Securely Optimized (Ethereum) Smart Contracts using Formal Methods

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Introduction

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- Main properties

1. Efficiency: huge volume of transactions, cost and response time increased notably
   - improve scalability to increase capacity
   - optimize execution of smart contracts

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1. Efficiency: huge volume of transactions, cost and response time increased notably
    - improve scalability to increase capacity
    - optimize execution of smart contracts
2. Security: smart contracts public and immutable
    - errors exploited by attackers, economic impact
    - formal methods key to ensure security and provide safety guarantees

What do we need to know about smart contracts?

- *Smart contract*: open-source software on the blockchain
  - Not necessarily restricted to the classical concept of contract
  - Collection of secured stored functions
  - All records of the transactions stored on a public and decentralized blockchain

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- *Ethereum Virtual Machine* is used to run smart contracts
  - Rather standard stack-based language
  - Words of 256-bits
  - Three memory regions
    - ⋆ Operational stack
    - ⋆ Local memory
    - ⋆ Replicated storage

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  - Three memory regions
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    - ⋆ Replicated storage
- Relevant features for optimization:
  - Gas-metered execution

Gas-Metered Execution

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- *Price*: gas priced in the cryptocurrencies (*Ether*).

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300.000 → | 21.000 + 25.000 execution | →

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300.000 → 21.000 + 25.000 execution → 254.000

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30.000 →

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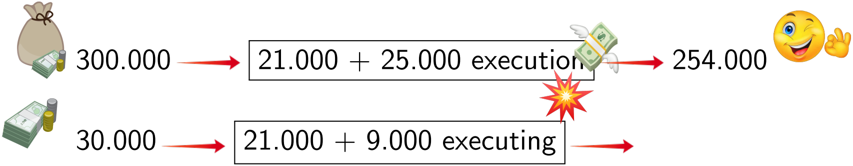

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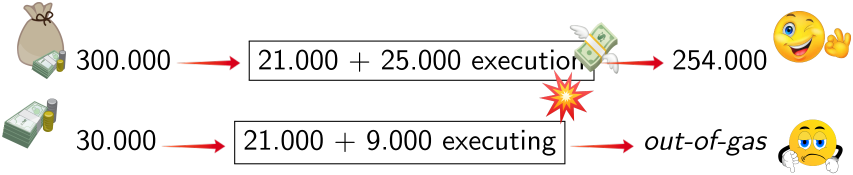

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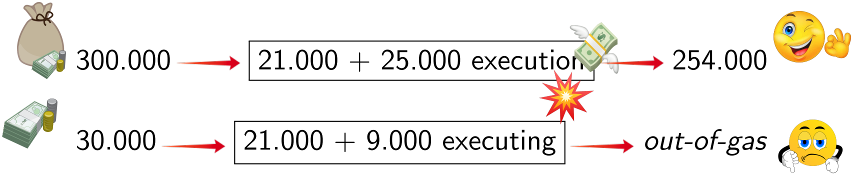

- Rationale of gas metering :
  - prevents attacks based on non-terminating executions;
  - avoids wasting *miners* computational resources;
  - discourages users to overuse replicated *storage*

Superoptimization

Superoptimization is a transformation technique that aims to find the optimal translation of a code by trying all posible loop-free sequences of instructions that produce the same result.

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Superoptimization

Superoptimization is a transformation technique that aims to find the optimal translation of a code by trying all posible loop-free sequences of instructions that produce the same result.

- **given:** loop-free sequence of code **s** and a cost function **C**
- **find:** target sequence **t** that
  1. has **minimal** cost **C(t)**
  2. correctly implements s
- **using:** constraint solver

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Superoptimization

Optimization criteria:

- GAS: fee for gas consumption of each EVM bytecode
- SIZE: fee for size in bytes

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Impact of gas size:

1. reduces the costs of transactions
2. enlarges Ethereum's capability to handle +transactions ...

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Superoptimization

Optimization criteria:

- GAS: fee for gas consumption of each EVM bytecode
- SIZE: fee for size in bytes

Impact of bytes-size

1. reduces deployment costs
2. maximum bytes-size allowed for deployment

GASOL: GAS Optimization tooLkit

ethereum foundation

Gas and size superoptimization tool for EVM smart contracts

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ethereum foundation

Gas and size superoptimization tool for EVM smart contracts

PUSH1 0x17	SWAP1
DUP1	SWAP3
SLOAD	AND
PUSH4 0xffffffff	SWAP2
NOT	SWAP1
AND	SWAP2
PUSH4 0xffffffff	OR
SWAP3	SWAP1

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Gas and size superoptimization tool for EVM smart contracts

```
PUSH1 0x17
DUP1
SLOAD
PUSH4 0xffffffff
NOT
AND
PUSH4 0xffffffff
SWAP3
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
SWAP1
```

Stack

s0

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ethereum foundation

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PUSH1 0x17	SWAP1
DUP1	SWAP3
SLOAD	AND
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NOT	SWAP1
AND	SWAP2
PUSH4 0xffffffff	OR
SWAP3	SWAP1

145 gas

25 bytes

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ethereum foundation

Gas and size superoptimization tool for EVM smart contracts

```
PUSH1 0x17
DUP1
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AND
PUSH4 0xffffffff
SWAP3
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
SWAP1
```

145 gas

25 bytes

Stack

0x17
OR(AND(0xffffffff, s0), AND(NOT(0xffffffff), SLOAD(0x17)))

GASOL: GAS OPTIMIZATION TOOLKIT

ethereum foundation

Gas and size superoptimization tool for EVM smart contracts

```
PUSH1 0x17          SWAP1
DUP1                SWAP3
SLOAD               AND
PUSH4 0xffffffff    SWAP2
NOT                 SWAP1
AND                 SWAP2
PUSH4 0xffffffff    OR
SWAP3               SWAP1
```

145 gas

25 bytes

Stack

0x17
OR(AND(0xffffffff, s0), AND(NOT(0xffffffff), SLOAD(0x17)))

```
PUSH4 0xffffffff
AND
PUSH32 0xff...00
PUSH1 0x17
SLOAD
AND
OR
PUSH1 0x17
```

