GasChecker: Scalable Analysis for Discovering Gas-Inefficient Smart Contracts

Ting Chen, Youzheng Feng, Zihao Li, Hao Zhou, Xiapu Luo†, Xiaqi Li, Xiuzhuo Xiao, Jiachi Chen, and Xiaosong Zhang

Abstract—Ethereum, the largest blockchain for running smart contracts, charges the people who send transactions to deploy or invoke smart contracts for thwarting resource abuse. The amount of transaction fee depends on the size of that contract and the operations executed by that contract. Consequently, smart contracts with inefficient code will waste money. In this paper, we propose and develop the first tool, named GasChecker, for automatically identifying gas-inefficient code in smart contracts, and conduct the first empirical study on the prevalence of gas-inefficient code in the deployed smart contracts. More precisely, we first summarize ten gas-inefficient programming patterns and propose a new approach based on symbolic execution (SE) to detect them in the bytecode of smart contracts. To make our approach scalable to analyze millions of smart contracts, we parallelize SE by tailoring it to the MapReduce programming model, and propose a new feedback-based load balancing strategy to effectively utilize cloud resources. Extensive experiments show that GasChecker scales well with the increase of workers. The empirical study demonstrates that lots of real smart contracts contain various inefficient code. Manual investigation demonstrates that only 2.5% of discovered gas-inefficient instances are false positives.

Index Terms—Smart contract, scalable analysis, gas-inefficient pattern, symbolic execution, parallelization, MapReduce

1 INTRODUCTION

The supporting of smart contracts is the landmark of blockchain 2.0, which allows running various applications on the blockchain other than cryptocurrency (e.g., bitcoin) [1]. A smart contract is an autonomous computer program that, once started, executes automatically and mandatorily according to the program logic defined beforehand [2]. Due to many unique advantages (e.g., automatic execution in a deterministic manner, without trusted intermediaries, highly resistant to forgery), smart contracts have the power to reshape a number of industries, in which retail banking, insurance, financial exchange, marketplaces, and content platforms are the most impacted [3]. Therefore, many blockchain systems support smart contracts, such as Ethereum, Counterparty, Stellar, Monax, Lisk [4]. Among them, Ethereum is the largest one with more than 10 billion USD market capitalization1, 8 million smart contracts and 200 million transactions2 until September 2019. Moreover, smart contract developers are in great demand [5]. Therefore, this study concentrates on smart contracts of Ethereum. The terms blockchain and smart contract refer to Ethereum blockchain and Ethereum smart contract hereinafter if not specified specifically.

Smart contracts are typically developed in a high-level language (e.g., Solidity) and then compiled into a special bytecode format using EVM bytecode, which can be executed in the Ethereum Virtual Machine (EVM), the runtime system of Ethereum. According to Ethereum’s specification [6], every node in Ethereum maintains a complete copy of blockchain, and will replay all transactions stored in the blockchain. In particular, a smart contract will be executed if it is the recipient of a transaction. Since every node needs to run all smart contracts in the bytecode format using EVM, the execution of smart contracts consumes the computing resources of every node. To prevent resource abuse, especially Denial-of-Service (DoS) attacks that exhaust the computing resources (e.g., CPU, disk, network) of nodes [7], Ethereum adopts the gas mechanism that charges the transaction senders. In other words, transaction senders have to pay for deploying or invoking smart contracts. The amount of money should be charged for deploying and invoking a smart contract depends on the size of the deployed smart contract and the operations executed in that smart contract, respectively.

We name a smart contract that costs more gas than necessary as a gas-inefficient smart contract. Such contracts will waste a lot of gas because gas-inefficient patterns are prevalent in deployed smart contracts (Section 6.3), which could be invoked an unlimited number of times. Many factors can result in gas-inefficient smart contracts, e.g., unawareness of gas waste, inexperienced developers, insufficient compiler optimizations, the absence of auxiliary tools.

In this paper, we first identify ten gas-inefficient patterns, which overcharge the developers and users of smart contracts. Then, we design and develop GasChecker, a novel system to automatically detect these patterns in the bytecode of smart contracts. GasChecker does not need source code, because the proportion of open-source smart contracts is less than 1% [8]. To make GasChecker scalable to process millions of smart contracts, we propose a new approach to parallelize SE by leveraging cloud computing platform. In particular, we tailor parallel SE into MapReduce programming model and propose a feedback-based load balancing strategy to improve the utilization of computing resources. The experimental results show that GasChecker has high precision and low false positive rate (i.e., 2.5%) (Section 6.2). Moreover, GasChecker scales well with the increase of workers, and our proposed load balancing strat-
Our position paper first points out the issue of gas-inefficient smart contracts [9]. This full paper extensively extends our previous work from four aspects. First, we identify ten gas-inefficient programming patterns whereas our position paper introduces seven patterns. Note that this work adds four new patterns, and excludes one pattern proposed in our position paper because our experiments show that such pattern is not appeared in practice. Second, we design and develop a new system named GasChecker for detecting all ten patterns automatically in EVM bytecode whereas only three patterns could be detected by our previous work [9]. Third, to make GasChecker scalable to handle millions of smart contracts, we propose a new approach to parallelize symbolic execution (SE) by leveraging cloud computing platform whereas sequential SE is used in our previous work [9]. Finally, we conduct much more experiments in this paper than the position paper, e.g., scalability, detection precision of GasChecker, amount of saved money by optimizing contracts.

Our previous tool, PACCI is the first work to parallel SE via MapReduce [10]. However, GasChecker is implemented from scratch rather than reuse PACCI for two reasons. First, GasChecker analyzes EVM bytecode while PACCI handles binaries. Second, PACCI does not consider load balancing.

This study can benefit developers in several domains. First, the developers of smart contracts can avoid the gas-inefficient patterns identified in this paper. Second, compiler developers can improve compilers by replacing gas-inefficient code with efficient code during compiling. Third, the developers of Ethereum can create a JIT compiler and embed it into the runtime system (i.e., EVM) for optimizing gas-inefficient code at runtime. Last but not least, this work may motivate a new optimization service that turns gas-inefficient code at runtime. Last but not least, this study can benefit developers in several domains. First, the developers of smart contracts can avoid the gas-inefficient patterns identified in this paper. Second, compiler developers can improve compilers by replacing gas-inefficient code with efficient code during compiling. Third, the developers of Ethereum can create a JIT compiler and embed it into the runtime system (i.e., EVM) for optimizing gas-inefficient code at runtime. Last but not least, this work may motivate a new optimization service that turns gas-inefficient code at runtime.

Overall, this work has four major contributions.

1. We propose ten gas-inefficient programming patterns.
2. We design and implement a novel tool, GasChecker which is based on SE to detect these patterns in the bytecode of smart contracts.
3. We propose to scalalize the automated analysis by parallelizing SE according to the MapReduce programming model and designing a feedback-based load balancing strategy (FBLB) to improve resource utilization.
4. We conduct a large-scale empirical study by applying GasChecker to the deployed smart contracts. Experiments show that GasChecker can find lots of gas-inefficient code in existing smart contracts with low false positives. Moreover, event recent compilers cannot eliminate all gas-inefficient patterns, and much money can be saved by optimizing the gas-inefficient code.

### 2 Background and a Motivating Example

**Blockchain.** A blockchain is a continuously growing list of records, called blocks which contains zero or more transactions [11]. A transaction refers to a signed data package that contains a message sent by an account [12].

**Ethereum.** Ethereum is the largest blockchain with the capability of running smart contracts. Ethereum runs smart contracts in a stack-based virtual machine, so-called the Ethereum Virtual Machine (EVM). Ethereum has two kinds of accounts, external owned accounts (EOAs) and smart contracts. A smart contract contains executable bytecode, while an EOA does not.

