Blockchain Superoptimizer

Julian Nagele **Maria A Schett**

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Overview

- Ethereum smart contracts are executed as bytecode on the Ethereum Virtual Machine (EVM)

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PUSH 0
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PUSH 3
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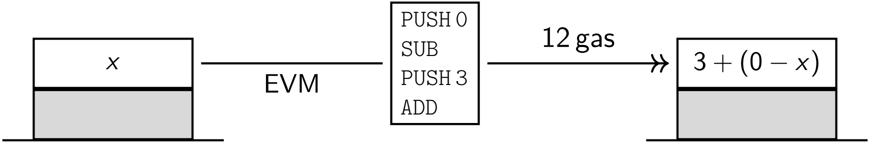

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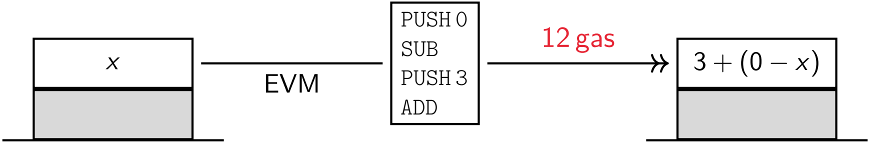

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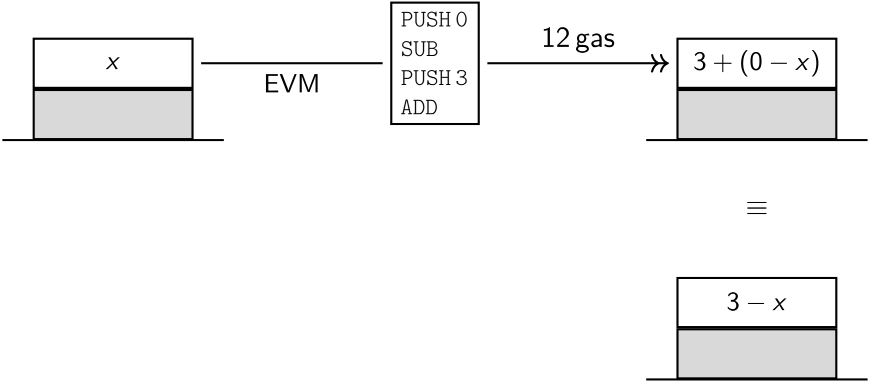

x

EVM

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12 gas

$3 + (0 - x)$

$\equiv$

$3 - x$

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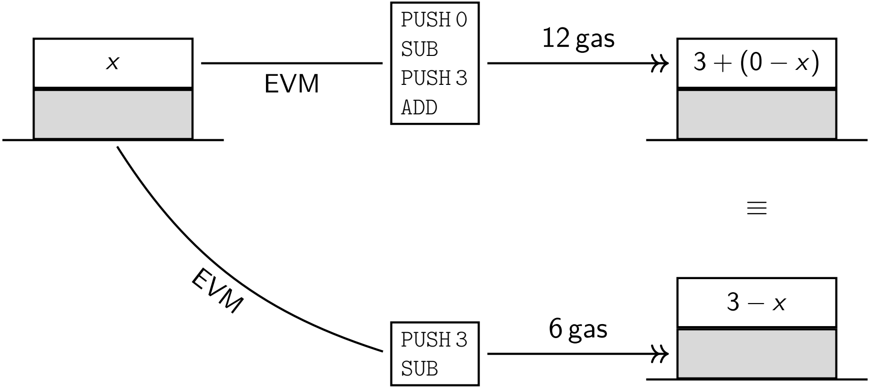

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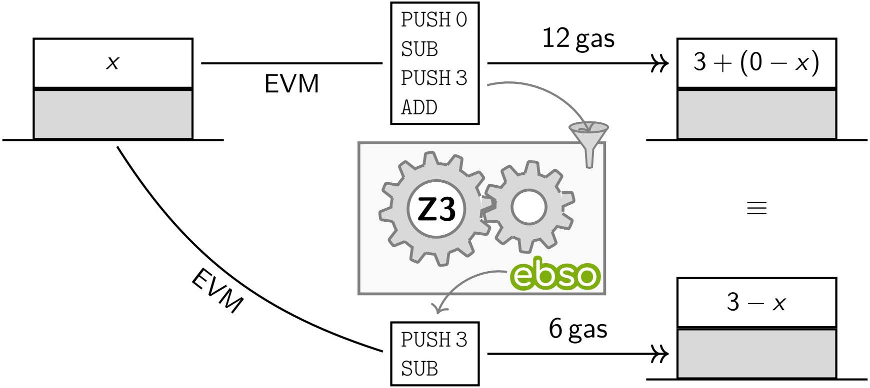

