

Violable Contracts and Governance for Blockchain Applications

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Abstract

We examine blockchain technologies, especially smart contracts, as a platform for decentralized applications. By providing a basis for consensus, blockchain promises to upend business models that presuppose a central authority. However, blockchain suffers from major shortcomings arising from an over-regimented way of organizing computation that limits its prospects. We propose a sociotechnical, yet computational, perspective that avoids those shortcomings. A centerpiece of our vision is the notion of a declarative, violable contract in contradistinction to smart contracts. This new way of thinking enables flexible governance, by formalizing organizational structures; verification of correctness without obstructing autonomy; and a meaningful basis for trust.

Keywords: Blockchain; Smart contracts; Contracts; Sociotechnical systems

1 Introduction

Blockchains have become prominent in the computing landscape. The idea of blockchains originated from the cryptocurrency Bitcoin [13]. Whereas previous approaches to digital currency relied upon a central entity to address integrity, specifically, avoiding double spending, Bitcoin ensures integrity without a central entity.

Blockchains provide a distributed, shared ledger by bringing together cryptographic hash functions to achieve immutability and Byzantine fault tolerance to achieve consensus—as to the definitive current state of the ledger—among mutually untrusting peers. Such robust consensus could enable any digital transaction involving parties who may not fully trust each other.

By providing a consistent system-wide view of events under weak trust assumptions, blockchain can enable decentralized applications, for which lack of trust between participants is a major obstacle. That’s how blockchain could upend business models in just about any sector: healthcare, manufacturing, and others [12, 25], especially in combination with technologies such as the IoT [5].

Consider electronic health records (EHRs) as a representative application for blockchain. Healthcare involves multiple stakeholders with multiple overlapping business relationships, some of a few hours (emergency room) and some stretching for decades. Yuan et al. [25] motivate the necessity of integrity, provenance tracking, portability, availability, and access control. Among the known data representations, only blockchain effectively provides these properties.

The theses of this paper are these. First, decentralized applications are naturally understood in terms of interactions between autonomous parties. Second, blockchain technologies as traditionally construed are inadequate for decentralized applications. Third, a perspective from *sociotechnical systems (STSs)* helps address these inadequacies via (1) an autonomy-preserving representation for *violable* contracts; and (2) an architecture of organizations that balances flexibility and rigor to engender trust.

Scope and contributions This paper focuses on the challenges relating to decentralized applications understood as STSs, deemphasizing concerns such as confidentiality and performance. Its main contributions are these:

- An analysis of opportunities for blockchain as a platform for decentralized applications and how they are stymied by fundamental shortcomings of blockchain.
- A vision of research challenges necessary to address those shortcomings from a sociotechnical perspective.

This paper is organized as follows. Section 2 introduces the relevant conceptual grounding for blockchains and allied concepts, such as smart contracts. Section 3 exposes key limitations of blockchains for our present purposes. Section 4 describes research opportunities in addressing those limitations. Section 5 concludes with a discussion of prospects.

2 Blockchain, Conceptually

Blockchain solves the longstanding distributed computing problem of achieving immutable agreement as to the current state of the system, despite failures and malice—as long as a majority of the computing power on the network remains in the hands of benevolent participants. Specifically, blockchain determines the indisputable order in which events have occurred.

We consider Bitcoin [13], the original blockchain formulation, to introduce key ideas. However, we elide Bitcoin-specific details, such as transaction costs and currency mining. Bitcoin is geared toward handling financial transactions, and provides a ledger of who owns how much of its designated currency, namely, bitcoins.

Any blockchain consists of a series of blocks, each pointing to, and including the cryptographic hash of, its predecessor. The series ends at the *genesis* block. Any peer can verify a block’s integrity by verifying its hash. Since a block contains a pointer to the previous block, the entire blockchain can be verified.

Each block includes a list of transactions, each transaction being a record of transfer of ownership of money. In Bitcoin, the party providing the coins signs the transaction, indicating consent. If a transaction is added to a block, then according to any chain that extends this block, the specified coins transfer to the recipient.

