A Comprehensive Survey on Smart Contract Construction and Execution: Paradigms, Tools and Systems

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Abstract—Smart contract has been regarded as one of the most promising and appealing notions in blockchain technology. Its self-enforcing and event-driven features make some online activities possible without a trusted third party, especially those related to financial and business. However, problems such as high security risk and low processing rate prevent it from being widely applied. In order to facilitate the construction of secure smart contract, and to improve the execution performance, various schemes and tools are proposed. However, to our best knowledge, a comprehensive survey for these proposals is absent, hindering new researchers and developers from a quick start.

This paper surveys the literature on constructing and executing smart contracts over the period 2008-2020. We review the literature in three categories: 1) design paradigms that give examples and patterns on contract construction; 2) design tools that facilitate the development of secure smart contracts by providing security analysis or other auxiliary helps; and 3) extensions and alternative systems that improve the privacy or efficiency of smart contract executions. We start by a brief introduction of essential backgrounds, and then investigate the contract construction schemes on the most prevalent and representative smart contract platforms, i.e., Bitcoin and Ethereum. We list and group them into the first two categories according to their utility. As for the last category, we review the existing contract execution mechanisms, and further divide the state-of-the-art solutions into three classes: private contracts with auxiliary tools, off-chain channels, and extensions on the core functionality. Finally, we summarize the future research directions towards secure and privacy-preserving smart contracts. As far as we know, our work is the first systematic survey on schemes of contract construction and execution.

Index Terms—smart contract; contract construction; contract execution; blockchain; security analysis; efficient development; privacy

I. INTRODUCTION

The advent of Bitcoin [1] in 2008 marks the birth of cryptocurrencies, which are maintained without trusted third parties (TTP). Since then, numerous cryptocurrencies have emerged. Unlike traditional fiat currencies issued by governments, cryptocurrencies circulate in specific computer programs through peer-to-peer (P2P) technology, where no leader or dominant node is responsible for message transmission. Cryptocurrencies are equipped with numerous cryptographic and game-theoretic schemes that ensure their safe circulation on the Internet.

The core technology that enables the cryptocurrencies is blockchain, which ensures data consistency among distributed nodes in a P2P network without mutual trust. Later in 2014, Ethereum [2, 3] extended Bitcoin and introduced the concept of smart contract [4] into blockchain, which greatly enriches the application scenarios of blockchain, and becomes one of the most promoting motivations of blockchain technology.

After the birth of Ethereum, applications of smart contracts gradually become prevalent, and many other platforms are derived. In 2016, Corda [5] came out as a distributed ledger platform for the financial services industry, aimed at improving the transaction processing rate. For the privacy concerns on smart contracts, Quorum [6] introduces private state trie and other technical methods into Ethereum, so as to support the execution of private contracts. The Hyperledger Fabric [7] system led by IBM further facilitates the application of smart contracts, by allowing companies or consortium to run it collaboratively, so as to improve the transaction processing rate while keeping the data consistent and non-malleable. Since 2015, smart contracts in Hyperledger Fabric have been widely used in supply chain, education, business and others.

From the academic perspective, researchers are mostly dedicated to the design schemes or improvements on public blockchains where everyone could join, especially Bitcoin and Ethereum, since the problems occur in these platforms are most typical and also influence the other derived systems. Also, the research results in these platforms can be easily migrated into others.

One of the biggest issues on blockchain and smart contract technology is that all transaction details are public. This might cause the leakage of users’ privacy, even with the pseudonym mechanism (i.e., identifying and clustering users with pseudonyms) [8, 9]. Moreover, since transactions are executed and validated by all participating nodes in a duplicated way, the transaction rate (or throughput) is quite limited in the blockchain system. Both the privacy and efficiency problems hinder many applications to be implemented as smart contracts. This makes the state-of-the-art smart contracts only applicable in a small number of fields.

Considering the security aspect, there are also concerns
that smart contracts are vulnerable to hacker attacks. One infamous example is the attack against the crowdfunding project Decentralized Autonomous Organization (DAO) in 2016. DAO relies on a smart contract on Ethereum. Developers collect crowdfunding for their blockchain-based applications, and investors are rewarded in return. However, there is a vulnerability in the contract code [10], which is exploited to transfer funds out of the DAO contract by the attacker, and finally causes a loss of funds worth about 60 million dollars at that time. This attack changes the attitude of investors towards smart contracts, and it consequently hinders the development of smart contract and blockchain technology.

The DAO event is just one of typical attacks against smart contracts. Since smart contracts usually involve financial transactions, any attack may cause a severe economic loss. Consequently, compared with normal programming, the design of smart contracts has higher security requirements. This makes it more difficult for ordinary users to write secure smart contracts by themselves, which further inhibits the popularity of smart contracts in other industries.

To sum up, issues on security, privacy and transaction rate are the main obstacles for the universal adoption of smart contracts. Though fresh this research field is, there have been various schemes on the construction and execution aspects of smart contracts, to overcome such barriers and promote the development and adoption of smart contracts. In this paper, we conduct a systematic survey of these schemes over the period 2008-2020, aiming at providing a comprehensive review of the smart contract technology, and helping new researchers and developers to have a quick start.

**Our Contributions.** We conduct a survey on the construction and execution schemes of smart contracts from the perspectives of paradigms, tools and systems, over the period 2008-2020. We believe that our work will give insights to researchers and developers who are new to smart contracts, and provide an holistic technical perspective on contract construction and execution schemes. Our main contributions are as follows:

1. We provide the essential background knowledge on blockchain and smart contracts, especially the contract execution mechanisms, to provide new incomers of this field an overall impression of the related concepts. Moreover, we give several necessary definitions to help readers have a better understanding of this work.

2. We divide existing blockchain systems that support smart contracts into script-based and Turing-complete blockchains, with Bitcoin and Ethereum as representatives, respectively. Then we systematically classify and analyze the contract construction schemes in these platforms.

3. We list several drawbacks and limitations of the existing mainstream blockchain execution mechanisms. We then investigate and categorize the extensions and alternative systems that are aimed at mitigating these problems.

4. We discuss the strengths and weaknesses of the state-of-the-art solutions that address the privacy and efficiency issues in both contract construction and execution aspects, and point out several future research directions on the aspects of smart contract construction and execution.

**Organization.** The remainder of this paper is as follows. Section II introduces the background, preliminaries and related work. Section III provides the systematization methodology of this paper. Section IV and Section V describe the construction schemes of smart contracts in script-based and Turing-complete blockchains, taking Bitcoin and Ethereum as representatives, respectively. Section VI discusses various solutions and extensions to improve the privacy and efficiency of the contract execution mechanisms. Section VII outlines several further research directions of smart contract construction and execution. Finally, Section VIII provides a conclusion of this paper.

**II. BACKGROUND, PRELIMINARY AND RELATED WORK**

In this section, we firstly provide the essential background in Section II-A, then give the relevant definitions and notations in Section II-B and finally present the related work in Section II-C.

**A. Background**

The background information for this study is given in the following: we first give a brief impression about the blockchain technology in Section II-A1 and then explain the concept of smart contract that is widely supported by mainstream blockchains in Section II-A2.

1) **Blockchain:** Informally, a blockchain is a sequence of blocks linked with hash values. Transactions that deliver messages among users and interact with the blockchain are stored in the body of each block, while digest information and other identifiers are recorded in the block header. A blockchain is maintained by the nodes participating in the network and the data consistency among the nodes is ensured according to some predetermined rules called consensus.

We take the Bitcoin blockchain as an example and illustrate its structure in Fig. 1. It is formed by linking multiple blocks in sequence with their hash values. Each block consists of a block header and a block body. Specifically, a block header includes a hash value of the previous block $H_{prev}$, a version number $v$ of current consensus rule, a current mining difficulty.
parameter \( d \), a timestamp \( t \), a Merkle root of transactions \( H_{\text{root}} \) and a random nonce \( n_r \). A block body includes transactions \( Tx_{j\in\mathbb{N}^n} \) that are used to calculate \( H_{\text{root}} \). As is shown in Fig. 1, every two adjacent hash values are combined to calculate the hash in the upper layer. If there is a single node left at the end, it will be duplicated and combined with itself, as shown in the path of \( H_5 \rightarrow H_{55} \rightarrow H_{5555} \). Note that the contents in the dotted box in Fig. 1 are only used to illustrate the calculation of \( H_{\text{root}} \) and not included in the block.

In the Bitcoin blockchain, the verification of new blocks is simplified due to the separation of block headers and bodies. Cryptographic schemes (such as hash function and Merkle tree) are adopted to guarantee the tamper resistance and consistency of data. Each node can individually calculate the final state by executing all transactions in order from the genesis block, i.e., the initial block of the blockchain. In this way, a central trusted third party is eliminated from the system, and any individual party cannot interrupt the operation in blockchain. For more technical details about Bitcoin blockchain, readers may refer to [11]. We remark that the blockchain structure discussed above is widely adopted by other derived systems, e.g., Ethereum, Corda, Quorum, etc., and the introduction of these blockchains are omitted here.

2) **Smart Contract:** The concept of smart contracts was first proposed by Szabo [4] in 1997, referred to a multi-party protocol that could be automatically enforced without a trusted third party. Without practical implementation, it did not receive enough attention at that time. Several years later, with the birth and development of blockchain, smart contracts are brought back into practice.

In the blockchain context, smart contracts are usually defined as event-driven computer programs executed and enforced by all participants in a P2P network. In each smart contract, there are public interfaces that deal with relevant events. These interfaces are invoked by the transactions with proper payload data (Definition 9), and all valid transactions are recorded on the blockchain. Formal definitions of smart contracts and some other related concepts are provided in Section II-B2.

Bitcoin supports a set of scripts that enable the auto-enforcement of some special financial affairs other than plain electronic cash exchange. This procedure can be considered as the prototype of smart contracts. In the early years, some researchers implement zero-knowledge contingent payment [12] to achieve fair exchange of electronic goods. From another point of view, the execution mechanism among different platforms varies. In the following, we give a brief introduction of the execution mechanisms in Section II-A2a and Section II-A2b, respectively, taking Bitcoin and Ethereum as representatives.

**a) Contract execution in Bitcoin:** Smart contracts in Bitcoin mostly refer to the transactions setting script hashes as output addresses (Pay to Script Hash, P2SH), which encode the hashes of scripts into Bitcoin UTXOs (Definition 10). P2SH transactions are the basis for multi-signature (MultiSig) [16] transactions, Lightning Network [17] and other technologies in Bitcoin ecosystem.

Fig. 1 shows a simplified payment process in Bitcoin, where the brown arrows represent the processes of deploying a smart contract through the creation transaction \( Tx_{\text{create}} \). In the development stage, some construction tools are used to facilitate the design of contracts. Then some analysis tools are used to confirm the security and correctness of the contract (Definition 13, 14). The blue and red arrows refer to the call from smart contracts and users, respectively. After receiving \( Tx_{\text{call}} \) and \( Tx_{\text{call}} \), the miners (i.e., executors) verify and package the transactions into the latest block, i.e., Block\(_{i+2}\). Finally, the World State, which contains all the states, is updated accordingly.

Fig. 2 shows the workflow of a blockchain that supports smart contracts, where the brown arrows represent the processes of deploying a smart contract through the creation transaction \( Tx_{\text{create}} \). In the development stage, some construction tools are used to facilitate the design of contracts. Then some analysis tools are used to confirm the security and correctness of the contract (Definition 13, 14). The blue and red arrows refer to the call from smart contracts and users, respectively. After receiving \( Tx_{\text{call}} \) and \( Tx_{\text{call}} \), the miners (i.e., executors of these transactions) verify and package the transactions into the latest block, i.e., Block\(_{i+2}\), following the execution mechanism. After the block is accepted by the whole network, the World State, which contains all the states, is updated accordingly.

From another point of view, the execution mechanism among different platforms varies. In the following, we give a brief introduction of the execution mechanisms in Section II-A2a and Section II-A2b, respectively, taking Bitcoin and Ethereum as representatives.

**b) Contract execution in Ethereum:** Ethereum introduces a new virtual machine structure and supports Turing-complete programming languages, which greatly enrich the functionalities of smart contracts. Specifically, Ethereum supports the execution of arbitrary deterministic computer programs in theory. The underlying Ethereum Virtual Machine (EVM) recognizes a low-level language called EVM bytecode. In order to reduce the learning cost and improve the efficiency of development, several high-level programming languages are proposed, e.g., Solidity [14] and Serpent [15], whose grammar is similar to that of mainstream programming languages. Contracts written in these high-level languages can be compiled into EVM bytecode with appropriate compilers.
that the transactions indeed take effect and cannot be erased or forked, with an overwhelming probability. This introduces a huge delay on the transaction confirmation, which further limits the implementation of Bitcoin smart contracts.

In addition, since the information on the Bitcoin blockchain is publicly available, the full scripts are exposed to the entire network. Even though Bitcoin is equipped with a pseudonym mechanism, the leakage of such private information is still inevitable. Curious readers may refer to the work of Conti et al. [18] for a more detailed survey on privacy issues in Bitcoin.

b) Contract execution in Ethereum: The Turing-complete programming languages in Ethereum greatly extend the application scenario of smart contracts. Theoretically, smart contracts in Ethereum can realize any deterministic program. These contracts are executed by the EVM, whose formal definition and execution mechanism are elaborated in Ethereum Yellow Paper [3].

Ethereum adopts the account model (Definition 11), where an account of a smart contract has the same status as that of a user. In other words, a contract account has the same ability to send transactions and trigger or create contracts as that of a personal account.

Transactions are handled by miners who run the EVM. After a transaction is included in the blockchain, the balance in the corresponding account and the variables in the contract are updated according to the transaction contents and the rules defined by the contract code.

In order to prevent potential Denial of Service (DoS) attacks (e.g., non-stop execution caused by an infinite loop), Ethereum introduces the gas mechanism. Namely, each operation consumes a certain amount of gas, and the upper bound of gas consumption is set and paid in advance in the transaction. If the execution of the contract function is not terminated before the exhaustion of gas, the contract will be reverted to the initial states before the triggering of this function, and all the consumed gas will be charged by the miners as execution fees. However, this on the other hand limits the complexity of smart contracts.

In addition, similar to Bitcoin, smart contracts in Ethereum also suffers from privacy leakage. Several schemes have been proposed to handle such privacy issues and will be discussed later in this paper.

B. Preliminary

For completeness and unity, we give the notations used in our work in Section I-B1. On the other side, to provide a better understanding, we list several essential definitions that occur frequently in this paper in Section I-B2.

1) Notations: As mentioned in Section I, the security problems on smart contracts are serious and should be carefully settled. Therefore, relevant solutions for contract construction and execution usually come with a formal security proof, which might involve mathematical models or cryptographic primitives. To make these schemes present in a uniform style, we make an effort to unify the notations in our work, as shown in the following.

Sets are denoted with upper-case calligraphic letters, e.g., \( \mathcal{T} \) denotes the set of valid transactions for a contract.

For most functions, \( F \) is used, along with a subscript denoting the particular usage of this function, e.g., \( F_{\text{neg}} \), the negligible function with some security parameter. Some other functions or primitives may be denoted with Greek letters, e.g., \( \phi \) for the primitive that evaluates the witness \( \omega \).

Tuples are denoted with upper-case letters, e.g., \( U \) denotes an unspent transaction output (UTXO, Definition 10). A dot operation is used to refer to the component inside a tuple, e.g., \( U.v \) denotes the value of a UTXO. \( Tx \) is used for a transaction, and \( Tx.in, Tx.out, Tx.id \) and \( Tx.pld \) denote a transaction’s input, output, identifier and payload data, respectively.

Arbitrary-length sequences are denoted as bold lower-case letters, e.g., \( \text{buf} \), the stack of buffers. Square brackets are used to index individual components, e.g., \( \text{buf}[0] \), the first item on the buffer stack.

Scalars and variables are denoted with a lower-case letter, e.g., \( n \) is often used to denote the number of participants, and \( i, j, k \) are often used as indexes to refer to the members in a set. Moreover, those with a special meaning may be Greek, e.g., \( \sigma \), denotes a digital signature.

For the names of proposed schemes, we adopt the original text styles in the literature, e.g. \text{OYENTE}, \text{Hawk}, etc.

Besides, some special representations are used for particular meanings. Hash values are denoted with \( H \), whose subscripts may be strings with special meanings, e.g., \( H_{\text{root}} \), the root hash of a Merkle tree. Time is denoted with \( t \). We use \( \beta_x \) to represent \( x \) bitcoins. Smart contracts are usually denoted with \( C \), while for those with particular meaning, the typewriter abbreviations are used, e.g., \( \text{HTLC} \), the hash timelock contract. Greek letters like \( \beta, \gamma \) are used to denote payment channels and state channels. Protocols are denoted with \( \pi \). The letter \( \mathcal{A} \) is used especially to denote an adversary. Participants in a protocol or contract are denoted as \( P \), which often comes with subscripts like numbers (e.g., \( P_1 \), the first participant) and letters (e.g., \( P_s \), the sender). Address, usually a string in the context of blockchain, is denoted with \( a \), and with subscripts denoting the usage of this address, e.g., \( a_{\text{mul}} \) is the multi-sig address in the Bitcoin context. Ideal functionalities are denoted with \( \mathcal{F}^* \), and the message headers in these functionalities are represented with the small capital letters, e.g., \text{DEPOSIT}.

As for operations, we use \( s \leftarrow 0 \) to denote the operation of assigning value 0 to \( s \), and \( s \leftarrow_s \{0, 1\}^{128} \) to denote that \( s \) is uniformly picked at random from the set \( \{0, 1\}^{128} \). The
operation $\rightarrow$ is used to denote the concatenation of several nodes that forms a path, as already shown in Fig. 1 the path $H_5 \rightarrow H_{55} \rightarrow H_{5555}$. $(P, V)$ is used to denote the interaction of two Turing machines $P$ and $V$. Concatenation of strings are denoted with $||$ and the XOR of same-length binary elements with $\oplus$.

2) Definitions: We give and rephrase some essential definitions and concepts frequently used in our work here. Definitions that are only used once are introduced when they first appear in the context.

First of all, with the development of blockchain technology, there have been several kinds of blockchains with distinct properties. According to the works of [19] and [20], blockchains can be divided into three categories as follows:

**Definition 1 (Public Blockchain):** In a public blockchain, any node is permitted to join the maintenance of data on blockchain, and the data is publicly visible and verifiable. Besides, anyone is allowed to deploy, call and execute smart contracts.

**Definition 2 (Consortium Blockchain):** In a consortium blockchain, the nodes that are responsible for maintaining the data are determined in advance, and only these consortium members can access data on the blockchain or deploy, call, and execute smart contracts.

**Definition 3 (Private Blockchain):** A private blockchain usually refers to a blockchain that is completely controlled by an individual party. It is only used to record private information, and only the owner has the rights to access and modify the data.

In practice, common public blockchains include Bitcoin [1], Ethereum [2], [3], etc., and common consortium blockchains include Corda [5], Quorum [6], Hyperledger Fabric [7], etc. Both public and consortium blockchains mentioned above can be considered as private blockchains when running locally.

Next, to better understand the execution mechanism of the blockchain, we give the definition of consensus that is one of the key techniques within the blockchain, according to the works of [21] and [22]:

**Definition 4 (Consensus):** A consensus mechanism enables all participating nodes, whether honest or malicious ones, to agree on the contents in a blockchain. In a consensus mechanism, the following properties must be satisfied:

- Liveness: any transaction should be finally processed;
- Persistence: if an honest party validates a transaction (accept or reject), all other honest nodes will eventually have the same operation.

In many related works, the notion of miners is used to refer to the participants in a blockchain system. We give a simple definition of it as follows:

**Definition 5 (Miner):** A miner refers to a node providing its non-trivial work in a consensus mechanism for the rewards in a blockchain.

During the maintenance of a blockchain within the consensus mechanism, there are cases when nodes disagree on the final results. This is called a fork in the context of blockchain:

**Definition 6 (Fork):** A fork refers to an disagreement on blockchain records among participating nodes.

Forks are usually temporal and will finally be eliminated by the consensus rule. But under other circumstances, a fork may be deliberately triggered, to launch an update of the blockchain system. The concept of fork can be further divided into the soft and hard forks, as defined below.