**Smart contract.** A smart contract is typically written in a high-level language (e.g., Solidity) and then compiled into EVM bytecode. A smart contract is deployed by sending a special transaction whose receiver field is empty and its input data field carries the bytecode [12]. A smart contract is invoked by a transaction, where the receiver field gives the address of the callee and the input data field indicates the function to be invoked and the arguments.

**Gas.** To prevent resource abuse, especially DoS attacks [7], Ethereum proposes gas mechanism to charge execution fee from transaction senders. Execution fee is computed by \( \text{gas price} \times \text{gas cost} \), where gas cost is the amount of gas consumed measured by the number of units [6]. The gas cost of individual operation is defined by Ethereum’s core protocol [12]. Some operations are cheap, e.g., ADD, AND, EQ, POP, because they are pure stack operations [6]. Some operations are expensive, e.g., SSTORE for updating the storage, CREATE for creating a smart contract [6].

**Symbolic execution.** Symbolic execution (SE) is a multi-path program analysis technique, which can exhibit different behaviors of the analyzed program corresponding to different paths. Moreover, by leveraging a theorem prover, SE can determine path feasibility, and therefore techniques based on SE can avoid analyzing dead code. Besides, SE maintains the symbolic expressions of variables, and therefore SE can reason about the relation of two expressions (e.g., whether two expressions are equal). The reasons for choosing SE rather than standard compiler techniques are explained in detail in Section 4.1.

**MapReduce.** MapReduce is a programming model and an associated implementation for processing and generating large data sets with a parallel, distributed algorithm on a cluster [13]. A MapReduce application consists of a Map procedure to perform filter and sort, a Reduce procedure to summarize, and a Driver procedure to integrate the Map and Reduce. MapReduce can launch multiple Map tasks (a Map task is an execution of the Map procedure) and run...
them independently and execute Reduce tasks (a Reduce task is an execution of the Reduce procedure) in parallel. MapReduce has several features. First, Reduce tasks will not be started until all Map tasks finish their jobs. Second, all Mappers (the workers run Map tasks) are independent, and hence there are no communications among Mappers. Hence, cloud services (e.g., Spark [14]) can simply re-execute a failed Map task on another worker for failure recovery. Third, a MapReduce application is expected to be scalable to the increase of workers since the communications among workers are greatly reduced by design.

A motivating example. Fig. 1(a) shows a smart contract containing a gas-inefficient pattern (i.e., P3, Section 3.2.1) and Fig. 1(b) gives its efficient version. It is worth noting that even a recent compiler (Solidity 0.5.10 released on Jun. 25, 2018) for smart contracts cannot perform this optimization. This contract declares a global variable num. Unlike traditional applications, global variables in a smart contract are stored in the storage. Since accessing the storage is expensive [6], reading and writing num in a loop repeatedly (Line 5) costs lots of gas. By contrast, the contract in Fig. 1(b) is more efficient with the same functionality as the costly contract. In particular, it reads num into a local variable y, then increases y in the loop, and finally writes y back to num. Hence, the number of access to storage reduces from 2x (1 read and 1 write in every iteration of the loop) to 2. Since the local variable y is stored in the stack and accessing the stack requires orders of magnitude less gas than operating storage [6], the code in Fig. 1(b) is gas-efficient.

It is worth noting that from the viewpoint of traditional program optimization, the code in Fig. 1(a) cannot be optimized for several reasons. First, accessing a local variable has no distinct difference with accessing a global variable in terms of speed. Besides, more memory is required to store the local variable when running the code in Fig. 1(b). Third, the code in Fig. 1(b) contains more instructions and hence more disk space is needed to store the code, more memory will be allocated to load the code, and more instructions will be executed. Hence, a traditional compiler would consider the code in Fig. 1(a) be better because it typically aims at improving runtime performance, reducing memory and disk consumptions. GasChecker can detect such gas-inefficient pattern in the bytecode of smart contracts as detailed in Section 4.6.

3 GAS-INEFFICIENT PROGRAMMING PATTERNS

We identify ten gas-inefficient programming patterns, and divide them into four categories.

3.1 Useless Code

3.1.1 P1: Opaque Predicate

An opaque predicate refers to a comparison that has only one outcome (i.e., True or False). Hence, the gas for invoking the smart contract can be reduced by removing the comparison, and the gas for deploying the smart contract can also be reduced by removing the code on the infeasible branch. It is non-trivial for the developers of smart contracts to avoid opaque predicates because opaque predicates do not alter program logic.

3.1.2 P2: Dead Code

The code that cannot be reached at runtime is dead. The gas for deploying smart contracts can be reduced by eliminating dead code. It is worth noting that opaque predicate is not always the same as dead code even if they often appear together (as shown in Fig. ??). Dead code is the code that cannot be executed in practice, and an opaque predicate (also termed by invariant opaque predicate in recent studies [15]) is a comparison which always produces the same result. First, an opaque predicate does not necessarily result in dead code. Fig. 2 shows an example. Blocks 1, 2, 3 are branch blocks which end with a JUMPi, and blocks 4, 5 are terminal blocks which end with a STOP. Note that since STOP terminates the execution of smart contracts [6] they do not have successors. A solid edge indicates a feasible branch, while a dashed edge stands for an infeasible branch. Hence, there is an opaque predicate in block 3, because only one branch from block 3 is feasible. However, there is no dead code in this example, because block 5 can be reached from block 2. On the other hand, dead code is not necessarily caused by opaque predicates, e.g., functions never been called, the code after a return statement.

3.2 Loop

3.2.1 P3: Expensive Operations in a Loop

Expensive operations in a loop are worthy of attention because a single transaction can execute expensive operations multiple times, resulting in high money cost. A transaction sender sets the field gas limit of the transaction, indicating the amount of gas the sender can afford to execute that transaction. As a consequence, if the execution of a transaction requires more gas than the gas limit, the transaction will fail and the gas in the amount of gas limit will be consumed. By moving expensive operations outside the loop, the gas for invoking smart contracts can be reduced. However, the size of bytecode after optimization will be increased (as shown in Fig. 1), thus the gas for deploying smart contracts will be raised. It is worth noting that a contract can be deployed only once but invoked many times. Hence, such optimization can reduce overall gas consumption.
3.2.2 **P4: Fusible Loops**

Two loops are fusible, if they can be merged into one loop without changing program behaviors. By loop fusion, the gas for deploying smart contracts can be reduced because the size of bytecode becomes smaller, and the gas for invoking smart contracts can be reduced because the executed instructions will be reduced. Moreover, other optimizations (e.g., common subexpression elimination) can be applied on the merged loop body so that gas consumption can be reduced further. Although loop fusion has been applied in modern compilers, compilers may fail to find all fusible loops, particularly the loops whose loop bounds are hard to determine using standard compiler techniques.

3.2.3 **P5: Repeated Computation in a Loop**

This pattern refers to the computation that produces the same result in each iteration of a loop. By moving the computation outside the loop and using a temporary variable to hold the result, the optimized version saves the gas for executing smart contracts at the price of larger bytecode (i.e., more gas for deploying smart contracts). Since a contract is deployed once and executed many times, such optimization is acceptable.

3.2.4 **P6: Unilateral Comparison in a Loop**

This pattern means a comparison in a loop whose outcome is fixed. Please note that it is not an opaque predicate (P2) because the comparison can produce different results under different contexts. By moving the unilateral comparison outside the loop and copies the loop body, the optimized version saves gas for executing smart contracts since it reduces the number of comparisons at the price of larger bytecode.

3.3 **Wasted Disk Space**

3.3.1 **P7: Redundant SSTORE**

This pattern indicates a storage that is never used (e.g., SLOAD after definition (i.e., SSTORE). Please note that not only SLOAD but also some other operations (e.g., BALANCE obtains the balance of an account) read storage. Redundant SSTORE operations waste disk space and much money as the gas cost of SSTORE (as shown in Table 1) is high. Standard compiler techniques for detecting redundant variable definitions (e.g., liveness analysis) may not be suitable for our purpose because storage is like a database on the disk rather than a data structure in physical memory. In particular, a storage can be written by a transaction and then read by a subsequent transaction. Therefore, we need multi-path analysis and we cannot say that an SSTORE is redundant if the written location is not read in one program path. After optimization, both the gas for deploying and invoking smart contracts can be reduced.

