Transaction Monitoring of Smart Contracts

Margarita Capretto\textsuperscript{1,2}, Martin Ceresa\textsuperscript{1}, and César Sánchez\textsuperscript{1}.

\textsuperscript{1} IMDEA Software Institute, Spain
\textsuperscript{2} Universidad Politécnica de Madrid (UPM), Madrid, Spain

Abstract. Blockchains are modern distributed systems that provide decentralized financial capabilities with trustable guarantees. Smart contracts are programs written in specialized programming languages running on a blockchain and govern how tokens and cryptocurrency are sent and received. Smart contracts can invoke other contracts during the execution of transactions initiated by external users.

Once deployed, smart contracts cannot be modified and their pitfalls can cause malfunctions and losses, for example by attacks from malicious users. Runtime verification is a very appealing technique to improve the reliability of smart contracts. One approach consists of specifying undesired executions (\textit{never claims}) and detecting violations of the specification on the fly. This can be done by extending smart contracts with additional instructions corresponding to monitor specified properties, resulting in an \textit{onchain} monitoring approach.

In this paper, we study transaction monitoring that consists of detecting violations of complete transaction executions and not of individual operations within transactions. Our main contributions are to show that transaction monitoring is not possible in most blockchains and propose different execution mechanisms that would enable transaction monitoring.

1 Introduction

Distributed ledgers (also known as blockchains) were first proposed by Nakamoto in 2009 \cite{nakamoto2009bitcoin} in the implementation of Bitcoin, as a method to eliminate trustable third parties in electronic payment systems. Modern blockchains incorporate smart contracts \cite{almeida2017governance,almeida2017smart}, which are state-full programs stored in the blockchain that describe the functionality of blockchain transactions, including the exchange of cryptocurrency. Smart contracts allow us to describe sophisticated functionality enabling many applications in decentralized finances (DeFi), decentralized governance, Web3, etc.

Smart contracts are written in high-level programming languages for smart contracts, like Solidity \cite{Wood2016} and Ligo \cite{Ligo}, which are then typically compiled into low-level bytecode languages like EVM \cite{EVM} or Michelson \cite{Michelson}. Even though smart contracts are typically small compared to conventional software, writing smart contracts has been proven to be notoriously difficult. Apart from conventional software runtime errors (like underflow and overflow), smart contracts also suffer
from new attack patterns \[17\] or from attacks towards the blockchain infrastructure itself \[18\]. Smart contracts store and transfer money, and are openly exposed to external users directly and through caller smart contracts. Once installed the code of the contract is immutable and the effect of running a contract cannot be reverted (the contract is the law).

There are two classic approaches to achieve software reliability, and there are attempts to apply them to smart contracts:

- **static techniques** using automatic techniques like static analysis \[21\] or model checking \[16\], or deductive software verification techniques \[3,15,8,10\], theorem proving \[7,5,19\] or assisted formal construction of programs \[20\].

- **dynamic verification** \[11,6,13\] attempting to dynamically inspect the execution of a contract against a correctness specification.

In this paper, we follow a dynamic monitoring technique. Monitors are a defensive mechanism where developers write properties that must hold during the execution of the smart contracts. If a monitored property fails the whole transaction is aborted. Otherwise, the execution finishes normally as stipulated by the code of the contract.

Most of the monitoring techniques inject the monitor into the smart contract as additional instructions \[11,6,13\], which is called inline monitoring \[12\]. The property to be monitored for a method of a given contract \(A\) is typically described as two parts: \(A_{\text{begin}}\), that runs at the beginning of each call, and \(A_{\text{end}}\), which is checked at the end. This monitoring code can inspect the storage of contract \(A\) and read and modify specific monitor variables. For example, monitors can compare the balance at the beginning and end of the invocation. However, monitors can only see the contents of \(A\) and cannot inspect or invoke other contracts. We call these monitors *operation monitors* as they allow us to inspect a single operation invocation. In this paper, we study a richer notion of monitoring that can inspect information across the running transaction, illustrated by our running example.

**Running example: Flash Loans** The aim of a flash loan contract is to allow other contracts to borrow balance *without any collateral*, provided that the borrowed money is repaid in the same transaction (perhaps with some interest) \[9\]. A simple way to specify the correctness of a flash loan contract \(A\) is by the following two informal properties:

| Property   | Description                                                                 |
|------------|-----------------------------------------------------------------------------|
| FL-safety  | No transaction can decrease the balance of \(A\)                            |
| FL-progress| A request must be granted unless FL-safety is violated                      |

Fig. 1(a) shows a simple smart contract attempting to implement a flash loan lender. Function \(\text{lend}\) checks that the lender contract has enough tokens to provide the requested loan, saves the initial balance to check that the loan has been repaid completely, and transfers the amount requested to the borrower. Upon return, \(\text{lend}\) checks that the loan has been paid back.

Unfortunately, the lender smart contract in Fig. 1(a) does not fulfill property **FL-progress**. Consider a client, for example Fig. 1(b), that borrows money from different lenders, then invests the borrowed money to obtain a profit and finally
contract Lender {
    function lend(address payable dest, uint amount) public {
        require(amount <= this.balance);
        uint initial_balance = this.balance;
        dest.transfer(amount);
        assert(this.balance >= initial_balance);
    }
}

(a) A flash loan implementation attempt

contract Client {
    Lender l1, l2;
    function borrowAndInvest() public {
        l1.lend(100); l2.lend(200);
        invest(300);
        l1.transfer(100); l2.transfer(200);
    }
}

(b) A flash loan client

contract MaliciousClient {
    Lender l;
    function borrowAndInvest() public {
        l.lend(100);
        invest(100);
    }
}

(c) A malicious flash loan client

Fig. 1. Pseudocode for contracts Lender, Client and MaliciousClient.

pays back to the lenders. In other words, the contract Client in Fig. 1(b) collects all the money upfront before investing it and then pays back the lenders. The contract Client will not successfully borrow from the lender in Fig. 1(a), because contract Lender expects to be paid back within the scope of method lend. However, the contract Client exercises correctly FL-safety and FL-progress, and returns the borrowed tokens before the transaction finishes. The problem is that contract Lender is too defensive and only allows repayments within the control flow of function lend and not in arbitrary points within the enclosing transaction. Alternatively, a lender contract could lend funds with the hope that the client returns the loan before the end of the transaction, but then a malicious contract, like in Fig. 1(c), would violate FL-safety easily. We cannot solve this problem with operation monitors because it is not possible within the scope of lend to successfully predict or guarantee whether the loan will be repaid within the transaction.