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- EVM gas provides **clear cost model**
- formal semantics [Yellow Paper, 2018]
- $\exists$ data sets for evaluation

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Today

- feedback on ideas for future work (post-proceedings)

Superoptimization

Superoptimization

- **given:** source program s & cost function C
- **find:** target program t that
  1. has minimal cost $C(t)$
  2. correctly implements s
- **using:** a constraint solver

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program $\iota_1 \; \iota_2 \; \cdots \; \iota_n$

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Satisfiability Modulo Theories (SMT) Solver

- first-order logic with background theories
  - bit vectors, integers, uninterpreted functions

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Uninterpreted Functions

functions a, f, f' s.t.

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- $f(1) = a(1) \wedge f'(1) = 42$ UNSAT

Superoptimization [Massalin 1987]

- enumerate all possible candidate programs t in increasing cost

$\exists \vec{x}$. to distinguish s & t?

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- `PUSH` *w* where *w* is a 256 bit word $\implies$ 2^{256} candidates

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Templates [Gulwani et al. 2011]

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Example

$$\texttt{PUSH 0 SUB PUSH 3 ADD} \quad \rightsquigarrow \quad \underline{\texttt{PUSH}\, a(1)}_1\ \underline{\texttt{SUB}}_2$$

$$a(1) = 3 \qquad a(j) = \_$$

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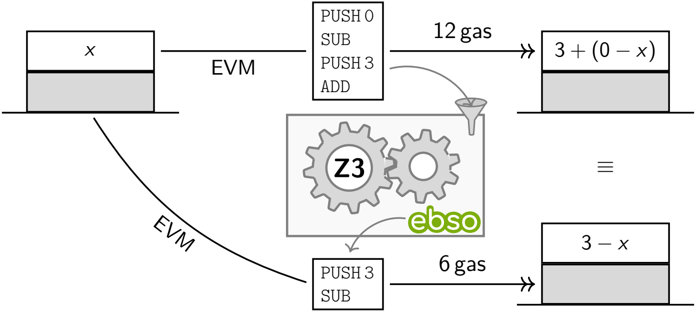
Unbounded Superoptimization [Jangda&Yorsh 2017]

- shift search in solver

$$\exists (t : \text{Pos} \to \text{Instr})\ \forall \vec{x}.\ t \text{ implements } s \ \&\ C(t) < C(s)?$$

SMT Encoding

Ingredients



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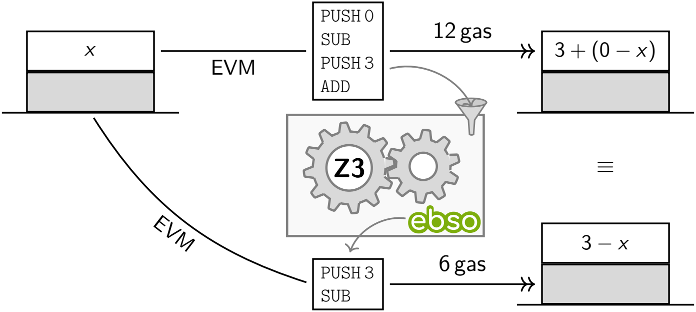

state stack, used gas, stack counter . . .

