Synthesis-Powered Optimization of Smart Contracts via Data Type Refactoring

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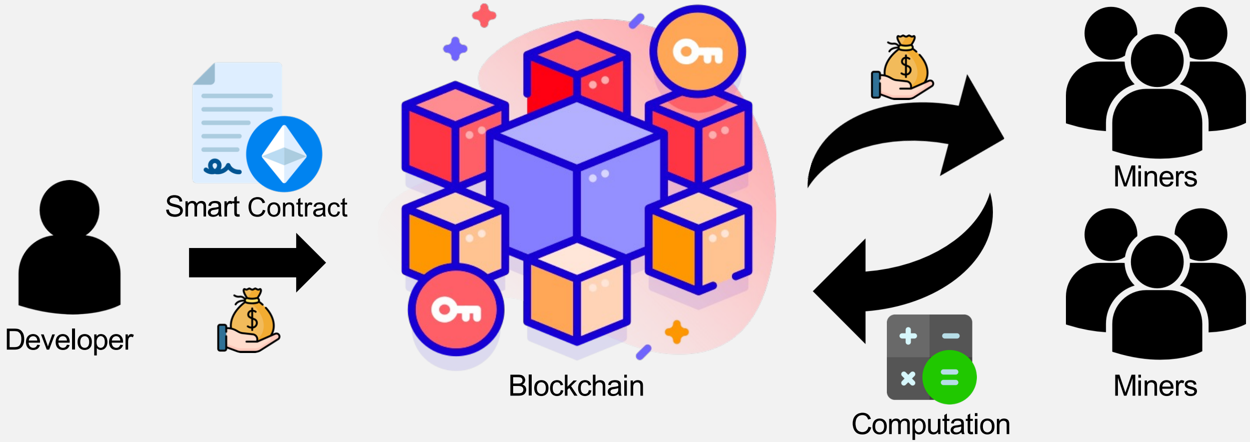
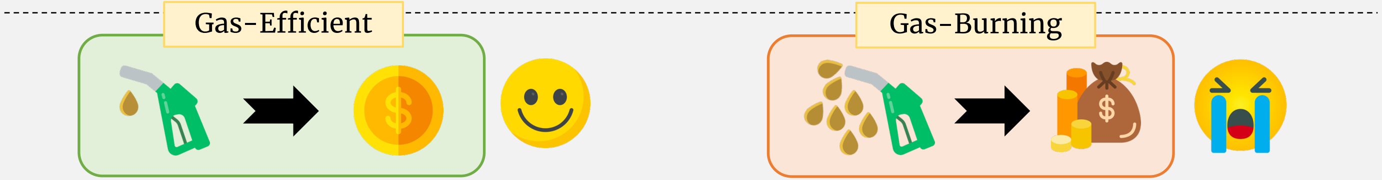
Gas Optimization of Smart Contracts





Developers typically invest significant effort in optimizing their code and making it as gas-efficient as possible.

Related Approaches

- Bytecode Superoptimization
  - SYRUP[1], GASOL[2]
- Anti-Pattern Detection
  - GASPER[3], GasReducer[4]

Reducing gas usage of some contracts requires significant changes to data layout, which is not addressed by any prior work.

[1] Synthesis of Super-Optimized Smart Contracts Using Max-SMT. *Elvira Albert, Pablo Gordillo, Albert Rubio, Maria A. Schett*. In CAV'20.
[2] GASOL: Gas Analysis and Optimization for Ethereum Smart Contracts. *Elvira Albert, Jesús Correas, Pablo Gordillo, Guillermo Román-Díez, Albert Rubio*. In TACAS'20.
[3] Under-optimized smart contracts devour your money. *Ting Chen, Xiaoqi Li, Xiapu Luo, Xiaosong Zhang*. In SANER'17.
[4] Towards saving money in using smart contracts. *Ting Chen, Zihao Li, Hao Zhou, Jiachi Chen, Xiapu Luo, Xiaoqi Li, Xiaosong Zhang*. In ICSE-NIER'18.

Example

```
contract CreditDAO {
    struct Election {
        address maxVotes;
        uint nextCandidateIndex;
        mapping(address => bool) candidates;
        mapping(address => bool) userHasVoted;
        mapping(uint => uint) candidateVotes;
        uint numMaxVotes;
        uint idProcessed;
    }
    uint public nextEId;
    mapping(uint => Election) public elections;
    constructor() public {
        nextEId++;
    }
    function sumbitForElection() public {
        elections[nextEId-1].nextCandidateIndex++;
        elections[nextEId-1].candidates[msg.sender] = true;
    }
    function vote(uint candidateId) public {
        elections[nextEId-1].candidateVotes[candidateId] += 1;
        elections[nextEId-1].userHasVoted[msg.sender] = true;
    }
    function finishElections(uint _iterations) public {
        uint currentVotes;
        Election election = elections[nextEId-1];
        uint nextId = election.idProcessed;
        for (uint cnt = 0; cnt < _iterations; cnt++) {
            currentVotes = election.candidateVotes[nextId];
            if (currentVotes > election.numMaxVotes) {
                election.numMaxVotes = currentVotes;
            }
            nextId++;
        }
        election.idProcessed = nextId;
    }
}
```