**Definition 7 (Soft Fork):** A soft fork refers to a fork caused by the update of backward compatible consensus.

After a soft fork [23], some transactions or blocks that are valid under the old rules may become invalid.

**Definition 8 (Hard Fork):** A hard fork refers to the fork caused by the update of non-backward compatible consensus.

A soft fork is mainly used to introduce new types of transactions, or to fix some bugs in the consensus protocol. It does not require all nodes to switch to the new consensus. Nodes running the old consensus can still recognize the transactions and blocks under the new rules. While in comparison, a hard fork usually arises when big events (e.g., the DAO attack) or major disputes in community occur, and all nodes have to choose one of the forks, and end up with two distinct blockchains that are not compatible with each other.

In blockchain systems, users and smart contracts rely on transactions to contact with each other. Therefore, we give a universal definition of a transaction as the following:

**Definition 9 (Transaction):** A transaction $tx$ is a tuple of 5 elements, i.e.: $tx = (t, in, out, s, pld)$

where $tx.t$ is the timestamp that a miner receives $tx$. We assume that at most one $tx$ could be received at time $t$, namely, $\forall i \neq j, tx_i.t \neq tx_j.t$ always holds. With this assumption, transactions will be executed in chronological order (this order may vary among miners). $tx.in$ (resp. $tx.out$) is the input (resp. output) of the transaction. $tx.s$ is the signature of the transaction, which is used to show the ownership of the fund to be transferred in the transaction. $tx.pld$ refers to arbitrary messages appended to the transaction, and it is called payload data in this paper.

In fact, the specific contents of a transaction vary among blockchains, according to the underlying user model. Taking Bitcoin and Ethereum as examples, Bitcoin adopts the unspent transaction output (UTXO) model, while Ethereum uses the account model. This is one of the key differences between these two platforms, and most existing blockchains also adopt either one of these two models. Therefore, we give the definitions of the UTXO and account model in the following:

**Definition 10 (UTXO Model):** In the UTXO model, unspent money is stored in UTXOs. Each transaction consumes existing UTXOs and generates new UTXOs, except the coinbase transaction which assigns the miner a UTXO without inputs as a reward. For a UTXO $U$, it contains information such as the source addresses and the values. For a transaction $tx$ within the UTXO model, the sum of values in the output UTXOs must be more than or equal to that in the input UTXOs, i.e.:

$$\sum_{U \in tx.out} U.v \geq \sum_{U \in tx.in} U.v$$
where \( U, v \) refers to the value of \( U \), and the extra value in the input is collected by the miners as the execution fee.

Definition 11 (Account Model): In the account model, each user or contract has a fixed account and address. The account records the balance, the contract codes, and the state data specified in the creating transaction. The balance \( F_{\text{balance}}(a) \) in the account corresponding to address \( a \) must be non-negative. In addition, for a transaction to be valid, the input amount \( \text{Tx.in} \) to be spent should be less than or equal to the balance in the account, i.e.:

\[
F_{\text{balance}}(a) \geq 0, \quad F_{\text{value}}(\text{Tx.in}) \leq F_{\text{balance}}(a)
\]

where \( F_{\text{value}}(\text{Tx.in}) \) indicates the value contained in \( \text{Tx.in} \).

As is mentioned before, the transaction data structure is different among blockchains within these two models. Specifically, in the UTXO model, \( \text{Tx.in} \) includes a set of UTXOs to be spent, while in the account model, it directly refers to the value to be transferred. Similarly, \( \text{Tx.out} \) includes a new UTXO set in the UTXO model, while it includes responses from the target address (e.g., returned messages from a smart contract) in the account model.

With the above definitions of transactions, UTXO and account models, we are able to give a formal definition of smart contracts here. We remark that our definition is inspired by the description of the world state and transactions in Ethereum Yellow Paper [3], and the ideal functionality \( F_{\text{StCon}}^a \) of smart contracts in [24].

Definition 12 (Smart Contract): A smart contract refers to a computer program \( C \) deployed on a blockchain with public interfaces and state variables, satisfying:

\[
C(S_i, \text{Tx.i}) = (S_j, R_j)
\]

where \( S = \{S_i\} \) is the set of all possible states in \( C \), \( T = \{\text{Tx.i}\} \) is the transaction set, and \( R = \{R_i\} \) is the set of all possible responses. \( R_j \) could be the success or failure symbol of execution, or any other predefined values. After \( C \) is called by a valid \( \exists \text{Tx.i} \), the new state \( S_j \) and the response \( R_j \) are produced accordingly.

We remark that the smart contracts discussed in this paper refer to those in the blockchain context, and we sometimes use the word contract for short.

Studies on smart contracts mainly focus on two aspects, which are defined as security and correctness in this paper:

Definition 13 (Security of Smart Contracts): The security of smart contracts refers to their ability to resist unauthorized state change, including fund transferring, state tampering, accidental self-destruction, etc.

Definition 14 (Correctness of Smart Contracts): The correctness of smart contracts refers to their ability to correctly realize the expected functionality.

To ensure the security and correctness of smart contracts, and to achieve other desired properties such as privacy, efficiency, etc., some cryptographic schemes and hardware equipment may be introduced. Here we briefly give the definitions of secure multi-party computation (SMPC), zero-knowledge proof (ZKP) and trusted execution environment (TEE) in the following:

Definition 15 (Secure Multi-party Computation): In a secure multi-party computation (SMPC) protocol \( \pi \), participants \( P_1, P_2, \ldots, P_n \) can jointly calculate a probabilistic polynomial time function \( f(x_1, x_2, \ldots, x_n) = (y_1, y_2, \ldots, y_n) \) where \( x_i \) (resp. \( y_i \)) is the secret input (resp. output) of \( P_i \) \( (i = 1, 2, \ldots, n) \), and the following two properties [25], [26] hold:

- Correctness: each \( P_i \) gets the correct result;
- Privacy: any \( P_i \) cannot get extra information except his own input and output, especially the inputs and outputs of other participants \( P_j \) where \( j \neq i \).

Definition 16 (Zero-Knowledge Proof): In a proof system \( \langle P, V \rangle(x) \), a prover \( P \) proves to a verifier \( V \) that \( x \) belongs to a language \( L \), which is an NP problem, i.e., \( x \in L, L \in NP \).

A protocol \( \pi \) is said to be a zero-knowledge proof protocol, if the following three properties [27] are satisfied:

- Completeness: any true statement can be accepted with an overwhelming probability.
- Soundness: any false statement can only be accepted with a negligible probability.
- Zero-knowledge: any probabilistic polynomial time verifier cannot get extra information other than \( x \in L \), and its view is indistinguishable from that of a simulator \( F_{\text{sim}} \).

Definition 17 (Trusted Execution Environment (TEE)): TEE [28] is a kind of hardware equipment, usually an enclave in the memory, which ensures that the execution environment is not influenced or manipulated. TEE guarantees the reliability of the execution results and the privacy of executed contents.

C. Related Work

Smart contract is an important aspect of the blockchain. Its execution characteristics, efficiency, and security are directly related to the acceptance of this emerging technology. Prior to our work, there have been several surveys on the characteristics of contract platforms (e.g., ease of use, efficiency, etc.), properties of the contracts (e.g., security, privacy, etc.) and related analysis tools, as shown in Fig. 4.

1) Characteristics of platforms: Seijas et al. [29] discuss the languages adopted by the blockchain systems such as Bitcoin, Nxt [40] and Ethereum, list the defects of these languages. Furthermore, they give some directions that may help to expand the functionality and enforce the security of smart contracts, such as zero-knowledge proofs, static analysis, etc. Bartoletti et al. [40] compare 6 smart contract platforms in 2017, which are Bitcoin, Ethereum, Counterparty [41].
of smart contract based on the statistical results. Bartoletti et al. and others fail to elaborate on the solutions to these problems. Harz et al. specifically summarize the vulnerabilities of smart contracts in Ethereum. They categorize the weaknesses in Ethereum to facilitate the future development or research on smart contracts, including: 1) dependence on the order of transactions; 2) dependence on timestamps; 3) mishandling of errors; 4) re-entrancy attacks, etc. (see more details in Section VII-B). Dika analyzes smart contracts in Ethereum from a higher point of view, and categorizes the weaknesses into three levels: blockchain, virtual machine (EVM), and programming language (Solidity). In addition, Dika also proposes a contract security analysis tool for detecting these weaknesses. Macrinici et al. collect 64 papers on the issues related to the smart contract applications, and outline 16 sub-problems, which can be further summarized into three categories: problems on blockchain mechanism, contract programs, and virtual machine. Among them, the problems on the contract programs and virtual machine are to some extent similar to the contract construction and execution schemes. However, the authors only list the problems, but fail to elaborate on the solutions to these problems. Harz et al. conduct an analysis of the languages and security tools designed for smart contracts in 2018, and give a classification and brief introduction.

In terms of analysis of application scenarios of smart contracts, Bartoletti et al. analyze smart contracts on Bitcoin and Ethereum up to 2017, and divide the application scenarios into: financial, notary, game, wallet, library and others. They focus on the qualitative statistics in the application layer, aiming to give an impression on the usage of contracts in different applications. Besides, Ayman et al. analyze the problems encountered by developers according to the number of questions in the StackOverflow forum, and conclude the trend in development of smart contract based on the statistical results.

3) Analysis tools: Angelo and Salzer investigate 27 tools for Ethereum contracts from the aspects of open source, maturity, adopted methods and security issues, etc. At the same time, 53 papers related to smart contract security are summarized in, and are classified from the aspects of security and correctness. Compared with these two studies, our work covers more up-to-date analysis tools and additionally describes the smart contract construction schemes, tools and execution mechanisms, forming a more systematic knowledge of the studies on smart contracts.

The latest work of Ante does a similar work to ours. They analyze the smart-contract-related literature and provide statistical results of related articles, such as the citation statistics, distribution of keywords and the most concerned smart contract platforms, etc. Finally, they identify 6 directions of state-of-the-art research about the smart contracts according to their quantitative analysis. Different from Ante’s work, we start from a high-level perspective and discuss the topics related to the contract construction and execution schemes with more details, aiming to provide a road map for the researchers and developers being interested in smart contracts.

III. Systematization Methodology

Intuitively, the schemes related to smart contracts can be divided into the construction-related and execution-related ones, where the former focus on the design paradigms within the current architecture, while the latter might involve modifications of the underlying execution mechanism, as discussed in the following. We remark that the notion of constructing and designing smart contracts are used synonymously in this paper.

A. Designing Smart Contracts

Forms of smart contracts are various, depending on the platforms they are running on. Therefore, design schemes of smart contracts also rely on the platforms, especially the language they support. Smart contracts written in script language are mostly used to describe financial transactions, while in turn, smart contracts written in Turing-complete languages could theoretically describe any deterministic protocol as a computer program.

Existing blockchain platforms can be categorized into two types: one that supports only limited expressions of operations is called script-based blockchain, represented by Bitcoin, while the other supports arbitrary operations with Turing-complete programming languages, is called Turing-complete blockchain, represented by Ethereum.

Since the smart contracts on these two kinds of platforms have significant differences in terms of expression (as well as execution), the construction schemes are also quite different. Therefore, we will discuss the smart contract construction schemes separately for these two kinds of platforms, i.e., script-based and Turing-complete blockchains. We remark that although the forms of smart contracts are completely different, the design concept may sometimes be migrated from one to the other.

Additionally, the schemes in each category are further divided into two parts: design patterns and design tools, where the former describe some common and useful paradigms, including paradigms for specific applications, best practices for general purpose, etc., and the latter discuss the tools available in the process of developing smart contracts. Some tools help developers to confirm the contracts security to avoid economic losses caused by potential vulnerabilities or bugs. They are called analysis tools, and they usually take effect after the contract is almost completed. Other tools work during the construction process of contracts, improving the efficiency of development, or reducing the concerns of security issues, and they are called auxiliary tools in this paper.
B. Executing Smart Contracts

Other than the expressivity of their supported programming language, the aforementioned two kinds of smart contract platforms also vary in the execution mechanisms. But from another point of view, the mainstream platforms in both categories suffer from several common problems in terms of transaction delay, contract complexity, privacy leakage, etc.

To solve these problems, numerous schemes are proposed. In this paper, we divide them into three classes: 1) private contracts with extra tools, 2) off-chain channels, and 3) extensions on core functionalities.

Generally speaking, schemes in the first two categories usually follow the original rules, while those in the last category often introduce new functionalities or properties by modifying the underlying execution mechanisms. Solutions in the first category often introduces useful cryptographic protocols or hardware to help protecting the user privacy during the executions of smart contracts. We remark that schemes in the second category are quite prevalent recently since they do not require extra tools nor modifications of the underlying mechanism. Their core idea is to migrate the execution off-chain, and only use blockchain for final state settlement or dispute handling, and we call them as off-chain channels. Schemes in the last category are designed to add to the functionality that the original platforms do not support, and their application require a fork of the existing system, or even launching a new one instead.

We classify the schemes related to smart contracts in the literature in Table I. In the “Theory” column, the symbols of ✓, ✓ and x show, respectively, that the work: has both complete description and formal security proof, has description but no proof, and has neither description nor proof. Similarly, in the “Realization” column, the symbols of ✓, ✓ and x show, respectively, that the work: has open-sourced implementation, has implementation but is not open-sourced, and has no implementation. The word open-sourced here means the source code is released online and available for all users. This is of great significance for succeeding researchers and developers to learn from these schemes. In addition, if there are multiple references in the same line, there will be multiple ✓, ✓ or x in the “Theory” and “Realization” columns in the same order.

IV. CONSTRUCTING SMART CONTRACTS WITH SCRIPTS

Script-based blockchains usually provide some simple stack-based opcodes to facilitate more flexible circulation of cryptocurrencies. For example, a payer could specify a condition under which the payee receives his payment. The primary purpose of such script languages is to facilitate simple financial affairs or demands. Therefore, smart contracts in script-based blockchains are relatively simple and limited compared with those in Turing-complete blockchains.

In this section, we discuss the construction schemes of smart contracts in script-based blockchains. We take Bitcoin as a representative. The reasons are as follows:

(1) Bitcoin is the first and the largest (with the most users) script-based smart contract platform.

(2) Most state-of-the-art script-based blockchains are derived from Bitcoin, thereby most construction schemes in Bitcoin could be easily applied to such blockchain systems with slight modifications.

(3) Most relevant studies also focus on the construction of smart contracts in Bitcoin.

We divide the schemes related to the contract construction into two categories: design paradigms and tools. Design paradigms here refer to the patterns that are modular in functionalities, applicable to different scenarios and widely considered secure. Such schemes may help to efficiently develop secure smart contracts (see Section IV-A). Design tools here refer to the solutions that are aimed at guaranteeing the security of smart contracts (see Section IV-B).

A. Design Paradigms

As is mentioned in Section II-A2, most smart contracts in Bitcoin [12] use P2SH transactions. Before the introduction of P2SH transaction in BIP16 [187], there have already been a few transactions realized the contract for data storage, by modifying (or abusing) the standard ones. With the P2SH solution, transactions are no longer restricted to ordinary payments, i.e., it becomes possible to implement some simple protocols in Bitcoin.

We divide the design paradigms in Bitcoin into four parts, according to their use and applications. Firstly, several schemes for data storage are proposed in the early years (see Section IV-A1), taking advantage of the tamper-resistant nature of the underlying blockchain. Secondly, based on the storage contracts, some researchers further regard the blockchain as a public bulletin board, and implement the SMPC protocol (Definition 15). SMPC could be viewed as a special form of smart contracts, as it intends to reach agreements on the execution results without a trusted third party. Related schemes focus on various features of SMPC, such as fairness and generalization (see Section IV-A2). Thirdly, layer-2 protocols are proposed to address the problem of long confirmation delay and low throughput of Bitcoin. Such protocols optimize both the money and time overhead by moving the calculation off-chain (see Section IV-A3). Finally, to avoid potential privacy leakage due to the public nature of Bitcoin, the concept of scriptless contract is proposed, with which the transaction reveals no information of the contract contents (see Section IV-A4).
| Class | Reference | Year | Keywords | Theory | Realization |
|-------|-----------|------|----------|--------|-------------|
| Designing Contracts with Scripts | [13] | 2012 | P2SH Transactions & Common Contracts | ✓ | ✓ |
| | [46, 48] | 2014-2018 | OP_RETURN Opcode | ✓/✓ | ✓/✓/✓ |
| | [49, 51] | 2014-2017 | Contracts for Lottery | ✓/✓/✓ | ✓/✓ |
| | [52] | 2015 | Contracts for On-line Poker | ✓ | ✗ |
| | [53] | 2014 | General Fair Multi-Party Protocols | ✓ | ✗ |
| | [54–56] | 2016 | Secure Multi-Party Computation on Public Blockchains | ✓/✓/✓ | ✗/✓/✓ |
| | [57–59] | 2015-2018 | Probabilistic Payment System | ✓/✓/✓ | ✗/✓/✓ |
| | [60–62] | 2016-2019 | Scriptless Contract | ✓/✓ | ✗/✓/✓ |
| | [63–67] | 2014-2018 | Security Models | ✓/✓/✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [68–72] | 2017-2019 | Languages | ✓/✓/✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| Design Tools | [71–73] | 2017 | Contracts for Lottery | ✓ | ✗ |
| | [74] | 2018 | Lending Contracts | ✓ | ✗ |
| | [75–78] | 2016-2020 | Contracts for e-Government | ✓/✓/✓ | ✗/✓/✓/✓ |
| | [79–80] | 2018 | Private Auction Protocol | ✓ | ✗ |
| | [81–84] | 2017-2019 | Off-chain Computation and Storage | ✓/✓/✓ | ✗/✓/✓/✓ |
| | [85–86] | 2016-2020 | Best Practices on Writing Smart Contracts | ✓/✓/✓ | ✗/✓/✓/✓ |
| | [87–88] | 2016-2018 | Classification & Common Patterns | ✓ | ✗ |
| | [89–92] | 2016-2020 | Common Vulnerabilities | ✓/✓/✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [93] | 2016 | Designing Models | ✓ | ✗ |
| | [94] | 2016 | Interfaces for Updating Smart Contracts | ✓ | ✗ |
| | [95–97] | 2017-2019 | Detecting Reentrancy Vulnerabilities | ✓ | ✗ |
| | [98–100] | 2017-2019 | Detecting Gas-Related Vulnerabilities | ✓/✓/✓ | ✗/✓/✓/✓ |
| | [101] | 2018 | Detecting Trace Vulnerabilities | ✓ | ✗ |
| | [102–104] | 2019 | Detecting Event-Ordering Bug | ✓ | ✗ |
| | [105–107] | 2018-2020 | Detecting Integer Bug | ✓ | ✗ |
| | [108–110] | 2016-2020 | General Detection by Symbolic Execution | ✓/✓/✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [111–112] | 2018 | General Detection by Syntax Analysis | ✓ | ✗ |
| | [113–114] | 2018 | General Detection by Abstract Interpretation | ✓/✓/✓ | ✗/✓/✓/✓ |
| | [115–116] | 2019 | General Detection by Data-Flow Analysis | ✓ | ✗ |
| | [117–118] | 2018 | General Detection by Topological Analysis | ✓ | ✗ |
| | [119–120] | 2018 | General Detection by Model Checking | ✓ | ✗ |
| | [121] | 2018 | General Detection by Fuzzing Test | ✓ | ✗ |
| | [122–124] | 2016-2019 | Frameworks | ✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [125–126] | 2016-2019 | Languages | ✓/✓/✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [127–128] | 2017-2019 | Basic Tools | ✓/✓/✓ | ✗/✓/✓/✓ |
| Design Tools | [129] | 2018 | General Detection by Satisfiability Modulo Theories | ✓ | ✗ |
| | [130–132] | 2018-2019 | General Detection by Symbolic Execution | ✓/✓/✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [133–134] | 2018-2019 | General Detection by Fuzzing Test | ✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [135–136] | 2016-2019 | Languages | ✓/✓/✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [137–138] | 2015–2018 | Private Contracts with Multi-Party Computation | ✓/✓/✓ | ✗/✓/✓/✓ |
| | [139–140] | 2015–2018 | Private Contracts with Zero-Knowledge Proof | ✓/✓/✓ | ✗/✓/✓/✓ |
| | [141–142] | 2017–2019 | Private Contracts with Trusted Execution Environment | ✓/✓/✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [143–144] | 2015–2019 | Payment Channel Network on Bitcoin | ✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [145–146] | 2015–2017 | Payment Channel Network on Ethereum | ✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [147–148] | 2017–2019 | State Channel Network | ✓/✓/✓/✓ | ✗/✓/✓/✓/✓/✓ |
| | [149–150] | 2016–2017 | Bitcoin Covenants | ✓ | ✗ |
| | [151–152] | 2018–2020 | Moving Contracts across Blockchains | ✓ | ✗ |
| | [153–154] | 2018 | Proof-Carrying Smart Contracts | ✓ | ✗ |
| | [155–156] | 2018 | Private Contracts with One-Step Proof | ✓ | ✗ |
| | [157–158] | 2018 | Complex Contracts Execution without Validation | ✓ | ✗ |
| | [159–160] | 2018 | Private Execution of Arbitrary Contracts | ✓ | ✗ |

*: If there are multiple references in the same line, there will be multiple marks of ✓, ✓ or ✗ in the “Theory” and “Realization” columns with the same order.
†: In the “Theory” column, the symbols of ✓, ✓ and ✗ show, respectively, that the work: has both complete description and formal security proof, has description but no proof, and has neither description nor proof.
♣: In the “Realization” column, the symbols of ✓, ✓ and ✗ show, respectively, that the work: has open-sourced implementation, has implementation but is not open-sourced, and has no implementation. The word open-sourced here means the source code is released online and available for all users.
1) Data storage: The tamper-resistant property of Bitcoin blockchain attracts some users to store short messages as witnesses or memorandums. The original version of Bitcoin does not support storing data other than transactions. Some users abuse the output field (i.e., the hash of the target address in Tx.out) in a standard transaction by filling it with meaningful strings, such as sentences, ASCII art [188], etc. However, the UTXOs in such transactions will never be spent, since it is almost impossible to solve the secret keys according to such arbitrary strings. Therefore, such UTXOs will stay in miners’ memory pool forever, which results in the loss of hardware capacity.