3.4 **Gas-Inefficient Operation Sequence**

This type of gas-inefficient patterns refer to consecutive EVM operation sequences that can be replaced with gas-efficient operation sequences. Although the following three patterns are specific to EVM bytecode, the basic idea can be extended to other smart contract platforms. After optimization, both the gas for deploying and invoking smart contracts can be reduced.

---

**Table 1** summarizes the effects by replacing gas-inefficient patterns with their gas-efficient counterparts.
the results of two computations in a loop are equal, even if operations or even depend on inputs. Similarly, SE can the loop bounds that are computed by bitwise/arithmetic operations or even depend on inputs. Such case is challenging to standard compiler techniques. Therefore, SE is more suitable than standard compiler techniques for detecting the gas-inefficient patterns, \( P_4 \) (Section 3.2.2) and \( P_5 \) (Section 3.2.3). To detect fusible loops (\( P_4 \)), we need to check whether the loop bounds of two adjacent loops are equal. SE is a rational choice to detect \( P_4 \) especially the loop bounds that are computed by bitwise/arithmetic operations or even depend on inputs. Similarly, SE can facilitate detecting \( P_5 \) because it is able to check whether the results of two computations in a loop are equal, even if the results are not constants.

Moreover, SE is able to determine path feasibility, which is also a challenge to standard compiler techniques. Hence, SE outperforms standard compiler techniques in detecting the gas-inefficient patterns, \( P_1 \) (Section 3.1.1), \( P_2 \) (Section 3.1.2) and \( P_6 \) (Section 3.2.4). Since SE attempts to explore all feasible paths, we consider any predicate with single outcome as an opaque predicate \( P_1 \), and the uncovered code as dead code (\( P_2 \)) after the completion of path exploration. Similarly, by leveraging SE, we know the results of a comparison in a loop under different contexts, thus SE facilitates the detection of \( P_6 \). Furthermore, our recent study discovers that SE is capable of identifying some control flow transfers which trouble standard compiler techniques [16]. Since control flow information is critical to program analysis, missing some control flow transfers may lead to inaccuracy in detecting gas-inefficient patterns. For example, if a control flow transfer from block \( A \) to block \( B \) is not discovered, block \( B \) may be misidentified as dead code. Besides, if the missed control flow transfer is the back edge of a loop, the loop structure may not be discovered and therefore the loop-related patterns (\( P_3, P_4, P_5, P_6 \)) may be missed.

### 4 GasChecker

#### 4.1 Why Symbolic Execution?

GasChecker is based on SE, which is a heavy-weight program analysis technique. We adopt it for the following reasons. First, SE is a multi-path program analysis technique, which facilitates the detection of \( P_7 \) (Section 3.3.1). More precisely, to detect redundant \texttt{SSTORE} (\( P_7 \)), we need to check the usage of \texttt{SSTORE} in every program path. Second, by leveraging a theorem prover (\( Z_3 \) used by GasChecker), SE is able to determine whether two expressions are equivalent, including the case where expressions are computed by bitwise/arithmetic operations or even depend on inputs. Such case is challenging to standard compiler techniques. Therefore, SE is more suitable than standard compiler techniques for detecting the gas-inefficient patterns, \( P_4 \) (Section 3.2.2) and \( P_5 \) (Section 3.2.3). To detect fusible loops (\( P_4 \)), we need to check whether the loop bounds of two adjacent loops are equal. SE is a rational choice to detect \( P_4 \) especially the loop bounds that are computed by bitwise/arithmetic operations or even depend on inputs. Similarly, SE can facilitate detecting \( P_5 \) because it is able to check whether the results of two computations in a loop are equal, even if the results are not constants.

Moreover, SE is able to determine path feasibility, which is also a challenge to standard compiler techniques. Hence, SE outperforms standard compiler techniques in detecting the gas-inefficient patterns, \( P_1 \) (Section 3.1.1), \( P_2 \) (Section 3.1.2) and \( P_6 \) (Section 3.2.4). Since SE attempts to explore all feasible paths, we consider any predicate with single outcome as an opaque predicate \( P_1 \), and the uncovered code as dead code (\( P_2 \)) after the completion of path exploration. Similarly, by leveraging SE, we know the results of a comparison in a loop under different contexts, thus SE facilitates the detection of \( P_6 \). Furthermore, our recent study discovers that SE is capable of identifying some control flow transfers which trouble standard compiler techniques [16]. Since control flow information is critical to program analysis, missing some control flow transfers may lead to inaccuracy in detecting gas-inefficient patterns. For example, if a control flow transfer from block \( A \) to block \( B \) is not discovered, block \( B \) may be misidentified as dead code. Besides, if the missed control flow transfer is the back edge of a loop, the loop structure may not be discovered and therefore the loop-related patterns (\( P_3, P_4, P_5, P_6 \)) may be missed.

#### 4.2 Overview

Fig. 4 shows the architecture of GasChecker, which consists of a \textbf{Master} to run the Driver procedure, multiple \textbf{Mappers} to run Map tasks and multiple \textbf{Reducers} to run Reduce tasks. Both Mappers and Reducers are workers, and there is at least one worker. GasChecker takes in a smart contract and produces a report containing the locations of gas-inefficient patterns discovered in the analyzed smart contract. \textbf{Master} first disassembles the bytecode and constructs the control flow graph (CFG) from it. CFG is a directed graph, where each node denotes a basic block without control flow transfers inside and each edge indicates a control flow transfer (i.e., unconditional jump, conditional jump). Since it is difficult for standard compiler techniques to determine some jump targets, we complete the CFG during path exploration. After that, multiple Map tasks and Reduce tasks are launched. GasChecker runs Map tasks and Reduce tasks iteratively until all program paths have been explored or timeout. \textbf{Master} collects runtime information (e.g., value of an expression, executed basic blocks) from \textbf{Reducers} for detecting gas-inefficient patterns, and performance information (e.g., time consumption for state recovery) for improving load balance. \textbf{Mappers} accept Map tasks from \textbf{Master}, run CFG symbolically, and then produce new tasks if any. \textbf{Reducers} recover the state, from which path exploration begins. New tasks are encoded in bit-vectors in order to improve the degree of parallelism by reducing network communications. The \textbf{Monitor} in each \textbf{Mapper} records runtime information and performance information.

Most work is completed by \textbf{Mappers} (e.g., path exploration) and the \textbf{Master} (e.g., gas-inefficient code detection), and the responsibility of Reduce tasks is to combine (i.e., reorganize) the outputs from Map tasks into a form that can be easily handled by the \textbf{Master} and then return the results to the \textbf{Master}. For example, if two Mappers output (\( P_1, \text{info1} \)) and (\( P_2, \text{info2} \)) where \( P \) and \text{info} stand for the encoded path prefix and information collected during SE, respectively, a \textbf{Reducer} combines them into \{\( P_1, P_2 \), \{\text{info1, info2}\}\}. After receiving the combined results (e.g., \{\( P_1, P_2 \), \{\text{info1, info2}\}\}) from \textbf{Reducers}, the \textbf{Master} generates new Map tasks from the first part \{\( P_1, P_2 \), then detects gas-inefficient patterns, and improves load balance using the second part \{\text{info1, info2}\}. We detail the key components of GasChecker in the following sections while omitting the details for implementing a standard SE engine. The components (in gray boxes) \textit{dis} for disassembling bytecode, \textit{CFG} for constructing the control flow graph and \textit{SE Block} for executing a basic block symbolically are reused from an existing sequential SE tool, \textit{OYENTE} for detecting security bugs [17].