GASOL: GAS Optimization tooLkit

ethereum foundation

Gas and size superoptimization tool for EVM smart contracts

```
PUSH1 0x17
DUP1
SLOAD
PUSH4 0xffffffff
NOT
AND
PUSH4 0xffffffff
SWAP3
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
SWAP1
```

145 gas
25 bytes

Stack

0x17
OR(AND(0xffffffff, s0), AND(NOT(0xffffffff), SLOAD(0x17)))

121 gas
46 bytes

```
PUSH4 0xffffffff
AND
PUSH32 0xff...00
PUSH1 0x17
SLOAD
AND
OR
PUSH1 0x17
```

GASOL: GAS OPTIMIZATION TOOLKIT

ethereum foundation

Gas and size superoptimization tool for EVM smart contracts

```
PUSH1 0x17          SWAP1
DUP1                SWAP3
SLOAD               AND
PUSH4 0xffffffff    SWAP2
NOT                 SWAP1
AND                 SWAP2
PUSH4 0xffffffff    OR
SWAP3               SWAP1
```

145 gas

25 bytes

127 gas

16 bytes

Stack

0x17
OR(AND(0xffffffff, s0), AND(NOT(0xffffffff), SLOAD(0x17)))

```
PUSH4 0xffffffff
DUP1
NOT
AND
PUSH1 0x17
SLOAD
AND
SWAP2
AND
OR
PUSH1 0x17
```

Plan of the talk

- Part I: Superoptimization framework (CAV'20, PLDI'24)

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- Part III: Neural-guided superoptimization (IST'25)
- Part IV: Proof-assistants to verify implementation (CAV'23)

Part I: Basic Superoptimization Framework

PART I: Basic Superoptimization Algorithm

Input: Program $\mathbf{P}$, Objective $\mathbf{Obj}$
Output: Optimized $\mathbf{P}'$, Gain $\mathbf{G}$
Ensures: $\mathbf{P} \equiv \mathbf{P}' \wedge \mathbf{Obj}(\mathbf{P}') \leq \mathbf{Obj}(\mathbf{P})$

PART I: Basic Superoptimization Algorithm

Input: Program **P**, Objective **Obj**
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```
procedure SUPEROPTIMIZATION(P,Obj)
    Seqs ← LoopFreeSequences(P)
    NewSq ←[ ]
```

LoopFreeSequences

Builds the CFG and extracts the sequences from the basic blocks (splits at jumps instructions and store operations)

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```
procedure SUPEROPTIMIZATION(P,Obj)
    Seqs ← LoopFreeSequences(P)
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    for (seq, ini) ∈ Seqs do
        final ←Symbolic(seq, ini)
        fin ←SimplificationRules(final)
```

Symbolic

Generates the symbolic state (initial state and final stack) from a given block and applies simplification rules

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        final ←Symbolic(seq, ini)
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        bounds ←ComputeBounds(seq, fin)
```

ComputeBounds

Infers a bound for the number of elements located in the stack and the number of instructions of the solution

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        bounds ← ComputeBounds(seq, fin)
        sol, gains ← SearchOptimal(ini, fin, Obj, bounds)
```

SearchOptimal

Finds the best equivalent sequence for the selected objective within the time limit using at Max-SMT solver

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        if gains > 0 ∧ CoqChecker(seq, sol) then
            NewSeq ← NewSeq.append((sol, gains))
        else
            NewSeq ← NewSeq.append((seq, 0))
        end if
    end for
```

CoqChecker

We use the Coq proof-assistant to ensure the optimal solution produces the same symbolic state as the initial state.

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            NewSeq ← NewSeq.append((sol, gains))
        else
            NewSeq ← NewSeq.append((seq, 0))
        end if
    end for
    P′,G ← BuildOptimizedCode(NewSeq)
end procedure
```

BuildOptimizedCode

There is a final step to reconstruct the bytecode from the optimized sequences (e.g., recalculate jump addresses)

From Smart Contracts to Sequences

Input: Program **P**, Objective **Obj**
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```

From Smart Contracts to Sequences

```

pragma solidity 0.8.9;
import "@openzeppelin/contracts/token/ERC20/IERC20.sol";
...
contract Bridge is Pool {
    using SafeERC20 for IERC20;

event Send(
    bytes32 transferId,
    ...
);
...
mapping(bytes32 => bool) public transfers;
uint32 public minimalMaxSlippage;
...
function setMinimalMaxSlippage(uint32 _minimalMaxSlippage)
  external onlyGovernor {
    minimalMaxSlippage = _minimalMaxSlippage;
}
...
```

From Smart Contracts to Sequences

...

```
JUMPDEST PUSH1 0x17 DUP1 SLOAD PUSH4 0xffffffff NOT AND PUSH4 0xffffffff
SWAP3 SWAP1 SWAP3 AND SWAP2 SWAP1 SWAP2 OR SWAP1 SSTORE JUMP
JUMPDEST CALLER PUSH1 0x00 SWAP1 DUP2 MSTORE PUSH1 0x8 PUSH1 0x20 MSTORE
PUSH1 0x40 SWAP1 SHA3 SLOAD PUSH1 0xff AND PUSH2 0x15d3 JUMPI
```

...

From Smart Contracts to Sequences

...

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...

CFG generator

...

(JUMPDEST PUSH1 0x17 DUP1 SLOAD PUSH4 0xffffffff NOT AND PUSH4 0xffffffff SWAP3 SWAP1 SWAP3 AND SWAP2 SWAP1 SWAP2 OR SWAP1 SSTORE JUMP)$_{B_1}$

(JUMPDEST CALLER PUSH1 0x00 SWAP1 DUP2 MSTORE PUSH1 0x8 PUSH1 0x20 MSTORE PUSH1 0x40 SWAP1 SHA3 SLOAD PUSH1 0xff AND PUSH2 0x15d3 JUMPI)$_{B_2}$

...

From Smart Contracts to Sequences

...