To avoid such abuse, OP_RETURN opcode [46] is introduced, enabling appending additional messages in a transaction. Bartoletti et al. [47] analyzed the usage of this opcode in 2017, and we rephrase the statistical results in Fig. 5. They conclude that at least 22 protocols adopt OP_RETURN to provide services like asset declaration, integrity proof of general SMPC protocols.

But it provides an inspiration for the subsequent works on general SMPC protocols. Andrychowicz et al. [49] first implement a timed commitment scheme in Bitcoin, where a commitment should be opened within a specified time period, otherwise the publisher will be penalized. They further propose a Bitcoin-based SMPC protocol. However, the amount of deposit grows rapidly when the number of participants increases in the multi-party case and the fairness is not guaranteed in practice, that is, the counterparty can abort or claim their deposits by trying to race other transactions on-chain. Nonetheless, two lottery schemes involving only two parties are proposed in [49] and [50], respectively, where the former works under an unrealistic assumption and the latter eliminates such assumption by strengthening the non-malleability of the Bitcoin transaction (i.e., the ability to prevent the adversary from generating valid transactions according to the collected transactions). As pointed out in [50], the scheme is more general and supports arbitrary two-party functions, but it only works in a two-party scenario.

To alleviate the deposit-explosion problem in the multi-party case, Bartoletti and Zunino [51] propose a multi-party lottery contact with fixed deposits, which requires a modification of the Bitcoin mechanism. They then implement the scheme on Ethereum (see Section V-A1a). Kumaresan et al. [52] consider a decentralized online poker protocol. They propose a primitive called secure cash distribution with penalties to guarantee the fair finalization of the poker game, which also utilizes the timed commitment to incentivize rational players to behave honestly. Their scheme requires some additional opcodes in Bitcoin and thus cannot directly apply to Bitcoin. But it provides an inspiration for the subsequent works on general SMPC protocols.

In addition to above-mentioned SMPC for specific applications, there are some studies dedicating to general SMPC protocols. Bentov et al. [53] introduced an ideal description of fair multi-party protocol in Bitcoin in 2014, which is more general and could also be applied to other script-based smart contracts. Their results are implemented into the decentralized online poker in [52], with the primitive called secure cash distribution with penalties that guarantees the fair finalization of the poker game. They also utilize the timed commitment to incentivize rational players to behave honestly. Kumaresan et al. [54], [55] improve the efficiency of the deposit-based general SMPC protocol in [52]. From another aspect, Kiayias et al. [56] further give the first fair and robust SMPC protocol based on the blockchain.

The general SMPC protocols described above [53]–[56] use the same ideal claim-or-refund functionality $\mathcal{F}_{CR}^*$ for secure cash distribution. We conclude the contents of $\mathcal{F}_{CR}^*$ in Fig. 6 where $\lambda$ is the security parameter, $sid$ and $ssid$ are two distinct session identifiers, and $\tau$ is the round number. A sender $P_s$ sends a fund of value $v$ to a receiver $P_r$, and $P_r$ should provide a witness $\omega$ such that $\phi(\omega) = 1$ within the $\tau$th round to claim the fund, where $\phi$ refers to the primitive predefined by $P_s$. $F_{send,x}$ (resp. $F_{receive,x}$) is the ideal function that sends (resp. receives) the message to (resp. from) $P_x$, where $x \in \{s,r\}$. $F_{broadcast}$, $F_{record}$ and $F_{delete}$ are the ideal functions that broadcast, record and delete messages. With this $\mathcal{F}_{CR}^*$, different schemes are designed in [52]–[56] to optimize the efficiency, fairness and robustness of SMPC.

3) Layer-2 protocols: Smart contracts written in scripts are limited in complexity and processing rate. To overcome these problems, layer-2 protocols are introduced. The main idea is to separate the computation from the validation process, that is, the executions of smart contract are performed off the blockchain, and only necessary steps, such as setup, recording, settlement, and dispute resolution, are carried out on blockchain. In this way, the limitation of opcodes and the effect of high delay can be avoided. Moreover, since the contents of smart contracts are only visible by the off-chain participants, the privacy of smart contracts are enhanced. Related schemes are classified and summarized in [189] (up
Hence, Alice’s payment channel networks (PCN) and state channel networks will finalize, so that Bob has the incentive to pay, she creates the transaction \( \text{Tx}_0 \) with Bob’s signature according to \( \text{mul} \). Then, Alice and Bob jointly sign \( \text{Tx}_0 \) with her own signature. Then, Alice and Bob jointly sign \( \text{Tx}_0 \) with Bob’s signature according to \( \text{mul} \), and generates the time-locked refund transaction \( \text{Tx}_1 \) for Bob and the rest for Alice, where \( \delta_i \) denotes the value in \( i^{th} \) payment, and \( \sum \delta_i \) refers the total amount to be transferred.

Fig. 7. Micropayment from Alice to Bob [13] (the time and payload field is omitted for simplicity). In (a), Alice deposits \( B x \) to the multi-signature address \( a_{mul} \) in \( \text{Tx}_0 \), and generates the time-locked refund transaction \( \text{Tx}_1 \) with Bob’s signature according to \( \text{Tx}_0 \). In (b), Alice sends a signed transaction \( \text{Tx}_{i+1} \) (\( i \) denotes the \( i^{th} \) update) as her payment. \( B x \) in \( a_{mul} \) will be divided into two parts: \( B(x(\sum \delta_i)) \) for Bob and the rest for Alice, where \( \delta_i \) denotes the value in \( i^{th} \) payment, and \( \sum \delta_i \) refers the total amount to be transferred.

to 2019), and they are divided into three types: off-chain channel, construction schemes for off-chain network and off-chain network management. Based on [189], we summarize the design patterns of contracts related to the layer-2 protocol, as described below.

Payment channel is one of the most significant components among layer-2 protocols. It is first introduced in [13], known as the micropayment channel, a protocol that conducts continuous micropayments to one recipient. It utilizes the multi-signature opcode \texttt{CHECKMULTISIG} provided in Bitcoin, so that to spend the UTXOs in such transactions, more than one signature is required.

According to [13], we restate the micropayment channel in Fig. 7 where the time and payload fields are omitted for simplicity. Suppose a channel is established between the payer Alice and the payee Bob. Initially, Alice creates (but does not broadcast) \( \text{Tx}_0 \) that deposits \( B x \) to a multi-signature address \( a_{mul} \), which requires both signatures of Alice and Bob to spend the UTXO. Alice then generates the refund transaction \( \text{Tx}_1 \), which returns the funds from \( a_{mul} \) to Alice. There is a timelock \( t \) in \( \text{Tx}_1 \); if \( B x \) is not claimed in \( t \), Alice can reclaim it freely with her own signature. Then, Alice and Bob jointly sign and broadcast \( \text{Tx}_1 \), and Alice simultaneously broadcasts \( \text{Tx}_0 \). Hence, Alice’s \( B x \) is locked in \( a_{mul} \). Whenever Alice wants to pay, she creates the transaction \( \text{Tx}_{i+1} \) (\( i \) denotes the \( i^{th} \) update) and sends the signed \( \text{Tx}_{i+1} \) to Bob. In \( \text{Tx}_{i+1} \), the fund \( B x \) in \( a_{mul} \) is divided into two parts: \( B(x(\sum \delta_i)) \) for Bob and the rest for Alice, where \( \delta_i \) denotes the value in \( i^{th} \) payment and \( \sum \delta_i \) is the total amount paid to Bob. Finally, Bob signs and broadcasts the latest transaction, so that the payment will be finalized, and both Alice and Bob will get what they deserve. Since the inputs of \( \text{Tx}_i \) all come from the same address \( a_{mul} \), only one finalization will take effect, so that Bob has the incentive to broadcast the latest payment to get the coins he deserves.

Based on the micropayment channel, the concepts of payment channel networks (PCN) and state channel networks are derived. Their main idea and the structure of scripts (or contract) are similar and related studies are dedicated on the fairness of the protocol execution which is off-chain, so we reserve the introduction of these schemes to Section IV-B1.

Probabilistic payment system is another research direction in layer-2 protocols. It was first implemented as smart contracts in [57] in 2015. The core idea is that the transactions only succeed in a probabilistic manner. In other words, for a fixed success probability \( p \) and amount \( B x \) per transaction, then on average, a recipient will get \( B x \) in every transaction. This can be applied in lotteries and other situations involving a large number of small payments. In such a system, senders are required to do two deposits, one for payment and the other for penalty. Further, the scheme in [57] requires a verifiable trusted service (VTS) for the validation of probabilistic payments, which makes the scheme impractical. Hu et al. [58] adopt a time-locked deposit in Bitcoin to improve the efficiency, which only needs one on-chain transaction to achieve the same functionality as the original scheme in [57]. Chiesa et al. [59] propose a concept of decentralized anonymous micropayment (DAM). With the fractional message transfer technique that transfers messages in a probabilistic manner, the privacy in probabilistic payment system is better protected. But they point out that the double-spending in their probabilistic payment system is inevitable and analyze the effect of this attack in their work.

Probabilistic payment system reduces the number of transactions, decreases transaction fee and improves transaction rate. We restate the probabilistic payment system [57] in Fig. 8. Similar to that in a micropayment channel, Alice firstly deposits the escrow \( B x \) and penalty \( B y \) to the multi-signature addresses \( a_e \) and \( a_p \), respectively. Next, Bob generates a random number \( r_1 \) and sends \( F_{SHA-256}(r_1) \) to Alice, along with his address \( a_B \), where \( F_{SHA-256} \) refers to the SHA-256 hash function. Afterwards, Alice generates the payment transaction \( \text{Tx}_1 \) and penalty transaction \( \text{Tx}_2 \) in Fig. 8(a), where the zero address \( a_0 \) is used to destroy the funds. \( \text{Tx}_1 \) and \( \text{Tx}_2 \) are sent to VTS after being signed. Note that there is a timelock \( t \) in \( \text{Tx}_1 \) and \( \text{Tx}_2 \), similar to that in the micropayment scheme. Next, Alice generates a random number \( r_2 \). If \( r_1 \oplus r_2 < r \) holds, where \( r \) is related to the pre-agreed probability, their message transcripts will be sent to VTS, and VTS will sign and broadcast \( \text{Tx}_1 \) if the message is correct, as is shown in Fig. 8(b). Note that during the whole process, when Bob and VTS receive a signature, they shall verify it before other operations. In addition, if Alice spends the \( B x \) before \( \text{Tx}_1 \) takes effect, the VTS will sign \( \text{Tx}_2 \) so that Alice’s penalty deposit will be destroyed.

4) Scriptless contracts: The aforementioned P2SH-based smart contracts require publishing the full scripts, which causes the privacy concern of users. Apart from the layer-2 protocols described above, scriptless contract is another solution for this problem. It is similar to a standard transaction, but achieves the same goal as smart contracts. Since there is no script, the contents of a smart contract would never be disclosed. It is first proposed in [60], and its original goal is to prevent miners from rejecting packaging P2SH transactions, because executing scripts consumes more time and space than...
standard transactions. In addition, an application instance of selling a factorization of an RSA modulus is provided in [60], which requires an additional opcode in Bitcoin.

Scriptless contracts are further summarized in [61], which present a way to construct a smart contract without exposing scripts. With Schnorr signature [190] (which is not currently compatible with Bitcoin), it is possible to execute scripts only among parties involved in the transaction and only the final settlement is updated on-chain. Such transactions for scriptless contract are indistinguishable from the standard ones, so the privacy of contract contents is well protected. However, the functionality of such contracts is quite limited, as the final output should be directly verifiable in the same way as a standard transaction.

In the subsequent work, Malavolta et al. [62] present scriptless contracts using ECDSA signature, which is compatible in both Bitcoin and Ethereum. Their work makes scriptless contracts more practical and applicable without requiring a hard fork.

Some may argue that the HTLC and RSMC contracts in Lightning Network [17] (see Section VI-B1) also include the idea of non-public execution, but in fact, they are only used for efficient payment, whose forms are almost fixed and monotonous, compared to the scriptless contracts described above. The privacy-preserving nature of such scriptless schemes makes it an appealing research direction in blockchain.

B. Design Tools

We have described some script-based smart contracts in the prior part, which may help developers start quickly under similar scenarios. From another point of view, due to the lack of readability and limitation in script operations, constructing script-based smart contracts is a hard work. In addition, since most smart contracts involve money transfer, a vulnerability in a smart contract may cause severe economic loss. This makes the security of smart contracts more critical than general computer programs. In this section, we introduce some design tools, which relieve the burden of smart contract developers to some extent and help developers to build smart contracts that meet security requirements with ease. We divide these tools into analysis tools and languages, where the former help validate the security of contracts, and the latter facilitate the writing of smart contracts.

1) Analysis tools: With regard to the security analysis in script-based smart contracts, contracts in Bitcoin are abstracted as timed automata in [63], where the states are finite and change chronologically. In this way, the model detection tool UPPAAL [191] for timed automata can be used to ensure that the contract runs as expectation.

As for the modeling of smart contracts, Bigi et al. [64] propose an ideal model in Bitcoin and provide a security analysis using game theory. The authors analyze the possible behaviors executed by two parties and explain the feasibility of their model. However, the model is limited in the two-party case, which excludes the multi-party situation.

2) Contract languages: Considering the difficulty in script programming, a variety of new languages for smart contracts are proposed, aimed at improving the expressivity, readability and verifiability of the Bitcoin scripts. These languages are shown in Table II, where ✓ denotes that the language has the corresponding properties, while ✗ means the opposite. They can be divided into high-level languages and intermediate expression (IR) languages according to their expressivity. High-level languages refer to those that are more expressive and can be directly used by ordinary developers with ease, while IR indicates an intermediate representation that is useful during the compilation and security analysis procedure of smart contracts.

On the expressivity aspect of contract languages, Ivy [68] is one of the earliest high-level languages designed for Bitcoin. Ivy’s syntax is similar to common high-level languages, and it adds some specialized keywords for operations in Bitcoin. Some examples are given in its documentation [68], e.g., Lock-
With PublicKey, hashed timelock contract (the core technique in Lightning Network, see more details in Section VI-B1). However, the security proof of Ivy itself and the compiled scripts is lacked, so that it could only be used for educational purposes. Atzei et al. [65], [66] propose another formal model of contracts in Bitcoin, which is the base of the high-level language BALZaC [67]. They also provide the corresponding analyzer and compiler that compiles BALZaC to standard transactions. In addition, the authors describe the existing smart contracts with their model, including: crowdfunding, timed commitments, micropayment channels, lotteries, etc. BALZaC enables developers to describe transactions in Bitcoin with concise syntax. However, it lacks security analysis.

On the verifiability aspect of smart contracts, O’Connor et al. [69] design a low-level Intermediate Representation (IR) language, Simplicity, which makes use of denotational semantics defined in Coq [192], a popular verification tool. With Coq and other auxiliary tools, Simplicity helps developers easily validate the security of smart contract. Besides, the authors claim that Simplicity also supports static analysis to analyze the efficiency of contract execution.

There are also studies considering both expressivity and verifiability of the script language in Bitcoin. Bartoletti et al. [70] propose a high-level language BitML, which encapsulates the complex instructions and provides a concise and convenient expression for smart contracts in Bitcoin. The authors also provide a compiler that converts BitML programs into standard Bitcoin transactions, and they prove the correctness of their compiler, i.e., it will cause no additional error or bug while converting. Other works [71], [72] implement some common smart contracts in BitML, such as covenants, timed commitments, etc. However, BitML language is still limited to some extent, that is, there are contracts that could not be expressed by BitML.

V. CONSTRUCTING SMART CONTRACTS WITH TURING-COMPLETE LANGUAGES

To extend the limited operations in Bitcoin’s script language, Ethereum comes out, which introduces a new virtual machine structure to support Turing-complete programming languages, greatly extending the application scenarios of smart contracts. The smart contracts are executed in Ethereum Virtual Machine in the form of EVM bytecode. In fact, to facilitate the definition of the execution rules in smart contracts, some high level programming languages are introduced, which can be converted into bytecode by compilers, such as Solidity [14], LLL (Lisp-Like Language) [193] and Serpent [15], etc. Such high-level languages are featured with high expressivity and can reduce the difficulty of writing contracts. Among these languages, Solidity is currently the most prevalent, and a lot of studies focus on the security of smart contracts in it.

There are also many derivatives from Ethereum, whose execution mechanisms are almost the same as EVM and support Turing-complete languages. In this paper, we call such systems Turing-complete blockchains. Similar to Bitcoin, most related research is conducted on Ethereum and the results could be easily transferred to its derivative systems. Therefore, we also take Ethereum as the representative to describe the contract construction schemes on Turing-complete blockchains and the schemes here are divided into two parts: design paradigms and tools, as discussed in Section V-A and Section V-B respectively.

A. Design Paradigms

In order to reduce errors caused during contract programming, developers are suggested to refer to contract design paradigms, which are carefully designed against common attacks and recognized safe. We divide the related schemes into two categories: paradigms for specific applications and for general purposes. The former refer to the specialized design patterns in some popular application scenarios (see Section V-A1), and the latter describe the patterns in general cases (see Section V-A2). We summarize and classify these schemes according to their application scenarios in Table III. The symbol ✓ (or ✗) in “Open Source” column indicates that the implementation can (or cannot) be publicly accessed online. When there are multiple references in a line, there will be multiple ✓ or ✗, correspondingly.