In this article, we propose to extend monitors with two additional functions: $A_{init}$, which executes before the first call to $A$ in a given transaction; and $A_{term}$,
contract Lender {
    function lend(address payable dest, uint amount) public {
        require(amount <= this.balance);
        dest.transfer(amount);
    }
} with monitor {
    uint initial_balance;
    init { initial_balance = this.balance; }
    term { assert(this.balance >= initial_balance); }
}

Fig. 2. A correct flash loan implementation using transaction monitors

which executes after the last call to A (equivalently, at the end of the transaction). As for \( A_{begin} \) and \( A_{end} \), \( A_{init} \) and \( A_{term} \) have access to the storage and can fail but cannot be called from other contracts or emit operations. We call these monitors transaction monitors since they can check properties of the whole transaction. With transaction monitors, we implement a lender contract that satisfies FL-safety and FL-progress by saving the balance at the beginning of a transaction in init and comparing it with the final balance in term as shown in Fig. 2.

As for future work, we envision even more sophisticated monitors that guarantee properties that involve two or more contracts—like checking that the combined balance of \( A \) and \( B \) does not decrease—or even that predicing about all contracts participating in a transaction of the whole blockchain. We refer to them as multicontract monitors and global monitors, respectively, but they are out of the scope of this paper, where we focus on transaction monitors. Fig. 3 shows the monitoring hierarchy.

In summary, the contributions of the paper are the following:
− The notion of transaction monitors and its formal definition.
− A proof that current blockchains cannot implement transaction monitors, and a list of simple mechanisms that allow their implementation.
− An exhaustive study of how the proposed mechanisms interact with each other and the basic building blocks to implement full-fledged transaction monitors.

The rest of the paper is organized as follows. Section 2 describes the model of computation. Section 3 studies transaction monitors. Section 4 introduces new execution mechanisms, and in Section 5 we study how these new mechanisms implement transaction monitors. Finally, Section 6 concludes.
2 Model of Computation

We introduce now a general model of computation that captures the evolution of smart contract blockchains.

An Informal Introduction. Blockchains are a public incremental record of the executed transactions. Even though several transactions are packed in “blocks”—which are totally ordered—, transactions within a block are also totally ordered. Therefore, we can interpret blockchains as totally ordered sequences of transactions.

Transactions are in turn composed of a sequence of operations where the initial operation is an invocation from an external user. Each operation invokes a destination contract (where contracts are identified by their unique address). Operations also contain the name of the invoked method, arguments and balance (in the cryptocurrency of the underlying blockchain), and an amount of gas. The execution of an operation follows the instructions of the program (the smart contract) stored in the destination address.

Given the arguments and state of the blockchain, the code of every smart contract is deterministic which makes the blockchain predictable and amenable to validation. We model smart contracts as pure computable functions taking their input arguments and the current local storage of the contract, and returning (1) the changes to be performed in the local storage; (2) a list of further operations to be executed. No effect takes place in their local storage until the end of the operation. This abstraction does not impose any restriction since every imperative program can be split into a collection of basic pure code blocks separated by the instructions with effects.

The execution of a transaction consists of iteratively executing pending operations, computing their effects (including updating the pending operations) until either (1) the queue of pending operations is empty, or (2) some operation fails or the gas is exhausted. In the former case, the transaction commits and all changes are made permanent. In the latter case, the transaction aborts and no effect takes place (except that some gas is consumed).

Model of Computation. We now formally model the state of a blockchain during the execution of the operations forming a transaction. We represent a blockchain configuration as a pair $(\Sigma, \Delta)$ where:

**Blockchain state** $\Sigma$ is a partial map between addresses and the storage and balance of smart contracts,

**Blockchain context** $\Delta$ contains additional information about the blockchain, such as block number, current time, amount of money sent in the transaction, etc.

---

3 The notion of gas is introduced to make all operations terminate because each individual instruction consumes gas and once the initial operation is invoked no more gas can be added to the transaction.
Blockchain contexts may vary since different blockchains carry different information, but either implicitly or explicitly, every blockchain maintains a blockchain state. The computation of a successful transaction begins with an external operation $o$ from a configuration $(\Sigma, \Delta)$ and either aborts or finishes into a final configuration $(\Sigma', \Delta')$.

We model a **smart contract** as a partial map $A : \Delta \times \mathcal{P} \times \mathcal{S} \times \mathcal{O} \rightarrow (\mathcal{S} \times [\mathcal{O}])$ where $\mathcal{P}$ is the set of all possible parameters of $A$, $\mathcal{S}$ the set of all possible storage states, $\mathcal{O}$ the set of operations and $[\cdot]$ is a set operator representing lists of elements of a given set. Smart contracts written in imperative languages with effects can be modeled as sequences of pure blocks where effects happen at the end in the standard way.

**Operations.** An operation is a record containing the following fields:

- `dest` the address to invoke;
- `src` the address initiating the operation;
- `param` parameters expected by the smart contract at address `dest`;
- `money` the amount of crypto-currency sent in the operation.

We use standard object notation to access each field, so $o.dest$ is the destination address, $o.src$ is the source address, $o.param$ the parameters and $o.money$ the amount transferred.

**Transactions.** A transaction results from the execution of a sequence of operations starting from an external operation placed by an external user. If an operation fails the transaction fails and the blockchain state remains unchanged. A successful operation $o$ results in a new storage and a list of new operations $ls$.

The blockchain updates the storage of smart contract $o.dest$ and balance of both smart contracts $o.dest$ and $o.src$ generating a new blockchain configuration and the list $ls$ is added to the current pending queue of operations. Operations are executed one at a time modifying the blockchain configuration until some operation fails or there is no more operations on the pending queue. In the second case, the transaction is successful and the last blockchain configuration consolidates.

We assume there is an implicit partial map from addresses to smart contracts $G : \text{Addr} \rightarrow \text{SmartContract}$. Moreover, we assume map $G$ does not change since we assume that smart contracts cannot install new contracts.

**Operation Execution.** Let $o$ be an operation and $(\Sigma, \Delta)$ a blockchain configuration. The evaluation of $o$ from $(\Sigma, \Delta)$ results in a new configuration and a list of operations $ls$, which we denote $(\Sigma, \Delta) \xrightarrow{o} (\Sigma', \Delta', ls)$ whenever:

1. The source smart contract has enough balance, $\Sigma(o.src) \geq o.money$
2. The invocation to the smart contract is successful:

$$G(o.dest)(\Delta, o.param, \Sigma(o.dst).st, \Sigma(o.dst).balance) = (st', ls)$$

The new blockchain configuration state $\Sigma'$ is the result of: 1) adding $o.money$ into the balance of $o.dest$ and subtracting it from $o.src$, and 2) updating the storage as $\Sigma'(o.dest).st = st'$. Note that we leave the evolution of $\Delta$ unspecified as it
is system dependent. In Section 5, we implement different additional blockchain features by inspecting (and possibly modifying) the blockchain context. For failing evaluation of operations, we use \((\Sigma, \Delta)^o\).

