the bid amount in corresponding blockchain, and releases the other for refund.

There are three implications in enhancing existing blockchains to support the interaction above. First, the Bid-

der contract must execute read queries from another contract. This warrants an access control mechanism which allows Bidder to specify and enforce policies on who can access which piece of data. Second, the conclude transaction in Auctioneer is a general, interactive transaction that involves cross-chain reads and cross-chain writes that are dependent of the read values. Unlike one-shot transactions or atomic cross-chain swaps, this type of transactions incurs more than two network round-trips to first execute and then commit the transaction. Third, both Auctioneer and Bidder must be able to send and receive messages from each other. For instance, Auctioneer must be able to send a read request and listen for the response value from Bidder. However, this is beyond the capability of current smart contracts.

2.2 Access Control

One may question the need for access control, since one important property of blockchain is transparency which means the blockchain nodes see all the data. We note that for permissionless blockchains, only primitive forms of access control (all-or-nothing access based on possession of private keys) is meaningful. However, for a permissioned blockchain there is a trust boundary between nodes inside and outside of the system. Therefore, access control is needed to determine blockchain membership. Furthermore, the nodes may wish to protect privacy of their data, therefore access from outside the system (be it from a user or a smart contract), especially write access, must be restricted. For example, a blockchain for financial transactions between major banks may only grant limited read access to auditors [39].

Existing permissioned blockchains have built-in support for coarse-grained access policy. For instance, Hyperledger Fabric provides a *membership service* that uses access control list (ACL) to determine who can read or write to the ledger and the event streams. Fine-grained policies, which give user more control over the data, are not supported. Examples of such policies include the following:

- *Data-dependent policies*: only give access when some predicates over the current data are true. In the auction example, the user can submit at most one bid (or write) to the Bidder contract only when the auction is still ongoing.
- *Time-dependent policies*: access is restricted by time. In the context of blockchains, a time duration may be represented as a range of blocks. In our example, the writing period for the Bidder contract can be set to expire after a certain number of blocks.
- *Provenance-dependent policies*: only give access when some predicates over the data history (or provenance) are true. In our example, the Bidder contract may only allow the Auctioneer contract to start an auction if the latter has not started more than a certain number of auctions in the last b blocks. Another policy may be to suspend a certain Auctioneer contract from starting an auction if it has accepted a bid from a corrupt user.
- *Aggregate policies*: only give access to summaries of the data. In the auction example, the Auctioneer contract may grant read access to the total values of all winning bids over a certain period to an auditor. Similarly, the Bidder contract may grant access to statistics of user

bids to an external data analyst. Further constraints such as the exposed statistics being differentially private may also be imposed.

— The first challenge is how to add support for these policies, particularly in a set-up where the information is dispersed across different blockchains. We note that they may all be implemented explicitly inside the smart contract if all the necessary information is self-contained in a blockchain, but even that has two major limitations. The first limitation is related to performance. In particular, in most blockchains the contract can only access the latest data. Thus, to support provenance-dependent policies the contract will need to explicitly keep track of historical data, for example, the VersionKVStore contract in [22]. This introduces redundancy and unnecessary performance overhead because historical data is already stored in the blockchain. The second limitation is related to software engineering. More specifically, smart contract development is an error-prone process often carried out by non-security experts, therefore the risk of implementing incorrect policies is high. Furthermore, many contracts share similar policies, and implementing them in every contract implies duplication of effort. These problems are amplified when data from across multiple blockchains are involved, due to concerns of correctness and consistency.

Another related challenge is the efficiency of enforcement. For example, aggregate and differentially private policies require non-trivial computation to answer queries. Although smart contract execution is not the performance bottleneck, long execution time may break the incentive mechanisms which are important for security [32].

In summary, the principal challenges for access control are: support for fine-grained policies, ease of development, and enforcement efficiency.