1) Paradigms for specific applications: In the early stage of smart contracts, lottery, loan, auction and data storage are the main applications in the market. These contracts are directly related to financial transactions, and their contents and logic are relatively simple. Though such contracts are only designed for the specific scenarios, they are still significant and helpful for similar applications. Nonetheless, in recent years, smart contracts have attracted attentions from governments, and they may provide benefits for municipal government processes. In the following, we will introduce five common patterns, i.e., lottery, loan, auction, e-government and off-chain computation and storage.

a) Lottery: Traditional lottery schemes require a trusted third party to receive bets from participants and distribute the deposits afterwards. However, there exist risks of collusion and

| Language | Year | Security Proof | Open-Sourced | Templates Available | Description |
|----------|------|----------------|--------------|---------------------|-------------|
| Ivy [68] | 2016 | ✗              | ✓            | ✓                   | High-level language, educational purposes only |
| Simplicity [69] | 2017 | ✓              | ✗            | ✗                   | Intermediary representations, verifiable with Coq |
| BALZaC [67] | 2018 | ✗              | ✓            | ✗                   | High-level language, no formal proof of security |
| BitML [70] | 2018 | ✓              | ✓            | ✓                   | High-level language, process-algebraic language |

Note: ✓ denotes that the language possesses the corresponding property in the column, while ✗ means the opposite.
abscoding for online lottery websites. Due to the anonymity and trustless property of blockchain, coupled with the inherent cryptocurrencies, smart contracts can replace such trusted third parties to eliminate these risks and minimize the leakage of privacy. Lottery thereby becomes one of the most popular applications of smart contracts.

Several lottery contracts implemented in Bitcoin have already been mentioned above in Section IV-A2. With the Turing-complete languages supported by Ethereum, lottery contracts could be implemented with better performance and less cost. As mentioned in Section IV-A2, Bartoletti and Zunino [51] give a multi-party lottery scheme with fixed collateral and implement it on Ethereum. Their solution comes from a tree of two-party games to determine the final winner among all the participants. The authors also describe a variant that reduces the number of transactions by a set of iteration games between adjacent players, but it cannot guarantee the fairness of the lottery protocol. Miller and Bentov [73] put forward another lottery scheme with zero collateral. They adopt a similar tree of two-party games as that in [51], but require an extra opcode to take effect in Bitcoin, and they also implement their scheme on Ethereum.

b) Loan: Similar to the motivations in lottery, loan is another popular application of smart contracts. However, in loan contracts, participants often want to borrow and lend fiat money, since the fluctuation of cryptocurrency market value may cause undesirable loss for either one of the participants. Moreover, loan contracts have to deal with the counter-party risk, where a borrower may abscond with funds.

To solve the problems above, Okoye and Clark [74] design a set of loan contracts named Ugwo with different methodologies. These contracts ensure the safety of funds for both borrowers and lenders. For the problem of unstable market value, the authors adopt an oracle contract (which provides current exchange rate with justification) to enable the users to settle the contract with fiat currency (e.g., USD). Moreover, methodologies such as mortgage and insurance are also employed in their contracts, for different security concerns of the money.

c) Auction: In addition to lottery and loan, auction contracts also make full use of the anonymity and no-third-party features of blockchain. Strain [79] is a private auction protocol, where participants’ identities and bids are hidden. In order to avoid using inefficient SMPC protocol, they improve the two-party comparison mechanism [194] and verify the results by using zero-knowledge proofs (Definition 16). Besides, a reversible commitment mechanism is applied to ensure the fairness when a malicious termination occurs. However, although the scheme avoids directly publishing the details of auction on-chain, it still leaks the order of bids. To solve this problem, Galal and Youssef [80] propose a verifiable secret auction protocol using Pederson commitment [195] and zero-knowledge proofs, and implement their work on Ethereum. Their scheme ensures that participants cannot learn any information about others during the auction process, and anyone is allowed to verify the auction results. However, a formal security proof is lacked.

d) e-government: Blockchain and smart contracts provide convenient verifiability and remove the need of trusting each other. Ølnes [75] argues that such advantages of smart contracts can be used for applications other than currencies, especially for online government processes (i.e., e-government). Ølnes et al. [76] further discuss the benefits and implications of blockchains for e-government applications. With a similar point of view, Hou [77] does a investigation of the blockchain applications of e-government in China. However, all the discussions above involves no practical implementations. Most recently, Krogsbøll et al. [78] give a prototype implementation of a governmental service in Denmark, with attractive properties (e.g., verifiability). The authors point out that the e-government applications are possible with smart contracts, if taking care of the privacy issues.

e) Off-chain computation and storage: Taking smart contracts off-chain is a promising way to avoid the side effects of the high confirmation delay while maintaining the trustless property offered by blockchain. With this idea, Eberhardt et al. [81] analyze the suitable scenarios of off-chain computation and storage, and give several design patterns for off-chain
schemes. The typical scenarios are payment channel network and state channel network. These solutions mainly focus on the execution protocol, so we leave the discussion to Section VI-B.

To attain advantages (e.g., privacy, latency, transaction fees, etc.) from both on-chain and off-chain implementations, Carlos Molina-Jiménez et al. [82] propose a hybrid solution that splits a smart contract into on-chain and off-chain components. However, this comes at the cost of complex implementation strategy, which depends on concrete applications. The authors provide a proof-of-concept implementation of a simple trading contract [83], to demonstrate the feasibility of their work. Similarly, Li et al. [84] separate a smart contract into the light/public parts and heavy/private parts, to avoid high transaction fees and confirmation delay caused by complex on-chain executions. Their solution also suffers from the absence of a general way to make such separation.

2) Paradigms for general purposes: We have described some design paradigms for specific applications in the prior part. From another aspect, some studies are trying to give a general pattern that applies to the design of all kinds of smart contracts. Some of them give out the so-called “best practices” that are aimed at mitigating common bugs and security risks during development. Some classify smart contracts according to application scenarios and give patterns for each category, which are referred as “classification and patterns of common contracts” in this paper. Some researchers focus on common errors in the contract construction process, as counterexamples for beginners to learn from, and we call them “common vulnerabilities and errors”. Finally, there are also “contract design models” describing the experience and methods for contract construction, from a higher perspective.

a) Best practices: It is recommended to refer to some best practices given by researchers or communities, to avoid vulnerabilities as much as possible. The Solidity document [14] serves as an official guidance for writing smart contracts, which provides tips, requirements, and some examples about contract construction. It is considered as a must-read document for beginners, because it has been verified and reviewed by most developers, and is being continuously improved and updated. Besides, Consensys Diligence [85] and OpenZeppelin [86] also provide rich open-sourced lists of best practices and libraries.

b) Classification and patterns of common contracts: Statistics and classification of existing contracts could help developers find their desired reference patterns for their target application scenarios, and further avoid contract vulnerabilities that may commonly occur in certain applications.

In terms of classification, Bartoletti et al. [30] firstly classify the application scenarios of smart contracts, and then list several common contract modes, including: token, authentication, oracle, randomness, poll, time constraint, termination, math, and fork check, etc. Their classification covers most smart contracts, and the numeric results are shown in Fig. 9 [30], which illustrates the number of transactions for different types of smart contracts on Bitcoin and Ethereum.

For the security of smart contracts, Wöhner et al. [87], [88] give several contract patterns according to some known secure contracts from the perspectives of access control, authentication, contract life cycle [196] and contract maintenance.

c) Common vulnerabilities and errors: Statistics and classification of common vulnerabilities and errors during contract construction may serve as counterexamples, and help developers form a good contract pattern.

In terms of common vulnerabilities, Luu et al. [89] are the first to summarize the security problems that commonly occur in smart contracts. These problems are categorized into four types, namely, transactions-ordering dependence, timestamp dependence, mishandled exceptions and re-entrancy vulnerability. The first three concepts are relatively easy to understand from their name, and the last one refers to a concept unique in the smart contract field. We leave the introduction of re-entrancy in Section V-B1 where the analysis tools especially designed for such vulnerability are discussed.

Later, Atzei et al. [32] also summarize the vulnerabilities on smart contracts and divide them into different layers, according to the effects of attacks, e.g., affecting the correctness of execution, or disturbing the underlying execution mechanism. The latest work of Groce et al. [94] makes a classification of 246 defects found in 23 Ethereum smart contracts. They utilize several open-sourced analysis tools (i.e., Slither [125], Manticore [113] and Echidna [134], see Section V-B1) along with manual auditing, and they find that there are 10 defects per contract on average.

In addition to common vulnerabilities, there are studies on the security properties that smart contracts should satisfy. Following the work of [89] and [32], Grishchenko et al. [90] conclude four security features that smart contracts should meet. The smart contracts with such features could automatically avoid some known vulnerabilities. Their classification is useful for subsequent development and contributes to the design of related vulnerability detection tools.

We integrate the results above in Table IV. The blanks in the table indicate that the corresponding vulnerabilities are not discussed in these papers. We remark that the authors of [91] and [92] respectively do a similar work that provide a taxonomy of the security issues according to the literature, and give the severity level of each vulnerability.

With regard to common errors, Delmolino et al. [95] elaborate some common problems found in their courses about
### TABLE IV
THE POTENTIAL VULNERABILITIES IN SMART CONTRACTS ON EVM [32, 89, 90]

| Level  | Causes          | Security | Attacks     |
|--------|-----------------|----------|-------------|
| Solidity | Call to the unknown | Call Integrity | The DAO attack |
|         | Reentrancy       |           |             |
|         | Gasless send     | –        | King of the Ether Throne |
|         | Exception disorders | Atomicity | King of the Ether Throne |
|         | Type casts       | –        |             |
|         | Keeping secrets  | –        | Multi-player games |
| EVM     | Immutable bugs   | –        | Robust      & Governmental |
|         | Ether lost in transfer | – |             |
|         | Stack size limit | –        | Governmental |
| Blockchain | Unpredictable state | Independence of mutable account | Governmental & Dynamic incentives |
|         | Transaction ordering dependence | – | Governmental |
|         | Generating randomness | – | Governmental |
|         | Time constraints | –        | Governmental |

smart contracts. Although they adopt Serpent [15] as the programming language, many problems reflected are universal for all languages when designing smart contracts. The authors summarize four types of errors, including: design errors on state machines, absence of cryptographic protocols, unreasonable incentive mechanisms, and vulnerabilities caused by Ethereum itself. These errors are of educational meaning for all developers, especially the beginners. Angelo et al. [96] also give a summary on their smart contract course, but they start from the perspective of a teacher, and focus more on the teaching process, rather than the design skills.

From a practical perspective, Pérez and Livshits [93] explore 6 frequently mentioned vulnerabilities in Ethereum, and find that the actual exploitation of these vulnerabilities are relatively rare: the hacked accounts of ETH only takes up to 0.27% of the total ETH marked as vulnerable by analysis tools (see Section V-B1). The authors explain that this is because most vulnerable ETH is held by several contracts that are not exploitable in practice (i.e., the exploitation requires a malicious majority).

**d) Design models:** From a higher perspective, some researchers put forward several design models for smart contracts. Clack et al. [97], [98] firstly discuss the basis, design method and research direction of smart contract templates, and then discuss the basic requirements of smart legal contracts, which refer to the contracts serving for legal purposes. They also propose a design model for the storage and release of contracts from a higher level. Marino et al. [99] summarize the available methods of contract modification and deletion without modifying the existing execution mechanism. They often require developers to reserve some interfaces at the beginning, and it is a good practice to consider such future updating demands.

### B. Design Tools

Design tools discussed here are used to help developers in building smart contracts more efficiently, and they usually come in the form of useful software rather than boring instruc-

### Prior to our work, there have been several studies conducting a survey on the contract design tools. Dika [33] conducted a detailed comparison of the analysis tools in 2017, from the aspects of the efficiency, accuracy, and types of supported vulnerabilities. Harz et al. [35] further analyzed the related languages and security tools in 2018. They make a brief introduction and classification of these languages and tools. Later on, Grishchenko et al. [122], [123] Angelo and Salzer [38], Liu and Liu [99] make a review on the smart-contract-related security tools, from several different aspects, respectively.

Based on the discussions above, we summarize, compare and analyze the existing (up to August 2020) contract languages and vulnerability detection tools in detail. Our work on the contract design tools can be viewed as a further extension to the surveys mentioned above.

1) **Analysis tools:** A smart contract is a piece of executable computer program deployed on a blockchain. So, traditional code analysis methods can be naturally extended to the field of security analysis. Since there are many vulnerabilities unique in smart contracts, many tools are specifically designed for these threats. Some of them focus on detecting certain kinds of vulnerabilities that frequently appear and may cause severe consequences. Others are aimed at general security analysis, which could simultaneously detect multiple potential vulnerabilities, or even user-defined properties of the smart contracts, and remind the developers of potential risks. The former tools usually work with higher accuracy and can help to mitigate the pressure caused by some specific attacks. The latter remind developers of the vulnerabilities and risks that are overlooked during development.

According to the type and number of vulnerabilities that the analysis tools detect, we divide them into 6 classes in this paper: (a) re-entrancy attacks related; (b) gas consumption related; (c) trace vulnerability related; (d) event-ordering bugs related; (e) integer bugs related; and (f) general detection tools. The first five classes of tools are all focused on some specific vulnerabilities, while the last type of tools achieve general detection of vulnerabilities. In addition, we further categorize the general detection tools by the technologies that they utilize, including symbolic execution, syntax analysis, abstract interpretation, data-flow analysis, topological analysis, model checking, deductive proof, satisfiability modulo theories and fuzzing test.

The analysis tools we discuss are listed in Table V. There are also some specially designed languages called Domain Specific Languages (DSL), which are used to support user-defined conditions in the process of security analysis. Such languages are not included in Table V because they usually...
come along with their corresponding tools. Moreover, contents in the column “Input” represent the form of smart contracts (e.g., Solidity or EVM bytecode) that the tool accepts as input. The symbol of ✓ in the column “Open-sourced” means that the source code of the tool can be referenced online, while ✗ means the opposite.

a) Re-entrancy attacks related: It is the re-entrancy attack that makes users suffer huge economic losses in the infamous DAO event [110]. In a re-entrancy attack, an attacker utilizes the fallback function in Ethereum smart contracts, to steal money from the smart contracts that are designed in a nonstandard manner. The fallback function stands for a predefined function that has no name or parameter. It is used to handle exceptional requests, such as calling a function that does not exist. Ideally, when a contract \( C_A \) calls a function in another contract \( C_B \), it waits until the executed function is completely finished, before getting back to the remaining part of \( C_A \). However, in some cases (e.g., when the invoked function is “call”, which is used to transfer money in Ethereum), after the invoked function is finished, the EVM would invoke the fallback function in \( C_B \), before returning to \( C_A \). If \( C_B \) calls the contract \( C_A \) in the fallback function, then it comes to a situation of recursive invocation. When the latter invocation starts, the former is not finished, and thus contract \( C_B \) re-enters \( C_A \). Such a re-entrancy is undesirable and may cause unexpected consequences.

Researchers have proposed various analysis tools to defend against such attacks, based on different methods and aspects. Grossman et al. [100] propose the concept of Effective Callback Freedom, which requires that the invocation of the callback (i.e., fallback) function should not affect the states or behaviors of the original program. The authors claim that this concept can be effectively used to detect re-entrancy attacks in Ethereum, and they integrate their idea into the online detector named ECFCChecker.

ReGuard [131] is another tool for detecting re-entrancy vulnerabilities, utilizing fuzzing test (see Section V-B1f). ReGuard accepts Solidity or EVM bytecode as input. It first parses the input into the Intermediate Representation (IR), and subsequently converts the IR into a C++ contract. Then the fuzzing engine is employed to generate random inputs. Finally, based on the fuzzing test results and the re-entrancy automaton model proposed by the authors, the final result of the vulnerability detection is generated.

From the perspective of sustainability, Michael et al. [101] point out that existing tools could only be used to detect potential vulnerabilities before the smart contracts are deployed. That is to say, deployed contracts are protected from attacks. To solve this problem, they propose the Sereum scheme, which extends EVM by introducing the method of taint tracking and an attacker detector. Sereum monitors the EVM bytecode instructions at runtime, and utilizes a write-lock mechanism which locks the states when calling outside functions. This mechanism fundamentally prevents the re-entrancy attack from the underlying execution layer.

b) Gas consumption related: To prevent DoS attacks, Ethereum introduces the gas mechanism to limit the number of operations in a contract. However, this may cause new problems. For instance, it increases the economic cost of users since the gas should be paid in advance for the contract execution. There are several tools for optimizing the gas consumption, with various methods and techniques. We summarize the relationship among these tools in Fig. 10, where the arrows between tools refer to the dependency, and the gray names refer to the tools that are not specifically designed for gas consumption.

Chen et al. [102] point out that non-standard design of smart contracts may lead to unnecessary cost of gas. By collecting and analyzing smart contracts on Ethereum, the authors enumerate 7 patterns that may cost more gas than expected. They further develop an analysis tool GASPER based on symbolic execution (see Section V-B1f). GASPER accepts EVM bytecode as input and detects three kinds of abuse patterns. The subsequent work [103] further lists a total of 24 gas abuse modes and develops a tool named GasReducer. The input that GasReducer accepts is also EVM bytecode. After code disassembling and pattern matching, it recognizes all the 24 abuse patterns. Moreover, it automatically replaces the costly operations with cheaper instructions that accomplish the same functionality. In addition, by recalculation and verification of the optimized codes, GasReducer ensures that the outcome contract still works as expected.

Similar to [102], Marescotti et al. [104] propose two algorithms for calculating the maximum amount of gas that may be consumed by smart contracts, where the latter can be seen as a simplified version of the former. These two algorithms also use the symbolic execution method as GASPER. But differently, by assuming that there is a one-to-one correspondence between the EVM and Solidity gas consumption path, both algorithms can directly analyze the contracts written in Solidity. However, their solution only helps to calculate the statistics of gas consumption, but does not provide optimization suggestions.

Grecch et al. [105] also analyze the gas consumption problem in Ethereum and propose an analysis tool MadMax based on the decompilation technology and logic-driven model offered by Vandal (see Section V-B1f). MadMax decompiles EVM bytecode into a Control-Flow Graph (CFG), and then uses a logic-based specification to further detect the predefined gas-related vulnerabilities. In addition, the authors give some suggestions for developers who write smart contracts with high-level languages, which is not accomplished in [104].