**Execution Order.** The execution can proceed in different ways. We consider two execution orders: new operations are added to the beginning of the pending queue (a DFS strategy) and new operations added to the end of the pending queue (a BFS strategy). This results in the following transition rules:

\[
\frac{(\Sigma, \Delta) \rightarrow (\Sigma', \Delta', l_s)}{(\Sigma, \Delta, o :: os) \not\rightarrow_a (\Sigma', \Delta', l_s)}
\]

\[
\frac{(\Sigma, \Delta) \rightarrow (\Sigma', \Delta', l_s)}{(\Sigma, \Delta, o :: os) \not\rightarrow_b (\Sigma', \Delta', l_s + os)}
\]

The execution starting from an external operation \(o\) is a sequence of steps \((\rightarrow_a)\)—with \(a\) fixed to be either dfs or bfs—until the pending operation list is empty or the execution of the next operation fails. Beginning from a blockchain configuration \((\Sigma, \Delta)\) and an initial operation \(o\), a transaction execution is a sequence of operation executions: \((\Sigma, \Delta, [o]) \rightarrow_a (\Sigma_1, \Delta_1, os_1) \rightarrow_a \ldots \rightarrow_a (\Sigma_n, \Delta_n, [])\) or that \((\Sigma, \Delta, [o]) \rightarrow_a (\Sigma_1, \Delta_1, os_1) \rightarrow_a \ldots \rightarrow_a (\Sigma_n, \Delta_n, os_n) \not\rightarrow_a\).

A transaction can fail either because of gas exhaustion or an internal operation has failed, and in that case, we have a sequence of \(\rightarrow_a\) leading to a final step marked as \(\not\rightarrow_a\) following the failing operation.

Finally, after every successful execution, the blockchain takes the last configuration and upgrades its global system.

The model of computation described in this section does not follow exactly a call-and-return model like the Ethereum blockchain does [23]. However, it is easy to see that it can be simulated in our model by having each contract explicitly keeping its stack of returned values.

## 3 Transaction Monitors and Execution Mechanisms

We now introduce transaction monitors and show that it is not possible to implement them in current blockchains. We present different extensions that allow us to implement transaction monitors.

### 3.1 Transaction Monitors

Transaction monitors allow us to reason about properties of transactions. Each smart contract \(A\) is equipped with a monitor storage and four especial methods \(A_{init}, A_{begin}, A_{end}\) and \(A_{term}\). These new methods cannot emit operations or modify smart contract storage, however, they have their own monitor storage. We assume that these new methods are interpreted by the blockchain and if one of these methods fail the whole transaction fails. Otherwise, the effect in the blockchain is the same as if it was executed without monitors. The functions
$A_{\text{init}}$ and $A_{\text{term}}$ can read the storage and balance of the smart contract and read and write the monitor storage. Function $A_{\text{init}}$ is executed before the first time $A$ is invoked in the transaction and function $A_{\text{term}}$ is invoked after the last interaction to $A$ finished in the transaction, and does not modify the monitor storage. Functions $A_{\text{begin}}$ and $A_{\text{end}}$ are executed at the beginning and at the end of each operation that is executed in $A$, as in operation monitors \[11\] (note that $A_{\text{begin}}$ and $A_{\text{end}}$ can be easily implemented by inlining their code around the methods of $A$). The method $A_{\text{begin}}$ takes the same arguments as any $A$ operation plus the monitor storage, while function $A_{\text{end}}$ has access to the result of the operation (list of the operation emitted and the new storage) plus the monitor storage. We call the resulting smart contracts monitored smart contracts.

**Operation Monitors.** We first extend the model of computation to include operation monitors. A monitored operation execution is a normal operation execution where the corresponding operation monitor is executed before and after the operation is executed.

We define $(\xrightarrow{o_{\text{mon}}})$ modifying $(\xrightarrow{o})$ as follows. Before executing $o$, (1) procedure $G(o.\text{dest}).\text{begin}$ is invoked, then (2) operation $o$ is executed, and (3) finally $G(o.\text{dest}).\text{end}$ runs. That is, operation monitors are simply restricted functions executed before and after each operation. We can then specialize $\xrightarrow{o}$ with operation monitors, that is, use relation $(\xrightarrow{o_{\text{mon}}})$ instead of relation $(\xrightarrow{o})$ to obtain transaction executions that use operation monitors.

Procedures $\text{begin}$ and $\text{end}$ can only modify the private monitor storage and fail, and thus, they cannot interfere in the normal execution of smart contracts (except by failing more often).

**Transaction Monitors.** We redefine transaction monitors execution as a restriction of the transaction execution relation so transactions invoke $\text{init}$ and $\text{term}$ when required. In this case, $\text{init}$ can change the monitor storage, and thus, can modify the blockchain state. We define a new relation $\xrightarrow{a}$ the smallest relation defined by the following inference rules:

\[
\begin{align*}
A_{\text{init}}(\Sigma(A)) &= \Sigma' \\
(\Sigma, \Delta, os) &\xrightarrow{a}(\Sigma', \Delta, os) \\
A_{\text{term}}(\Sigma(A)) &= (\Sigma, \Delta, o :: os) \xrightarrow{a}(\Sigma', \Delta', os') \\
(\Sigma, \Delta, [\]) &\xrightarrow{a}(\Sigma, \Delta, [\])
\end{align*}
\]

Note that we sacrifice a deterministic operational semantics in favor of a clearer set of rules. As before, we use $(\xrightarrow{\times})$ to represent failing transactions.

\[
\begin{align*}
(\Sigma, \Delta) &\xrightarrow{\times} \\
(\Sigma, \Delta, os) &\xrightarrow{\times} \\
A_{\text{init}}(\Sigma(A)) &\xrightarrow{\times} \\
(\Sigma, \Delta, os) &\xrightarrow{\times} \\
A_{\text{term}}(\Sigma(A)) &\xrightarrow{\times} \\
(\Sigma, \Delta, [\]) &\xrightarrow{\times}
\end{align*}
\]