Whenever a peer receives a transaction, from a client or forwarded from a peer, it verifies the transaction by checking the signatures and establishing that the transferrer owns the requisite coins through previous transfers. Next, it forwards that transaction to its peers, who verify and forward it along to their peers, and so on. Therefore, potentially, every peer can learn of a new transaction.

Every so often, a peer may build a new block consisting of some or all of the transactions it has received, by inserting them in a new block. It creates a block header containing a hash of these transactions and a hash of the “previous” (front of the current *active* chain) block.

Distribution may lead to competing blocks extending the same predecessor. Bitcoin introduced *proof of work* to combat such branching and promote consensus. Every block header includes designated bits called a *nonce*. Given the rest of the header, the “work” is to produce a nonce such that the hash of the entire block header satisfies a criterion, namely, being smaller than a systematically determined number, called the *target*. The target adjusts up or down to make block creation or *mining* easier (faster) or harder (slower), respectively.

Upon mining a block, a peer broadcasts it, in essence proposing to extend the blockchain. Any recipient can verify the block’s integrity by checking that its hash is within the target. If the incoming block extends the (known) active chain, it extends it and treats it as active. Otherwise, it

treats the longest of the known branches as active. Other features of Bitcoin, including how coins are generated and miners (peers who create blocks) rewarded, are not relevant here.

The cryptographic hashes in Bitcoin’s consensus protocol yield immutability: any change to the contents of a prior block would invalidate its hash. Therefore, an attacker would need to engender consensus on an alternative active chain. Assuming the difficulty of inverting cryptographic hashes, it is not feasible to come up with a block whose hash equals the hash value stored in its successor block. And, the consensus mechanism ensures that an attacker cannot fabricate a new blockchain with different hash values in the chain, as alternative facts to the “real” blockchain—unless the attacker controls a large fraction of the computational resources in the network.

2.1 Smart Contracts

The notion of a smart contract [22] predates blockchain. In general, a smart contract specifies contractual conditions programmatically, such that the contract would automatically execute when input data meets the stated conditions. Szabo [22] characterizes a vending machine as a smart contract that takes in coins and outputs a product. Smart contracts could potentially be attached to any real-world object [5], e.g., a house for rent.

Here, a smart contract is placed on the blockchain, digitally signed by its creator, with its conditions specified in a program. Since a smart contract is public, the parties wishing to exercise it can know in advance how it will function—provided they understand it. Hence, smart contracts can enable commerce in an open setting.

Bitcoin transactions are a simplified form of smart contracts, since Bitcoin’s limited language allows little more than verifying signatures. But newer approaches, including Ethereum, ambitiously support Turing-complete languages for smart contracts that initiate transactions based on observed events.

2.2 Permissioned Blockchains

Bitcoin exposes every transaction in a public ledger. Moreover, Bitcoin is slow: it auto-tunes the target so a new block is mined no more often than once in 10 minutes, the amount of work required being instrumental in achieving consensus in Bitcoin’s untrusted setting.

Permissioned blockchains, such as Hyperledger [8], address these shortcomings. A permissioned blockchain assumes that it is carried out over a restricted network. Only approved parties may create transactions and smart contracts, and validate blocks. In effect, such an architecture gives up the openness of blockchains but gains in practicality and an ability to ensure legality of transactions, which are essential for most serious purposes. Such transactions arise commonly—a pharmaceuticals company wouldn’t source its medications from an unknown party, and a physician is legally required to check credentials of recipients of patient health data.

2.3 Upcoming Enhancements

Blockchain seeks to determine a definitive linear order of events across the entire system. Linearizing otherwise unrelated events is superfluous at best and can cause unacceptable performance loss, which has led to approaches that relax the linear structure into a directed acyclic graph [11] and change the consensus mechanics accordingly. We focus instead on how to construct applications that avoid the conceptual limitations of blockchains no matter what form a blockchain takes.