#### 4.3 Task Encoding and State Recovery

\textbf{Mapper} receives a Map task from \textbf{Master}, explores the paths of the tested smart contract, forks new states when encounters conditional jumps (i.e., \textit{JUMP}!), selects an unexplored state to execute, and outputs the unexplored states after the Map task finishes. The \textit{state} in SE contains all necessary
information (e.g., program counter, symbolic expressions of all variables, constraints of the executed branches) that SE needs, and therefore SE can start path exploration from any states. In a decentralized environment, the Master should tell Mappers where (i.e., which basic block) to start path exploration and how much work should do (Section 4.5).

An intuitive way for Master to assign tasks to a Mapper is sending the exact state from which path exploration should start to that Mapper. After the Mapper finishes its work, all unexplored states are sent to Reducers. Then, Reducers aggregate the states from all Mappers, and return the states to the Master for subsequent iterations of Map and Reduce routines. Although simple by design, this approach consumes considerable network resources, resulting in weak scalability when the number of workers increases.

To address this issue, we employ task encoding and state recovery for reducing the consumption of network resources. In particular, a Map task is represented by a bit-vector, indicating a path prefix. The state from which to start path exploration, can be recovered by symbolically executing the analyzed smart contract following the path prefix. For example, “0101” tells a Mapper to take False, True, False, True of the first four encountered branches when executing the analyzed smart contract, and then start path exploration after the fourth branch. Please note that state recovery neither check branch feasibility nor fork another state when encountering a branch, because the path prefix is feasible and the smart contract is executed along the path prefix during state recovery.

After the Mapper finishes, all unexplored states are encoded into path prefixes, indicating the paths from the beginning of the analyzed smart contract to the unexplored states. All path prefixes are feasible since their feasibility is validated by previous path exploration. The advantage of our method is that considerable network resources can be saved by sending bit-vectors rather than states. Therefore, compared to state transferring, our approach is more scalable at the expense of computing resources for state recovery. To increase the utilization of the computing resources of workers, we propose a feedback-based load balancing strategy, which is able to reduce the proportion of CPU resources for state recovery by dynamically adjusting the amount of work Mappers should do (Section 4.5).

4.4 Map Task

The Map procedure is the core component to implement SE. Beside the path prefix for state recovery and the CFG to explore, a Map task accepts a parameter SN from the Master, which stands for the number of EVM operations to be executed by the Map task. Hence, by changing SN, the Master can adjust the amount of work Mappers should do. After launching a monitor to collect runtime and performance information, the Mapper recovers the state from the given path prefix. After that, the Mapper begins path exploration until all paths have been explored or the designated amount of tasks, i.e., SN has been finished. A Mapper will not stop executing EVM operations until it executes a JUMPI or an operation (e.g., STOP) for terminating the execution of the smart contract, even if the number of executed operations exceeds the designated amount of tasks. The rationale lies in the fact that the Map task may not produce new Map tasks if SE terminates in the middle of a basic block. Operations are executed in sequence and a counter increases by 1.

When reaching a conditional jump (i.e., JUMPI), a new state will be generated if one branch can be taken and a new constraint will be added in the path condition, which is stored in the new state. The Mapper will select an unexplored state for subsequent SE. Any path exploration algorithms (e.g., depth-first search, random search) can be implemented in Select_state() to determine the execution priority of states. In the current implementation, GasChecker reuses the code of OYENTE for state prioritization, which is depth-first search. After the Mapper finishes its work, all unexplored states will be encoded into path prefixes. Finally, the Mapper outputs path prefixes together with the information collected during SE.

4.5 Feedback-based Load Balancing Strategy

MapReduce may result in low utilization of computing resources, because, Mappers are independent and cannot communicate with each other, and therefore a Mapper cannot obtain new tasks which are generated by other Mappers in the current iteration of MapReduce. That is, a Mapper has to wait until all Mappers finish their jobs, and then the Reducers process the outputs of Mappers and return the combined data to Master. After that, Master launches new Map tasks. Consequently, the resource utilization would be low if some workers have to wait a long time for the other workers to finish their jobs.

To improve resource utilization, we propose a feedback-based load balancing strategy (FBLB), which adjusts the amount of work that should be completed by Mappers after each iteration. We first define two metrics to measure the performance of Mappers. Replay ratio stands for the proportion of time required for state recovery to the time for running Map tasks. Obviously, the lower the replay ratio is, the better. That is, more computing resources will be used for path exploration. Another metric is working ratio, which indicates the proportion of time for running tasks to the time the worker is available. Working ratio will be low if many workers wait for the completion of another worker. FBLB attempts to decrease the replay ratio and increase the working ratio. To this end, our approach limits the amount of work a Mapper should do to SN, which is an upper bound of the operations to be symbolically executed by a Mapper (does not count the operations executed during state recovery). Since there is a tradeoff between the two ratios, we cannot simply set SN with a fixed value. Section 5.2 will show that fixing SN is not an optimal solution.

Replay ratio will be lowered by increasing SN because a Mapper will use more time to execute more EVM operations with a larger SN. Working ratio can also be influenced by changing SN, however, the influence should be determined at runtime. For example, a large SN means that a Mapper needs a long time to finish its job, and hence the other workers may wait for it (i.e., working ratio of the current iteration may be low), especially in the case where workers outnumber tasks (i.e., there are workers that have no tasks to do at all). However, the larger SN is, the more new tasks may be generated by Mappers, and hence working ratio in subsequent iterations may be improved.
FBLB adjusts the amount of work as follows. First, GasChecker computes replay ratio \((rr_i)\) and working ratio \((wr_i)\) of iteration \(i\) from the performance data collected by the monitor of the Mapper. GasChecker increases \(SN_{i+1}\) from \(SN_i\) if \(rr_i\) is higher than a threshold \(td\). Otherwise, GasChecker considers the adjustment of \(SN\) as a search problem and borrows the idea of simulated annealing algorithm [18] to approach the global optimal of working ratio. In particular, if \(wr_i > wr_{i-1}\) (indicating the previous adjustment increases working ratio), we accept the previous adjustment and adjust \(SN_{i+1}\) based on \(SN_i\) (i.e., \(SN_{i+1}\) is a neighbor around \(SN_i\)). If \(wr_i < wr_{i-1}\) (indicating that the previous adjustment decreases working ratio), we accept the adjustment with a probability defined as \(e^{(wr_{i-1} - wr_i) / T}\), where \(T\) is the temperature in simulated annealing. If the previous adjustment is rejected, \(SN_{i+1}\) will be set based on \(SN_{i-1}\). Since the simulated annealing algorithm has a probability to accept a “bad” adjustment, our method could escape a local optimal.

4.6 Pattern Detection

\(P_1\). During SE, GasChecker records the result of each executed predicate. After SE, GasChecker regards a predicate as opaque, if the predicate has only one outcome. 

\(P_2\). After CFG construction, GasChecker obtains all basic blocks of a smart contract. During SE, GasChecker records all executed blocks. After SE, GasChecker regards a basic block as dead, if it belongs to the smart contract but it is not executed by SE.

\(P_3\). To detect loop-related patterns (i.e., \(P_3 - P_6\)), GasChecker first identifies loops through three steps. First, GasChecker scans the CFG to find back edges that indicate the existence of a loop, and identifies the entry block and exit block of a loop. We define the distance between two blocks as the least number of edges from one block to the other. Second, for each block, GasChecker calculates the distance between it and the entry block as well as the distance between it and the exit block. Finally, a block is regarded as being in a loop if it is closer to the exit block than to the entry block, because the block in a loop should go through the exit block to reach the entry block. Our method can also detect nested loops because it captures the structure of a loop in CFG. After identifying loops, P3 detection is simple. Technically, GasChecker scans each block in a loop for expensive operations. The current implementation of GasChecker can detect three expensive operations: SLOAD, SSTORE and BALANCE. The extension to support other operations is straightforward.