Finally, we define a monitored trace of a transaction same as before, given a blockchain configuration $(\Sigma, \Delta)$ and an external operation $o$:

\[
(\Sigma, \Delta, o) \xrightarrow{a}(\Sigma_1, \Delta_1, os_1) \xrightarrow{a}(\Sigma_2, \Delta_2, os_2) \xrightarrow{a} \ldots \xrightarrow{a}(\Sigma_n, \Delta_n, [\])
\]
To remove the non-determinism we add a new relation that restricts the legal runs. This relation knows the set of visited addresses (smart contracts), and invokes an initialization method, and at the very end of the evaluation of a transaction uses the same set to invoke their corresponding term method.

\[(\Sigma, \Delta, os) \rightarrow^a (\Sigma', \Delta', os') \quad o.\text{dest} \in E\]

\[E \vdash (\Sigma, \Delta, o :: os) \Rightarrow_a E \vdash (\Sigma', \Delta', os')\]

\[(\Sigma'', \Delta, os) \rightarrow^A_a (\Sigma', \Delta', os') \quad o.\text{dest} \notin E\]

\[E \vdash (\Sigma, \Delta, o :: os) \Rightarrow_a E \cup \{o.\text{dest}\} \vdash (\Sigma', \Delta', os')\]

As a result, we only accept traces generated by relation \((\Rightarrow_a)\), beginning with a blockchain configuration \((\Sigma, \Delta)\) and an external operation \(o\) resulting in failure or a new blockchain configuration \((\Sigma', \Delta')\): \(\emptyset \vdash (\Sigma, \Delta, [o]) \Rightarrow_a \ldots \Rightarrow_a \emptyset \vdash (\Sigma', \Delta', []).\)

### 3.2 Transaction Monitors in BFS/DFS

Unfortunately, transaction monitors cannot be implemented in blockchains that follow DFS or BFS evaluation strategies. We show now a counter-example. Consider a transaction monitor for \(A\) that fails when smart contract \(A\) is called exactly once in a transaction. The monitor storage contains a natural number which function \(\text{init}\) sets to 0, \(\text{begin}\) adds one to the counter, \(\text{end}\) does nothing, and \(\text{term}\) fails if the monitor storage is exactly one.

Now let \((\Sigma, \Delta)\) be a blockchain configuration, and let \(A\) and \(B\) be two smart contracts, where \(A\) is being monitored for the “only once” property. Consider the following two executions of external operations from \((\Sigma, \Delta)\):

- \(o_1\) invokes \(B.f\) which then invokes \(o_{A1}\) in \(A\).
- \(o_2\) invokes \(B.g\) which then invokes \(o_{A1}\) and \(o_{A2}\) in \(A\).

The monitor for “only once” must reject the transaction beginning with \(o_1\), but accept the transaction beginning with \(o_2\).

Consider a DFS strategy. Starting from \(o_1\), the execution trace is

\[(\Sigma, \Delta, [o_1]) \Rightarrow_{dfs} (\Sigma_1, \Delta_2, [o_{A1}]) \Rightarrow_{dfs} (\Sigma_2, \Delta_2, as_1)\]

with corresponding sequence of pending operations \([o_1], [o_{A1}], as_1\). Starting from \(o_2\) the sequence of pending operations is \([o_2], [o_{A1}; o_{A2}], as_1 + [o_{A2}], \ldots, [o_{A2}], as_2\). It is not possible to distinguish between the traces generated by \(o_1\) and \(o_2\), as anything that operation \(o_{A1}\) and its descendants \(as_1\) do will happen before the execution of \(o_{A2}\) in the second transaction. In other words, \(o_1\) and all the operations that can be generated by it or its descendants cannot know that some other invocation to \(A\) is pending so \(A\) cannot fail preventively. At the same time
\( o_{A1} \) is the only chance in \( A \) to make the first transaction fails because there is no other operation in \( A \). Therefore, the two runs are identical up to the end of \( o_{A1} \) and one must fail and the other must not fail.

A BFS scheduler can distinguish between the execution of operations \( o_1 \) and \( o_2 \) by using a recurring operation. Since new operations are added to the end of the pending queue, \( A \) can inject an operation that checks \( A \)'s state and conditionally (if the test that would make \( \text{term} \) fail is true) injects itself at the end of the pending queue. If the condition that makes \( \text{term} \) accept is never met, the transaction fails because the recurring operation injects itself ad-infinitum, exhausting gas. In Section 5.1 we use recurring operations thoroughly. However, a simple variation of this example that includes comparing with a third transaction where \( A \) is invoked three times shows that BFS cannot implement “only once” either (as BFS cannot distinguish between the third invocation to \( A \) and a first invocation to \( A \) in a transaction following the one originated by \( o_2 \)). For a detailed proof see Appendix B.

4 Execution Mechanisms

We propose new mechanisms and study if they help to implement transaction monitors. However, adding features to blockchains is potentially dangerous since it can introduce unwanted behaviour[17]. We focus on simple mechanisms that are easy to implement and are backwards compatible.

Since \( A_{\text{begin}} \) and \( A_{\text{end}} \) can already be implemented using inlining, we focus on mechanisms that allow executions at the beginning and end of transactions, which can aid to implement \( A_{\text{init}} \) and \( A_{\text{term}} \). We present two kinds of mechanisms, ones that introduce a new instruction, and others that add a new special method to smart contracts. In the next section, we compare their relative power and if they can implement transaction monitors.

Mechanisms that Add New Instructions. The first four mechanisms add new instructions and can be easily implemented by bakers/miners collecting the information required in the context \( \Delta \).

– First. We consider a new instruction, \( \text{first} \), which returns true if the current operation is the first invocation to the smart contract in the current transaction. The context \( \Delta \) can be extended to contain the set of contracts \( F \) that have already run an operation in the current transaction, which allows us to implement \( \text{first} \) as \( A \notin F \), where \( A \) is the smart contract that executes \( \text{first} \).

– Count. We introduce now a new instruction, \( \text{count} \) that returns how many invocations have been performed to methods of the contract in the current transaction. Again, the context \( \Delta \) can easily count how many times each contract has been invoked.

– Fail/NoFail. This mechanism equips each contract with a new flag \( \text{fail} \) that can be assigned during the execution of the contract (and that is false by default). The semantics is that at the end of the transaction, the whole
transaction would fail if some contract has the `fail` bit to true. For example, the failing bit allows us to implement flash loans as follows. A lender smart contract can set `fail` to true when is lending money and change it to false only when the money is returned.

- **Queue Info.** We add a new operation, `queue`, indicating if there is no more interaction between smart contracts. Or equivalently, if the only operations permitted in the pending queue are recurrent operations (which can only inject operations to the same contract). These operations must also be specially qualified in the contract, and the runtime system must make sure that they only generate operations to the same contract.