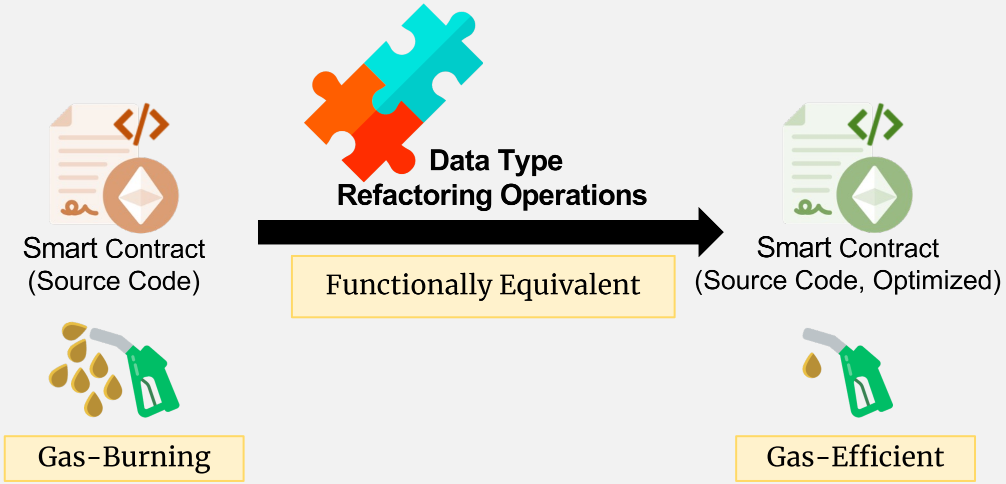
Figure. A motivating real-world smart contract that is not gas efficient.

Example

```
contract CreditDAO {
    struct Election {
        address maxVotes;
        uint nextCandidateIndex;
        mapping(address => bool) candidates;
        mapping(address => bool) userHasVoted;
        mapping(uint => uint) candidateVotes;
        uint numMaxVotes;
        uint idProcessed;
    }
    uint public nextEId;
    mapping(uint => Election) public elections;
    constructor() public {
        nextEId++;
    }
    function sumbitForElection() public {
        elections[nextEId-1].nextCandidateIndex++;
        elections[nextEId-1].candidates[msg.sender] = true;
    }
    function vote(uint candidateId) public {
        elections[nextEId-1].candidateVotes[candidateId] += 1;
        elections[nextEId-1].userHasVoted[msg.sender] = true;
    }
    function finishElections(uint _iterations) public {
        uint currentVotes;
        Election election = elections[nextEId-1];
        uint nextId = election.idProcessed;
        for (uint cnt = 0; cnt < _iterations; cnt++) {
            currentVotes = election.candidateVotes[nextId];
            if (currentVotes > election.numMaxVotes) {
                election.numMaxVotes = currentVotes;
            }
            nextId++;
        }
        election.idProcessed = nextId;
    }
}
```

Figure. A motivating real-world smart contract that is not gas efficient.

Gas Optimization via Type Refactoring



Example

How about a syntax-based rewriting?

```
contract CreditDAO {
    struct Election {
        address maxVotes;
        uint nextCandidateIndex;
        mapping(address => bool) candidates;
        mapping(address => bool) userHasVoted;
        mapping(uint => uint) candidateVotes;
        uint numMaxVotes;
        uint idProcessed;
    }
```

```
contract CreditDAO {
    struct Election {
        address maxVotes;
        uint nextCandidateIndex;
        mapping(address => Participant) userMap;
        mapping(uint => uint) candidateVotes;
    }
    struct Count {
        uint numMaxVotes;
        uint idProcessed;
    }
    struct Participant {
        bool isCandidate;
        bool hasVoted;
    }
```

1. It's often difficult to determine which of the rewriting strategies would result in equivalent code;
2. It can't ensure gas-optimality of the generated code.