(JUMPDEST PUSH1 0x17 DUP1 SLOAD PUSH4 0xffffffff NOT AND PUSH4 0xffffffff SWAP3 SWAP1 SWAP3 AND SWAP2 SWAP1 SWAP2 OR SWAP1 SSTORE JUMP)$_{B_1}$

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...

Block generation

...

JUMPDEST (PUSH1 0x17 DUP1 SLOAD PUSH4 0xffffffff NOT AND PUSH4 0xffffffff SWAP3 SWAP1 SWAP3 AND SWAP2 SWAP1 SWAP2 OR SWAP1)$_{S_1}$ SSTORE JUMP

JUMPDEST (CALLER PUSH1 0x00 SWAP1 DUP2 MSTORE PUSH1 0x8 PUSH1 0x20)$_{S_2}$ MSTORE

(PUSH1 0x40 SWAP1 SHA3 SLOAD PUSH1 0xff AND PUSH2 0x15d3)$_{S_3}$ JUMPI

...

Symbolic Execution

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end procedure
```

Symbolic Execution

```
PUSH1 0x17
DUP1
SLOAD
PUSH4 0xffffffff
NOT
AND
PUSH4 0xffffffff
SWAP3
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
SWAP1
```

Symbolic Execution

```
PUSH1 0x17
DUP1
SLOAD
PUSH4 0xffffffff
NOT
AND
PUSH4 0xffffffff
SWAP3
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
SWAP1
```

$\boxed{s_0}$

Symbolic Execution

```
PUSH1 0x17
DUP1
SLOAD
PUSH4 0xffffffff
NOT
AND
PUSH4 0xffffffff
SWAP3
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
SWAP1
```

0x17
s_0

Symbolic Execution

```
  PUSH1 0x17
→ DUP1
  SLOAD
  PUSH4 0xffffffff
  NOT
  AND
  PUSH4 0xffffffff
  SWAP3
  SWAP1
  SWAP3
  AND
  SWAP2
  SWAP1
  SWAP2
  OR
  SWAP1
```

0x17
0x17
s_0

Symbolic Execution

```
  PUSH1 0x17
  DUP1
→ SLOAD
  PUSH4 0xffffffff
  NOT
  AND
  PUSH4 0xffffffff
  SWAP3
  SWAP1
  SWAP3
  AND
  SWAP2
  SWAP1
  SWAP2
  OR
  SWAP1
```

SLOAD(0x17)
0x17
s_0

Symbolic Execution

```
  PUSH1 0x17
  DUP1
  SLOAD
  PUSH4 0xffffffff
  NOT
  AND
→ PUSH4 0xffffffff
  SWAP3
  SWAP1
  SWAP3
  AND
  SWAP2
  SWAP1
  SWAP2
  OR
  SWAP1
```

0xffffffff
AND(NOT(0xffffffff), SLOAD(0x17))
0x17
s_0

Symbolic Execution

```
PUSH1 0x17
DUP1
SLOAD
PUSH4 0xffffffff
NOT
AND
PUSH4 0xffffffff
SWAP3   ←
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
SWAP1
```

s_0
AND(NOT(0xffffffff), SLOAD(0x17))
0x17
0xffffffff

Symbolic Execution

```
PUSH1 0x17
DUP1
SLOAD
PUSH4 0xffffffff
NOT
AND
PUSH4 0xffffffff
SWAP3
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
→SWAP1
```

0x17
OR(AND(0xffffffff,s_0), AND(NOT(0xffffffff), SLOAD(0x17)))

Rule-based Simplification

Input: Program **P**, Objective **Obj**
Output: Optimized **P′**, Gain **G**
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    end for
    P′,G ← BuildOptimizedCode(NewSeq)
end procedure
```

Rule-based Simplification

0x17
OR(AND(0xffffffff, s_0), AND(NOT(0xffffffff), SLOAD(0x17)))

Rule-based Simplification

0x17
OR(AND(0xffffffff,s_0), AND(NOT(0xffffffff), SLOAD(0x17)))

Rule-based Simplification

$$OP(X_{int}) \mapsto eval(OP, X_{int})$$

$$\texttt{NOT(0xffffffff)}$$

0x17
OR(AND(0xffffffff,s_0), AND(NOT(0xffffffff), SLOAD(0x17)))

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`0xffffffffffffffffffffffffffffffffffffffffffffffffffffffff00000000`

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OR(AND(0xffffffff,s_0), AND(0xfff...000, SLOAD(0x17)))

Compute Bounds

```
PUSH1 0x17
DUP1
SLOAD
PUSH4 0xffffffff
NOT
AND
PUSH4 0xffffffff
SWAP3
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
SWAP1
```

Bound on the number of instructions of the solution:

Initial length of the block ⇒ **16**

Compute Bounds

```
PUSH1 0x17
DUP1
SLOAD
PUSH4 0xffffffff
NOT
AND
→ PUSH4 0xffffffff
SWAP3
SWAP1
SWAP3
AND
SWAP2
SWAP1
SWAP2
OR
SWAP1
```

Bound on the stack elements:

Max elements stored in the stack ⇒ **4**

0xffffffff
AND(NOT(0xffffffff), SLOAD(0x17))
0x17
s_0

Searching for the Optimal Sequence

Input: Program **P**, Objective **Obj**
Output: Optimized **P′**, Gain **G**
Ensures: $\mathbf{P} \equiv \mathbf{P'} \wedge \mathbf{Obj}(\mathbf{P'}) \leq \mathbf{Obj}(\mathbf{P})$

```
procedure SUPEROPTIMIZATION(P,Obj)
    Seqs ← LoopFreeSequences(P)
    NewSq ←[ ]
    for (seq, ini) ∈ Seqs do
        final ← Symbolic(seq, ini)
        fin ← SimplificationRules(final)
        bounds ← ComputeBounds(seq, fin)
        sol, gains ← SearchOptimal(ini, fin, Obj, bounds)
        if gains > 0 ∧ CoqChecker(seq, sol) then
            NewSeq ← NewSeq.append((sol, gains))
        else
            NewSeq ← NewSeq.append((seq, 0))
        end if
    end for
    P′,G ← BuildOptimizedCode(NewSeq)
end procedure
```