By improving and integrating some existing tools, Albert et al. [106] propose GASTAP. First, they improve the OYENTE
| Targets* | Ref. | Year | Tool† | Main Methods | Input♣ | Open-Sourced△ |
|---------|------|------|------|-------------|--------|--------------|
| Re-Rentrancy Attacks-Related | [100] | 2017 | ECFChecker | Modular Reasoning | Solidity | ✓ |
| | [101] | 2019 | Sereum | Taint Tracking | EVM bytecode | ✗ |
| Gas-Related | [102] | 2017 | GASPER | Symbolic Execution | EVM bytecode | ✗ |
| | [103] | 2018 | GasReducer | Pattern-Matching | EVM bytecode | ✗ |
| | [104] | 2018 | – | Symbolic Execution | Solidity | ✗ |
| | [105] | 2018 | MadMax | Decompiling & Logic-based Specification | EVM bytecode | ✓ |
| | [106] | 2019 | GASTAP | Symbolic Execution | Solidity, EVM bytecode | ✗ |
| | [107] | 2019 | GASOL | Symbolic Execution | Solidity | ✗ |
| Trace Vulnerability | [108] | 2018 | MAIAN | Symbolic Execution | EVM bytecode | ✓ |
| Event-Ordering Bugs | [109] | 2019 | ETHERRACER | Symbolic Execution & Fuzzing | EVM bytecode | ✗ |
| Integer Bugs | [110] | 2018 | OSIRIS | Symbolic Execution & Taint Analysis | Solidity, EVM bytecode | ✓ |
| | [111] | 2020 | VERIS | CEGIS-style Verification | Solidity | ✓ |
| | [89] | 2016 | OYENTE | Symbolic Execution | EVM bytecode | ✓ |
| | [112] | 2018 | ETHIR | Symbolic Execution | EVM bytecode | ✓ |
| | [113] | 2019 | SAFEVM | Symbolic Execution | Solidity, EVM bytecode | ✓ |
| Symbolic Execution | [114] | 2018 | Mythril | Symbolic Execution & SMT solving & Taint Analysis | EVM bytecode | ✓ |
| | [115] | 2019 | Manticore | Symbolic Execution | Solidity | ✓ |
| | [116] | 2018 | tEITHER | Symbolic Execution & Constraint solving | EVM bytecode | ✓ |
| | [117] | 2019 | sCompile | Symbolic Execution | EVM bytecode | ✗ |
| | [118] | 2019 | SMARTSCOPY | Summary-based Symbolic Evaluation | ABI | ✗ |
| General-purpose | [119] | 2018 | SECURIFY | Abstract Interpretation & Symbolic Execution | Solidity, EVM bytecode | ✓ |
| | [120] | 2020 | VERX | Symbolic Execution & Abstract | Solidity | ✗ |
| | [121] | 2018 | SmartCheck | Syntax Analysis | Solidity | ✓ |
| Abstract Interpretation | [122, 123] | 2018 | EtherTrust | Abstract Interpretation | EVM bytecode | ✓ ✓ |
| | [124] | 2018 | Vandal | Abstract Interpretation Logic-driven Analysis | EVM bytecode | ✓ |
| | [125] | 2019 | Slither | Dataflow Analysis & Taint Tracking | Solidity | ✓ |
| | [126] | 2018 | SASC | Topological Analysis & Syntax Analysis & Symbolic Execution | Solidity | ✗ |
| | [127] | 2018 | – | Model-Checking | Solidity | ✗ |
| | [128] | 2018 | ZEUS | Abstract Interpretation & Symbolic Model Checking | High-level languages | ✗ |
| Model Checking | [129] | 2019 | – | Deductive Proof | Why3 | [197] ✓ |
| | [130] | 2018 | – | SMT-solver | Solidity | ✗ |
| | [131] | 2018 | ReGuard | Fuzzing | Solidity, EVM bytecode | ✗ |
| Fuzzing | [132] | 2018 | ContractFuzzer | Fuzzing | ABI, EVM bytecode | ✓ |
| | [133] | 2019 | ILF | Fuzzing | Solidity | ✓ |
| | [134] | 2020 | Echidna | Fuzzing | Solidity, Vyper | [198] ✓ |

*: ∼ means that the taxon is trivial for a single object.
†: If the corresponding tool has no name, then the blank is filled with –.
♣: The input only refers to the form of smart contracts, so the analysis specification required in some tools is not included.
△: ✓ here means that the corresponding tool is open-sourced and can be referenced online, while ✗ means the opposite.
tool (see Section V-B1f) to generate a CFG with more information. Then they improve the ETHERIR tool \cite{112} so that it can convert the CFG into a rule-based representation. Based on these two improvements, along with other auxiliary tools for calculation, GASTAP finally gets the upper bound of gas consumption of each function in the contract, as is done in \cite{104}. The GASOL \cite{107} tool further extends GASTAP to provide suggestions to optimize the gas consumption.

c) Trace vulnerability: As Nikolić et al. \cite{108} point out, most existing tools for security analysis only focus on a single call of a contract, but ignore the problems that may occur when it is called multiple times. For the latter case, they find a new type of vulnerability named trace vulnerability. Contracts containing such vulnerabilities may: 1) be destroyed by any user; 2) be unable to withdraw funds; 3) transfer funds to any address. To fix this problem, the authors propose the MAIAN tool based on symbolic execution. MAIAN accepts EVM bytecode as input along with user-defined analysis targets, and it confirms the existence of trace vulnerabilities after symbolic execution.

d) Event-ordering bugs: Event-ordering bugs evolve from the transaction ordering dependence described in \cite{89}, where the original concept describes the case when the order of transactions influences the final states in the contracts. Kolluri et al. \cite{109} define the notion of event-ordering bug, that is, when users call the same function in the contract, the order of calling may lead to inconsistent results among the miners, some of which may be undesirable. To eliminate such risks, the authors combine the methods of symbolic execution and fuzzing test, and propose the ETHERRACER tool, which directly works on EVM bytecode. To get better performance and accuracy, some optimizations are made to avoid the problem of resource-explosion during symbolic execution. With fuzzing test, ETHERRACER directly provides a counter-example to intuitively explain the existence of the bugs, that is, two sets of inputs of different orders that result in distinct outputs.

e) Integer bugs: Integer bugs refer to the bugs that are related to integer arithmetic in smart contracts. Torres et al. \cite{110} firstly sort the integer bugs in smart contracts into: 1) arithmetic bugs that include integer overflow, underflow, and divided by zero, etc; 2) truncation bugs that occur when converting longer integers into shorter ones; 3) sign-related bugs that occur during the conversion between signed and unsigned integers. Then they propose the OSIRIS tool for these integer bugs, based on symbolic execution and stain analysis methods. OSIRIS accepts Solidity or EVM bytecode as input. Compared with ZEUS \cite{128} and other general tools that detect multiple vulnerabilities (see Section V-B1f), OSIRIS could detect more integer bugs with the same data set and has a lower false positive rate. Torres et al. point out that ZEUS could not detect integer bugs, so the claimed zero false negative is not accurate.

Based on the works above, VERISMAART \cite{111} further improves the accuracy and efficiency of the integer bug detection. The authors point out that arithmetic-related vulnerabilities account for more than 90% of the reported vulnerabilities. In addition, existing tools usually come with inevitable false positive or false negative reports, making manual checks necessary. To address these two problems, the authors develop the VERISMAART tool that detect all known arithmetic bugs with almost negligible false alarms. VERISMAART accepts contracts written in Solidity as input. It draws on the idea of the counter example-guided inductive synthesis (CEGIS) framework \cite{199}, by constantly searching candidate invariants to check whether the contract meets security requirements. VERISMAART manages to avoid expensive operations through a well-designed decision procedure, which helps to improve the scalability of the tool as well. Further, it is claimed that with appropriate improvements, VERISMAART can be used to detect other vulnerabilities.

f) General analysis: Apart from the tools that are specifically designed to detect some specific vulnerabilities, many tools are designed to detect multiple kinds of vulnerabilities at once. We classify these general detection tools according to the main technique they adopt, including: symbolic execution, syntax analysis, abstract interpretation, data-flow analysis, topological analysis, model checking, deductive proof, satisfiability modulo theories solving, and fuzzing test. Among them, symbolic execution, as the mainstream technology used in software analysis, also occupies a dominant position in the research of security analysis tools of smart contracts. According to our observation, the technique of fuzzing test is attracting more attention for contract analyzing recently. These tools are introduced in terms of the main technique they adopt, as follows.

i) Symbolic execution

Symbolic execution is a commonly used method to analyze the security of computer programs. Informally, it uses symbolic values to find out the value or range of the inputs that triggers the execution of each part of the program, and then helps to determine whether the program works according to the developer’s expectation.

On the one hand, symbolic execution has higher accuracy compared with other methods such as taint tracking or data-flow analysis. On the other hand, the consumption of memory grows rapidly as the size of target program grows, and this is called memory explosion. Related research mainly focuses on the accuracy rate, operation efficiency and calculation cost in the process of analysis.

OYENTE \cite{89} is the first symbolic-execution-based tool for smart contract validation. It detects four types of vulnerabilities categorized by the authors. The input of OYENTE is EVM bytecode. OYENTE is improved in \cite{112} so that the results can be used to generate control flow graphs (CFG), and it is the basis of the ETHIR \cite{112} tool. The CFG generated by ETHIR contains both control-flow and data-flow information of the input EVM bytecode. In addition, ETHIR also generates the corresponding rule-based representation (RBR) for further code analysis basis. Utilizing OYENTE and ETHIR, Albert et al. \cite{113} design the tool SAFEVM. It employs the above tools to convert the Solidity program or EVM bytecode into RBR, and further converts it into a special C program \cite{200}. After that, existing analysis tools are applied to verify the security of the converted C program. Mueller \cite{114} combines symbolic execution with other tech-
nologies such as SMT-solver and taint analysis, and proposes the analysis tool Mythril [201], which works with a symbolic execution backend LASER-Ethereum [202]. Mythril accepts EVM bytecode as input. Compared with OYENTE, it has better supports from the community, and is under constant optimization. By the time of writing (August 2020), Mythril has evolved into a security analysis tool supporting smart contracts on various platforms that are derived from Ethereum, and can be used to analyze various common bugs and vulnerabilities. Manticore [115] is another widely used and flexible analysis tool based on symbolic execution and satisfiability modulo theories. It supports user-defined analysis by providing several API for the access of the core engine. Moreover, it is able to infer concrete inputs for a given program state, and it supports various computer programs in traditional environments (e.g. x86, ARM, WASM) other than Ethereum.

As mentioned before, symbolic execution only works well to analyze short contracts due to the efficiency issues (i.e., the memory explosion problem). Krupp and Rossow [116] optimize the procedure of symbol execution with the help of CFG. They propose TEETHER, focusing on the automatic detection and utilization of vulnerabilities in smart contracts. According to the EVM bytecode input, TEETHER first generates a CFG and sorts the critical paths related to the fund transfer. Then, by constraint solving, the results of symbolic execution are used to enumerate possible attacks against these critical paths. In this way, TEETHER provides the witness of detected vulnerabilities, while making the detection more automated. Chang et al. [117] adopt a similar idea of partial analysis, and propose the tool sCompile, which only works on the critical part of a smart contract involving fund transfer. Given the EVM bytecode, sCompile first generates the corresponding CFG and then analyzes whether the transfer-related path meets the predefined security properties. Paths are ranked according to the results and some predefined rules. After that, sCompile performs the symbolic execution on the higher-ranked paths and finally generates an analysis report. This partial analysis solution improves the scalability of symbolic execution.

To solve the same scalability problem, Feng et al. [118] propose the idea of summary-based symbolic evaluation and the corresponding tool SMARTSCOPY. SMARTSCOPY not only supports analyzing large contracts efficiently, but also generates counterexample attacks for the detected vulnerabilities. In order to reduce the space and time overhead for large contracts, SMARTSCOPY symbolically evaluates the methods indicated by the Application Binary Interface (ABI) [203] of contracts, and summarizes the impact of each method on the blockchain. It then conducts the range splitting and pruning procedure, and finally the symbolic execution. The authors argue that SMARTSCOPY can detect the newly-defined BatchOverflow bugs that other tools previously overlooked.

In the aforementioned solutions for scaling symbolic execution [116]–[118], some less important paths are skipped or ignored during the analysis. Although this improves the efficiency, it may lead to false negative results. Tsankov et al. [119] propose an analysis tool SECURIFY which combines the method of abstract interpretation with symbolic execution. SECURIFY guarantees to traverse all possible paths in a contract, thereby reducing the false negative results caused by the incomplete symbolic execution. Its input is EVM bytecode, along with a security model defined by a domain specific language. Through steps of decompiling, semantic fact inferring, and security pattern checking, it determines whether a contract meets the predefined properties in the security model. Moreover, the security models in SECURIFY are apart from the analysis tool itself, therefore, by optimizing the security model, the accuracy of vulnerability detection could be further raised.

From another point of view, to improve the efficiency of analysis, VERX [120] adopts the concept of delayed predicate abstraction. Its main idea is to combine the methods of symbolic execution and abstraction together: symbolic execution is used in the individual execution of transactions, while abstraction is conducted between transactions. The delayed abstract process reduces the infinite state space brought by unlimited transactions to a limited space. VERX takes smart contracts written in Solidity as input, along with the security requirement, and it outputs the predicate whether the contract meets the given properties.

### ii. Syntactical analysis

Syntactical analysis is a method to analyze computer programs by parsing them into a tree and analyzing the relation of each component. Tikhomirov et al. [121] first summarize some potential problems in the smart contract programming process, including: 1) security-related issues; 2) function-related issues; 3) execution-related issues; 4) development-related issues. They design a static analysis tool SmartCheck that can find such problems. SmartCheck converts the Solidity source code into an XML parse tree [204], and then uses XPath queries [205] to find the matched patterns. As the authors point out, SmartCheck can not guarantee the accuracy or work without manual check. Still, this method provides an efficient way to detect potential vulnerabilities.

### iii. Abstract interpretation

The basic idea of abstract interpretation is to verify whether a program meets certain specific properties according to the approximation of the semantics of the program. Related research mainly focuses on the usability and accessibility of the tool, and abstract interpretation in these studies usually comes with some other tools, such as Horne-clause resolution, control flow graph, etc.

Based on the work of [90] which defines the full semantics of EVM bytecode, Grishchenko et al. [122] propose the tool EtherTrust. It first abstracts the EVM bytecode as a series of Horn clauses, and then uses the resolution of such clauses to verify the reachability of the contract. The authors also give the security analysis on the reliability of this tool. Moreover, the authors clarify the mechanism and details of EtherTrust in their later work [123].

Vandal [124] is an analysis framework with the idea of abstract interpretation. It creatively converts the input EVM bytecode into a logical relationship, and then uses the logic-driven methods to verify the correctness and security of such a logical relationship. Using this framework, users could easily define security requirements and conduct security analysis.
Brent et al. [124] also compare the performance of Vandal with aforementioned OYENTE [89] and Mythril [201]. They show that Vandal and Mythril find more types of vulnerabilities than OYENTE, and Valdal is the most efficient among these three. Based on the Vandal framework, Grech et al. [105] further propose the Madmax tool to find gas-related vulnerabilities in Ethereum contracts.

iv. Data-flow analysis

In data flow analysis, the runtime information of the variables is collected to check whether a program meets the expected property during the execution. Slither [125] is an analysis tool based on this method. It can automatically detect vulnerabilities and help developers to have a better understanding of smart contracts. Slither converts a Solidity contract to the corresponding control flow graph and compiles it to an intermediate representation SlithIR, which is also specified in [125]. Utilizing data-flow analysis and taint tracking technologies, the tool can analyze large contracts that are infeasible for symbolic execution.

v. Topological analysis

Topological analysis for smart contracts is mainly based on the topological structure graphs that illustrate the relations among multiple interrelated smart contracts. Taking use of the Solidity-parser [206], Zhou et al. [126] analyze the calling and dependency relationships in and between contracts, based on the Solidity source code. They propose a method to form a topological graph for developers that helps to analyze the structure of their contracts. In addition, this method also uses symbolic execution, syntax analysis and other methods to find potential logical vulnerabilities in a contract.

vi. Model checking

Model Checking is a method that verifies whether a system meets certain properties by modeling it into a finite state machine. Regarding the security analysis of smart contracts, related studies mainly focus on model construction, accuracy and efficiency.

On model construction, Nehai et al. [127] propose a model-checking-based solution to check the security of contracts. They build a three-layer model for the smart contracts on Ethereum, namely, the core layer, application layer and environment layer. In the application layer, they propose a method that compiles the Solidity source code into the NuSMV language [207], which is model-checking friendly. Then, they perform model checking on the compiled program to determine whether the contract meets the user-defined security properties.

On the aspect of accuracy and efficiency, Kalra et al. [128] combine the methods of abstract interpretation, symbolic model checking and constrained horn clauses (CHCs), and propose the ZEUS tool. They claim that the tool achieves zero false negative results, with lower false positive rate compared with tools like OYENTE. In addition, ZEUS works faster than OYENTE. Theoretically, ZEUS accepts smart contracts written in various high-level languages as input, and thereby can be extended to support platforms other than Ethereum, such as Hyperledger Fabric [7]. It converts a smart contract into an intermediate representation by a specially-designed compiler and inserts some check points into the intermediate representation according to user-defined rules. Finally, with CHCs-based verification tools, ZEUS verifies the security of the smart contract (Definition 13).

vii. Deductive proof

The aforementioned model checking only works on small-scale contracts, as the states in the model grow with the contract size. Nehai and Bobot [129] propose a deductive proof method, where they compile the Solidity contracts into programs in Why3 language [197]. They then use the Hall-Logic-based detection tools brought by Why3 to analyze the properties of a contract. They also provide a compiler that compiles the contracts written in Why3 into EVM bytecode, so that developers can directly write contracts in Why3.

viii. Satisfiability modulo theories

Satisfiability modulo theories (SMT) involve a formula where the parameters are functions or predicate symbols, and the goal of SMT is to determine the satisfiability of this formula. It usually comes with other methods, serving as an auxiliary method. However, some studies have used it as the main technology to complete the security analysis of smart contracts. Alt and Reitwiessner [130] assert that SMT can be directly integrated into the Solidity compiler to enable users to conduct security analysis while compiling, and meanwhile provide counterexamples to the vulnerabilities. However, the authors only provide the idea and some use cases, but not provide a complete plan nor an implementation of this idea.

viv. Fuzzing test

Fuzzing test is a prevalent technique for bug detection in recent years. The core idea is to generate random data as input, and monitor the abnormal behaviors of the target program under these inputs. A large number of random inputs are used. Bugs that are unreachable in normal cases could be found by random collision in this way. Existing research on smart contract analyzing mainly focuses on the completeness and efficiency of the analyzing process.

ContractFuzzer [132] is the typical example that is based on fuzzing test to detect multiple types of vulnerabilities in smart contracts. It first generates the random inputs according to the Application Binary Interface (ABI) of a smart contract, and then records the execution results of these inputs. Afterwards, it performs security analysis with predefined test oracles which describe the characteristics of specific vulnerabilities. Evaluation results show that ContractFuzzer has a lower false positive rate than OYENTE, but a higher false negative rate under certain circumstances.

Regarding the completeness and efficiency of fuzzing test, He et al. [133] argue that tools like ContractFuzzer [132] could not reach some paths in depth, thereby failing to find related vulnerabilities (i.e., causes false negative results). While on the other hand, tools based on symbolic execution can reach deep paths, but they consume enormous resources. Combining these two methods, the authors propose the concept of Imitation Learning based Fuzzer (ILF). ILF learns the procedure of the symbolic-execution-based tools, imitating the behavior of symbolic execution paradigm. After that, the test set is generated for the Solidity contract. In this way, fuzzing test can be used to find more vulnerabilities efficiently.
To support user-defined analysis, the tool Echidna \cite{echidna} is proposed. It can be used to check user-defined properties and assertions, and it further provides an estimation of worst-case gas consumption for the contracts. Echidna accepts contracts written in Solidity and Vyper \cite{vyper}, and has been used in the auditing service in \cite{auditing}.  

2) **Auxiliary tools:** Apart from the analysis tools discussed above, there are many other tools for auxiliary purposes, such as frameworks, languages, and basic tools. The “framework” refers to a set of tools or schemes that simplify or facilitate the development of smart contracts. “Language” indicates the new smart contract languages, such as high-level languages with high expressivity (e.g., Solidity), and intermediate representation (IR) that is used during the process of compilation or analysis. “Basic tool” refers to the basic tool for other high-level tools (e.g., the analysis tools discussed in Section \ref{sec:analysis} and the high-level languages and frameworks in Section \ref{sec:languages} and Section \ref{sec:frameworks}), such studies are much more fundamental, and could not be applied to the construction of smart contracts directly. 

The auxiliary tools discussed in this paper are summarized in Table \ref{table:auxiliary} where the ✓ (resp. ✗) in the “Open-sourced” column represents that the corresponding tool is open-sourced (resp. not). When there are multiple references in the same line, there will be multiple ✓ or ✗ in the same order.  

a) **Frameworks:** Frameworks refer to the auxiliary tools available to developers during the contract construction process, simplifying the development of smart contracts. Some of them help developers to achieve the privacy goal of the contract, or to analyze the security properties of a contract, while others provide developers with simpler tools or familiar languages, thereby reducing the learning cost and enabling a quick start for the beginners. 