\(P_4\). GasChecker first identifies two adjacent loops and then computes their loop bounds. GasChecker considers two adjacent loops are fusible if their loop bounds are equal. If loop bounds are constants, it is easy to identify whether they are equal. If their loop bounds depend on symbols, we apply SE to determine whether they are equal. Our detection of fusible loops may introduce false positives because we do not consider data dependency (e.g., the second loop reads a variable which is set in the first loop) of loops. Manual analysis reveals that the false positive rate is low in practice (Section 6.2).

\(P_5\). GasChecker detects \(P_5\) in third steps. First, it detects loops by the approach described above. Second, for each computation in a loop, GasChecker records its outcome in each iteration of the loop during SE. Third, after SE, for each computation in a loop, GasChecker checks whether it results in the same outcome for every iteration. If so, GasChecker detects a repeated computation in a loop.

\(P_6\). GasChecker detects \(P_6\) in three steps. First, it detects loops by the approach described above. Second, it records the outcome of each branches inside loop during SE. Third, after SE, GasChecker detects a unilateral comparison, if the following two conditions are satisfied. First, the comparison produces two feasible branches, i.e., it is not an opaque predicate (P2). Second, the comparison produces only one outcome under the same context. Here, we define the context as the path condition before entering the loop.

\(P_7\). GasChecker detects \(P_7\) in two steps. First, during SE, GasChecker records the places of storage operations happened on each explored path, including SSTORE for writing and the operations for reading (e.g., SLOAD, BALANCE, EXTCODESIZE, EXTCODECOPY). Second, after SE, GasChecker regards an SSTORE as redundant, if the place written by the SSTORE can never be read in all paths. Note that we do not consider an SSTORE is redundant, if it sets a storage value to zero from non-zero, because such operation clears the storage [6]. Storage clearance reclaim disk space, so Ethereum refunds the transaction sender [6]. Therefore, such SSTORE does not waste gas.

\(P_8 - P_{10}\). GasChecker detects \(P_8 - P_{10}\) in two steps. First, GasChecker records each executed EVM operation during SE. Second, after the exploration of each program path, GasChecker checks whether the recorded EVM operations contain these patterns.

5 Scalability Evaluation

In this section, we evaluate the scalability of GasChecker by answering the following research questions.

\(RQ_1\): How is the scalability of GasChecker with the increase of workers?

\(RQ_2\): How is the effectiveness of FBLB?

5.1 Scalability of GasChecker

We use the top 10 most popular smart contracts (how to obtain smart contracts is described in Section 6.1), each of which is involved in at least 93,038 transactions, to evaluate the efficiency of GasChecker. By default, FBLB is turned on, and the threshold of replay ratio and initial SN (i.e., SN for the first iteration of MapReduce) are set as 30% and 200, respectively. To fairly compare the time consumptions required for analyzing contracts using different number of workers, we first record the number of paths explored for each analyzed contract when providing one worker. When testing with more workers, we stop analyzing a contract if the number of explored paths reaches the recorded number. We rent cloud resources from Google Cloud, and each node is equipped with 4 processors and 20GB main memory. Fig. 5 illustrates that the time needed for GasChecker to accomplish the analysis declines with the increase of workers.

We define speedup as the ratio of the time consumption given one worker to that given \(N\) workers, and define speedup ratio as the ratio of speedup to the number of
Fig. 5. Time consumption and speedup with various number of workers. Fig. 5 shows that GasChecker is scalable because the speedup keeps increasing with the number of workers. In other words, we can expect even better acceleration providing more workers. For example, GasChecker with 16 workers need 489 seconds to complete analysis while GasChecker with 1 worker requires 4,377 seconds. In other words, by leveraging 16 workers, GasChecker obtains 9x speedup and the speedup ratio is about 56% (replay ratio is 15%, working ratio is 69%). It is worth noting that the speedup ratio of a practical distributed system cannot achieve 1 due to many practical issues such as the consumptions of communication, task dispatching, results collection. Moreover, GasChecker needs to consume CPU resources for state recovery, and there are some restrictions from MapReduce programming model (e.g., a Mapper cannot get new tasks directly from other Mappers), preventing full utilization of computing resources. We will show the effectiveness of FBLB in improving resources utilization in Section 5.2.

Answer to RQ1: GasChecker scales well with the increase of workers.

5.2 Effectiveness of FBLB

To evaluate the effectiveness of FBLB, we turn off it and launch GasChecker with fixed SN. Fig. 6 gives the execution time for analyzing the top 10 most popular smart contracts using different SN. We observe a downward trend and then an upward trend with the increase of SN. To find the reason for this observation, we draw the replay ratio in Fig. 7, and observe that replay ratio decreases with the increase of SN. Hence, GasChecker is inefficient with small SN, because considerable computing resources are used for state replay. For example, replay ratio is as high as 72% when SN is fixed as 100. Moreover, working ratio fluctuates with the increase of SN, and it becomes low given a large SN because some workers do lots of work, resulting in insufficient tasks for the other workers. For example, working ratio is as low as 20% when SN is fixed as 2,000. Another observation is that FBLB (489 seconds) is even better than the best result of fixed strategy (i.e., 549 seconds with a fixed SN, 550). The result is reasonable since our load balancing adjusts SN in every iteration of MapReduce to improve resource utilization while the fixed strategy uses the same SN in every iteration.

Answer to RQ2: FBLB is effective in improving resource utilization.

6 Results of the Empirical Study

This section reports the empirical study on the gas-inefficient patterns in the deployed smart contracts by answering the following questions.

RQ3: What is the analysis precision of GasChecker?

RQ4: How prevalent is gas-inefficient code in the deployed smart contracts?

RQ5: What is the difference of different compilers in terms of producing gas-inefficient code?

RQ6: How much money can be saved if the gas-inefficient code is optimized?

6.1 Data Set

We download all smart contracts (i.e., 599,934) that were deployed on the public blockchain of Ethereum from the launch of Ethereum, July 30th, 2015 to June 10th, 2017, and then choose the representative contracts from all contracts according to some criteria. We first describe how to obtain all smart contracts in two steps. The first step is to collect the addresses of all smart contracts. The second one is to get the bytecode of contracts by invoking an API that takes in the address of a contract. We detail the two steps as follows.

It is non-trivial to get the addresses of all smart contracts because the address space is $2^{20}$ (an address is 20 bytes), and we cannot determine whether an address is used by a contract only according to the address. We propose to collect the addresses that are specified by transactions and internal messages, because both a transaction and internal message can deploy a smart contract. To collect the addresses of smart contracts which are deployed by transactions, we instrument the function ApplyTransaction() in \core\state_processor.go of the Ethereum client, which is responsible for executing transactions. To collect the addresses of smart contracts which are deployed by internal messages, we instrument the handlers of all operations (i.e., CREATE, CALL, CALLCODE, DELEGATECALL, STATICCALL and SELFDESTRUCT) that are able to send internal messages [6]. For each address, we download the bytecode of the smart contract by invoking the API GetCode() provided by the client of Ethereum\(^3\). The API returns the bytecode, or empty if the address corresponding to an EOA or the corresponding smart contract has been removed from the blockchain. Eventually, the bytecode of 599,934 smart contracts is downloaded.

We select 1,500 representative smart contracts for analysis from all 599,934 contracts according to the following criteria. First, since we find that many contracts have identical bytecode, we only consider contracts with unique bytecode. Second, we include all open-source contracts. In particular, we search open-source smart contracts in Etherscan, and find 803 open-source contracts with unique bytecode. We also collect the source code of those 803 contracts from Etherscan for the comparison of different compilers (Section 6.4). Then, we choose 500 most popular smart contracts

---

GasChecker covers the most basic block when the loop bound is set to 4. More precisely, Table 2 demonstrates that there are covers the most basic block when the loop bound is set to 4. GasChecker may achieve low code coverage, resulting in inaccurate detection results, because long program paths (especially due to loops) will be explored without setting a loop bound. Therefore, the top 500 contracts are involved in about 74% of the transactions sent to smart contracts.