SMT Encoding Step 1: Flattening

0x17
OR(AND(0xffffffff,s_0), AND(0xff...00, SLOAD(0x17)))

SMT Encoding Step 1: Flattening

$s_1 \mapsto$ `0x17`
$s_2 \mapsto$ `0xffffffff`
$s_3 \mapsto$ `0xff...00`

0x17
OR(AND(0xffffffff, s_0), AND(0xff...00, SLOAD(0x17)))

SMT Encoding Step 1: Flattening

$s_1 \mapsto$ 0x17
$s_2 \mapsto$ 0xffffffff
$s_3 \mapsto$ 0xff...00

s_1
OR(AND(s_2,s_0), AND(s_3,SLOAD(s_1)))

SMT Encoding Step 1: Flattening

$s_1 \mapsto \texttt{0x17}$

$s_2 \mapsto \texttt{0xffffffff}$

$s_3 \mapsto \texttt{0xff...00}$

$s_4 \mapsto \texttt{AND}(s_2, s_0)$

$s_5 \mapsto \texttt{SLOAD}(s_1)$

s_1
$\texttt{OR}(s_4,\texttt{AND}(s_3,s_5))$

SMT Encoding Step 1: Flattening

$s_1 \mapsto \texttt{0x17}$
$s_2 \mapsto \texttt{0xffffffff}$
$s_3 \mapsto \texttt{0xff...00}$
$s_4 \mapsto \texttt{AND}(s_2, s_0)$

$s_5 \mapsto \texttt{SLOAD}(s_1)$
$s_6 \mapsto \texttt{AND}(s_3, s_5)$
$s_7 \mapsto \texttt{OR}(s_4, s_6)$

s_1
s_7

SMT Step 2: Modeling the Stack & Opcodes

`INITIAL`	s_0
`PUSH1 0x17`	$s_1 \mid s_0$
`DUP1`	$s_1 \mid s_1 \mid s_0$
...	...
`SWAP2`	$s_3 \mid s_6 \mid s_2$
`OR`	$s_7 \mid s_1$
`SWAP1`	$s_1 \mid s_7$

SMT Step 2: Modeling the Stack & Opcodes

	0	1	2	3
`INITIAL`	s_0	$\perp$	$\perp$	$\perp$
`PUSH1 0x17`	s_1	s_0	$\perp$	$\perp$
`DUP1`	s_1	s_1	s_0	$\perp$
...	...			
`SWAP2`	s_3	s_6	s_2	$\perp$
`OR`	s_7	s_1	$\perp$	$\perp$
`SWAP1`	s_1	s_7	$\perp$	$\perp$

18

SMT Step 2: Modeling the Stack & Opcodes

$x_{0,0}$	$x_{0,1}$	$x_{0,2}$	$x_{0,3}$
$x_{1,0}$	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$
$x_{2,0}$	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$
...			
$x_{15,0}$	$x_{15,1}$	$x_{15,2}$	$x_{15,3}$
$x_{16,0}$	$x_{16,1}$	$x_{16,2}$	$x_{16,3}$
$x_{17,0}$	$x_{17,1}$	$x_{17,2}$	$x_{17,3}$

18

SMT Step 2: Modeling the Stack & Opcodes

	$x_{0,0}$	$x_{0,1}$	$x_{0,2}$	$x_{0,3}$	
t_1	$x_{1,0}$	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$	
t_2	$x_{2,0}$	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$	
$\cdots$		$\cdots$			18
t_{15}	$x_{15,0}$	$x_{15,1}$	$x_{15,2}$	$x_{15,3}$	
t_{16}	$x_{16,0}$	$x_{16,1}$	$x_{16,2}$	$x_{16,3}$	
t_{17}	$x_{17,0}$	$x_{17,1}$	$x_{17,2}$	$x_{17,3}$	

SMT Step 2: Modeling the Stack & Opcodes

	$x_{15,0}$	$x_{15,1}$	$x_{15,2}$	$x_{15,3}$
t_{16}	$x_{16,0}$	$x_{16,1}$	$x_{16,2}$	$x_{16,3}$

SMT Step 2: Modeling the Stack & Opcodes

	$x_{15,0}$	$x_{15,1}$	$x_{15,2}$	$x_{15,3}$
t_{16}	$x_{16,0}$	$x_{16,1}$	$x_{16,2}$	$x_{16,3}$

$t_{16} = \texttt{SWAP2}$

SMT Step 2: Modeling the Stack & Opcodes

	$x_{15,0}$	$x_{15,1}$	$x_{15,2}$	$x_{15,3}$
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t_{16}	$x_{15,2}$	$x_{16,1}$	$x_{15,0}$	$x_{16,3}$

$$t_{16} = \texttt{SWAP2} \rightarrow (x_{16,0} = x_{15,2}) \wedge (x_{16,2} = x_{15,0})$$

SMT Step 2: Modeling the Stack & Opcodes

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	$x_{15,0}$	$x_{15,1}$	$x_{15,2}$	$x_{15,3}$
t_{16}	$x_{15,2}$	$x_{15,1}$	$x_{15,0}$	$x_{15,3}$

$$t_{16} = \texttt{SWAP2} \rightarrow (x_{16,0} = x_{15,2}) \wedge (x_{16,2} = x_{15,0}) \wedge (x_{16,1} = x_{15,1}) \wedge (x_{16,3} = x_{15,3})$$

Max-SMT Encoding

- Complete encoding

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  1. Constraints to describe the initial stack

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  4. Non-stack operations considered as uninterpreted functions

$$hard = \bigwedge_{0 \leqslant j < Lbound} 0 \leq t_j \leq Ins \ \wedge I \ \wedge F \ \wedge C_{\texttt{PUSH}}(j) \ \wedge \ C_{\texttt{SWAP}k}(j) \ \wedge .. \bigwedge_{f \in Ins_U} C_U(j, f$$

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  - SMT formula ⇒ hard constraints

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  - SMT formula ⇒ hard constraints
  - Cost of every EVM instruction ⇒ soft constraints
  - Two different criteria to optimize (original 145 gas and 25 bytes)
    - Gas model: 121 gas and 46 bytes
    - Bytes-size model:127 gas and 16 bytes