The public information on the blockchain causes the privacy issues during the executions of smart contracts. Kosba \textit{et al.} \cite{hawk} propose the Hawk framework. Developers could write Hawk contracts and set privacy portion $\phi_{priv}$ and public portion $\phi_{pub}$ in the contract, where $\phi_{priv}$ helps to hide the private input of users, while $\phi_{pub}$ refers to the data that is allowed to be publicly disclosed. Accordingly, a standard contract will be generated automatically in the framework, along with cryptographic protocols that ensure the correctness of the contract (Definition \ref{def:privacy}) and privacy of the users. Therefore, developers with little knowledge of the complex cryptographic schemes can also efficiently construct a privacy-preserving smart contract. Hawk implements zero-knowledge succinct non-interactive argument of proof (zk-SNARK) \cite{zksnark} and other cryptographic schemes to ensure the privacy of the smart contract. The authors also give the security proof under the UC framework \cite{uc}. However, Hawk has not yet been open-sourced (up to August 2020). Eberhardt and Tai \cite{fsolid} adopt a similar idea to describe off-chain computation using zk-SNARK, and propose a toolbox named ZoKrates. ZoKrates includes a special high-level language for describing off-chain computation, and a compiler that compiles the contract to a zero-knowledge proof protocol. The toolbox is open-sourced, but a formal security proof is absent, compared to Hawk. 

Other than frameworks that simplify the designing of smart contracts, there are also frameworks aimed at facilitating the security analysis, based on verifiable languages, game theory, finite state machine model, etc. Smart contracts under these frameworks are more suitable with security analysis, thus making the analysis results more accurate and convincing, as is discussed in the following. 

F* \cite{fstar} is a specially designed language targeted for security analysis. Bhargavan \textit{et al.} \cite{fstar} propose a framework that translates smart contracts into F* to further conduct the security analysis. Concretely, it compiles (resp. decompiles) the Solidity code (resp. EVM bytecode) into F*, and evaluates the equivalence between these two results. Such equivalence reveals the correctness of the functionality (on the source code layer) and the runtime security (on the bytecode layer). However, the authors only give several simple examples, and a complete scheme for the compilation and decompilation is not provided. 

Smart contracts usually involve multiple parties with conflicting interests, where the game theory works well. Chatterjee \textit{et al.} \cite{smartcontractgames} describe smart contracts as a two-party game, and further propose a quantitative stateful game-theoretic framework. The core technique in this framework is the refinement of abstraction, which is used to avoid state space explosion during the modeling of two-party game. A simplified contract language without loop instructions is also proposed, to support concurrent instructions of the parties. It is used in the game-theoretic model, and the authors claim that it can be translated into Solidity. However, the corresponding compiler is not provided in their work. 

Besides, state machine can also be applied to describe the state transitions in smart contracts. Movridou \textit{et al.} \cite{smartcontractsm} regard the smart contracts as finite state machines, and propose the FSolidM framework. They build a graphical user interface to efficiently design smart contracts. In addition, they provide several plugins that can be used to detect some known vulnerabilities on the generated smart contracts. In their later work \cite{verisolid}, the authors propose the VeriSolid framework, which extends the supported Solidity expressions and updates the code generator. Formal operational semantics are also provided in the latter work. VeriSolid enables developers to describe the security properties of a contract, and verifies whether the generated contract meets such targets. Xu and Fink \cite{smartcontractsm} also apply the state machine model on smart contracts, but they focus on the behavior of smart contracts in the business field. They propose the Temporal Logic of Actions (TLA) model, which is written in TLA+ language \cite{tlaplus}, to describe the properties that a contract must satisfy. Finally, the Temporal Logic model Checker (TLC) is also proposed in \cite{tlaplus}, to ensure that the contract meets the user-defined properties. However, the state machine model may fail to describe some smart contracts because of the space explosion problem. This could be a research direction for future optimization. 

Apart from those popular and well-known models, there are also some other models that are useful in contract designing frameworks. Banchi \cite{smartcontractframeworks} proposes a framework using the Event-B model \cite{event-b}, which is designed to describe and verify the discrete event system. With this model and framework, smart contracts can meet specific properties in the designing
layer, and in turn, the security analysis becomes relatively easier. However, this work needs further improvement, on both completeness of description and syntactic complexity, to be brought into real practice.

There are also studies introducing general programming languages into the context of smart contracts. Spoto [143] proposes the framework Takamaka that implements Java as the programming language. In Takamaka, Java programmers can easily develop smart contracts with the familiar tools. Takamaka specially designs a Storage class for smart contracts, and a gas computing mechanism related to Ethereum. To avoid malicious programs or abused functions in Java, it also maintains a whitelist of permitted functions for contract developing. In addition, the framework also allows clients to use Java Virtual Machine (JVM) to run smart contract bytecode, taking advantage of JVM’s excellent bytecode execution rate and garbage collection mechanism. But this also makes it incompatible with the state-of-the-art Ethereum. In other words, it requires a hard fork to take effect. Moreover, the framework is still under development and not released yet.

b) Contract languages: Researchers for contract languages are devoted to improving the security of smart contracts (Definition 13), including avoiding common errors, and making it more suited for security analysis. Some schemes restrict the functionalities that the language can achieve, so that errors will be less likely to occur. Others do some further semantic abstraction and (or) modifications on the basis of the original language, to facilitate vulnerability detection. In this section, we summarize the contract languages proposed in these studies.

Most languages for contract programming, (e.g., Solidity, Serpent), are used for procedural (or imperative) programming, where the states in the contract are changed by multiple statements. While in the functional programming, programs are composed of multiple functions. Pettersson and Edström [144] argue that functional programming can help to avoid many common errors during the construction. In addition, it is easier to apply detection tools in contracts written by functional languages. Accordingly, the authors propose a Idris [214] library (Idris is a functional programming language), taking advantage of its dependent type. They further design a compiler from Idris to Serpent, to illustrate the feasibility of their conclusion.

In addition to functional programming languages, some researchers have proposed several domain specific languages to improve the security of contracts under specific scenarios. Findel [145] is a language for financial contracts. By separating the contract description and execution methods, financial contract developers can just pay attention to the contents of the contract itself, without concerning about how the contracts are executed. The authors argue that Findel can be used in common financial derivatives, and they conduct a test of this language on Ethereum.

Based on the formalization of the syntax and semantics in Solidity, Lolisa [146] is a language aimed at making the contract more suitable for security analysis. Lolisa and Solidity could be converted into each other with proper compilers.

### Table VI

**Auxiliary Tools for Smart Contract Construction**

| Ref. | Year | Type | Main contributions | Open-sourced* |
|------|------|------|--------------------|--------------|
| 135  | 2016 | Framework | Hawk framework for writing & compiling privacy-preserving smart contracts. | x |
| 136  | 2018 | Framework | ZoKrates framework for writing & executing off-chain contracts. | ✓ |
| 137  | 2016 | Framework | A framework for verifying smart contracts by translating both Solidity and EVM bytecode to E*. | x |
| 138  | 2018 | Framework & High-level language | A quantitative game-theoretic framework for analysis & a corresponding contract programming language. | x |
| 139  | 2018 | Framework | FSolidM framework modeling smart contracts as finite state machines, and a GUI for creating contracts. | ✓ |
| 140  | 2019 | Framework | VeriSolid framework extending FSolidM, supporting specifying and verifying the desired properties of a contract. | ✓ |
| 141  | 2019 | Framework | A framework defining business smart contracts in the state machine model, with a programming called TLA+ [208]. | x |
| 142  | 2019 | Framework | A framework using the Event-B formal modeling for easier verification. | x |
| 143  | 2019 | Framework | Takamaka framework for writing & executing smart contracts in Java. | x |
| 144  | 2016 | High-level language | A functional programming language library for smart contracts. | ✓ |
| 145  | 2017 | High-level language | A domain specific language (DSL) for financial purpose. | ✓ |
| 146  | 2018 | High-level language | A formal definition of the syntax and semantics for a large subset of Solidity, designed for symbolic execution and formal proof of smart contracts. | x |
| 147  | 2018 | High-level language | Flint language for inherently safer contracts. | ✓ |
| 148  | 2019 | High-level language | Featherweight Solidity, a calculus for Solidity, supporting precise definition of the behavior of smart contracts | ✓ |
| 149  | 2018-2019 | IR language | A Intermediate language suitable for formal analysis and verification. | ✓ ✓ |
| 150  | 2017 | Basic tools | A formal definition of EVM in Lem language, which can be combined with multiple theorem provers to verify smart contracts. | ✓ |
| 151  | 2018 | Basic tools | An extension of [151] with a sound programe logic at the bytecode level. | ✓ |
| 152  | 2018 | Basic tools | A semantic framework of EVM bytecode and its formalization in Z. | ✓ |
| 153  | 2018 | Basic tools | A formal definition of EVM using Z framework, which can be combined with multiple theorem provers to verify smart contracts. | ✓ |

* ✓ (resp. x) here represents that the corresponding tool is open-sourced (resp. not). When there are multiple references in the same line, there will be multiple ✓ or x in the same order.
Moreover, it is more convenient to do symbolic execution on contracts written in Lolita. It comes with an interpreter that converts it to Coq\textsuperscript{[192]}, a specially designed language for semantic verification. Taking Lolita as the intermediary, the security of smart contracts in Solidity can be easily analyzed. Based on a similar idea, Crafa et al.\textsuperscript{[148]} define the formal semantics in the core of Solidity, and propose a high-level language named Featherweight Solidity. The behavior of the Solidity contract could be accurately defined with it. In this way, analysis tools can directly analyze contracts in Solidity without converting them into EVM bytecode. In addition, the analysis results show that there are defects in the type system of Solidity, i.e., runtime type errors are unavoidable in current systems. Further suggestions are provided in\textsuperscript{[146]}.

Apart from the semantic abstraction and definition of the original language, other studies focus on the design of intermediate languages (IR) that are useful in the process of contract compilation and verification. Sergey et al.\textsuperscript{[149],[150]} point out that most high-level languages sacrifice verifiability in order to improve their expressivity. In other words, the security verification on contracts in these languages is more complex than those in low-level languages (e.g., bytecode). To address this problem, they propose an intermediate language SCILLA. High-level languages can be compiled into SCILLA for security analysis, before being further compiled into EVM bytecode. It is designed based on the automaton model, and it separates the modules of communication, calculation, and state transition. Such modulation enables the analysis tool to work in a focused manner. The contract compiled into SCILLA will be further converted into the Coq\textsuperscript{[192]}, so as to utilize the powerful analysis function of Coq. However, the scheme has not yet been fully realized.

Adding security mechanisms to the original programming language also helps to avoid potential security issues, since Solidity only focuses on the expressivity and completeness aspects, but does not consider the convenience for security analysis. Schrans et al.\textsuperscript{[147]} propose a high-level language Flint, which: 1) adds a permission mechanism to limit undesirable function calls; 2) optimizes the fund-related operations to ensure safe transfer; 3) introduces an unmodifiable property to limit the modification of key states; 4) uses the same ABI as Solidity to ensure that contracts written in these two languages can interact with each other. The above features reduce the difficulty of designing contracts and the corresponding analysis tools. The authors also provide an analysis tool that performs syntax analysis on Flint contracts, and a compiler that compiles the contract into EVM bytecode.

c) Basic tools: Basic tools refer to some basic theories that are used to develop higher-level tools (e.g., security analysis tools, high-level languages, frameworks). Such research usually involves the formal definition of the underlying infrastructure (virtual machine, bytecode, etc.).

Some studies adopt different tools to formally define the EVM. Such formal definitions are the key to designing contract analysis tools. Hirai\textsuperscript{[151]} gives a formal definition of EVM in the Lém language that can be combined with analysis tools (or framework), such as Coq\textsuperscript{[192]}, Isabelle/HOL\textsuperscript{[215]}, to check the property of EVM. The author further proves some security properties of EVM with Isabelle/HOL. Amani et al.\textsuperscript{[152]} extend Hirai’s work, and propose the sound program logic for EVM, so that the correctness of a smart contract can be verified with Isabelle/HOL. They also prove the correctness of their program logic in their work. After\textsuperscript{[151]}, Hildenbrandt et al.\textsuperscript{[153]} propose KEVM, another formal definition of EVM under the \textsuperscript{12} framework\textsuperscript{[216]}. KEVM is unambiguous, readable and executable, which can be used as a theoretical foundation for formal analysis of smart contracts. As an example, the authors briefly describe a KEVM-based gas analysis tool and a DSL for analyzing the ABI of smart contracts. Further, with specially designed interpreters, KEVM passes the official test suite\textsuperscript{[217]} provided by Ethereum community. The results show that KEVM is more efficient than the EVM defined in\textsuperscript{[151]}, and can detect more types of vulnerabilities.

There are also studies formally defining EVM bytecode, which contribute to designing high-level languages and analysis tools. Grishchenko et al.\textsuperscript{[90]} argue that the semantics in the Ethereum Yellow Paper\textsuperscript{[3]} are incomplete and do not follow the standard rules of definition. They for the first time give the definition of the small-step semantics of EVM bytecode. They use the same \textsuperscript{F}\textsuperscript{⋆} language as the preceding work\textsuperscript{[89]}, and their complete semantic framework of EVM serves as the theoretic foundation of \textsuperscript{F}\textsuperscript{⋆}-based analysis tools.

VI. Executing Smart Contracts

In 2017, Buterin\textsuperscript{[218]} made a speech on the design challenges of blockchain and smart contract mechanism, focusing on the security and application aspects. In this section, we list and group the studies on execution mechanisms of smart contracts, most of which aiming at improving the privacy and performance. Before we introduce these studies, we first summarize the deficiencies on existing contract execution mechanisms in the following, taking Bitcoin and Ethereum as representatives. We remark that these deficiencies mainly occur in the public blockchains (Definition\textsuperscript{[1]}), while if these issues are handled properly, both public and consortium blockchains will be benefited.

1) Forced disclosure of smart contract contents. Although pseudonyms are used in most blockchain systems to protect users’ privacy, due to the inherent execution mechanisms of blockchains, the contents of smart contracts are still forced to be disclosed in public, so that miners can execute the contracts and all nodes can agree on the final states. To fully guarantee the anonymity, some blockchain systems even directly remove the smart contract functionality, e.g., Zerocash\textsuperscript{[219]}. But this is not an ideal strategy, since smart contracts are quite attractive for several application scenarios, if the privacy concerns are eliminated.

2) Low processing rate. In most blockchains, a transaction must be verified, executed and packaged by all miners before taking effect. But this duplicated and resource-consuming strategy puts huge limitations on the processing rate. Technically, the processing rate is subject to basic parameters of a blockchain such as block size and time interval between blocks. Although it is not difficult
to modify these parameters, new problems may arise afterwards. For example, a bigger block size would consume more space for storage, and a smaller interval may result in frequent and undesirable forks. Therefore, existing smart contract platforms are not suitable for applications with high demands on the processing rate.

3) **Limited contract complexity.** To ensure the liveness (Definition 4) of a blockchain, some mechanisms to prevent DoS attacks are introduced. For instance, Bitcoin only supports a limited set of operations, which essentially prevents the occurrence of endless loops. As for Ethereum, which supports Turing-complete language, introduces the gas mechanism that limits the number of instructions in a single transaction. On the one hand, these protective mechanisms guarantee the liveness, while on the other hand, they also limit the possibility of executing complex smart contracts on-chain. That is, the applications with sophisticated operations and heavy overheads are not applicable in the existing blockchains.

As mentioned in Section IV, script-based blockchains are only suitable for implementations of simple financial-related contracts. Such systems are used more as a public ledger than a smart contract platform in practice. Therefore, most related research focuses on the improvement of Turing-complete blockchains, and we divide them into three categories as follows.

1) **Private contracts with extra tools.** To avoid revealing sensitive information in a contract, auxiliary tools such as zero-knowledge proof (Definition 16), trusted execution environment (Definition 17) are adopted in several studies. These schemes are aimed at solving the forced content disclosure problem mentioned above, and they at the same time may help to mitigate the problems of processing rate and complexity, as we will discuss in Section VI-A.

2) **Off-chain channels.** In these schemes, the executions of contracts are moved off-chain, to avoid the low transaction processing rate and high confirmation delay. Meanwhile, such methods also protect the privacy of contract contents to some extent. We group the existing off-chain schemes into payment channels and state channels in this paper, as we will discuss in Section VI-B.

3) **Extensions on core functionalities.** The core functionalities here refer to the way of processing and executing smart contracts in a blockchain. The improvements on such functionalities usually require a (hard) fork (Definition 6), or even an alternative blockchain would be proposed, either increasing the functionalities a smart contract could achieve, or improving the performance of a blockchain. Among them, some are less relevant to smart contracts, e.g., SegWit, side-chain and Sharding, so they are omitted in this paper.

We summarize the schemes discussed in this section in Table VII according to the classification above. In the “Theory” column, ✓ denotes the scheme has both description and its corresponding security proof, ✓ means the scheme is implemented and open-sourced, ✓ denotes the scheme is implemented but not open-sourced, and ✗ represents that the scheme is not implemented.

## A. Private Contracts with Extra Tools

In most mainstream public blockchains, smart contracts are stored on-chain in a way that everyone can see and validate their contents. In other words, to process a transaction that calls a smart contract, all miners will operate accordingly to the transaction and contract, and finally agree on the execution results. Such a mechanism may cause privacy issues, e.g., a business company may be curious about its competitor’s daily sales and big orders. This will prevent the implementations of some business contracts.

To deal with the privacy issues in smart contracts, some cryptographic schemes or hardware tools are introduced, and we call such solutions as private contracts with extra tools. In the following, we group them into private contracts based on secure multi-party computation (Definition 15), zero-knowledge proof (Definition 16) and trusted execution environment (Definition 17), and discuss them in Section VI-A1, Section VI-A2 and Section VI-A3, respectively.

1) **Secure multi-party computation:** The goal of secure multi-party computation (Def.15) is similar to that of smart contracts, both of which involves multiple parties that do not trust each other, and expects to generate the correct execution results. To some extent, SMPC could be viewed as a special form of smart contracts, apart from the fact that SMPC is almost conducted off-chain. When combined with smart contracts, SMPC could improve the privacy of contract executions, and at the same time alleviate the problems caused by the high latency and low throughput in a blockchain. Related studies focus on the privacy, fairness and correctness of blockchain-based SMPC, as in the following.

Some researchers are dedicated to improving data privacy with the help of SMPC. Enigma [154] is a privacy-preserving computation platform without a trusted third party. It records the hash of key data on-chain to guarantee the integrity, and utilizes SMPC to conduct the private computation. In this way, no one gets any extra information except its own inputs and outputs, according to the privacy property of SMPC.

In SMPC, fairness is another non-negligible problem. Choudhuri et al. [155] regard blockchain as a tamper-resistant public bulletin board that anyone can write on, and they adopt the witness encryption (WE) method to solve the fairness problem in SMPC. According to their scheme, all participants will get their desired outputs, or no one gets them at the end of the protocol.