3 Sociotechnical Limitations of Smart Contracts

Let's consider the hazards of smart contracts to motivate the limitations of blockchain. The Decentralized Autonomous Organization (DAO) fiasco [3] is telling. DAO, a venture funding entity created as a smart contract on the Ethereum blockchain, was hacked to the tune of \$50M, by exploiting a flaw in the DAO's smart contract and the underlying Ethereum virtual machine. The specific flaw is merely a symptom that it is impossible to establish correctness for a program in a Turing-complete language.

Interestingly, this mistake was remedied by causing a fork in the blockchain. Specifically, several Ethereum users colluded to extend a prior block as a way to exclude the undesirable transactions, discarding legitimate ones as well. (Now there are at least two versions of Ethereum, though the details don't concern us here.) Of course, a fork was possible only because a large fraction of the active participants agreed to it. A minority would not be able to take such remedies.

The success of the fork undermines the very point that motivated blockchains, namely, their immutability. For something like DAO, it may be appropriate to discard several days of legitimate transactions to avert a loss of \$50M. But what would the tradeoffs be in practice? Would it be fair to discard an hour's worth of real commerce at the national scale to save \$50M? We suspect not. Or, a less greedy attacker may succeed by causing only small amounts of harm at a time, for which detection and reversion are infeasible.

On Hyperledger, because of its permissioned nature, the risk is presumably better contained. However, errors in smart contracts are unavoidable and undesirable outcomes would be difficult to reverse.

We now discuss three major shortcomings in the current conception of smart contracts.

3.1 Lack of Control

The independence of participants with respect to their beliefs and actions is a crucial aspect of decentralization. Blockchain supports independence with regard to private beliefs since consensus applies only to shared events, which is essential for achieving interoperation.

However, smart contracts fail independence for actions. They automate processing, removing control from the participants. A smart contract once launched cannot be overridden. Indeed, no one can even contemplate overriding a smart contract because it executes automatically.

How can we reconcile blockchain with autonomy?

3.2 Lack of Understanding

Since the meaning of a smart contract is hidden in a procedure, even though the procedure is public, it is not apparent if it meets stakeholder requirements, and how it may be exercised by a participant. Since blockchains are immutable, any mistake in capturing requirements cannot be corrected without violating immutability. Therefore, a powerful language for smart contracts placed on a blockchain poses a huge risk [14], as the DAO incident illustrates.

Instead, we need a language in which we can capture the essential stakeholder requirements directly. To improve verification, such a language would be limited in expressiveness. To enhance confidence in capturing valid requirements, it would offer constructs close to the stakeholders' conception.

How can we develop such a language including an appropriate semantics?

3.3 Lack of Social Meaning

Any software application involves contact with the real world. In some cases, the real world can be readily abstracted out. Bitcoin, being designed for cryptocurrency, is *endogenous*, meaning that bitcoins exist entirely within the blockchain, which can therefore ensure their integrity. Bitcoin is an atypical application since it excludes considerations other than of transactions involving bitcoins.

More commonly, applications such as healthcare and commerce are entwined with the real world, social or technical. For example, in healthcare, surgical equipment may fail or a patient may deny having been adequately informed when giving consent. For physical or communication failures, the possible resolutions lie in the social sphere, as traditionally handled through contracts and laws.

The DAO hack demonstrated an integrity violation, indicating a platform failure. In a decentralized scenario, any response to an interoperation failure, including a platform failure, *must* be social. Indeed, the response to fork the blockchain was social—it’s just that it was an ad hoc and unverifiable response entirely outside the computational realm.

How can we enhance blockchain and smart contracts with abstractions to express and compute with social meaning?

4 Vision: Compacts, Governance, Verification, Trust

The foregoing discussion shows that smart contracts are inadequate for describing interoperation between autonomous parties: they take over control of decision making, are opaque, and omit social meaning. We now describe our vision that avoids these shortcomings and enables natural interactions between autonomous parties.