The empirical study is conducted on 17 nodes, consisting of 1 Master and 16 workers. By default, FBLB is turned on. We set the timeout for analyzing each smart contract as 10 minutes. Besides, we need to set a loop bound $n$ to control how many times a loop can unfold; otherwise, GasChecker may achieve low code coverage, resulting in inaccurate detection results, because long program paths (especially due to loops) will be explored without setting a loop bound. Consequently, much code may remain unexecuted when timeout. However, setting a proper loop bound is not easy, given that we have limited time to analyze each contract.

We propose to evaluate a loop bound by the number of the transactions sent to smart contracts. Investigation shows that for loops, those 23 false positives, and reveal that all false positives of $P1$ and $P2$ are due to the reason that there are some feasible program paths which are not explored during path exploration. Moreover, we find that all false positives of $P4$ are due to data dependency of loops that is not considered by GasChecker.

Fig. 9 presents a misidentified opaque predicate (P1) in an open-source contract which was deployed at 0xf066A53269Fa9DB8a9DA9F1e568d3687A6000. The variable numOptions is initialized as 0, so the outcome of the comparison (Line 55) should be always True if the loop count is smaller than 20. On the contrary, the outcome of the comparison becomes False if the loop count is no smaller than 20. However, GasChecker misidentifies the comparison as an opaque predicate, because it unfolds the loop (Line 54) four times. Fig. 9 presents misidentified dead code (P2) in an open-source contract which was deployed at 0x7698392ff47d84CeE21295aD1F1b6ed9ad66. We keep the line numbers in the source file. GasChecker considers Line 205 is dead code, which is a false positive. Before Line 205, there is a nested loop that the basic blocks inside the inner loop can execute up to 16 times. However, GasChecker sets the loop bound as four, so the program path will be terminated before it reaches Line 205. Fig. 10 shows misidentified fusible loops (P4) in an open-source contract which was deployed at 0x61F9d1e56aC1623ed4e949dD420251ef0896. GasChecker considers the two loops at Line 274 and Line 281 are fusible, because they have the same loop bounds. Unfortunately, it is a false positive because the second loop reads a variable totalDisPctx10 (Line 283) whose value is computed by the first loop (Line 278). Therefore, the second loop should be executed after the execution of the first loop due to such data dependency.

Then, we investigate whether we can eliminate the false positives of $P1$ and $P2$ by simply setting a larger loop bound. Therefore, we keep all default settings but set the loop bound to 50. Interestingly, all false positives are not removed and the analysis of the corresponding contracts triggers timeout. The result is accordant with the observation that GasChecker executes fewer basic blocks when the loop bound is set as ten than the number when the loop bound is set as four, given the same timeout setting (Section 6.1).
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TETC.2020.2979019, IEEE

JOURNAL OF IT EX CLASS FILES, VOL. 14, NO. 8, AUGUST 2015

TABLE 2
Statistics of 1,500 smart contracts

<table>
<thead>
<tr>
<th># methods</th>
<th>Size (byte)</th>
<th>Time(s)</th>
<th># blocks</th>
<th># paths</th>
<th># JUMP</th>
<th># JUMP</th>
<th># checks</th>
</tr>
</thead>
<tbody>
<tr>
<td>19,877</td>
<td>5,363,932</td>
<td>626,130</td>
<td>235,877</td>
<td>96,967</td>
<td>650,485</td>
<td>375,138</td>
<td>750,270</td>
</tr>
</tbody>
</table>

Fig. 11. Number of smart contracts containing gas-inefficient patterns. Please note that a smart contract of size 3,576 bytes. The analysis is completed in 626,130 seconds (about 174 hours, column 3). Table 2 also gives the number of executed basic blocks (column 4), the number of explored paths (column 5), the number of unconditional jumps (column 6), the number of conditional jumps (column 7) and the number of queries to the theorem prover, 2,3. The figure before “/” is the number of queries for identifying branch feasibility while the figure after “/” is the number of queries for solving the constraints for detecting P4 and P5 (e.g., query whether two loop bounds are equal). Table 3 presents the number of dead blocks (i.e., uncovered basic blocks), so the total number of basic blocks in 1,500 contracts are 290,223 (235,877 + 54,346), and thus there are 193 basic blocks per contract on average.

Fig. 12. Contracts with expensive operations in a loop. We then set the timeout for analyzing each contract as 300 minutes, which is 30 times longer than the default setting. In this setting (i.e., timeout = 300m, loop bound = 50), all false positives of P1 and P2 are eliminated, and the time consumed by analyzing the corresponding contracts (19 contracts) is 3,842 minutes.

Answer to Q3: GasChecker produces low false positive ratio (2.5%), which can be further reduced to 0.4% (4/914) by setting a larger loop bound and giving longer time for analysis.

6.3 Prevalence Analysis

Table 2 presents the statistics of the analyzed 1,500 smart contracts. Column 1 is the number of methods which can be invoked. Column 2 presents the overall size of those contracts in bytes. Hence, the average size of a smart contract is 3,576 bytes. The analysis is completed in 626,130 seconds (about 174 hours, column 3). Table 2 also gives the number of executed basic blocks (column 4), the number of explored paths (column 5), the number of unconditional jumps (column 6), the number of conditional jumps (column 7) and the number of queries to the theorem prover, 2.3. The figure before “/” is the number of queries for identifying branch feasibility while the figure after “/” is the number of queries for solving the constraints for detecting P4 and P5 (e.g., query whether two loop bounds are equal). Table 3 presents the number of dead blocks (i.e., uncovered basic blocks), so the total number of basic blocks in 1,500 contracts are 290,223 (235,877 + 54,346), and thus there are 193 basic blocks per contract on average.

Fig. 13. Relationship between the occurrence of patterns with the occurrence of patterns with the size of bytecode. Fig. 14. Relationship between the occurrence of patterns with the occurrence of patterns with the # of involved transactions. The third row gives the averages. For example, five (row 3, column 3) means that there are five opaque predicates on average for each contract. The remaining rows concern the 803 open-source smart contracts, which will be explained in Section 6.4.

Answer to Q4: A large proportion of smart contracts contains gas-inefficient patterns. Besides, opaque predicates, dead code, expensive operations in a loop and three low-level patterns occur frequently per contract.

6.4 Effectiveness of Compiler in Eliminating Gas-Inefficient Code

Developers can use different compilers (e.g., Solidity, Serpent, LLL) to convert the source code of smart contracts into EVM bytecode. Each compiler may have many different versions with different capabilities to optimize the bytecode. For example, Solidity has more than 350 versions whose first version is 0.1.1, released in 2015. Developers can also turn...
on/off optimizations. In this section, we investigate whether different compilers can remove gas-inefficient code. For this experiment, we collect the bytecode as well as the source code of 803 open-source smart contracts from Etherscan. We term the bytecode downloaded from Ethereum as original bytecode. Then, we use GasChecker to detect gas-inefficient code in the original bytecode. After that, we compile those contracts using eight different versions of Solidity with full optimizations. We name the produced bytecode as optimized bytecode. Then, we also employ GasChecker to discover gas-inefficient code in optimized bytecode. Finally, we compare the results of checking original bytecode and optimized bytecode. Note that we select Solidity, whose versions range from 0.4.0 (released on September 6, 2016) to 0.4.24 (released on May 16, 2018) because Solidity is the most popular language for developing Ethereum smart contracts [12], which undergoes hundreds of upgrading. We do not select Solidity whose versions are lower than 0.4.0 because we find that many contracts cannot be compiled successfully by earlier versions of Solidity due to the new features introduced in new versions.