2.3 Cross-Chain Transactions

Transaction is an important abstraction in modern distributed databases [23, 43]. Blockchains assume a much stronger failure model, namely Byzantine model, than the crash failure model in databases. Consequently, supporting transactions in blockchains is more challenging. We consider only cross-chain transactions, instead of the normal, intra-chain transactions which are executed serially by all nodes in the blockchain and therefore satisfying all of the ACID properties.

Read-only transactions, often considered the simplest type of transaction, must ensure that responses from the blockchain are correct *and* fresh. In our example, the Auctioneer issues a read query to the Bidder and waits for the response. It needs to verify that the response has not been tampered with, and that it is fresh (not a replayed message). Freshness can be achieved by including a nonce in the request, and verifying it in the signatures of at least $f + 1$ blockchain nodes.⁶ For query correctness, we note that blockchain nodes can execute read queries directly on top of the storage, or through the smart contract. The former is applicable only when the values are mapped directly to the ledger data structure, for example block information or key-value tuples. In this case, each node reads the values directly from the storage, then includes integrity proofs as part of the response. However, complex smart contracts do

⁶ f is the fault-tolerance threshold, usually expressed in terms of the number of Byzantine nodes.

not map their data directly to the ledger data structure. For example, bid tuples (`user`, `auction_id`, `bid`) are stored in a list or a set as opposed to as key-value tuples. Therefore, in general case, read queries must be executed through smart contracts, and the responses are signed by correct blockchain nodes, which ensures correctness and authenticity. However, the cost is significant because every query must go through consensus. Reducing this cost is a major challenge.

Concurrency arises due to cross-chain transactions. In our example, when the Auctioneer contract wants to conclude an auction, it sends a read request to Bidder and waits for the response. The Bidder contract executes the read query as a transaction, but it does not understand that the read is part of another, larger transaction from another blockchain. Before Auctioneer finishes its transaction, the Bidder contract accepts another bid that is the highest. Without coordination, the Auctioneer transaction is unaware of this new bid and its execution becomes invalid. In other words, the transaction is not serializable. State-of-the-art blockchain systems use lock based concurrency control to achieve serializability [19]. Specifically, smart contracts maintain one lock per key-value tuple, and a transaction must acquire all locks before it can commit. This strategy is safe, but as demonstrated in [19], it results in high abort rate and significantly reduced throughput.

Atomicity in the context of cross-chain transactions, like in traditional databases, means that the transaction executes to completion or not at all. In our example, the transaction that concludes auction must be atomic; otherwise it could so happen that the highest bidder gets the ticket without paying, or users who submitted lower bids fail to get their refunds. The classic solution to atomicity is the two phase commit (2PC) protocol, which is run by a transaction coordinator. Implementing 2PC in blockchain is more challenging than in databases, because the coordinator is not trusted. Both [19, 26] propose to run 2PC in a Byzantine fault-tolerant network, i.e. in another blockchain.

State-of-the-art atomic cross-chain transactions, namely [19, 26, 25], consider only one-shot transactions [42]. Like in databases, this type of transaction does not require communication between the blockchains during both the execution and commit phase. As a result, the transaction can be executed and committed in two network round trips from the coordinator to the blockchains. Atomic swaps and cross-chain deals [26] involve only write operations to the blockchain, therefore they are both one-shot. In particular, cross-chain deals are modeled as $n \times n$ write matrix for n users.

We argue that support for more general transactions is needed. In our example, the conclude transaction at the Auctioneer contract is not one-shot, because the write operations are dependent on the read values. This type of interactive transactions, like in databases, is expensive because they require multiple network round trips to execute and commit. Therefore, the challenge is to design an efficient protocol for cross-chain transactions that are more general than one-shot. We note that [26] mentioned support for conditional swaps, which are similar to our example above, but did not describe how it works.

In summary, the challenges in supporting cross-chain transaction are how to provide efficient read transactions, how to extract more concurrency, and how to reduce communication for general transactions. They are the same chal-

lenges the database community wrestles with [23, 37, 36].