### Mechanisms that Add New Methods or Storage

The following mechanisms modify the definition of smart contracts either by adding new methods that are executed at particular moments in a transaction or by adding special storage/memory.

- **Transaction Memory.** Smart contracts are equipped with a special volatile memory segment that exists only during the execution of a transaction and which is created and initialized at the beginning of the transaction. We add a new segment in the smart contract indicating the initial values to be assigned. In concrete, each contract `A` indicates a new storage type for the transaction memory and a procedure that initializes it (which can read but not change the conventional storage). We use `trmem` to refer to this mechanism.

- **Storage Hookup, Bounded and Unbounded.** The idea is to equip smart contracts with a new method that updates the storage after the last local operations in the transaction. These methods can only modify the storage but not invoke other methods. A bounded version of this mechanism is restricted to terminating non-failing functions (for example, by restricting the class of programs). In addition, the unbounded version is arbitrary code that can fail. We use `bstore` and `ustore` to refer to these mechanisms.

### 5 Implementing Transaction Monitors

We say a mechanism `M` implements another mechanism `N` if and only if assuming a blockchain equipped with `M` can write every smart contract that a blockchain equipped with mechanism `N` can write. We say that two mechanisms are equivalent if and only if they can implement each other. We disregard gas consumption here, only considering infinite computations (i.e. we assume that one can always assume sufficient gas).

**Theorem 1.** The following are equivalent: `trmem`, `first`, `count`, and `bstore`.

If contracts can know when their first invocation in the transaction occurs, they can set the storage in different ways simulating `count` and `trmem`. Also, `count` and `trmem` can simulate `first`, by checking if the count is 0 and initializing a volatile bit to `true`. More interesting is that `first` can simulate bounded
storage hookup by applying the effect on the storage of bounded storage hookup at the beginning of the next transaction. Detailed proofs are included in Appendix A.

Lemma 1. Mechanism ustore implements bstore and fail.

Proof. Mechanism ustore implements bstore trivially as it is just less restrictive. For fail we add in the storage of A a new field, fl to represent the failing bit which is initialized to false when the contract is installed and updated to simulate the fail instruction. At the end of the transaction, the ustore hookup checks if fl is true and fail. Otherwise, it does nothing. □

It can be proven that the other direction is not always possible. Fig 4 shows graphically the previous results where an arrow indicates that one mechanism implements another. In this diagram, an absence of an arrow does not necessarily imply impossibility but perhaps that the result depends on the execution order. For example, in BFS blockchains first can implement ustore, but this is impossible with DFS.

Since first, count, bstore and trmem are all equivalent, from now on we only refer to mechanism first. It is easy to see that this mechanism is enough to implement init.

To implement term, we can either implement fail or ustore, where fail is simpler, and ustore is more powerful but requires a bigger change to blockchains.

Theorem 2. Mechanisms first + fail implement transaction monitors.

Proof. Let B be a blockchain that implements first and fail. Given a monitored smart contract A, we want to implement A in blockchain B. We define a new smart contract A' extending its storage to also contains A's monitor storage. Then, we equip A' with a new method f' for every method f in A, such that, f' first checks first and executes Ainit if needed. Then, before exiting, f' executes Aterm with the current state but instead of failing explicitly f' set the failing bit. Function Ainit is executed exactly once and Aterm may be executed multiple times, but it does not modify the contract storage and it does not generate operations. The last execution of Aterm in A' will simulate Aterm in A. If the
semantics of the blockchain were such that the balance of pending outgoing operation would subtract balance from $A$ when it executes, then these calculations can be made in the monitor storage when the operations are generated.

Since $ustore$ implements $first$ and $fail$, it follows that $ustore$ implements transaction monitors.

**Corollary 1.** $ustore$ implements transaction monitors but transaction monitors cannot implement $ustore$.

Transaction monitors can only make contracts fail but not change the storage. Our results are summarized in Fig. 5.

5.1 BFS Blockchains

We now study more in detail the mechanism for BFS based blockchains. The first result is that unless equipped with further mechanisms, BFS blockchains cannot implement transaction monitors. The essence of the proof is to create two transactions on a monitored contract $A$ (like in “only once”) in which corresponding invocations to the same contract $A$ receive identical information, and one must fail and the other commit.

**Theorem 3.** A BFS blockchain does not implement transaction monitors.

A BFS blockchain guarantees that new operations are executed after all pending operations, which enables the implementation of implement $fail$ using recurring operations. A recurring operation is a private function that can read and write the storage and that either terminates or reinjects itself again to the pending queue. Since every time the operation is executed the blockchain consumes gas, and eventually, failure follows from an attempt to inject itself ad-infinitem.

**Lemma 2.** Recurring operations in BFS blockchain allow to implement $fail$.

Since transaction monitors cannot be implemented within a BFS blockchain (see Appendix B), we conclude that $fail$ does not implement transaction monitors in BFS blockchains. The missing element is $first$ which allows to implement $ustore$. And, since $ustore$ implements transaction monitors (Corollary 1), $first$ can also implement transaction monitors.

**Lemma 3.** Mechanism $first$ implements $ustore$ in BFS blockchains.
Proof. Assume a BFS blockchain implementing first. Let A be a smart contract. We modify A to contain a second copy $S'$ of its storage. Upon the first call of A, we update the current storage using the values in $S'$. We add a new private method hookup in A that mimics the code of ustore but (1) it applies the changes in $S'$, and (2) instead of failing (if ustore fails) it calls itself as a recurring operation. Finally, we modify A so that function hookup is invoked at the end of each method in A. In effect, hookup is preventively evaluating ustore on the side memory $S'$, and simulating the failure as a recurring operation (when ustore fails). Therefore, if the operation is the last one on the contract and it does not fail, then $S'$ contains the correct storage, which will then be copied at the beginning of the next transaction. 

In the previous proof, we split mechanism ustore into two parts: one in charge of updating the storage, the other in charge of failing. If we also add queue, we can implement ustore without failing by gas exhaustion because now the hookup executed recurrently can know if there are only recurrent operations and then execute the ustore code (including the failure).

Lemma 4. Mechanism queue implements ustore in BFS blockchains.

In a BFS blockchain, ustore implements transaction monitors (Corollary 1), and thus, by the previous lemma, queue also implements transaction monitors. Next, we will show that queue cannot be implemented with ustore when a BFS strategy is used. Intuitively, mechanism queue adds a way for smart contracts to know the state of the blockchain, i.e. if there is still interaction between smart contracts, and thus, smart contracts can take different actions based on the state of the blockchain, while mechanism ustore adds a way to execute a procedure at the end of transactions, but smart contracts are oblivious about interactions between smart contracts. Since ustore implements all other mechanisms, we have that no other mechanism can implement queue.