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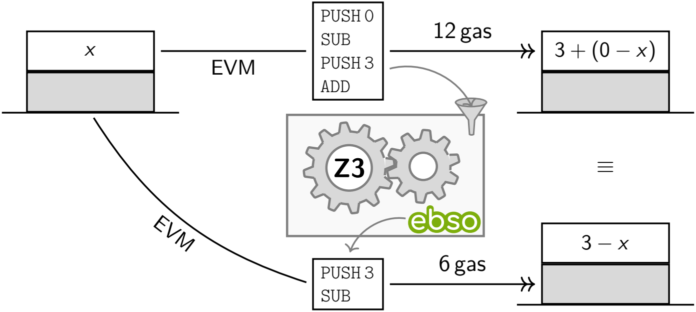

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$\twoheadrightarrow$ operational semantics of EVM

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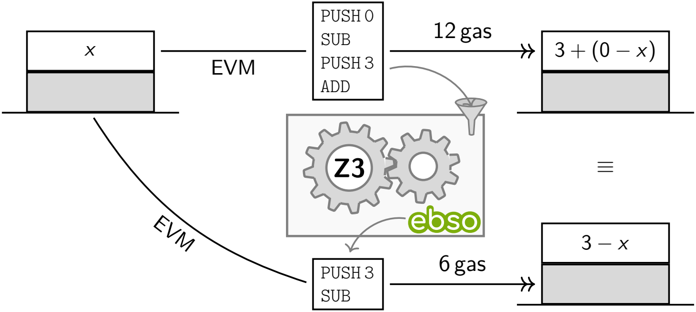

state	stack, used gas, stack counter . . .
$\twoheadrightarrow$	operational semantics of EVM
$\equiv$	equality on states

State & $\twoheadrightarrow$

state $\sigma = \langle \mathsf{stk}, \mathsf{c}, \mathsf{g} \rangle$ consists of

- stk(j, ℓ): ℓ-th word on **stack** after j instructions (on input $\vec{x}$)
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  $\mathsf{stk}(j+1, \top_{j+1}) = 3$ for $\iota = \mathtt{PUSH}\,3$ and s
  $\mathsf{stk}(j+1, \top_{j+1}) = a(j)$ for $\iota = \mathtt{PUSH}$ and t

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for program $p = \iota_0, \ldots, \iota_n$, define $\sigma_0 \overset{p}{\twoheadrightarrow} \sigma_{|p|}$ as $\bigwedge_{0 \leqslant j \leqslant n} \sigma_j \overset{\iota_j}{\to} \sigma_{j+1}$

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$\underline{\texttt{PUSH}\ a(1)}_1\ \underline{\texttt{SUB}}_2$

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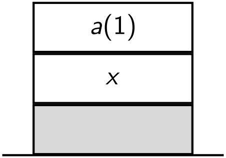
$j = 0:$ $\quad \mathsf{stk}(j,1) = x$ $\qquad \mathsf{g}(j) = 0 \quad \top_j = \ 1$

Example

$\underline{\texttt{PUSH}\ a(1)}_1\ \underline{\texttt{SUB}}_2$

$j = 0:$	$\mathsf{stk}(j,1) = x$		$\mathsf{g}(j) = 0$	$\top_j = 1$
$j = 1:$	$\mathsf{stk}(j,1) = x$	$\mathsf{stk}(j,2) = a(j)$	$\mathsf{g}(j) = 3$	$\top_j = 2$



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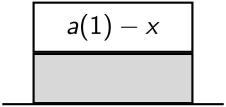
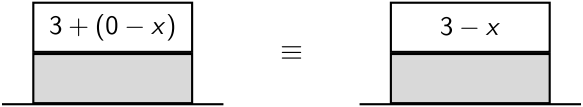
j = 1: & \mathsf{stk}(j,1) = x & \mathsf{stk}(j,2) = a(j) & \mathsf{g}(j) = 3 & \top_j = & 2 \\
j = 2: & \mathsf{stk}(j,1) = a(1) - x & & \mathsf{g}(j) = 6 & \top_j = & 1
\end{array}$$



Equality

$\sigma_j \equiv \sigma'_{j'}$ states σ and σ' after j and j' instructions



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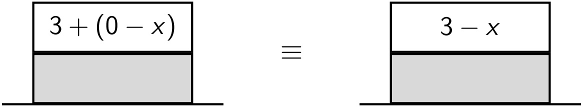

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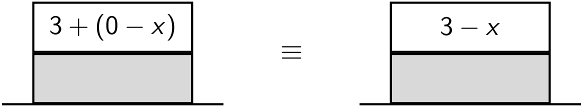