2.4 Communication

One major limitation of current smart contracts is that they do not talk to the outside world. They can only access resources on the blockchain such as the ledger and execution engine. The contract treats local states and user inputs as ground truth, and makes no assumption about data from other sources. Some external services, such as Oracleize [8], provide authentic data feeds, such that messages signed by them are accepted by the contract. Towncrier [46] and PDFS [24] also address authenticity problem, but without relying on trusted parties. The former leverages trusted hardware [14], while the latter depends on users to audit transparent logs. For real-world data, we believe authenticity (as opposed to trustworthiness) is the best that can be achieved. On the other hand, data that comes from another blockchain can be considered trustworthy, under the assumption that the blockchain as a whole is trusted.

Our goal is to design an efficient communication infrastructure for sending and receiving messages between blockchains. Interledger protocol (ILP) [6] and Cosmos' inter-blockchain communication (IBC) [3] are two recent proposals for connecting blockchains. ILP is specific to cryptocurrencies, and its design is optimized for sending payments from one blockchain to another. It is based heavily on payment channels [35], and therefore does not generalize to other blockchain applications. IBC proposes a more generic communication protocol which handles data transport, authentication and connection reliability. Beside being in early stage of development, IBC requires intrusive changes to the blockchain stack, as it needs to be deeply integrated with the state-machine component of the blockchain node. Another limitation of IBC is that it is a networking-layer protocol, therefore it leaves much complexity to the application layer (i.e., the smart contracts). For example, IBC only relays messages and does not distinguish between ones carrying data versus carrying proof. Finally, IBC is connection-oriented, which means both communication endpoints have to maintain connection states. This connection model is suitable when the endpoints are responsive, for example in a client-server model, and when the network is often reliable. However, it is not suitable for blockchains, because the network is hostile (it may have Byzantine nodes) and transaction latency is high.

In summary, the challenge is to design a stateless communication protocol that ensures timely and reliable delivery of messages. The protocol needs to work at the application layer, which understands and contains optimizations for common requirements of cross-chain communication. Finally, the protocol needs to be resilient to network failures.

3. POSSIBLE SOLUTIONS

Figure 3 shows our proposed architecture for interoperable blockchains. The current blockchain stack, consisting of a storage, consensus and smart contract components [22], remains unchanged. We add new components that implement support for access control, transactions, and communication. This architecture avoids designing a new blockchain from scratch, and allows for incremental adoption. In the following, we sketch our high-level design for each of the new components. We describe how we expect to overcome the challenges discussed in the previous section. We stress that

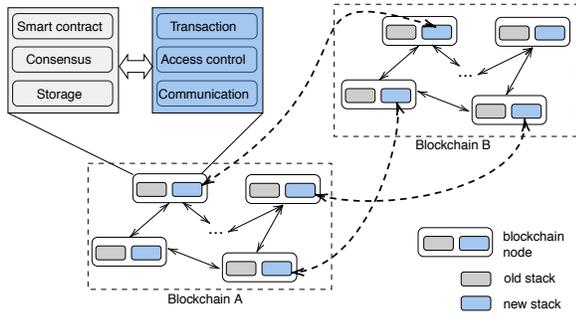


Figure 3: The architecture for interoperable blockchains, with newly added components for transaction, access control and communication. The old software stack remains unchanged.

our approach builds on existing solutions, and it is only to start the discussion. More research is needed to find better solutions and to validate them.

3.1 Access Control

We decouple access control from user smart contracts and implement it as a *system contract*. As shown in Figure 4[a], the user contracts can invoke the access control mechanism by calling another contract within the same blockchain. We implement it as a contract as opposed to a system library because it allows users to update policies without changing the software at all the nodes. This design solves the ease-of-development challenge.

To support fine-grained policies, we propose to design a policy language that is expressive and easy to use. This language is declarative and can be based on either Google Firestore [13] or Datalog [30]. The access control contract contains the language interpreter to parse and then enforce the policy. To support access to historical data during enforcement, we propose to use LineageChain [41], a state-of-the-blockchain storage providing rich data access to smart contracts. LineageChain and its underlying engine called Forkbase [45] have been evaluated on Hyperledger Fabric. More work is needed to port them to Ethereum runtime. Finally, to improve enforcement efficiency, we propose to add concurrency to the smart contract execution engine [21]. The fact that current blockchains execute transactions sequentially means there is plenty of room for improvement.