Experimental Evaluation

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  3. Gas optimized: 0.64%
     - ⋆ ⇒ 167.440,98 USD in one day
     - ⋆ ⇒ more than 61M USD in one year (assuming they are uniformly distributed)

Part II: Extension to Memory Operations

Motivation

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- Our basic framework can potentially achieve more savings by including operations beyond stack operations
- Idea: extend the basic framework to handle *memory* operations
- Limitation: great overhead when modelling *memory* extensions in superoptimization
  - In fact, EBSO and SOUPER superoptimizers avoid it
- Proposal: leverage our basic two-staged method
  - Detecting redundant memory accesses as simplification rules
  - Extend the Max-SMT encoding using a *dependency order* among instructions

Superoptimization Algorithm With Memory

Input: Program **P**, Objective **Obj**
Output: Optimized **P′**, Gain **G**
Ensures: $\mathbf{P} \equiv \mathbf{P'} \wedge \mathbf{Obj}(\mathbf{P'}) \leq \mathbf{Obj}(\mathbf{P})$

```
procedure Superoptimization(P,Obj)
    Seqs ← LoopFreeSequences(P)
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    for (seq, ini) ∈ Seqs do
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    end for
    P′,G ← BuildOptimizedCode(NewSeq)
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Symbolic Execution

```
PUSH1 0x80
PUSH1 0x40
MSTORE
...
SLOAD
...
SSTORE
...
SLOAD
...
SSTORE
...
CALLVALUE
DUP1
ISZERO
```

Stack:

Memory:

Storage:

Symbolic Execution

```
PUSH1 0x80
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MSTORE
...
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```

Stack:

Memory:

$\texttt{MSTORE}_3(\texttt{0x80,0x40})$

Storage:

Symbolic Execution

```
PUSH1 0x80
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MSTORE
...
▶SLOAD
...
SSTORE
...
SLOAD
...
SSTORE
...
CALLVALUE
DUP1
ISZERO
```

Stack:

Memory:

$\texttt{MSTORE}_3(\texttt{0x80,0x40})$

Storage:

$\texttt{SLOAD}_{10}(\texttt{0x01})$

Symbolic Execution

```
PUSH1 0x80      SLOAD
PUSH1 0x40      ...
MSTORE          SSTORE
...             ...
SLOAD           CALLVALUE
...             DUP1
SSTORE        ▶ ISZERO
...
```

Stack:

CALLVALUE
ISZ(CALLVALUE)

Memory:

$\mathtt{MSTORE}_3(\mathtt{0x80,0x40})$

Storage:

$\mathtt{SLOAD}_{10}(\mathtt{0x01})$	$\mathtt{SSTORE}_{23}(\mathtt{0x01},V1)$	$\mathtt{SLOAD}_{31}(\mathtt{0x01})$	$\mathtt{SSTORE}_{44}(\mathtt{0x01},V2)$

Rule-based Memory Simplifications

Notion of Conflict

Two memory instructions A and B have a *conflict*, denoted as conf(A,B) if:

(i) A is a store and B is a load and the positions they access might be the same;

(ii) A and B are both stores, the positions they modify might be the same, and they store different values.

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- If a `STORE`(p, v) is followed by a `LOAD`(p) instruction with no conflicting `STORE` in between, replace the `LOAD`(p) with v

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- If a $\texttt{STORE}(p, v)$ is followed by a $\texttt{LOAD}(p)$ instruction with no conflicting `STORE` in between, replace the $\texttt{LOAD}(p)$ with v
- If two `STORE` instructions access the same position with no `LOAD` in between, remove the first `STORE`
- If there is a $\texttt{STORE}(p, \texttt{LOAD}(p))$ instruction and position p is not modified by another `STORE` instruction, remove this instruction

Memory Simplifications - Example

$\texttt{SLOAD}_{10}(\texttt{0x01})$	$\texttt{SSTORE}_{23}(\texttt{0x01},V1)$	$\texttt{SLOAD}_{31}(\texttt{0x01})$	$\texttt{SSTORE}_{44}(\texttt{0x01},V2)$

Memory Simplifications - Example

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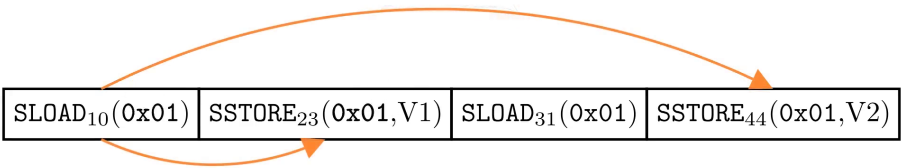
Memory Simplifications - Example

0x01 0x01

$\texttt{SLOAD}_{10}(\texttt{0x01})$	$\texttt{SSTORE}_{23}(\texttt{0x01,V1})$	$\texttt{SLOAD}_{31}(\texttt{0x01})$	$\texttt{SSTORE}_{44}(\texttt{0x01,V2})$

Memory Simplifications - Example



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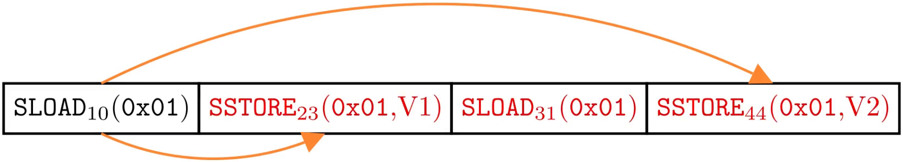

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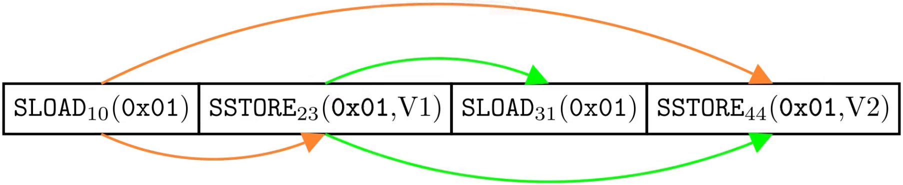