Evaluation results are presented in row 4 to row 21 of Table 3. The row sum gives the number of gas-inefficient instances in 803 open-source smart contracts and the row ave presents the average number of gas-inefficient instance in each open-source contract. We have several observations from the experimental results. First, the number of each gas-inefficient instances in the contracts compiled by a newer version is no more than that of the contracts compiled by an older version. In other words, compilers have been improved to reduce gas-inefficient code. Interestingly, P9 could be totally eliminated since Solidity 0.4.8. Second, many gas-inefficient code snippets still cannot be removed by recent compilers (e.g., 0.4.24). For example, Solidity 0.4.24 leaves 987 instances of PUSHx/JUMPI which are comparable to the number (1,040) of gas-inefficient code instances compiled by Solidity 0.4.0, which was released 20 months before (Sep. 2016).

We find several potential reasons to explain why compilers cannot eliminate all gas-inefficient code. First, among all tasks in developing compilers (e.g., introducing new features, fixing bugs), reducing gas consumption may not be the primary task. Second, compilers are unlikely to incorporate heavy-weight techniques (e.g., symbolic execution) to optimize smart contracts because compilers need to produce bytecode quickly. Consequently, some gas-inefficient patterns discovered by GasChecker are not identified by the latest Solidity. For instance, compilers may feel difficult to determine path feasibility, and hence they may leave many gas-inefficient patterns (i.e., P1, P2, P6) in the produced bytecode. Besides, it is non-trivial for compilers to determine whether two expressions are equivalent if those expressions are computed by bitwise/arithmetic operations or depend on inputs, and therefore compilers may fail to detect many instances of P4, P5. Moreover, as suggested in Section 4.1, compilers may fail to identify some control flow transfers (e.g., the jump targets computed by bitwise/arithmetic operations), which hinders thorough program optimization. Answer to Q5: The improvement of compilers can reduce some gas-inefficient code, but many pieces of gas-inefficient code were still left.

Table 3

<table>
<thead>
<tr>
<th>Type</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>sum</td>
<td>7,532</td>
<td>534,346</td>
<td>28,192</td>
<td>15</td>
<td>182</td>
<td>401</td>
<td>99</td>
<td>9,238</td>
<td>9,810</td>
<td>6,464</td>
<td></td>
</tr>
<tr>
<td>ave</td>
<td>3</td>
<td>3</td>
<td>1.5</td>
<td>4</td>
<td>0.0037</td>
<td>0.017</td>
<td>10</td>
<td>1,620</td>
<td>13</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Open source</td>
<td>2.6</td>
<td>2.28</td>
<td>10.3</td>
<td>0.0079</td>
<td>0.085</td>
<td>0.15</td>
<td>0.025</td>
<td>4.2</td>
<td>2.3</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>(original)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sum</td>
<td>2.274</td>
<td>11,706</td>
<td>9,161</td>
<td>5</td>
<td>13</td>
<td>171</td>
<td>14</td>
<td>1,040</td>
<td>1,174</td>
<td>1,291</td>
<td></td>
</tr>
<tr>
<td>ave</td>
<td>2.8</td>
<td>14.6</td>
<td>11.4</td>
<td>0.0062</td>
<td>0.016</td>
<td>0.21</td>
<td>0.017</td>
<td>1.3</td>
<td>1.5</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Open source</td>
<td>2.274</td>
<td>11,699</td>
<td>9,153</td>
<td>5</td>
<td>13</td>
<td>148</td>
<td>13</td>
<td>1,034</td>
<td>1,118</td>
<td>1,283</td>
<td></td>
</tr>
<tr>
<td>(0.4.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sum</td>
<td>2.274</td>
<td>11,629</td>
<td>9,022</td>
<td>5</td>
<td>145</td>
<td>10</td>
<td>1,038</td>
<td>1,275</td>
<td>1,420</td>
<td>1,567</td>
<td></td>
</tr>
<tr>
<td>ave</td>
<td>2.8</td>
<td>14.5</td>
<td>11.3</td>
<td>0.0062</td>
<td>0.015</td>
<td>0.18</td>
<td>0.012</td>
<td>1.3</td>
<td>1.5</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Open source</td>
<td>2.177</td>
<td>11,169</td>
<td>8,007</td>
<td>5</td>
<td>14</td>
<td>10</td>
<td>1,070</td>
<td>1,243</td>
<td>1,423</td>
<td>1,567</td>
<td></td>
</tr>
<tr>
<td>(0.4.12)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sum</td>
<td>2.7</td>
<td>13.9</td>
<td>10</td>
<td>0.005</td>
<td>0.014</td>
<td>0.18</td>
<td>0.012</td>
<td>1.3</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>ave</td>
<td>2.101</td>
<td>10,323</td>
<td>7,981</td>
<td>4</td>
<td>11</td>
<td>37</td>
<td>10</td>
<td>1,086</td>
<td>1,248</td>
<td>1,423</td>
<td></td>
</tr>
<tr>
<td>Open source</td>
<td>2.6</td>
<td>13.4</td>
<td>9.9</td>
<td>0.005</td>
<td>0.014</td>
<td>0.071</td>
<td>0.012</td>
<td>1.3</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>(0.4.16)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sum</td>
<td>2.861</td>
<td>10,646</td>
<td>7,929</td>
<td>3</td>
<td>11</td>
<td>57</td>
<td>998</td>
<td>1,212</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ave</td>
<td>2.3</td>
<td>13.3</td>
<td>9.9</td>
<td>0.0073</td>
<td>0.014</td>
<td>0.071</td>
<td>0.012</td>
<td>1.2</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Open source</td>
<td>1.620</td>
<td>10,508</td>
<td>7,870</td>
<td>3</td>
<td>10</td>
<td>54</td>
<td>990</td>
<td>986</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0.4.21)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sum</td>
<td>2.131</td>
<td>9.7</td>
<td>0.0073</td>
<td>0.012</td>
<td>0.067</td>
<td>0.011</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>ave</td>
<td>1.977</td>
<td>10.551</td>
<td>7.981</td>
<td>3</td>
<td>10</td>
<td>56</td>
<td>997</td>
<td>987</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

6.5 Money Saved Analysis

It is interesting to present how much money can be saved by optimizing gas-inefficient code since saving money is the ultimate goal of detecting and optimizing gas-inefficient code. Here, we optimize the smart contracts containing the last three gas-inefficient patterns (i.e., gas-inefficient operation sequence: P8, P9, P10) through the following steps, because this work focuses on the detection of gas-inefficient code. We leave the optimization for the other seven patterns in future work. First, based on the report produced by GasChecker which gives the locations of all detected gas-inefficient instances, we replace each gas-inefficient instance with its efficient counterpart (Section 3.4). During replacement, we record the new locations of the basic blocks after the replaced code. For instance, if there is a basic block locating at 0x40 in the bytecode and there is a piece of gas-inefficient code SWAP1/DUP2/SWAP1 (P8) before the basic block, the new location of the basic block should be 0x3f because the gas-efficient counterpart is DUP1/SWAP2 which is one byte shorter than the gas-inefficient code.

After that, we modify the jump targets of JUMP and JUMPI which jump to the basic blocks whose locations are adjusted. Note that a smart contract will trigger an exception if a jump operation jumps to an incorrect location [6]. We use a semi-automated way to modify jump targets. In particular, we automatically search the bytecode of the code patterns PUSHx/JUMP and PUSHx/JUMPI whose jump targets need to be adjusted, and then change the operand of PUSHx to the new locations. Note that in the patterns PUSHx/JUMP and PUSHx/JUMPI, the targets of the jump operations are given as the operands of the push operations [6]. For the jump operations whose targets are obtained by the other fashions (e.g., the push operation locates in a different place, the target is computed by bitwise/arithmetic operations), we manually modify EVM operations to ensure the correctness of jump targets.