Lemma 5. In BFS blockchains ustore cannot implement queue.

The main idea is to create two executions that are identical unless one can inspect the pending operation queue, and in which one operation must fail if queue returns that the queue of pending operations is empty. The complete proof is in Appendix B. Fig 6 summarizes the relations between mechanisms and transaction monitor in BFS blockchains.

5.2 DFS Blockchains

We now study DFS blockchains, that is, when the resulting list of operations from smart contracts execution are appended at the beginning of the list. This is the most conventional execution order in most blockchains, like Ethereum. We now prove several impossibility results.

Mechanisms ustore and first plus fail implement transaction monitors (Corollary 1 and Theorem 2). In a DFS blockchain, those are the only two
ways using our mechanisms to implement transaction monitors. We show that transaction monitors cannot be implemented by combining \texttt{queue} with either \texttt{first} or \texttt{fail}, and as a consequence none of these mechanisms on their own can implement transaction monitors.

**Lemma 6.** A DFS blockchain implementing \texttt{queue} and \texttt{first} does no implement transaction monitors.

**Proof.** Let $B$ be a DFS blockchain and $A$ a smart contract installed in $B$. Consider the “only once” monitor that fails if and only if the smart contract $A$ is called exactly once. We show that this monitor cannot be implemented in DFS even with \texttt{first} and \texttt{queue}.

Let $B, C$ be two other smart contracts. We analyze the pending queue of execution of two possible external operations originated by $B$:

1. $o_1$ where $B$ calls $A$ \textit{once} and then $C$
2. $o_2$ where $B$ calls $A$ \textit{twice} and then $C$

We assume that there are no additional invocations to $A$ aside from the described above. When we execute both operations in a $(\Sigma, \Delta)$ blockchain system, we have the following two traces:

- $t_1 : (\Sigma, \Delta, [o_1]) \rightsquigarrow_{dfs} (\Sigma', \Delta', [a_1, c_1]) \ldots$
- $t_2 : (\Sigma, \Delta, [o_2]) \rightsquigarrow_{dfs} (\Sigma', \Delta', [a_1, a_2, c_1]) \ldots$

Note that the presence of operation $c_1$ in the pending execution queue is forcing mechanism \texttt{queue} to return false. Since the occurrence of operation $a_1$ in both cases execute in the same configuration, the behavior must be the same. The transaction executing $o_1$ must fail because $A$ is called only once, but this will make the second transaction fail as well.

We can conclude that neither \texttt{queue} nor \texttt{first} alone would implement transaction monitors.
Lemma 7. Under DFS queue and fail cannot implement transaction monitors.

The main difference between these mechanisms and transaction monitors is that the latter can execute functions without a contract being invoked at particular moments in the execution of transactions. Take for example procedure init, neither queue nor fail can simulate init, as there is no way for these mechanisms to distinguish the first execution of a smart contract in a given transaction.

Combining fail with first one can implement transaction monitors in any execution order, including DFS (Theorem 2), but fail is not enough to implement transaction monitors in DFS. Therefore, we conclude that DFS blockchains do not implement first. Moreover, putting all previous lemmas together, we conclude that a DFS blockchains cannot implement any of the mechanisms listed in Section 4 directly.

Corollary 2. DFS blockchains cannot implement first, fail, usstore or queue.

All proofs are in Appendix C.

6 Conclusion and Future Work

We have studied transaction monitors for smart contracts. Transaction monitors are a defense mechanism enabling smart contracts to explicitly state wanted or unwanted behaviour at the transactional level. This kind of properties are motivated by contracts like flash loans, which are not implementable in their full generality in current blockchains. We propose a solution based on adding new mechanisms to the blockchain. Transaction monitors can be incorporated directly into contracts or simulated if some of these mechanisms are implemented. This could be preferable since some of these mechanisms are very simple and backward compatible, while others extend the functionality of smart contracts. We have studied how some mechanisms simulate each other, both for any execution order, and specifically for BFS and DFS blockchains. The conclusion is that the simplest mechanism that allows us to implement transaction monitors is the combination of first and fail.

For simplicity, we have neglected a specific analysis of gas consumption, except for recurrent operations that purposefully fail by exhausting gas. Even though transaction monitors will consume additional gas which can influence the failure of the transaction (as with operation monitors), we claim that for all our development there is an amount of gas that can be calculated which will not make accepting transactions fail. However, we leave a detailed study for future work.

Other avenues of future work include the study of new features, particularly views that allows contracts to inspect the state of other contracts. We are also performing a thorough study of how exposing new mechanisms to contracts—that can use them for implementing functionality—can break (or not) implementations of monitors that are correct without adding the mechanisms.
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A  Mechanisms Equivalence

Lemma 8. Mechanisms first and count are equivalent.

Proof. Assume count. we implement first by checking that its value is 0.

Assume first. For each smart contract A installed in the blockchain, we extend the storage of A with a natural variable \( A_{count} \), and we replace each method in A with a new one where we first check first: if it is true set \( A_{count} = 1 \), if it not, add one to \( A_{count} \).

Lemma 9. Mechanisms first and trmem are equivalent.

Proof. Assume trmem. For each smart contract A installed in the blockchain, we define a new volatile boolean value \( b_{init} \). The variable \( b_{init} \) is initialized to true and set to false at the end of every method in A. Therefore, the value \( b_{init} \) is true only at the first interaction with A and false afterward.

Assume first, let B be a smart contract and TM be the volatile memory segment of B. Extend B storage with TM, a copy of TM. At every method in B, we check first, if it is true we initialize TM in the same way as the procedure from trmem.

Lemma 10. Mechanisms first and bstore are equivalent.

Proof. Assume first. Let A be a smart contract defining a hook up function updating the storage of A. We expand the storage of A with a copy of the storage, \( s_{hookup} \). Moreover, at the end of every method in A, we apply hook up with the current storage and store its result at \( s_{hookup} \). Since function hook up cannot fail, it does not matter if it is executed at the end of a transaction or at the very beginning of the next one. Finally, we can check with first and update the storage with the value stored in \( s_{hookup} \).

Note that if the contract A is never invoked again the last change will not happen. However, from the point of view of A, it is equivalent.

Assume bstore, and let B be a smart contract. Extend B storage with a boolean field \( b_{fst} \) to represent first, such that it is initialized to true, each invocation set it to false and bstore set it back to true.
B Impossibility of Monitorability in BFS

Theorem 3. A BFS blockchain does not implement transaction monitors.