3.2 Cross-Chain Transactions

Figure 4[b] shows the key components for transactions implemented as a system library which a smart contract can invoke. To improve efficiency for read-only transactions, it is necessary to avoid going through consensus. This means the storage must be able to produce integrity proofs for the read values. We propose to enhance blockchain storage with more expressive, high-level data structures that are verifiable and can be directly used by the smart contract. Examples include map and list structure. Trillian [9] provides strong security properties for map structures. Forkbase [45] provides weaker guarantees for both map and list structure. Our proposed solution is based on Forkbase.

To extract more concurrency from cross-chain transactions, we propose to add support for optimistic concurrency control (lock-based mechanisms are still provided, because

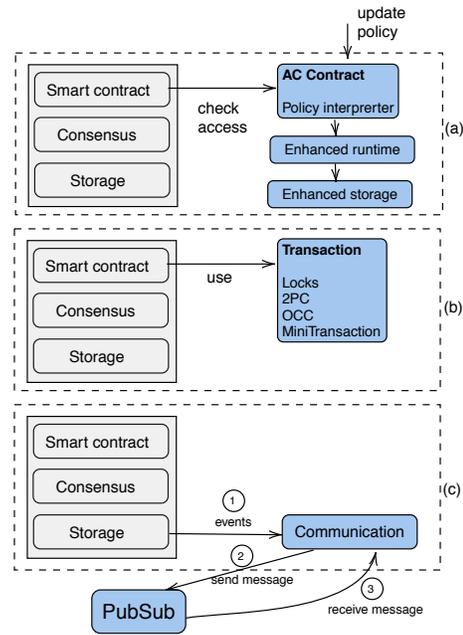


Figure 4: Main components of access control, transactions and communication.

they work well under high contention). The OCC protocol works the same way as in databases: it keeps track of read/write sets and aborts when there are newer versions. We directly use the version tracking feature provided by the storage [45] to implement this.

Finally, to reduce transaction communications, we propose to implement the mini-transaction abstraction [15] which captures conditional data swaps. A mini-transaction comprises a compare, a read, and a write phase with known read and write sets. Although it does not capture all general, interactive transactions, its execution and commit phase can be optimized to finish in two network round trips. For other unsupported types of transactions, we provide general locks and 2PC implementation. During execution, all locks are acquired. During commit, the Byzantine-tolerant 2PC is run by one of the blockchains.

3.3 Communication

Figure 4[c] shows our communication infrastructure which is stateless, efficient, and works at the application level. It is based on publish-subscribe system. A communication library runs at every blockchain node and subscribes to the event streams produced by the blockchain stack. It then publishes the events to the pub-sub system, which delivers them to the destination blockchain. A cross-chain event contains names of the source, destination blockchain, and identifier of both the source and destination contract.

The communication library automatically adds unique nonces to every sent event to guarantee freshness. We also propose running a dedicated gateway node to which all nodes forward their events. This gateway then waits and batches $f + 1$ signatures of the same event before publishing them to the pub-sub system, which significantly reduces network cost.

We note that the pub-sub system is not a centralized

component. One way to realize this system is to have the communication blockchains running their own P2P pub-sub system. However, a more practical approach is to use a third-party service such as Amazon SNS. This service does not have to be trusted for security, because messages between blockchains are cryptographically signed. Furthermore, multiple services from different providers can be used at the same time, without coordination among them, to increase quality of service and avoid denial of service attacks (such as dropping of messages).

4. CONCLUDING REMARKS

We have discussed related work extensively in the previous sections. Here, we highlight three orthogonal research directions that may benefit from our work. First, off-chain scaling systems such as Plasma [40] and sidechains [16] use multiple blockchains to improve overall throughput. Our work can be applied to make communication between the sub-chains more efficient and richer. Second, there is a trend towards decentralized systems, of which blockchain is only one example. Other examples include identity management [34], personal storage [11], and social network [27]. These systems exist in silos, and our work can be applied to build novel applications on top of them. Finally, our approach can help realize general purpose distributed workflows [33].