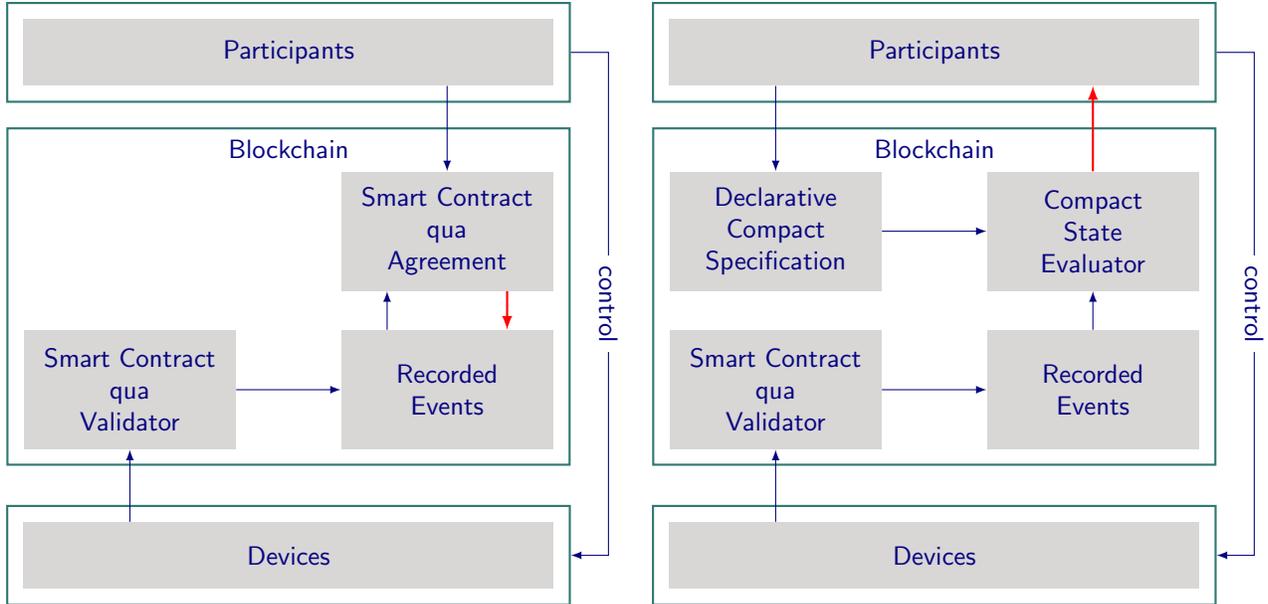
4.1 Declarative Violable Contracts

We introduce the term *compact* (<https://www.ldoceonline.com/dictionary/compact>) for our conception of contracts to avoid confusion with both smart contracts and traditional contracts.

In contrast to a smart contract, a compact is not a program executed by the blockchain but a *specification of correct behavior*. A compact would be stored on the blockchain. However, a compact is a computational artifact: its formal semantics determines which blockchains satisfy and which violate the compact. A query processor based on the semantics would determine the state of each instance of a compact—whether it is expired, satisfied, or violated.

Figure 1 illustrates how compacts differ from smart contracts. In both settings, participants (social entities) own and control devices (technical entities), such as computers, sensors, and vehicles. The blockchain records events produced by the devices, upon validation by a smart contract. In the traditional conception of Figure 1a, the participants additionally specify their business agreements as smart contracts that carry out actions and record events on the blockchain. In our conception, in Figure 1b, the participants specify the compacts corresponding to their business relationships. Given the recorded events, the evaluator determines whether a compact is satisfied, violated, or neither. It informs the participants about states of relevant compacts, but does *not* record events. That is, of the two functions of smart contracts in Figure 1a, Figure 1b retains only one.