To evaluate the money saved in deploying the optimized smart contracts, we deploy the original contracts and the optimized contracts in our private Ethereum blockchain, which is isolated from the public Ethereum blockchain, for
the purpose of experiments. The amount of gas consumed for contract deployment is returned by the transaction for deploying that contract. By comparing the gas consumption for deploying the original contracts with that for deploying the optimized ones, we find that 3,991,702 units of gas are saved. Considering that gas_price is about $5 \times 10^{-6}$ Ether and 1 Ether can be exchanged into around 200 USD in September, 2019, the saved money in deploying the optimized smart contracts is about 40 USD.

To evaluate the money saved in invoking the optimized smart contracts, we first instrument the EVM and record the execution trace for each execution of smart contracts during synchronization with the public Ethereum blockchain. An execution trace consists of all executed EVM operations of a smart contract triggered by one transaction. Then, we calculate the gas consumption for invoking the original smart contracts by accumulating the gas cost for each executed EVM operation in execution traces. After that, we replace the gas-inefficient instances in execution traces with the gas-efficient counterparts. Then, we compute the gas consumption for invoking the optimized smart contracts by accumulating the gas cost for each EVM operation in the adjusted execution traces. By comparing the gas consumption for invoking the original smart contracts with that for invoking the optimized contracts, we find that 147,908,132 units of gas are saved. Thus, the invoking of the optimized contracts saves about 1,480 USD. Considering that there are more than 8 million smart contracts and more than 500 million transactions in total until September 2019, and this experiment just optimizes 1,500 smart contracts which are involved in about 7 million transactions, the amount of money that can be saved by optimizing all 8 million smart contracts should be several orders of magnitude than the amount by optimizing 1,500 smart contracts.

**Answer to Q6:** About 1,520 USD can be saved by optimizing three gas-inefficient patterns in 1,500 smart contracts. We reasonably expect significantly more money can be saved if we optimize all deployed smart contracts to eliminate all ten gas-inefficient patterns.

### 6.6 Case Studies

This section conducts case studies on 4 deployed smart contracts covering 4 gas-inefficient patterns. For the ease of presentation, we show open-source smart contracts and keep their line numbers unchanged. We neither show the practical cases of the first 3 patterns because they have been presented in our previous position paper, nor show last 3 patterns because they are low-level which have been explained in Section 3.4.

#### 6.6.1 Big: P4

*Big* is deployed at 0xb36ce92cad11e7a9b03531f0590deb0e2e991e6, which has two fusible loops at Line 97 and Line 101, Fig. 15 (Top) respectively. By asking a theorem prover, `GasChecker` can find that their loop bounds (i.e., `category.VotesCount`) are equal, though they are not constant. Though they are not constant, the first loop (Line 97) resets `totalVotes` to zero, and the second loop (Line 101) checks whether `totalVotes` is zero. Hence, the two loops can be combined and the comparison at Line 102 can be removed, as shown in Fig. 15 (Bottom).

![Fig. 15. Top: two fusible loops at Line 97 and 101. Bottom: efficient version](image)

#### 6.6.2 Honestgamble: P5

*Honestgamble* is deployed at 0x7c4a690585e89c01aebfce188b66.1.Big: P4

#### 6.6.3 PassFunding: P6

*PassFunding* is deployed at 0x055a9c349cDC2A598439d6A45D0A83CAd3864FD, containing a repeated computation `Payout_id + number_of_players` in a loop at Line 112, Fig. 16 (Top). Since the two variables do not change in the loop, the computation result is the same in each iteration. As the two variables are in storage, the computation involves two expensive SLOAD operations to read them into the stack. It can be optimized by moving the comparison outside the loop, as shown in Fig. 16 (Bottom), so that the execution number of SLOAD is reduced from 2 $\times$ `number_of_players` to 2.

![Fig. 16. Top: a repeated computation in a loop at Line 112. Bottom: efficient version](image)

#### 6.6.4 Oraclize: P7

*Oraclize* is deployed at 0xf05782932dBABDe1D657a5311FC3b78db81c60E7 (Fig. 18), which has two functions with the same name setBasePrice(), each of which has a redundant SSTORE (Line 110 and 116), because the private variable `baseprice` is never read on every feasible path in the smart contract. Therefore, the efficient code removes the declaration and storage operations of `basePrice` to save gas.
GasChecker when it is deployed on more workers due to inherent limitations of SE. For example, to prevent path

The first threat to the validity of our study results is the threat, we evaluate the scalability of GasChecker. To reduce the threat, we cross-validated the results by asking three Ph.d. students to check the reports independently.

8 RELATED WORK

8.1 Gas-Related Studies

Chen et al. propose to defend against DoS attacks of Ethereum by adjusting gas costs dynamically [7]. By doing so, DoS attacks exploiting under-priced EVM operations will be terminated quickly [7]. MadMax compiles EVM bytecode, and then detects gas-related security problems from the decompiled code [19]. Gastap derives the sound gas upper bounds for all public functions of a given smart contract, by inferring size relations, generating gas equations and solving the equations [20]. Gasol extends Gastap by replacing multiple accesses to the same storage location with one access [21]. GasFuzz applies feedback-directed fuzz testing to automatically generate inputs which could lead to a high gas consumption of contract functions [22]. Marescotti et al. leverages symbolic model checking to compute the exact worst-case gas consumption for smart contracts [23].

Yang et al. conduct an empirical study of gas consumption, and they have several observations, including some under-priced EVM operations that can be exploited by DoS attacks [24]. GrUB dynamically stores data in smart contracts or offline to reduce gas cost of data-intensive smart contracts [25]. Zhang et al. propose a novel data structure, so-called GEM²-Tree to substitute the original Merkle hash tree in Ethereum to reduce gas cost [26]. SmartCheck [27] detects 21 kinds of code issues in Ethereum smart contracts. Two of them are related to gas-inefficient code. The first is byte[] because it can be replaced with bytes which is cheaper. The second is the loops with function calls inside because repeated function invocations will result in considerable gas consumption. GasChecker is different with SmartCheck mainly because SmartCheck relies on the source code of smart contracts. Unfortunately, open-source contracts only account for less than 1% [8]. For example, since there is no type information in EVM bytecode, it is difficult to distinguish byte[] from bytes without the source code.

8.2 Parallel Symbolic Execution

Staats et al. propose static task partition to divide the whole execution tree into disjoint subtrees and explore the subtrees in parallel [28]. Their method cannot balance the workload because the whole execution tree is unknown before execution [28]. Other parallel SE approaches [29], [30], [31], [32], [33], [34] partition the task dynamically, and move workload from busy nodes to idle nodes to improve resource utilization. However, Ibing’s work [29] cannot always achieve good balancing due to the high coordination cost, low parallelism of tested units, and the operation delay of shared data-structures etc. Cloud9 [30] balances well because an idle worker can directly acquire jobs from other busy workers, so the resources of workers can be well utilized. SCORE [32], LCT [33], and ParSym [34] are similar to Cloud9 in task partition and workload migration. The major difference between those parallel SE tools [29], [30], [32], [33], [34] and GasChecker lies in that they are not tailored to the MapReduce framework. Hence, those
approaches cannot enjoy the benefits of commodity cloud services (e.g., scalability, flexibility, and fault tolerance).

9 Conclusion
We identify and summarize ten gas-inefficient patterns, and then propose and develop the system named GasChecker to detect gas-inefficient code in the bytecode of smart contracts. GasChecker is scalable to millions of smart contracts by parallelizing SE through MapReduce. Evaluation shows that it (1) scales well with the increase of workers; (2) FBLB is effective in improving resource utilization; (3) produces only a few false positives.

Acknowledgement
Ting Chen is partially supported by National Natural Science Foundation of China (61872857) and National Key R&D Program of China (2018YFB0804100). Xiapu Luo is partially supported by Hong Kong RGC Project (No. 152193/19E).

References