We presented our vision of making blockchains interoperable, as a solution to the current fragmented blockchain ecosystem. We discussed three challenges in realizing our vision: fine-grained access control, cross-chain transactions, and cross-chain communication. Finally, we proposed solutions to address these challenges, which serves as starting points for future research.

5. REFERENCES

- [1] Blockcerts: open standard for blockchain credentials. <https://www.blockcerts.org>.
- [2] Chromaway: power to the public. <https://chromaway.com>.
- [3] Cosmos network: interconnected blockchains. <https://cosmos.network>.
- [4] The dao attacked: Code issue leads to \$60 million ether theft. <https://www.coindesk.com/dao-attacked-code-issue-leads-60-million-ether-theft>.
- [5] Hyperledger. Blockchain technologies for business. <https://www.hyperledger.org>.
- [6] Interledger: the protocol for connecting ledger. <https://interledger.org>.
- [7] Medilot: transforming healthcare for all. <https://medilot.com>.
- [8] The provable blockchain oracle for modern dapps. <http://provable.xyz>.
- [9] A transparent, highly scalable and cryptographically verifiable data store. <https://github.com/google/trillian>.
- [10] uport: Open identity system for the decentralized web. <https://www.uport.me>.
- [11] Upspin: A framework for naming everyone's everything. <https://github.com/upspin/upspin>.
- [12] xrp: Digital asset for payments. <https://www.ripple.com/xrp>.
- [13] Writing conditions for cloud firestore security rules. <https://firebase.google.com/docs/firestore/security/rules-conditions>, 2016.
- [14] Intel SGX. <https://software.intel.com/en-us/sgx>, 2017.
- [15] AGUILERA, M. K., MERCHANT, A., SHAH, M., VEITCH, A., AND KARAMANOLIS, C. Sinfonia: a new paradigm for building scalable distributed systems. In *SOSP* (2007).
- [16] BACK, A., CORALLO, M., DASHJR, L., FRIEDENBACH, M., MAXWELL, G., MILLER, A., POELSTRA, A., TIMĂȘN, J., AND WUILLE, P. Enabling blockchain innovations with pegged sidechains. <https://blockstream.com/sidechains.pdf>.
- [17] BUTERIN, V. Ethereum: A next-generation smart contract and decentralized application platform. <https://github.com/ethereum/wiki/wiki/White-Paper> (2014).
- [18] COWLING, J., AND LISKOV, B. Granola: Low-overhead distributed transaction coordination. In *Usenix ATC* (2012).
- [19] DANG, H., DINH, T. T. A., LOGHIN, D., CHIEN CHANG, E., LIN, Q., AND OOI, B. C. Towards scaling blockchain systems via sharding. In *SIGMOD* (2019).
- [20] DECRED. Decred cross-chain atomic swapping. <https://github.com/decred/atomicswap>.
- [21] DICKERSON, T., GAZZILLO, P., HERLIHY, M., AND KOSKINEN, E. Adding concurrency to smart contracts. In *PODC* (2017).
- [22] DINH, T. T. A., WANG, J., CHEN, G., LIU, R., OOI, B. C., AND TAN, K.-L. Blockbench: A framework for analyzing private blockchains. In *SIGMOD* (2017).
- [23] ET AL., J. C. C. Spanner: Google's globally-distributed database. In *OSDI* (2012).
- [24] GUARNIZO, J., AND SZALACHOWSKI, P. Pdfs: Practical data feed service for smart contracts. <https://arxiv.org/pdf/1808.06641.pdf>.
- [25] HERLIHY, M. Atomic cross-chain swaps. In *PODC* (2018).