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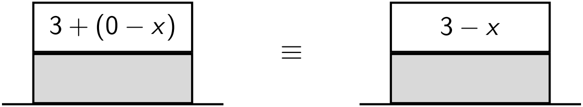
  $$\forall \ell < \top_j.\, \sigma.\mathsf{stk}(j,\ell) = \sigma'.\mathsf{stk}(j',\ell)$$
- not equal **gas**



Basic Superoptimization

$$\exists (a : \mathrm{Pos} \to \mathrm{Word})\ \forall \vec{x} \text{ s.t. } t \text{ implements } s?$$

Unbounded Superoptimization

$$\exists (t : \mathrm{Pos} \to \mathrm{Instr})\ \forall \vec{x} \text{ s.t. } t \text{ implements } s \;\&\; C(t) < C(s)?$$

Basic Superoptimization

$\exists(a : \text{Pos} \to \text{Word})\ \forall\vec{x}$ s.t. t implements s?

$$\exists a\ \forall\vec{x}.\, \sigma_0 \overset{s}{\twoheadrightarrow} \sigma \wedge \sigma_0 \overset{t}{\twoheadrightarrow} \sigma' \wedge \sigma_{|s|} \equiv \sigma'_{|t|}$$

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$\exists(t : \mathsf{Pos} \rightarrow \mathsf{Instr})\ \forall \vec{x}$ s.t. t implements s & $C(t) < C(s)$?

$$\exists n\ \exists t\ \forall \vec{x}.\, \sigma_0 \overset{s}{\twoheadrightarrow} \sigma \wedge\ \sigma_0 \equiv \sigma'_0 \wedge \sigma_{|s|} \equiv \sigma'_n \wedge \sigma.\mathrm{g}(|s|) > \sigma'.\mathrm{g}(n) \wedge$$

$$\forall j < n.\ \bigwedge_{\iota \in \mathsf{Instr}} t(j) = \iota \implies \sigma'_j \xrightarrow{\iota_j} \sigma'_{j+1} \wedge \bigvee_{\iota \in \mathsf{Instr}} t(j) = \iota \wedge$$

Implementation

Implementation

- available at

`github.com/juliannagele/ebso`

- implemented in OCaml
- $\sim$1.6 kloc (encoding 1 kloc), 635 tests
- using Z3 as SMT solver

Interface

```
$ ./ebso -direct "600003600301"
Optimized PUSH 0 SUB PUSH 3 ADD to
PUSH 3 SUB
Saved 6 gas,
this instruction sequence is optimal.
```

Translation Validation

- **given:** large word size of EVM 256 bit $\implies$ scalability problems
- **solution:** find t for small word size & validate for 256 bit

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- for word size 2 bit
  - `PUSH 0 SUB PUSH 3 ADD` optimizes to `NOT`
  - because the binary representation of 3 is `11`.

ebso Blocks

- **smart contract**

```
60806040526040805190810160405280600481526020017f48312e3000000000000000000000000
0000000000000000000000000000000008152506006908051906020019062000051929190620001
6e565b503480156200005f57600080fd5b50620186a06000803373fffffffffffffffffffffffff
fffffffffffffff1673ffffffffffffffffffffffffffffffffffffffff16815260200190815260
200160002081905550620f424060...
```

`LOG EXP JUMP CALLVALUE DUP1 ISZERO PUSH81 MLOAD`

ebso Blocks

- **smart contract**

60806040526040805190810160405280600481526020017f48312e3000000000000000000000000

000000000000000000000000000000000008152506006908051906020019062000051929190620001

6e565b503480156200005f57600080fd5b50620186a06000803373fffffffffffffffffffffffff

fffffffffffffff1673ffffffffffffffffffffffffffffffffffffffff16815260200190815260

2001600020819055550620f424060...

- split at **ebso blocks**

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    1. unencoded/unencodable instructions (memory!)