Proof. Consider a transaction monitor for $A$ that fails smart contract $A$ is called exactly once in a transaction. The monitor storage contains natural number, function $init$ sets the monitor storage to 0, $begin$ adds one to the counter, $end$ does nothing, and $term$ fails if the monitor storage is exactly one.

Now, let $(\Sigma, \Delta)$ be a blockchain configuration, and let $A$ and $B$ be two smart contracts, where $A$ is being monitored for the “only once” property. Consider the following family of executions of external operations originated by $B$:

- operation $o$ where $B$ calls $A$ once,
- operation $o_k$ where $B$ calls to method $f$ at smart contract $B$ with parameter $k$ and also calls $A$. The method $f$ calls itself recursively $k$ times and then it will call $A$.

When we execute previous operations in $(\Sigma, \Delta)$, we have the following traces:

- $t : (\Sigma, \Delta, [o]) \rightsquigarrow_{bfs} (\Sigma_1, \Delta_1, [a_1]) \ldots$
- $t_0 : (\Sigma, \Delta, [a_0]) \rightsquigarrow_{bfs} (\Sigma_1, \Delta_1, [b_0, a_1]) \rightsquigarrow_{bfs} (\Sigma_2, \Delta_2, [a_1, a_2]) \rightsquigarrow_{bfs} (\Sigma_3, \Delta_3, [a_2] + as_1) \rightsquigarrow_{bfs} (\Sigma_4, \Delta_4, as_1 + as_2) \ldots$
- $t_1 : (\Sigma, \Delta, [a_1]) \rightsquigarrow_{bfs} (\Sigma_1, \Delta_1, [b_1, a_1]) \rightsquigarrow_{bfs} (\Sigma_2, \Delta_2, [a_1, b'_1]) \rightsquigarrow_{bfs} (\Sigma_3, \Delta_3, [b'_1] + as_1) \rightsquigarrow_{bfs} (\Sigma_4, \Delta_4, as_1 + [a_2]) \ldots$

Monitor “only once” rejects transaction $t$, but accepts transactions $t_k$, for all $k \geq 0$. Notice that $a_1$ is executed in the same blockchain configuration in all transactions, therefore it must behave the same in all cases. The execution of $a_1$ in $t$ has three options:

1. do nothing/modify the storage,
2. fail,
3. generate a new invocation to $A$.

In the first case $t$ will not satisfy the property “only once” as the transaction will not fail since $A$ never regains the control. On the other hand, in the second case all transactions $t_k$ will violate the monitor as all of them will fail while executing $a_1$. Therefore, $a_1$ must generate a new invocation to $A$, $op_a$. When $op_a$ executes it will have the same options as $a_1$, and by making a similar analysis as before, we can conclude that it must also generate a new invocation. The only difference with $a_1$ is in the transaction $t_0$ where $a_2$ has already executed and therefore $op_a$ can do nothing. By repeating this argument, we have that the operation generated by $a_1$ must be a recurring operation (see Section 5.1) that keeps invoking itself until another method of $A$ is invoked. If no other method of $A$ is invoked in the same transaction, the recurring operation will fail by gas exhaustion. This will work correctly for transactions $t$ and $t_k$ with $k \geq 0$. However, this will not work for all transactions. Let’s consider a transaction
similar to \( t_0 \) where \( A \) is invoked three times. It is originated by an operation \( o'_0 \) where \( B \) calls to method \( f \) at smart contract \( B \) with parameter 0, then calls \( A \) and finally calls method \( f \) with parameter 0 again. When we execute \( o'_0 \) in \((\Sigma, \Delta)\), we have the following trace:

\[
\begin{align*}
\bullet \quad & t'_0 : (\Sigma, \Delta, [o_0]) \sim_{bfs} (\Sigma_1, \Delta_1, [b_0, a_1, b_0]) \sim_{bfs} (\Sigma_2, \Delta_2, [a_1, b_0, a_2]) \sim_{bfs} \\
& (\Sigma_3, \Delta_3, [b_0, a_2] \; \# \; as_1) \sim_{bfs} (\Sigma_4, \Delta_4, [a_2] \; \# \; as_1 \; \# \; [a_3]) \ldots
\end{align*}
\]

Notice that the third invocation of \( A \) originated by \( B \) will execute after the recurring operation generated by \( a_1 \) stops.\(^4\) So, if we compare it with the case where \( t \) is executed after \( t_0 \) we have that \( a_3 \) and \( a_1 \) will execute in the same state. Therefore, they must have the same behaviour. As explained before, when \( a_1 \) executes it must call the recurring operation. However, \( a_3 \) is the last invocation of \( A \) in \( t'_0 \), then its recurring operation will keep calling itself until it fails by gas exhaustion, violating the property of monitor only once. \( \square \)

**Lemma 5.** In BFS ustore cannot implement queue.

**Proof.** Assume a BFS blockchain that implements queue. Let \( A \) be a smart contract that fails if and only if queue is false. Let \((\Sigma, \Delta)\) be a blockchain system, and consider the following two executions of external operations in \((\Sigma, \Delta)\):

- operation \( o_1 \) calls \( B.f \) which then generates two operations: \( o_{A1} \) to \( A \) and \( o_{C1} \) a call to \( C \) which does not generate any new operation.
- operation \( o_2 \), which calls \( B.g \) which in turn generates \( o_{A1} \), a call to \( A \).

Clearly, \( A \) will fail in the execution of \( o_1 \) but not on \( o_2 \). In both cases the execution \( o_{A1} \) will run in the same blockchain configuration and with same parameter and without queue it is not possible for \( A \) to know that there are pending operations as they will execute in another smart contract. Therefore, \( o_{A1} \) will behave exactly the same in both transactions. As this is the only operation in \( A \) in both transactions, the hookup method from the ustore will also have the same behaviour in both cases. As consequence, either both transactions fail (making the transaction generated by \( o_2 \) fail incorrectly) or none (making the transaction generated by \( o_1 \) succeed incorrectly). Therefore, the smart contract \( A \) cannot be implemented in a BFS blockchain equipped with ustore but without queue. \( \square \)

\(^4\) if the recurring operation does not stop immediately after it see that other method in \( A \) was invoked it must still stop after a finite number of steps and therefore we can still create a transaction where the third invocation to \( A \) executes after it stops.
Lemma 7. Under DFS queue and fail cannot implement transaction monitors.

Proof. Consider a transaction monitor for $A$ that fails smart contract $A$ is called exactly once in a transaction. The monitor storage contains natural number, function $\text{init}$ sets the monitor storage to 0, $\text{begin}$ adds one to the counter, $\text{end}$ does nothing, and $\text{term}$ fails if the monitor storage is exactly one.