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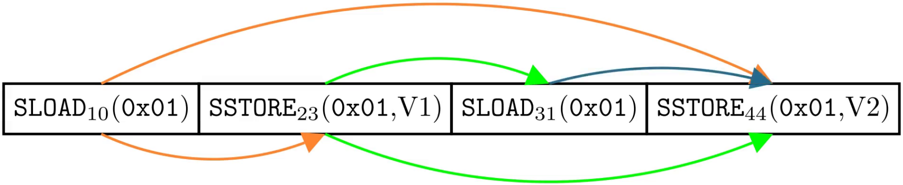

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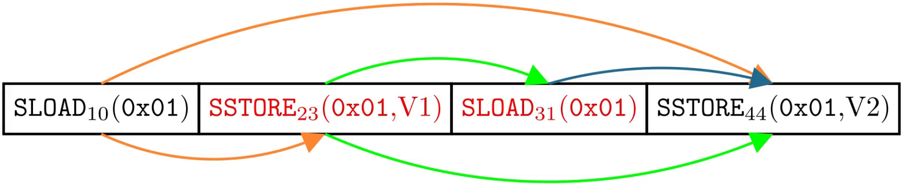

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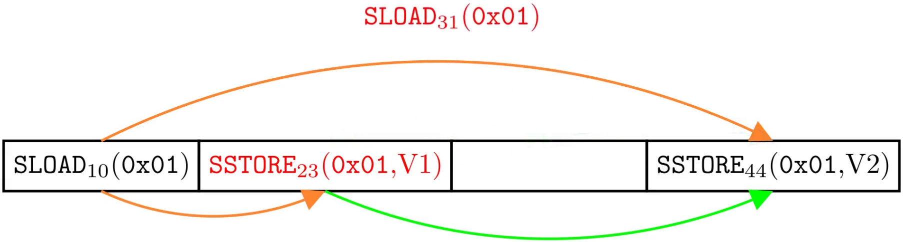

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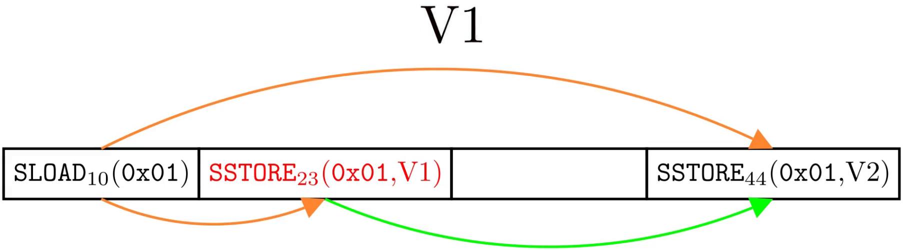
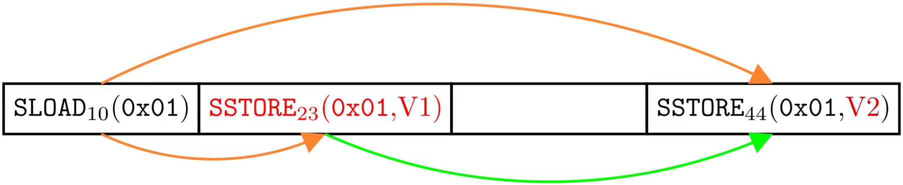


Memory Simplifications - Example

$$V2' = V2[\mathtt{SLOAD}_{31} \mapsto V1]$$



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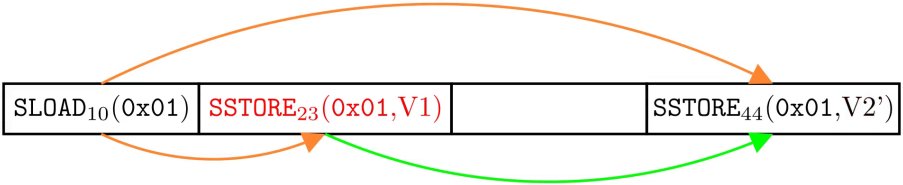

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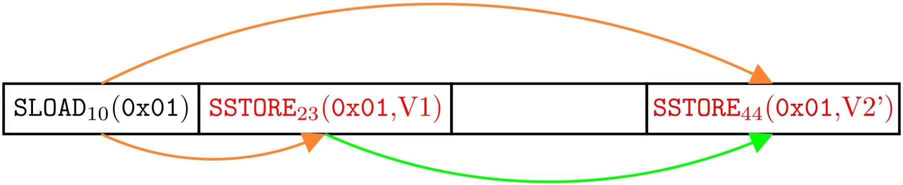

Memory Simplifications - Example

Dependency Order

Dependency Order

Let A and B be two instructions in a sequence S. We say that B has to be executed after A in S, denoted as $A \sqsubset B$ if conf(A,B).

i) There is no conflict between LOADS

ii) Dependencies are added after simplification

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⇒Introduce variables l_A, l_B to track their positions

$$l_A < l_B \text{ where } A \sqsubset B$$

$$l_{10} < l_{44} \text{ where } \texttt{SLOAD}_{10} \sqsubset \texttt{SSTORE}_{44}$$

Experimental Evaluation

- 1 benchmark set:
  - 30 latest verified smart contracts compiled with latest **solc** version at the moment (0.8.9)

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  3. 0.72%⇒ 185,754.82 USD in one day
  4. 0.1% ⇒ 26,162.65 USD in one day

Part III: Neural-Guided Superoptimization

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- Motivation
  - Quite often the blocks to superoptimize are already optimal
  - The initial bound is often larger than needed, resulting in an unnecessary overhead
- Proposal: incorporate machine learning techniques to tackle the previous issues
  - Our superoptimization framework provides us with an unlimited source of information for the supervised learning
  - There are patterns of code identify the previous behaviour