A compact helps balance autonomy and correctness. A party to a compact, exercising its autonomy, may violate it. For example, a compact in healthcare may specify that a hospital prohibits a nurse to share a patient’s data without the patient’s consent. Yet, a nurse Bob may share patient Charlie’s data with cardiologist Alice without Charlie’s consent. From the semantics, given recorded events, we can compute whether the compact was satisfied or violated. But, of



(a) Smart contracts not only validate received events but can insert additional events into the blockchain.

(b) Compacts provide a declarative standard of correctness but do not insert events into the blockchain.

Figure 1: Comparing compacts and smart contracts in a blockchain architecture.

course, the violation in the present example doesn't entail that Bob was malefasant. It could be that Charlie had a medical emergency and was in no condition to give consent. Bob could be rewarded for saving Charlie's life for his workaround [10]. The compacts view highlights the importance of detecting and resolving conflicting requirements [6].

To recover understanding, control, and make the social meaning explicit, we need a declarative representation for compacts that captures the essence of traditional contracts. A compact would explicitly state what each concerned party may expect from the others. To this end, the formal notion of *norms* yields promising constructs. As motivated by Georg von Wright, the father of deontic logic, this kind of norm expresses regulatory force [24]. This form of norm is directed from its subject to its object, and states logical conditions under which it goes in force and under which it completes [20]. For example, a prohibition is a kind of norm in this sense.

4.2 Organizations and Governance

Consensus on what has transpired can support decentralized applications by averting disputes as to the public facts. But, as envisioned here, the parties may nevertheless violate applicable compacts.

An *organizational context* for a norm is the organization in which the norm arises [18]. The context is a principal on par with any other, and may feature as a subject or object of another norm. This simple representation can be valuable: The context can serve as an adjudicating authority for disputes; norms involving it help mitigate violations of norms in a compact [21].

Let us extend the above patient information example to make the hospital the context of the prohibition norm and to introduce a commitment from the hospital to the patient to investigate any sharing of the patient's data without the patient's consent. Now when Bob reveals Charlie's data without Charlie's consent, the hospital's commitment to Charlie is activated. The hospital can satisfy the commitment by conducting its investigation, upon which it may exonerate and reward Bob or penalize him.

The above example illustrates *governance*, i.e., how coherence is achieved in interactions, in the absence of a central authority [7, 15, 20]. Governance is a prerequisite for accountability and trust, which are means with which to balance autonomy and correctness.

Decentralized applications cannot avoid governance: the choice is whether to leave it ad hoc and manual or to make it formal and computational, as we envision. In our conception, every decentralized application is associated with an organization, which serves as the context of the compact that defines the application. Today, we see nebulous communities, such as the Ethereum network, or somewhat more crisp organizations such as on permissioned blockchains. However, these organizations lack a computational representation such as a compact. Consequently, there is no precise characterization of what an organization can expect from its members and vice versa.

How can we represent and compute with formal organizations in relation to compacts on blockchain? How can we treat an organization as an entity on par with other parties in a decentralized application?

4.3 Programming and Verifying Interactions

Achieving coordination is nontrivial in decentralization applications. Existing approaches hardcode coordination in the participants, i.e., their agents. Doing so reduces flexibility in interoperation and hides essential details, thereby preventing composing compacts. Therefore, it is important to specify the coordination declaratively. Doing so requires not just formal semantics for data [23] but also models of causality and integrity constraints on interactions underlying the data [19]. To facilitate integrity preservation of decentralized applications, we can capture information-level integrity constraints in a smart contract that validates received transactions. Doing so would prevent entering an information state wherein the applicable compact’s state would be confused.

To enable interoperation, we must formalize how an interaction proceeds, not just who participates or what data they exchange. Blockchains, e.g., Hyperledger [8], provide coordination abstractions such as a *channel*—a subnet on which only participants can access information. A channel supports confidentiality and helps decouple participants by hiding irrelevant information. In essence, we would enhance channels into formal *protocols*. Moreover, to support declarative compacts, we must specify a protocol declaratively so that the state of a compact can be computed and satisfaction or violation determined based exclusively on information in the blockchain [16].