From another aspect, Sánchez [156] combines SMPC with proof-carrying code [225], and proposes Raziel to guarantee the correctness of smart contract codes and their executions. In Raziel, SMPC is used to guarantee the correctness and privacy of contract executions, and proof-carrying code ensures the correctness and verifiability of the contract codes. In addition,
TABLE VII
EXECUTION SCHEMES OF SMART CONTRACTS

| Classification                                      | References | Scheme Name* | Year | Keywords                                           | Theory† | Realization♣ |
|----------------------------------------------------|------------|--------------|------|----------------------------------------------------|---------|--------------|
| Secure Multi-Party Computation                     | [154]      | Enigma       | 2015 | Blockchain-Based Multi-Party Computations         | ✔       | ✓            |
|                                                   | [155]      | –            | 2017 | Fairness of Multi-Party Computation               | ✔       | ✓            |
|                                                   | [156]      | Raziel       | 2018 | Private Contracts Through Multi-Party Computation | ✔       | X            |
| Zero-Knowledge Proof                               | [6]        | Quorum       | 2016 | Public Contract & Private Contract                | ✓       | ✔            |
|                                                   | [135]      | HiAwk        | 2016 | Integrating zk-SNARK into Contracts               | ✔       | X            |
|                                                   | [136]      | ZoKrates     | 2018 | zk-SNARK Toolkit for Private Contracts             | ✔       | ✔            |
|                                                   | [155]      | –            | 2017 | Multi-Party Computation through TEE              | ✔       | ✔            |
|                                                   | [157]      | –            | 2018 | Contract Privacy in Hyperledger Fabric             | ✔       | ✔            |
|                                                   | [158]      | PDO          | 2018 | Private Data Object                                | ✔       | ✔            |
| Smart Contracts with Auxiliary Tool                | [159]      | Ekiden       | 2019 | General Private Contract on TEE                   | ✔       | ✔            |
|                                                   | [160]      | FASTKITTEN   | 2019 | Complex Contracts on Bitcoin                      | ✔       | ✔            |
|                                                   | [161]      | ELI          | 2019 | Enclave-Ledger Interaction                        | ✔       | ✔            |
|                                                   | [162]      | Teechain     | 2019 | Settlement of Lightning Network                   | ✔       | ✔            |
|                                                   | [163]      | –            | 2015 | Duplex Network (BTC)                               | ✔       | X            |
|                                                   | [17]       | RSMC & HTLC  | 2016 | Lightning Network (BTC)                           | ✔       | ✔            |
|                                                   | [164]      | –            | 2016 | Comparison of Payment Channel Networks (BTC)      | ✔       | X            |
|                                                   | [165] [166] | –, Bolt      | 2016-17 | Anonymous Payment Channel Network (BTC)       | ✔       | X            |
|                                                   | [167]      | Fulgor & Rayo| 2017 | Concurrency of Payment Channel Network (BTC)      | ✔       | ✔            |
|                                                   | [62]       | AMHL         | 2019 | Payment Channel against Wormhole Attacks (BTC)    | ✔       | ✔            |
|                                                   | [168] [169] | –, Sparky    | 2015-2016 | Lightning Network (ETH)       | ✔       | X            |
|                                                   | [170]      | Raiden       | 2017 | Advanced Payment Channel Network (ETH)            | ✔       | ✔            |
|                                                   | [171]      | PERUN        | 2017 | Virtual Payment Channel (ETH)                     | ✔       | ✔            |
|                                                   | [24]       | –            | 2018 | State-Channel for Online Poker                    | ✔       | ✔            |
|                                                   | [172]      | –            | 2018 | General State Channel                             | ✔       | X            |
|                                                   | [173]      | Sprites      | 2017-2019 | Worse-Case Time Optimization                   | ✔       | ✔            |
|                                                   | [174]      | –            | 2019 | Multi-Party Virtual State Channels                | ✔       | X            |
|                                                   | [175]      | –            | 2018 | Conflicts in State Channel                        | ✔       | ✔            |
|                                                   | [176]      | –            | 2018 | Protecting Honest Party                           | ✔       | ✔            |
|                                                   | [177]      | –            | 2019 | State Assertion Channel                           | ✔       | ✔            |
|                                                   | [178]      | PISA         | 2019 | State Channel Outsourcing                         | ✔       | ✔            |
| State Channel Network                              | [179] [180] | Bitcoin covenants | 2016-2017 | Limiting the Spending of UTXOs        | ✔       | X            |
|                                                   | [81] [182] | –            | 2019-2020 | Moving Smart Contracts Cross-Chain             | ✔       | ✔            |
| Extending Opcode on Core Functionalities           | [183]      | PCSCs        | 2018 | Proof-Carrying Smart Contracts                   | ✔       | X            |
|                                                   | [184]      | Arbitrum     | 2018 | One-Step Proof of Execution                       | ✔       | ✔            |
|                                                   | [185]      | YODA         | 2018 | Complex Contracts without Validation              | ✔       | ✔            |
|                                                   | [186]      | ZEUXE        | 2018 | Private Execution of Arbitrary Contract           | ✔       | ✔            |

*: – denotes the proposed scheme is not named in the literature.
†: ✔ denotes the scheme has description and security proof, ✓ means the scheme has description without a security proof.
♣: ✔ denotes the scheme is implemented and open-sourced, ✓ means the scheme is implemented but closed-sourced, X represents the scheme is not implemented.

Raziel also adopts non-interactive zero-knowledge proofs to prevent the proof-of-code from revealing extra information.

Smart contracts in the format of SMPC protocols are more flexible and not constrained by the inherent execution mechanisms of blockchain. These schemes are usually applied on the application layer that does not rely on the execution mechanisms too much, and they only disclose contract contents among the participants, thus protecting the privacy of users. However, such solutions require all participants online to complete the computation protocol, which may be unrealistic in some cases. Moreover, existing SMPC schemes are featured with high computational and communication complexity, which can be new obstacles for smart contracts to be widely adopted. In comparison, the solutions with zero-knowledge proof described below can slightly reduce the overhead of communication.

2) Zero-knowledge proofs: Zero-knowledge proof (Def.16) is a popular and relatively mature cryptographic technique to protect users’ privacy. Several efficient non-interactive solutions are proposed in recent years, which are quite suitable in the context of blockchain and smart contracts. For example, zero-knowledge succinct non-interactive arguments of knowledge (zk-SNARK) [209] [210] is widely used in blockchain, with which the correctness of computation can be verified in a
non-interactive way and fewer resources are required. Related studies mainly focus on improving the transparency of the ZKP adoption in the blockchain, i.e., enable developers to write private contracts even when they do not know the detail of ZKP protocols.

Quorum [6] is a typical example to protect the privacy of contract contents using ZKP. It is derived from Ethereum, while the smart contracts are divided into two types: public and private contracts. The public ones are the same as those in Ethereum, while the private ones interact among contract participants using zk-SNARK, and update corresponding states without revealing extra information, thus avoiding privacy leakage during the contract execution procedures.

Rather than propose an alternative system, there are also some researchers attempting to automatically integrate the ZKP protocol into the Ethereum smart contracts within the design process. Hawk [135] framework is a typical example that applies zk-SNARK. It automatically generates smart contracts and the corresponding protocols that guide the users to protect their legitimate rights and interests during the contract execution. Eberhardt and Tai [136] also present a toolkit named ZoKrates based on zk-SNARK for private contracts. Different from Hawk, the contracts constructed in ZoKrates are mostly executed off-chain. ZoKrates comes with a high-level domain specific language, which is used to describe the off-chain computation. The authors also give a compiler to generate transactions that submit the final results on-chain. Using the specialized language and compiler provided by ZoKrates, developers could easily and implicitly write a private contract without understanding zk-SNARK.

We remark that the schemes mentioned above are irrelevant to the core execution mechanisms of smart contracts (e.g., virtual machine). There are also some schemes that apply ZKP to the underlying mechanisms to protect privacy. We leave such solutions to Section VI-C.

Although the ZKP-based execution schemes effectively hide the contents of smart contracts, they inevitably introduce more time and space overhead, increasing the burden of miners for validating and executing the transactions. Besides, ZKP schemes such as zk-SNARK require a trusted setup, and how to remove such a setup in an efficient way remains a challenge.

To sum up, although ZKP-based private contract schemes avoid the heavy multi-round communication introduced by SMPC, problems in the aspects of efficiency, storage and trusted setup are still suspending. The contract execution schemes based on the trusted execution environment (Definition [17]) increase the efficiency by adding new assumptions on the hardware security, i.e., assuming the reliability of TEE itself, as discussed below.

3) Trusted execution environment: Taking advantage of trusted execution environment (Definition [17]) hardware, such as Intel SGX [276] and ARM TrustZone [227], the privacy of contract contents can also be guaranteed. Relevant studies mainly focus on the practical applications and execution efficiency, as well as weakening the dependence on specific types of TEE.

TEE solves some problems that are difficult for traditional cryptographic schemes, such as privacy and fairness. There are several studies discussing the ways to protect contract contents with TEE. Brandenburger et al. [157] introduce SGX into Hyperledger Fabric, to enable trusted private executions of smart contracts. In their scheme, efficiency is sacrificed to some extent, due to the employment of extra hardware. However, since the efficiency of Hyperledger Fabric has been greatly improved compared with other public blockchains like Ethereum, such loss is acceptable. Almost simultaneously, Bowman et al. [158] propose the so-called private data objects (PDOs), which utilizes TEE to execute contracts and update the state. However, PDO is designed for consortium blockchains, and thus many security threats are excluded from consideration in their work.

Some researchers point out that TEE can also be used to solve the problem of fairness in SMPC. Choudhuri et al. [155] propose a solution to achieve fairness in SMPC that combines TEE with blockchain. However, their scheme only achieves one-time SMPC, that is, each invocation requires a new setup, so it is only suitable for some special contracts, for example, one-time lottery, voting, etc. Enclave-Ledger Interaction (ELI) [161] is a general blockchain-based SMPC solution, which converts the multi-step computation into a protocol involving three parties: a public ledger (i.e., a blockchain), TEE and a host application. The scheme only uses the blockchain as an underlying component, but puts no requirement on the mechanism of blockchain.

To address the privacy and fairness issues in Bitcoin, Teechain [162] is proposed to prevent the malicious behaviors during the establishment and settlement of Bitcoin Lightning Network [17]. In Teechain, TEE serves as the trust root to ensure the legitimate rights and interests of all parties, during the execution of the off-chain payments.

Actually, the introduction of TEE brings in a new security assumption, i.e., assuming the adopted TEE hardware is secure. Some studies try to weaken this assumption to some extent. In Ekiden [159], the executions of transactions are moved into TEE, and the TEE provides the proof of the correct execution. In this way, no one except the participants knows the content of a contract, and each participant only knows the inputs and outputs of the private computation. Since it does not put limitation on the specific types of TEE, Ekiden to some extent avoids trusting a single TEE provider. Besides, Ekiden also manages to optimize the processing rate in TEE. While keeping the contents private, it handles thousands of transactions per second, which is nearly 100 times compared with that in Ethereum.

TEE could also be used to support complex smart contracts that are infeasible otherwise. FASTKITTEN [160] is a typical TEE-based scheme that extends Bitcoin to support arbitrary smart contracts. It focuses on the efficiency of off-chain contract execution. In FASTKITTEN, smart contracts are executed in an operator’s TEE, where the operator works like a miner in a way that it obtains no trust from the others, and it will not learn anything about the contract. To improve the efficiency of validation, check points are introduced. Any one can start from any check point to calculate the final state in the blockchain. In addition, FASTKITTEN adopts the mechanisms of challenge-response and deposit-penalty, where
the former is used to identify malicious behaviors and the latter is used to charge a penalty if someone misbehaves. In this way, rational participants will behave themselves and honest ones can always get their deserved money. FASTKITTEN also describes the process of off-chain transactions, and further provides a formal security proof.

By assuming the reliability of TEE, the efficiency loss of contract executions caused by the complex and heavy cryptographic schemes is avoided. However, this strategy increases the cost of contract executors (or miners), since they have to update their hardware, and validate the proof of correct executions before packaging the transactions. In addition, the assumption of TEE being always secure might not be realistic because there can be bugs and vulnerabilities in the TEE equipment, which will bring in new points of attack. For example, the latest study [228] shows a subsersive attack for SGX. Moreover, in terms of reliability, there are concerns that device providers may insert backdoor into their products.

B. Off-Chain Channels

In order to resist various attacks against blockchain (e.g., DoS attacks), smart contracts inevitably have bottlenecks in transaction processing performance. Therefore, to improve the efficiency, one solution is to execute contracts in off-chain channels, and only release the settling transactions on the blockchain. To some extent, this also hides the contract contents and the details of users’ interactions. We divide the state-of-the-art off-chain schemes into payment and state channels, and we conclude that related research mainly focuses on the security, fairness, efficiency, and feasibility issues. In the following, Section VI-B1 interprets payment channels, and Section VI-B2 discusses the state channels.

1) Payment channels: We have discussed the micropayment channel protocol in Section IV-A3, which derives many advanced payment channel network (PCN) schemes. Most of these schemes are aimed at achieving fair and efficient payments off-chain. In the following, we will introduce PCN schemes in Bitcoin and Ethereum respectively, in Section VI-B1a and Section VI-B1b. The main difference between the two categories is due to the transaction model (Definition 10) and contract language, and the design of PCN schemes in Ethereum is more convenient because of the general-purpose language.

a) Payment channel networks in Bitcoin: Since Bitcoin only supports limited operations in smart contracts, off-chain protocols must be carefully designed. The initial design of micropayment channel only supports one-way payment (see Section IV-A3), that is, a receiver cannot use the same channel to send money back to the sender. For this issue, several solutions for bidirectional channels are proposed, some of which try to realize the functionality of such off-chain payments, while others improve the preceding schemes for privacy or security issues, as is discussed below.

Based on the micropayment channel [13] scheme, Lightning Network [17] is proposed. It is a network composed of many bidirectional payment channels and enables the duplex transfer of funds between two users without a direct channel.

To establish bidirectional channels, revocable sequence maturity contract (RSMC) [17] is introduced. Informally, in RSMC, two parties generate a deposit transaction that collateralizes the funds to a multi-signature address. Then they sign the refund transactions as a refund commitment, which includes an expiration time. The party that broadcasts the refund transaction first is restricted to claim the refund after the expiration time, while the other party cannot immediately get the refund. Thereby, it prevents the deliberate refund operation. Then, the refund commitments are signed and broadcast. Thereafter, both parties update the payment value off-chain. This will involve multiple public and private key pairs and addresses. Each time a new transaction is generated, the two parties have to send the old key pair to the other, which is regarded as an agreement to accept the new transaction and give up the old one. During the update process, if either party broadcasts the old refund commitment, the other can get all the funds that are deposited earlier.

In payment channel networks, there are cases when two users without a direct channel want to make an off-chain payment. In this situation, hashed timelock contract (HTLC) is used. We show a brief description of HTLC in Fig. 11, where there is a path from \( P_1 \) to \( P_4 \) (i.e., \( P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4 \)). To get \( B_x \) from \( P_1 \), \( P_2 \) selects a random number \( r \) and sends its hash value \( H_r = H_{f}(r) \) to \( P_1 \). Next, \( P_1 \) generates a HTLC \( \text{HTLC}_3 \)(\( P_1, P_2, y, x + 2\delta \)), where \( \delta \) is the timelock, and \( \delta \) is the fee that an intermediary charges. Similarly, \( P_2 \) (resp. \( P_3 \)) sends their HTLC to \( P_1 \) (resp. \( P_4 \)), where the lock time decreases. \( P_4 \) uses \( R \) to claim the \( B_x \) in \( \text{HTLC}_2 \), and passes \( r \) to \( P_3 \), and \( P_3 \) is passed through the channel in the same manner.

The Lightning Network is the combination of RSMC and HTLC, and is one of the most popular PCN solutions. It is implemented in many languages, such as C language [229], Scala language [230], etc.

Most steps in the Lightning Network protocols are off-chain and conducted in a fixed way, and only the establishment and settlement is done on-chain. Therefore, the Lightning Network reduces the frequent small transactions on-chain, avoids the transaction delay, and somehow improves the transaction throughput of the blockchain.
Almost simultaneously, Decker and Wattenhofer [163] propose another duplex micropayment channel scheme, which uses a diminishing time lock to prevent the other party from aborting. In Fig. 12(a) [163], we give an illustration of the one-way micropayment channel like that in [13], and in Fig. 12(b) [163], we show the method to update the channel with the reducing time lock. The branch with a smaller time lock can be confirmed earlier in the system, so that the values in the bidirectional channel are updated. With this method, the duplex micropayment channel is shown in Fig. 12(c) [163].

Firstly, both parties set the maximum and minimum value of $t$, additional branches per node $n = 1$, maximum invalidation depth $d = 3$. When the funds in one of the channels in the first line are exhausted, both parties update the channel, reset the initial funds, and decrease the value of $t$ in order, as shown in the second and third lines. Similarly, by connecting channels end by end, such duplex payment channels can also be extended into a PCN.

The above two bidirectional payment channel schemes [17], [163] are compared and analyzed in [164], in terms of on-chain privacy, operational overheads, outsourcing, etc.

From another point of view, the above two PCN schemes can not fully protect users’ privacy. For example, the hash lock in HTLC could be used to track the participants in the same path. Heilman et al. [165] adopt blind signature [231] and realize a fair, anonymous and off-chain exchange of BTC with vouchers issued by an untrusted third-party. This scheme is compatible with both Lightning Network and duplex micropayment channels described above. Green and Miers [166] introduce an opcode OP_BOLT, to achieve the anonymity in three forms of micropayment channels (one-way, bidirectional, and PCN). However, this solution is only applicable to platforms that are born with anonymity (e.g., ZeroCash [219]) or other cryptocurrencies that support coin mixing. Intuitively, both the solutions of [165] and [166] require a soft fork (Definition 7) to take effect.

Some researchers point out that the aforementioned PCN solutions could not handle the concurrency of off-chain payments well, which might cause problems such as transaction blocking or conflicting. Malavolta et al. [167] propose two protocols for the concurrency issues in PCN, namely, Fulgo and Rayo. Fulgo comes with formal provable privacy within the UC model [211], and it is compatible with Bitcoin’s script language. When a conflict occurs, all the conflicting transactions will be cancelled and resent after a certain delay, to prevent the permanent blocking. Rayo is another scheme guaranteeing that at least one of the payments will be completed, yet it to some extent sacrifices privacy compared with Fulgo. They also propose an advanced multi-hop HTLC, which introduces randomness to the time lock and combines ZKP (Definition 16) to avoid privacy leakage of the routing information.

In terms of the fairness in PCN, based on [167]. Malavolta et al. [62] propose a new PCN protocol that’s secure against the wormhole attack, where an adversary that controls multiple intermediaries can exclude the honest nodes in the path, by directly passing the random preimage $r$ to other corrupted nodes. Their solution assigns a random number to each intermediary so that the adversary can no longer conduct the original attack, and thereby honest participants have sufficient incentives to serve as intermediaries. This solution improves the fairness of PCN, and preserves the interests of honest participants. Moreover, the authors provide a formal security proof within the UC model.

b) Payment channel networks in Ethereum: The aforementioned payment channel networks are also useful in Turing-complete blockchains such as Ethereum, and the deployment of PCN in these systems is more convenient. Related research can be divided into studies in the theoretic and application aspects, as discussed in the following.

In the theoretic aspect, Tremback and Hess [168] propose a general model for payment channels, where smart contracts in Turing-complete languages are used (they are called smart conditions in their work). However, the implementation and security proof are not given. The authors also propose a routing protocol that finds suitable path for the payment, but the concept of routing is beyond the scope of our paper, so we omit the description here.

In the application aspect, Peterson [169] implements the Lightning Network on Ethereum with the Solidity language. While Raiden [170] is another advanced version of the Lightning Network that improves the throughput of blockchain system. What’s more, Raiden tries to add more functionalities other than the processing of standard transactions, such as updating variables in smart contracts. However, it is still under development and only supports the standard off-chain payment for now.

Similar to the PCNs mentioned in the previous part, earlier PCN solutions in Ethereum also suffer from the problems of
feasibility and privacy. As pointed out by Dziembowski et al. [171], although such schemes support efficient off-chain payment, they require the intermediaries to be always online, so that they could forward the necessary messages along the path and monitor possible misbehaviors of others. Besides, from the privacy perspective, the intermediaries will know the identities of the sender and receiver, and the amount of transaction. To address these problems, the virtual payment channel PERUN [171] is proposed. It builds a virtual payment channel between two users basing on the established payment channels, as shown in Fig. [3] [171]. In this way, the intermediaries are only involved during the establishment and settlement of the virtual channel. In addition, paper [171] also gives the security proof of the scheme within the UC model, and gives a proof-of-concept implementation on Ethereum.

The virtual payment channel implemented by PERUN is illustrated in Fig. [13] [171]. There is a payment channel between Alice and Ingrid, denoted as $\beta_A$. Similarly, $\beta_B$ represents the payment channel between Bob and Ingrid. There are two corresponding smart contracts $C_A$ and $C_B$ on the blockchain. In $\beta_A$, the amounts deposited by Alice and Ingrid (resp. Bob and Ingrid) are $y_A$ and $y_I$ (resp. $z_B$ and $z_I$), respectively. With $\beta_A$ and $\beta_B$, the virtual payment channel $\gamma$ is created. Alice’s and Ingrid’s deposits in $\beta_A$, $y_A$ and $y_I$, are partially frozen, which goes similarly for $z_B$ and $z_I$ in $\beta_B$.