Now, let $(\Sigma, \Delta)$ be a blockchain configuration, and let $A$, $B$ and $C$ be three smart contracts, where $A$ is being monitored for the “only once” property. We analyze the pending queue of execution of two possible external operations originated by $B$:

1. $o_1$ where $B$ calls $A$ once and then $C$
2. $o_2$ where $B$ calls $A$ twice and then $C$

We assume that there are no additional invocations to $A$ aside from the described above. When we execute both operations in a $(\Sigma, \Delta)$ blockchain configuration, we have the following two traces:

- $t_1: (\Sigma, \Delta, [o_1]) \rightsquigarrow_{dfs} (\Sigma', \Delta', [a_1, c_1]) \ldots$
- $t_2: (\Sigma, \Delta, [o_2]) \rightsquigarrow_{dfs} (\Sigma', \Delta', [a_2, a_3, c_1]) \ldots$

Note that the presence of operation $c_1$ in the pending execution queue is forcing the mechanism queue info to return false. Operations $a_1$ and $a_2$ are exactly the same operation invoking smart contract $A$. Since operations $o_1$ and $o_2$ execute on the same blockchain configuration, i.e. $(\Sigma, \Delta)$, the result of executing $a_1$ and $a_2$ should be same on $A$.

The transaction executing $o_1$ must fail because $A$ is called only once. Then, this execution of $A$ must fail, and thus, $a_1$ should fail directly, set the failing bit to true, or call another operation that will fail later.

The transaction executing $o_2$ should not fail. Therefore, $a_1$ cannot fail directly, and thus, it must either set the failing bit to true or call another operation, $a_4$. In the latter case, since the scheduler strategy is DFS, operation $a_4$ replaces $a_1$ as the head of the pending execution queue in both cases. Moreover, every operation resulting from the execution of operation $a_4$ is going to be appended to the head of the pending execution queue.

- $t_1: (\Sigma, \Delta, [o_1]) \rightsquigarrow_{dfs} (\Sigma', \Delta', [a_1, c_1]) \rightsquigarrow_{dfs} (\Sigma'', \Delta'', [a_4, c_1]) \ldots$
- $t_2: (\Sigma, \Delta, [o_2]) \rightsquigarrow_{dfs} (\Sigma', \Delta', [a_2, a_3, c_1]) \rightsquigarrow_{dfs} (\Sigma'', \Delta'', [a_4, a_3, c_1]) \ldots$

If operations $a_1, a_4$ or any of its decedents explicitly fail, then the execution of operation $o_2$ is doomed to fail too.

However, if none of these operations, $a_1, a_4, \ldots$, fail then the first run will finish without failing, violating the property of monitor only once.
Therefore, \( a_1 \) or any of its decedents must set the failing bit to true. This will work correctly for the execution of operation \( o_1 \). In order for this to also work for the execution of operation \( o_2 \) it is enough if \( a_3 \) sets the failing to false. However, if we consider the transaction that begins with two external operations \([o_2; o_1]\) and the execution of the transaction \( t_2 \) followed by \( t_1 \). We have that \( o_1 \) will run in both cases in the same blockchain configuration, and therefore it will have the same behaviour in both cases. As explained before, when \( a_1 \) executes it or one of its descendants must set the failing bit to true. This implies that the execution originated by \([o_2; o_1]\) will finish with \( A \)'s failing bit set to true and thus the whole transaction will fail, violating the property of monitor only once. \( \square \)

**Lemma 11.** A DFS blockchain does not implement \texttt{queue}.

*Proof.* Let \( B \) be a DFS blockchain and \( A \) a smart contract installed in \( B \) that fails if and only if \texttt{queue} is false. Let \((\Sigma, \Delta)\) be a blockchain system, and consider the following two executions of external operations in \((\Sigma, \Delta)\):

- operation \( o_1 \) calls \( B.f \) which then generates two operations: \( o_{A1} \) to \( A \) and \( o_{C1} \) a call to \( C \) which does not generate any new operation.
- operation \( o_2 \), which calls \( B.g \) which in turn generates \( o_{A1} \), a call to \( A \).

Clearly, \( A \) will fail in the execution of \( o_1 \) but not on \( o_2 \). In both cases the execution \( o_{A1} \) will run in the same blockchain configuration and with same parameter and without \texttt{queue} it is not possible for \( A \) to know that there are pending operations as they will execute in another smart contract. Therefore, \( o_{A1} \) will behave exactly the same in both transactions. As consequence, either both transactions fail (making the transaction generated by \( o_2 \) fail incorrectly) or none (making the transaction generated by \( o_1 \) succeed incorrectly). Therefore, the smart contract \( A \) cannot be implemented in a DFS blockchain without \texttt{queue}. \( \square \)


```solidity
contract Lender {
    uint initial_balance;
    function lend(address payable dest, uint amount) public {
        require(amount <= this.balance);
        dest.transfer(amount);
    }
    function check_balance() private {
        if(this.balance < initial_balance){
            this.fail = true;
        } else {
            this.fail = false;
        }
    }
}
```

Listing 1.1. A correct Flash Loan implementation using U. Storage Hookup

```solidity
contract Lender {
    uint initial_balance;
    function lend(address payable dest, uint amount) public {
        require(amount <= this.balance);
        dest.transfer(amount);
        check_balance();
    }
    receive() external payable {
        check_balance();
    }
    function check_balance() private {
        if(this.balance < initial_balance){
            this.fail = true;
        } else {
            this.fail = false;
        }
    }
}
```

Listing 1.2. A correct Flash Loan implementation using First + Fail/NoFail Hookup

D Implementations of Flash Loan
contract Lender {
  uint initial_balance;
  function lend(address payable dest, uint amount) public {
    if(this.first){
      initial_balance = this.balance;
    }
    return [system.gen_op(dest, (), amount), system.
      gen_op(this.check_balance, (), 0)];
  }
  receive() external payable {
    return [system.gen_op(this.check_balance, (), 0)];
  }
  function check_balance() private {
    if(this.balance < initial_balance){
      return [system.gen_op(this.check_balance, (), 0)];
    }
    return [];
  }
}

Listing 1.3. A correct Flash Loan implementation using BFS Scheduler and First. Each function returns the list of generated operations.

class Lender {
  function lend(address payable dest, uint amount) public {
    require(amount <= this.balance);
    dest.transfer(amount);
    check_balance();
  }
  receive() external payable {
    check_balance();
  }
  function check_balance() private {
    if(system.queue) {
      assert(this.balance >= initial_balance);
      initial_balance = this.balance;
    } else {
      check_balance();
    }
  }
}

Listing 1.4. A correct Flash Loan implementation using BFS + Queue Info