Neural-Guided Superoptimization Algorithm

Input: Program **P**, Objective **Obj**
Output: Optimized $\mathbf{P'}$, Gain **G**
Ensures: $\mathbf{P} \equiv \mathbf{P'} \wedge \mathbf{Obj}(\mathbf{P'}) \leq \mathbf{Obj}(\mathbf{P})$

```
procedure SUPEROPTIMIZATION(P,Obj)
    Seqs ← LoopFreeSequences(P)
    NewSq ←[ ]
    for (seq, ini) ∈ Seqs do
        optimize ← PredictOptimizable(s,Obj)
        if optimize then
```

PredictOptimizable

`PredictOptimizable` classifier that predicts two classes: *already optimal* or *not optimal*

Neural-Guided Superoptimization Algorithm

Input: Program **P**, Objective **Obj**
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        if optimize then
            final ← Symbolic(seq, ini)
            fin ← SimplificationRules(final)
            bounds ← ComputeBounds(seq,fin)
```

ComputeBounds

ComputeBounds determines an **upper bound** and a **lower bound** on the minimum number of instructions

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            bounds ← ComputeBounds(seq,fin)
            sz ← PredictBlockSizeBound(seq, bounds,Obj)
            sol, gains ← SearchOptimal(ini, fin, Obj, sz, bounds)
            if gains > 0 ∧ CoqChecker(seq, sol) then
                NewSeq ← NewSeq.append((sol, gains))
            else
                NewSeq ← NewSeq.append((seq, 0))
            end if
        end if
    end for
    P′,G ← BuildOptimizedCode(NewSeq)
end procedure
```

PredictBlockSizeBound

PredictBlockSizeBound regression model to predict the length needed to compute an optimal sequence

Experimental Setup

- Training:

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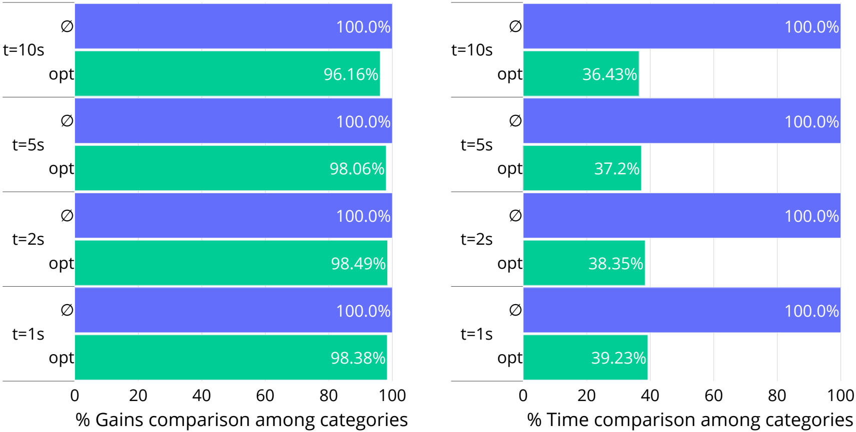
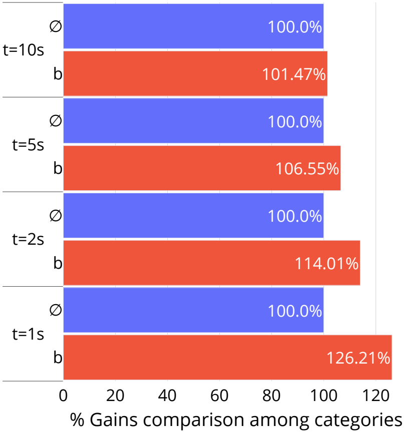
- Experimental Setup:
  - 100 most-called contracts deployed on Ethereum compiled with recent versions of solc
    - 41,106,276 transactions in total
  - We run different configurations that with combinations of:
    - Different timeouts $n = 10, 5, 2, 1s$
    - Selectively enabling each of the previous two models

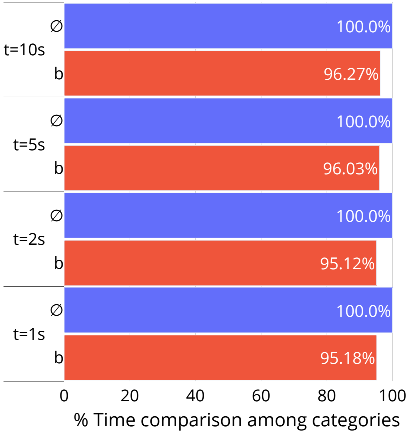
Experimental Evaluation



- `PredictOptimizable`:
  - Preserves more than 96% of the savings!
  - Time reduction up to 40% of the initial configuration

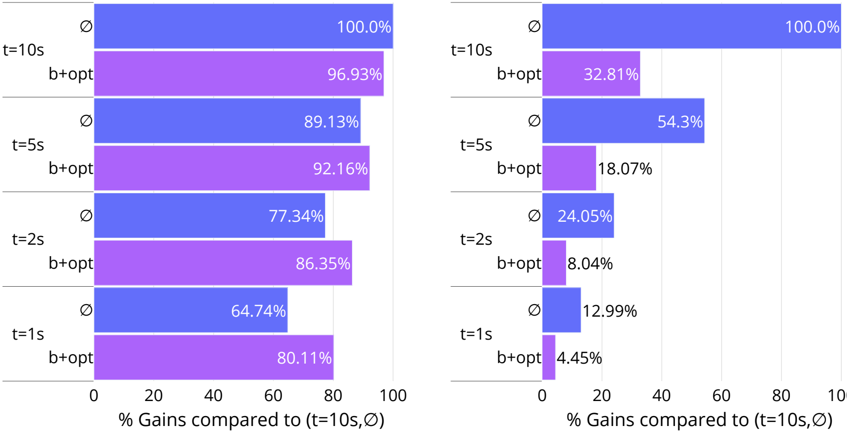
Experimental Evaluation





- `PredictBlockSizeBound`:
  - Achieves $>$ 100% of the gains consistently
  - Greater percentage of gains when decreasing the time limit

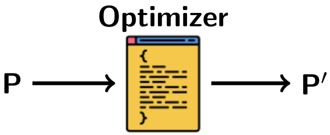
Experimental Evaluation



- Configuration chosen: $(t = 2s, \texttt{b+opt})$ with both models enabled
  - Average optimization time per contract: $\sim$3 min
  - $1.24 M savings on these contracts!