2) State channels: Inspired by PCN, the updates of variables in smart contracts can also be conducted off-chain, which is the key point of state channel networks [232] [233]. A state channel updates the states in smart contracts according to the predefined functions and algorithms in an off-chain way. Similar to PCN, only the establishing and settling transactions are conducted on-chain. Related research mainly focuses on the generalization, usability, efficiency and privacy of state channel networks.

One typical application of state channel network is the online poker. Bentov et al. [24] design and implement an efficient online poker contract on Ethereum, i.e., secure cash distribution with penalty, which transfers the money from losers to winners as soon as the game is finalized. The authors also give the security proof within the UC model. In fact, the online poker scheme is just a special case of state channel, and this scheme can also be used for bidirectional payment channels and other applications that involve smart contracts.

The online poker scheme mainly implements the ideal multiple sequential cash distribution functionality $F_{\mathcal{MSCD}}$, as rephrased in Fig. [14] [24], where $sid$ and $ssid$ are session identifiers, $P_1, P_2, \ldots, P_n$ are $n$ participants, $A$ is the adversary, whose corrupted nodes are represented as $\{P_i\}_{i \in C}$. $\mathcal{H}$ is the set of honest participants, namely, $\mathcal{H} = \{1, \ldots, n\} \setminus \mathcal{C}$, $h = |\mathcal{H}|$, $d$ is the deposit amount, $q$ is the penalty amount, $b$ is the fund distribution vector, $b_i$ represents the funds that $P_i$ deserves, $m$ is the number of functions, $F_{\text{receive},P}$ (resp. $F_{\text{send},P}$) is the ideal function that receives (resp. sends) messages from (resp. to) $P$, and $F_{\text{broadcast}}$ is the ideal broadcast function. The last field in the messages with header SETUP, ADDMONEY, RETURN, PENALTY, EXTRA and REMAINING is the value of fund.

There are three phases in $F_{\mathcal{MSCD}}$. In the deposit phase, it accepts deposits of value $d$ from honest parties, as well as the penalty of value $hq$ adversary $A$. In the execution phase, each participant takes part in the multi-party functions for several times with input payload $p_i, i \in \{1, \ldots, n\}$. The execution results include the change $Z$ on contract state $S$ and that on fund distribution vector $b$. In this phase, participants can also increase their deposits. When the execution phase is completed, or the adversary $A$ aborts, the participants enter the claim phase. If it is the former case, the honest participant $P_i$ will receive his deposit the fund of value $d$ and his deserved fund recorded in $b_i$; if it is the latter case, the honest participants can further share the adversary’s deposited penalty of value $hq$ and the additional penalty $q_i$ (if any). Finally, $F_{\mathcal{MSCD}}$ returns the remaining funds to $A$.

In addition to online poker, state channels can also facilitate the application of payment channels. Miller et al. [173] specifically describe the model of state channels within the UC framework, and construct an improved payment channel, Sprites, that reduces the worst-case time to settle a transaction. It constructs a global preimage manager $PM$ contract to verify the hash preimage instead of transferring it among participants, as is done in the Lightning Network. The receiver directly submits the preimage of the hash lock to $PM$ for verification, thereby reducing the time cost brought in by the transfer of preimage. Besides, Sprites also supports dynamic deposit and withdraw of fund, which greatly improves the usability of the payment channels. However, it does not take the privacy issues into consideration. The ideal functionality $F_{\text{State}}$ of a state channel given in their work under the UC model is rephrased in Fig. [15] [173]. $F_{\text{State}}$ initializes the variables, and receives auxiliary input messages $m$ from the smart contract $C$, appends it to the stack $\text{buf}$ and $\text{aux}_{\text{in}}$, and sets the pointer $\text{ptr}$. During the $\tau$th round of execution, it receives the payload data $p_{r,i}$ ($i = 1, \ldots, n$) from each $P_i$ within $O(\lambda)$ time, and forwards these messages to the adversary $A$. After receiving all messages, it updates the function $F_{\text{contract}}$ with inputs including: contract state $S$, inputs $p_{r,i}$ ($i = 1, \ldots, n$) and other data in the stack. If there is any non-empty output $o$ in $F_{\text{State}}$, it will be handled according to the output rule $C.output$.

Inspired by the concept of virtual payment channel in
Deposit phase (sid, H):
Upon invocation by any P_j or \( \mathcal{A} \):
- Initialize \( f_{lg} = \perp \).
- For each \( j \in \{1, 2, \cdots, n\}, \) if \( \mathcal{A} \) receives (resp. sends) messages from (resp. to) \( \mathcal{A} \),
  \( F_{\text{receive}, P_j}(\text{SETUP}, sid, ssid, j, d) \) for all \( j \in \mathcal{H} \),
- For each \( j \in \{1, 2, \cdots, n\}, \) \( \mathcal{A} \) receives (resp. sends) messages to (resp. from) \( \mathcal{A} \),
  \( F_{\text{receive}, \mathcal{A}}(\text{SETUP}, sid, ssid, hid, hq) \) where \( h = |H| \).

Execution phase (sid):
Upon invocation by any P_j:
- Initialize \( f_{lg} = 0 \) and \( b = 0 \).
  For id = \( 1, 2, \cdots \), sequentially do:
  1) If \( F_{\text{receive}, P_j}(\text{EXIT}, sid, ssid, side) \),
      \( F_{\text{broadcast}}(\text{EXIT}, sid, ssid, j) \),
      \( b \leftarrow b + 0 \).
    2) If \( F_{\text{receive}, P_j}(\text{ADDMESSAGE}, sid, ssid, [id, b]) \) for each \( k \neq j \),
      \( F_{\text{broadcast}}(\text{ADDMESSAGE}, sid, ssid, [id, b]) \) for each \( k \neq j \),
    3) Initialize state \( S = \perp \).
      \( F_{\text{receive}, P_j}(\text{FUNCTION}, sid, ssid, [id, g^{(id)}]) \) for all \( j \in \mathcal{H} \),
      \( F_{\text{broadcast}}(\text{FUNCTION}, sid, ssid, [id, g^{(id)}]) \) for all \( j \in \mathcal{H} \).
    4) Parse \( g^{(id)} = (g^{[k]}_{id})_{k \in \{1, \cdots, m\}} \). For \( k = 1, \cdots, m \), sequentially do:
      a) If \( F_{\text{receive}, P_j}(\text{INPUT}, sid, ssid, [id, k, j, p]) \) for all \( j \in \mathcal{H} \),
      b) If \( F_{\text{receive}, \mathcal{A}}(\text{INPUT}, sid, ssid, [id, k, j, p]) \) for all \( j \in \mathcal{H} \).
    5) If no such message was received:
      * update \( f_{lg} = 1 \) and go to the claim phase.
        * Compute \( (Z, E, \gamma) = \gamma^{(id)}_{k_1, p_1, \cdots, k_n, p_n} \).
      d) \( F_{\text{send}, \mathcal{A}}(\text{OUTPUT}, sid, ssid, [id, k, \gamma]) \) for all \( P_i \),
    e) If \( F_{\text{receive}, \mathcal{A}}(\text{CONTINUE}, sid, ssid, [id, k, E]) \),
      \( F_{\text{send}, P_j}(\text{OUT}, sid, ssid, [id, k, Z, \gamma]) \) for all \( P_i \),
    f) If \( F_{\text{receive}, \mathcal{A}}(\text{ABORT}, sid, ssid, [id, k, \gamma]) \):
      set \( f_{lg} = 1 \) and go to the claim phase.
      \( g \leftarrow b \).

Claim phase (sid, lg, \( \mathcal{H} \), C):
Upon invocation by any \( P_j \) or \( \mathcal{A} \):
- \( F_{\text{receive}, \mathcal{A}}(\text{EXTRA}, sid, ssid, \{id, q_i\}_{id \in C \subseteq \mathcal{H}}, q_i = 0 \) if not received.
- If \( f_{lg} = 0 \) or \( \perp \), \( F_{\text{send}, \mathcal{A}}(\text{RETURN}, sid, ssid, d + b) \) for all \( i \in \mathcal{H} \).
- If \( f_{lg} = 0 \), \( F_{\text{send}, \mathcal{A}}(\text{RETURN}, sid, ssid, bq + \Sigma_{k \in C} b_k) \).
- If \( f_{lg} = 1 \), \( F_{\text{send}, \mathcal{A}}(\text{PENALTY}, sid, ssid, d + b + q_1 + q_i) \) for all \( i \in \mathcal{H} \),
  \( F_{\text{send}, \mathcal{A}}(\text{REMAINING}, sid, ssid, \Sigma_{k \in C} \gamma_k) \).

PERUN [171], Dziembowski et al. [172] give the definition of general state channel, which supports the off-chain execution of arbitrary smart contracts. Similar to PERUN, a higher-level channel is built upon two existing channels with a common third party. These higher-layer channels are called virtual state channels. The users only need to interact with their common third party, rather than the blockchain, to open and close the higher channel. Conflicts are firstly resolved by this third party, and if it fails, contracts on the blockchain are then invoked. As shown in Fig. [16][172], there are 5 state channels recorded by on-chain smart contracts from \( P_1 \) to \( P_6 \), and \( \gamma_1 \) (resp. \( \gamma_2 \)) is the first-layer virtual state channel between \( P_1 \) and \( P_3 \) (resp. \( P_4 \) and \( P_5 \)). Further, \( \gamma_3 \) is a higher-level virtual state channel, and \( \gamma_4 \) is built upon \( \gamma_3 \) and \( \gamma_2 \). The authors also give the ideal functionality of state channel and virtual state channel within the UC framework, and a formal security proof. At the same time, Coleman et al. [234] propose the Counterfactual framework, which is aimed at building a general state channel that enables the update of arbitrary smart contracts. In their framework, developers no longer have to design specific state channels for their application. However, the scheme lacks formal security proof, and their framework is still under development.

The aforementioned schemes of state channel network in [24], [172], [173], [234] only support 2-party smart contracts. In other words, contracts that involve more parties are not applicable in such state channels. Dziembowski et al. [172] propose a multi-party virtual state channel. It retains the advantages of the virtual state channel [172], that is, a state channel could be opened and closed without interacting with the blockchain (in the best case). Moreover, the process is almost instantaneous and zero-cost. As for the worst case, they reduce the time for conflict resolution from \( O(n\Delta) \) to \( O(\Delta) \), where \( \Delta \) is the maximum time delay for on-chain settlement. When multiple parties are involved, the potential
security threats and conflicts become more complicated. To alleviate this concern, Dziembowski et al. [174] apply the UC framework and give a formal security proof in their work. Intuitively, the multi-party virtual state channel requires that all participants stay in a common state channel network, as shown in Fig. 17 [174], where five parties from $P_1$ to $P_5$ are connected by 4 on-chain channels. $P_1$, $P_3$, $P_4$, and $P_5$ jointly build the multi-party virtual state channel $\gamma$ that excludes $P_2$. The $\text{mpVSCC}$ between them refers to the instance of the multi-party virtual state channel contract. The $x/y$ at the end of each channel indicates the initial/final amount of participants in a contract.

![Fig. 17. An example of multi-party virtual state channel](image)

security proof of their scheme. Moreover, a proof-of-concept implementation based on a simplified version of Sprites [173] is also provided in [178]. Compared with other outsourcing solutions, such as Monitor [235] and WatchTower [236], it only takes $O(1)$ storage space for the third party (which is $O(N)$ in Monitor, where $N$ is the number of transactions generated off-chain), and it directly applies to Ethereum, while WatchTower is not compatible with platforms such as Bitcoin and Ethereum.

C. Extensions on Core Functionalities

Off-chain channels discussed above mainly focus on the off-chain protocols, while retaining the original execution mechanisms of the underlying blockchain. In this section, we discuss several schemes that extend the core functionalities of the smart contract platform. Specifically, Section VI-C1 introduces the extensions on opcodes that adds to the functionalities of smart contracts could achieve; Section VI-C2 introduces the schemes that enhance the security of deployed smart contracts; Section VI-C3 describes the solutions that improve the efficiency and privacy of contract execution.

1) Extension on opcodes: By adding new opcodes, more appealing functionalities could be achieved in smart contracts, making them better meet the needs of daily use.

The covenant in Bitcoin refers to a mode that the future transfer of the fund is restricted according to some user-defined rules. This functionality enriches the application scenario of Bitcoin. From this point of view, Möser et al. [179] extend Bitcoin with an opcode that enables the so-called covenant mode. This makes it possible to track the flow of a specific payment. In addition, it also enables the vault transaction which takes more time to take effect than a standard one. Within this time, the owner possessing the recovery key can invalidate the vault transaction, avoiding the economic loss caused by the private key theft, and enhancing the security of private key. O’Connor and Piekarska [180] propose another opcode that only involves computational operations and leaves out the transaction data, realizing the same functionality as covenant. They also introduce an opcode that realizes the vault mode. Intuitively, both solutions above require a soft fork (Definition 7) on Bitcoin.

There are also demands to move smart contracts across blockchains, to get a better performance (which is relevant to the target platform) or simply as backup. Fynn et al. [181] introduce an opcode $\text{OP\_MOVE}$ in EVM, as well as a corresponding keyword in Solidity, to realize the cross-chain moving of smart contracts. Intuitively, such movement could only be done between two blockchains with same execution environment (i.e., EVM). In fact, Westerkamp [182] has already proposed a similar moving protocol before [181], whose solution does not involve the modification of opcodes, but requires a large gas overhead for the migration.

2) Improvements on security: As mentioned in Section 4, smart contracts are hard to update due to the tamper-resistant nature of blockchain. When a bug or vulnerability is found in a deployed contract, users and developers can do nothing with it to remedy the situation. To mitigate this risk, Dickerson
et al. [133] propose the concept of Proof-Carrying Smart Contracts (PSCCs) based on the idea of Proof-Carrying Codes. Its implementation involves the modification of the underlying consensus and execution mechanism, namely, the blockchain only maintains the key properties of the deployed contracts. The creator firstly uploads some key properties of the contract to the blockchain as a commitment. After that, the miners check that such key features remain unchanged before and after the update operation. In this way, the upgrade of smart contracts could be realized without harming the security of the system.

3) Improvements on efficiency and privacy: With regard to the privacy issues of smart contracts, we have introduced several private contract schemes that utilize zero-knowledge proofs in Section VI-A2. Schemes discussed here also use cryptographic techniques including ZKP. But unlike the prior solutions, the core functionalities of the original execution mechanisms are modified and extended, to support efficient and privacy-preserving executions of contracts, as will be discussed in the following.

To improve the efficiency and privacy during smart contract executions, Arbitrum [184] comes out with a re-designed virtual machine. In Arbitrum, users delegate the off-chain executions of smart contracts to trusted nodes. With the one-step proof delivered by Arbitrum virtual machine, the correctness of the execution is guaranteed. Such a proof only leaks a very small part of privacy, and since the computation is totally off-chain, no extra information of the contract will be leaked. Moreover, the authors claim that with techniques like Bulletproofs [237], zk-SNARKs [209], the leakage of privacy could be further reduced. Arbitrum requires a reasonable incentive and penalty mechanism to ensure the correct execution offered by rational participants. Since not all nodes participate in the execution of a smart contract, the efficiency is also improved.

As mentioned at the beginning of this section, the complexity of smart contracts is limited due to the execution mechanisms (e.g., limiting the gas consumption). For traditional smart contracts, the execution result is easy to verify. However, for the complex contracts, the verification procedure is non-trivial and it consumes a large amount of resources, making it impossible to be performed on-chain. To solve this problem, YODA [185] is proposed to help reach agreement on the execution results of such complex contracts. It introduces a non-deterministic off-chain execution mechanism, with randomly selected nodes and a probability model to determine the execution result. The most prominent feature of YODA is that it eliminates the step of verifying the results on-chain.

To fully protect users’ privacy, Zerocash [219] introduces the zk-SNARK scheme into its underlying execution mechanism, but it gives up the functionality of smart contracts as a consequence. Bowe et al. [136] extend Zerocash and propose ZEXE. It utilizes the technique of 2-layer recursive proof with properly selected cryptographic parameters, to achieve the succinct zero-knowledge proof of arbitrary predicates defined by users. With such recursive proofs, the contents and results of smart contracts can be entirely hidden. The overhead of this solution is comparable to that of Zerocash [219] and Hawk [135]. In addition, the authors further provide the security proof within the UC model.

To improve the efficiency and throughput of blockchains, Poon and Buterin [238] construct a child-chain scheme Plasma, with a series of contracts anchored on Ethereum. Plasma uses the bitmap to map the funds spent to a single bit, reducing the size of a transaction. It further alleviates the problems of transaction congestion and limited throughput on Ethereum. Participants can submit fraud proofs to Ethereum to ensure the correct execution in child-chain. However, such systems focus more on the security of consensus, and less on the execution mechanism of smart contracts. Therefore, such schemes are beyond the scope of this paper. Similar child-chain schemes such as Cosmos [239], Polkadot [240], and side chain schemes like [222], [223] are also out of our scope.

VII. Future Research Directions

Smart contract is still a new and fresh concept, and is attracting more and more researchers and developers into this field. Since smart contracts are usually related to financial affairs, their security requirements and criteria are quite distinct from those on general computer programs, which make the construction of smart contracts a very skill-oriented work. In addition, there are also many problems on existing smart contract platforms such as privacy leakage, execution efficiency, and contract complexity, which have also attracted widespread attention. In this section, we summarize the previous research results and propose the future research directions from the perspective of the construction and execution of smart contracts.

- **Design paradigms for script-based blockchains.** Due to the limitation of the expressivity of script languages and opcodes in script-based blockchains, coupled with the popularity of Turing-complete blockchains, contract construction schemes on script-based blockchains have once faded out from researchers’ perspectives. However, with the emergence and implementation of off-chain channel networks, designing a fair, efficient, and economic off-chain network on script-based blockchains might be a new promising research direction.

- **Design tools for script-based blockchains.** Similar to the previous point, due to the limitation on script languages, there is not much research on the design tools for script-based blockchains. In contrast, design tools for Turing-complete blockchains have grown rapidly in recent years. Some analysis techniques for contracts may be adopted into these script-based blockchains. Moreover, high-level languages for script-based blockchains with formal security proofs may also be a promising research direction.

- **Design paradigms for Turing-complete blockchains.** Smart contracts in Turing-complete blockchains are attracting most institutions and communities, which are devoted to the exploration of best practices and design paradigms. Additionally, some practical cryptographic protocols, such as the distributed key generation protocol (DKG) [241], are migrated to Turing-complete blockchains like Ethereum for the efficient realization
without a trusted third party. Design paradigms for such migrations might be a new research hotspot in the future.

**Design tools for Turing-complete blockchains.** Blockchains with Turing-complete languages support a wide variety of smart contracts. While on the other side, contract vulnerabilities are also emerging. As a result, many contract analysis tools based on various methods have emerged in recent years. Apart from commonly used techniques such as symbolic execution, detection tools based on fuzzing test are expected to become a new main research direction. Besides, high-level languages for Turing-complete blockchains with formal proofs may also become a new research direction.

**Private contract systems.** Many users are very cautious about privacy issues and are thus reluctant to apply smart contracts in their business activities. In recent years, some researchers combine cryptographic solutions such as secure multi-party computation, blind signatures, ring signatures, group signatures, and zero-knowledge proofs to propose private contract execution solutions. However, due to the limitations on the state-of-the-art cryptographic technology, existing solutions still have a large space for improvements in terms of efficiency, storage and others. Therefore, exploring efficient solutions for privacy protection in smart contracts will be a promising research direction as well.

### VIII. Conclusion

In this paper, we have reviewed the studies on smart contracts in the period 2008-2020 from the perspectives of design paradigms, tools and systems. Firstly, we discuss and group the contract construction schemes for two types of contract platforms, i.e., script-based and Turing-complete blockchains. The contract design paradigms and tools in these schemes are designed to lower the technical barriers for smart contract developers and facilitate the design of contracts. Secondly, we summarize the deficiencies of the existing contract execution mechanisms, and then explore and categorize the relevant improvement solutions. Finally, we summarize the future research directions on the aspects of contract construction and execution schemes, aiming at providing insights for new researchers and developers in this field.

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