- [26] HERLIHY, M., LISKOV, B., AND SHRIRA, L. Cross-chain deals and adversarial commerce. <https://arxiv.org/abs/1905.09743>.
- [27] JAHID, S., NILIZADEH, S., MITTAL, P., BORISOV, N., AND KAPADIA, A. Decent: A decentralized architecture for enforcing privacy in online social networks. In *PerCom* (2012).
- [28] KALRA, S., GOEL, S., DHAWAN, M., AND SHARMA, S. Zeus: Analyzing safety of smart contracts. In *NDSS* (2018).
- [29] KOKORIS-KOGIAS, E., JOVANOVIĆ, P., GASSER, L., GAILLY, N., AND FORD, B. Omniledger: A secure, scale-out, decentralized ledger. *IACR Cryptology ePrint Archive* (2017).
- [30] LI, N., AND MITCHELL, J. C. Datalog with constraints: A foundation for trust management languages. In *PADL* (2003).
- [31] LUU, L., CHU, D.-H., OLICKEL, H., SAXENA, P., AND HOBOR, A. Making smart contracts smarter. In *CCS* (2016).
- [32] LUU, L., TEUTSCH, J., KULKARNI, R., AND SAXENA, P. Demystifying incentives in the consensus computer. In *CCS* (2015).
- [33] MADSEN, M., GAUB, M., KIRKBRO, M., HOGNASON, T., SLAATS, T., AND DEBOIS, S. Collaboration among adversaries: Distributed workflow execution on a blockchain. In *Symposium on Foundations and Applications of Blockchain* (2018).
- [34] MELARA, M. S., BLANKSTEIN, A., BONNEAU, J., FELTEN, E. W., AND FREEDMAN, M. J. Coniks: Bringing key transparency to end users. In *USENIX Security* (2014).
- [35] MILLER, A., BENTOV, I., KUMARESAN, R., CORDI, C., AND MCCORRY, P. Sprites and state channels: payment networks that go faster than lightning. <https://arxiv.org/pdf/1702.05812.pdf>, 2017.
- [36] MU, S., CUI, Y., ZHANG, Y., LLOYD, W., AND LI, J. Extracting more concurrency from distributed transactions. In *OSDI* (2012).
- [37] MU, S., NELSON, L., LLOYD, W., AND LI, J. Consolidating concurrency control and consensus for commits under conflicts. In *OSDI* (2016).
- [38] NAKAMOTO, S. Bitcoin: A peer-to-peer electronic cash system, 2008.
- [39] NARULA, N., VASQUEZ, W., AND VIRZA, M. zkledger: Privacy-preserving auditing for distributed ledgers. In *NSDI* (2018).
- [40] POON, J., AND BUTERIN, V. Plasma: Scalable autonomous smart contracts. <https://plasma.io/plasma-deprecated.pdf>, 2017.
- [41] RUAN, P., CHEN, G., DINH, T. T. A., LIN, Q., OOI, B. C., AND ZHANG, M. Fine-grained, secure and efficient data provenance on blockchain systems. In *VLDB* (2019).
- [42] STONEBRAKER, M., MADDEN, S., ABADI, D. J., HARIZOPOULOS, S., HACHEM, N., AND HELLAND, P. The end of an architectural era (it's time for a complete rewrite). In *VLDB* (2007).
- [43] THOMSON, A., DIAMOND, T., WENG, S.-C., REN, K., SHAO, P., AND ABADI, D. J. Calvin: Fast distributed transactions for partitioned database systems. In *SIGMOD* (2012).
- [44] TSANKOV, P., DAN, A., DRACHSLER-COHEN, D., GERVAIS, A., BĂLĂNȚLI, F., AND VECEV, M. Securiq: Practical security analysis of smart contracts. In *CCS* (2018).
- [45] WANG, S., DINH, T. T. A., LIN, Q., XIE, Z., ZHANG, M., CAI, Q., CHEN, G., FU, W., OOI, B. C., AND RUAN, P. Forkbase: An efficient storage engine for blockchain and forkable applications. In *VLDB* (2018).
- [46] ZHANG, F., CECCHETTI, E., CROMAN, K., JUELS, A., AND SHI, E. Town crier: An authenticated data feed for smart contracts. In