Part IV: Verification of Optimization Results

Verification of Results



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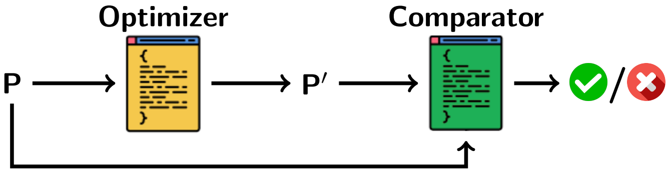

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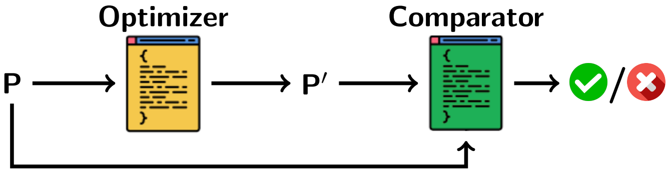
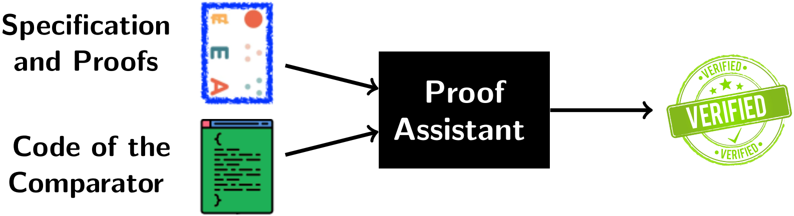


We develop the comparator using the proof assistant's (programming) language, and prove its correctness.



Spec: If it returns ✓, then P and P' are semantically equivalent.

Optimization Example

```
PUSH1 0x17, DUP1, SLOAD, PUSH4 0xffffffff, NOT, AND, PUSH4
0xffffffff, SWAP3, SWAP1, SWAP3, AND, SWAP2, SWAP1, SWAP2,OR, SWAP1
```

```
PUSH4 0xffffffff, AND PUSH32, 0xff...00000000, PUSH1 0x17, SLOAD,
AND, OR, PUSH1 0x17
```

Optimization Example

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PUSH1 0x17, DUP1, SLOAD, PUSH4 0xffffffff, NOT, AND, PUSH4
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s_0

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s_0

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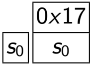

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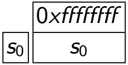

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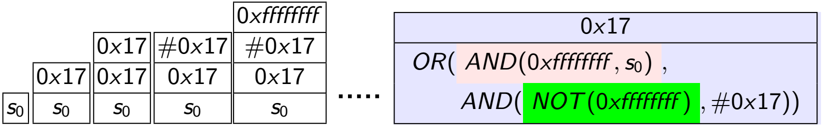


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PUSH4 0xffffffff, AND PUSH32, 0xff...00000000, PUSH1 0x17, SLOAD,
AND, OR, PUSH1 0x17
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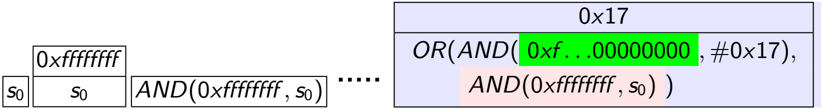

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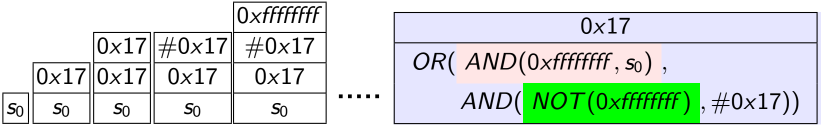


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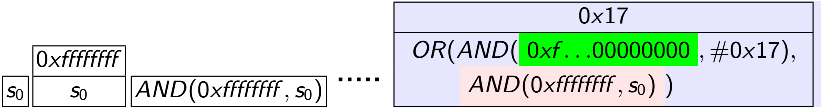
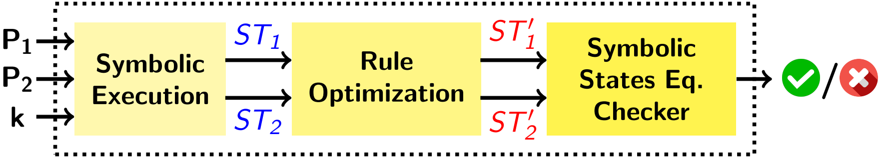


The final stacks are equivalent due to:

- Simplification rule: $NOT(0xffffffff) = 0xf\ldots00000000$.
- Comutativity of OR

Verification of Results




```
Theorem opt_correct:
  forall (p1 p2 : prog) (k: nat),
    eq_chkr p1 p2 k = true →
      forall (s : stack), length s = k → evmSem p1 s = evmSem p2 s.
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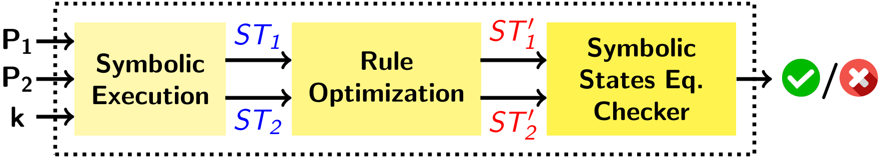

ST_1:

0x17
$OR(AND(0xffffffff, s_0), AND(NOT(0xffffffff), \#0x17))$

ST_2:

0x17
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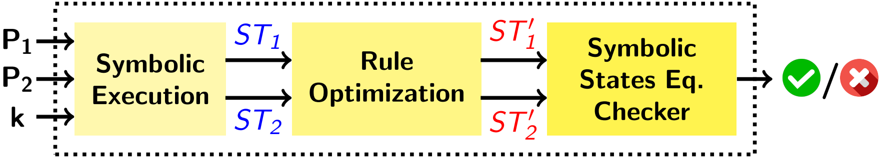

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Future Work

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- Superoptimization of other Stack-Based Languages

Thank you for your attention!