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ebso Blocks

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6e565b503480156200005f57600080fd5b50620186a06000803373fffffffffffffffffffffffff
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200160002081905550620f424060...
```

- split at **ebso blocks**
  1. unencoded/unencodable instructions (memory!)
  2. change in control flow

`~~LOG~~ ~~EXP~~ ~~JUMP~~ CALLVALUE DUP1 ISZERO PUSH 81 ~~MLOAD~~`

Evaluation

EvaluationS

1. **“Optimize the Optimized”**
    - ⋆ Gas Golfing Contest: 199 `Solidity` contracts
    - ⋆ $\implies$ 2743 ebso blocks
2. **“Basic vs. Unbounded”**
    - ⋆ bytecode of 2500 most called contracts from Etherum Blockchain
    - ⋆ $\implies$ 61217 ebso blocks

- 60 min/15 min time-out on 1 core at 2.40 GHz with 1 GiB RAM
- validation with pseudo-random input on `go-ethereum` EVM

Optimize The Optimized (1)

$s = \texttt{CALLVALUE DUP ISZERO PUSH 81}$

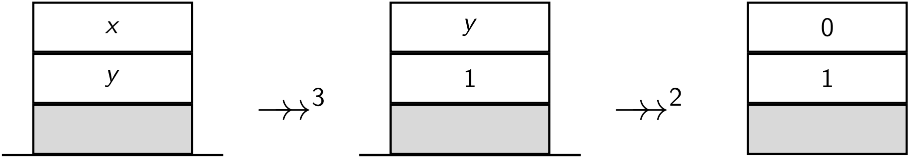
to $t = \texttt{CALLVALUE CALLVALUE ISZERO PUSH 81}$

- $C(\texttt{DUP}) = 3\,\text{gas} > C(\texttt{CALLVALUE}) = 2\,\text{gas}$

Optimize The Optimized (2)

$s = \texttt{POP PUSH 1 SWAP POP PUSH 0}$

to $t = \texttt{SLT DUP EQ PUSH 0}$



Basic vs. Unbounded (1)

- in our setting

Basic vs. Unbounded (1)

- in our setting

$$\textbf{Unbounded} > \textbf{Basic}$$

Basic vs. Unbounded (2)

	Unbounded	
	#	%
optimized		
time-out		
proved optimal		

Basic vs. Unbounded (2)

	Unbounded	
	#	%
optimized[1]	943	1.54 %
time-out		
proved optimal		

---

[1] shown optimal: 393

Basic vs. Unbounded (2)

	Unbounded	
	#	%
optimized[1]	943	1.54 %
time-out	56 392	92.12 %
proved optimal		

---

[1] shown optimal: 393

Basic vs. Unbounded (2)

	Unbounded	
	#	%
optimized[1]	943	1.54 %
time-out	56 392	92.12 %
proved optimal	3882	6.34 %

---

[1] shown optimal: 393

Conclusion

Future Work (1)

- performance/time-outs

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Feedback

Future Work (1)

- performance/time-outs

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1. tune encoding
   - not use theory of integers *and* bit vectors, remove storage constraints, . . .

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   - ⋆ not use theory of integers *and* bit vectors, remove storage constraints, ...
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   - ⋆ exclude rare instructions from Instr, ...

Future Work (1)

- performance/time-outs

Feedback

1. tune encoding
    - not use theory of integers *and* bit vectors, remove storage constraints, . . .
2. use domain knowledge
    - exclude rare instructions from Instr, . . .
3. tune solver
    - strategy, different solvers

Future Work (2)

- generate peephole optimization rules

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- SuperOptimization-based Rule Generator **sorg**[2]

---

[2] available at `github.com/mariaschett/sorg`

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sorg

- $s =$ `CALLVALUE DUP ISZERO PUSH 81`
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- $s =$ `CALLVALUE DUP ISZERO PUSH 81`
  to $t =$ `CALLVALUE CALLVALUE ISZERO PUSH 81`
- **rule**: `CALLVALUE DUP` → `CALLVALUE CALLVALUE`

---

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Future Work (2)

- generate peephole optimization rules
- SuperOptimization-based Rule Generator **sorg**[2]

- $s =$ `CALLVALUE DUP ISZERO PUSH 81` to $t =$ `CALLVALUE CALLVALUE ISZERO PUSH 81`
- **rule**: `CALLVALUE DUP` → `CALLVALUE CALLVALUE`
- found **397** distinct rules from 943 optimized ebso blocks

---

[2] available at `github.com/mariaschett/sorg`

Thank you & questions?

ebso

available at `github.com/juliannagele/ebso`

`[mail@]jnagele.net` `[mail@]maria-a-schett.net`

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