To capture the intuition that a decentralized application is specified via a compact, we would need to generate protocols automatically from a compact such that each involves only the relevant participants. What causality and integrity constraints on protocols arise naturally from a compact? What causality and integrity constraints arise from application-specific considerations such as which parties controls what events? And, which pieces of information are generated atomically, and so on? Recent work on generating protocols that guarantee alignment of commitments provides a start [9].

How can we ensure the protocols yield the information transfer needed by each party to enact its part of the application and to verify *compliance* of other parties with the compact? Notice that a closed system approach for compliance does not apply in blockchain. Specifically, contrary to recent suggestions [12], we *cannot* determine compliance based on internal details of a participant, such as its beliefs, intentions, or sincerity. In contrast, verifiability in an open setting demands a *public semantics* [17], which is what a shared ledger offers—a major point in favor of blockchain.

4.4 Meaningful Trust and Reputation

The autonomy of participants and embedding in the real world suggest that participants would need to trust one another to interoperate. The possibility of violation of a compact creates a *vulnerability*, a hallmark of trust [4]. Blockchain obviates the need for trust only to the extent that the governance structures provide assurance against malfeasance by another participant and the structures themselves are trusted.

However, blockchain can serve as a platform for promoting meaningful trust between parties. First, quite naturally, the states of relevant compacts provide an opportunity to make evidential trust judgments. Violation and satisfaction of a norm would mean a lowering and raising, respectively, of trust in the concerned party with respect to similar norms. Second, explicit governance engenders trust because parties that may otherwise not transact with each other would do so because compacts for governance would give them assurance that malefactors would be sanctioned. A party may violate a compact by failing to satisfy its conditions, but if it does so its violation would be determinable from the blockchain. The aggrieved party [2] may file a complaint, also recorded in the blockchain, presumably triggering a governance compact.

Third, governance can provide a basis for capturing the trust assumptions by formalizing what counts as evidence for what norm. Consensus on blockchain concerns the events observed. But armed with a governance structure, we can encapsulate norm-relevant evidence within an event in a manner that reflects the application semantics. For example, a norm may rely upon a patient having a benign tumor. But, in medical practice [1], whether a tumor is benign is a fact that is established by the tumor board of the hospital. That is, the tumor board’s assertion counts as the tumor being benign.

5 Discussion

The emergence of blockchain as a platform for decentralized applications exposes new usage scenarios. Concomitantly arise new expectations from computing—specifically, in terms of governance (organizations, norms, privacy) and trust. Consequently, it becomes essential to bring forth sociotechnical considerations into computing.

Table 1 highlights how our vision of compacts contrasts with existing approaches. Here, the blockchain declaratively represents contractual relationships; maintains relevant events; enables a participant to violate a contract if it so desires; computes whether the contract is satisfied, violated, expired, or otherwise pending; thereby activating applicable governance contracts and providing a basis for trust.

Table 1: Contrasting compacts with traditional and smart contracts.

	Traditional	Smart	Compacts
Specification	Text	Procedure	Formal, declarative
Automation	None	Full	Compliance checking
Participants’ Control	Complete	None	Complete
Venue	External	Within blockchain	Recorded on blockchain
Trust Model	Hidden	Hardcoded	Explicit
Social Meaning	Informal	None	Formal
Standard of Correctness	Informal legal	Whatever executes	Formal legal
Scope	Open but ad hoc	Closed	Sociotechnical

In this manner, we envision computational representation and reasoning about sociotechnical

considerations. Specifically, we advocate developing approaches for programming interactions on or through the blockchain that build on and support effective governance and trust.

This vision yields valuable research opportunities concerning how participants (1) preserve autonomy in being able to violate a contract and verify each other’s compliance; (2) deal with events in the real business or social worlds, external to the blockchain; (3) maximize flexibility in having their interactions minimally constrained to interoperate successfully; and (4) most importantly, build and realize governance structures to deal with autonomy and exceptions.

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