Example

```
contract CreditDAO {
    struct Election {
        address maxVotes;
        uint nextCandidateIndex;
        mapping(address => bool) candidates;
        mapping(address => bool) userHasVoted;
        mapping(uint => uint) candidateVotes;
        uint numMaxVotes;
        uint idProcessed;
    }
    uint public nextEId;
    mapping(uint => Election) public elections;
    constructor() public {
        nextEId++;
    }
    function sumbitForElection() public {
        elections[nextEId-1].nextCandidateIndex++;
        elections[nextEId-1].candidates[msg.sender] = true;
    }
    function vote(uint candidateId) public {
        elections[nextEId-1].candidateVotes[candidateId] += 1;
        elections[nextEId-1].userHasVoted[msg.sender] = true;
    }
    function finishElections(uint _iterations) public {
        uint currentVotes;
        Election election = elections[nextEId-1];
        uint nextId = election.idProcessed;
        for (uint cnt = 0; cnt < _iterations; cnt++) {
            currentVotes = election.candidateVotes[nextId];
            if (currentVotes > election.numMaxVotes) {
                election.numMaxVotes = currentVotes;
            }
            nextId++;
        }
        election.idProcessed = nextId;
    }
}
```

```
contract CreditDAO {
    struct Election {
        address maxVotes;
        uint nextCandidateIndex;
        mapping(address => Participant) userMap;
        mapping(uint => uint) candidateVotes;
    }
    struct Count {
        uint numMaxVotes;
        uint idProcessed;
    }
    struct Participant {
        bool isCandidate;
        bool hasVoted;
    }
    uint public nextEId;
    mapping(uint => Election) public elections;
    mapping(uint => Count) public counts;
    constructor() public {
        nextEId++;
    }
    function sumbitForElection() public {
        elections[nextEId-1].nextCandidateIndex++;
        elections[nextEId-1].userMap[msg.sender].isCandidate = true;
    }
    function vote(uint candidateId) public {
        elections[nextEId-1].candidateVotes[candidateId] += 1;
        elections[nextEId-1].userMap[msg.sender].hasVoted = true;
    }
    function finishElections(uint _iterations) public {
        uint currentVotes;
        Election election = elections[nextEId-1];
        Count count = counts[nextEId-1];
        uint nextId = count.idProcessed;
        for (uint cnt = 0; cnt < _iterations; cnt++) {
            currentVotes = election.candidateVotes[nextId];
            if (currentVotes > count.numMaxVotes) {
                count.numMaxVotes = currentVotes;
            }
            nextId++;
        }
        count.idProcessed = nextId;
    }
}
```

Figure. Differences between the smart contract ***before (left)*** and ***after (right)*** refactoring for gas optimization (~30% reduction).

Reducing the gas usage requires significant changes to data layouts ***and*** re-implementing significant part of the contract code.

Overview of Solidare

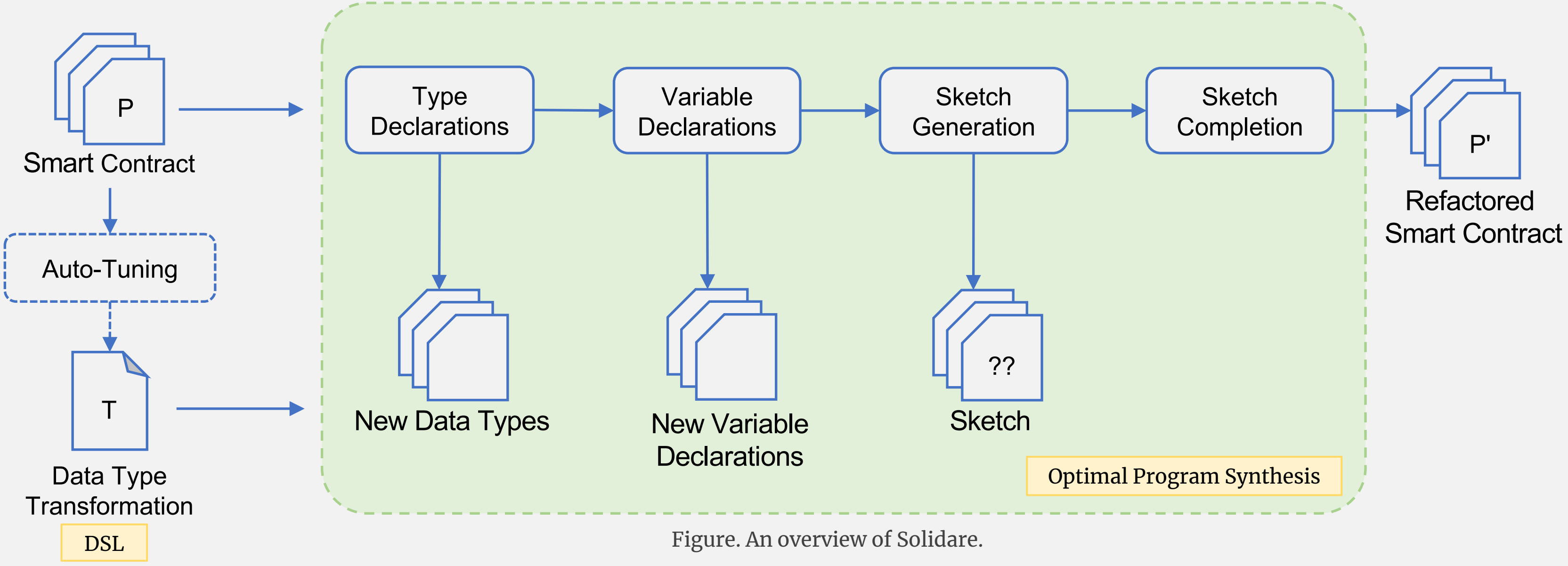


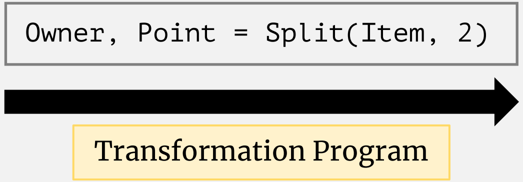
Figure. An overview of Solidare.

A Running Example

```
contract SimplePoint {
    struct Item {
        bool activated;
        address owner;
        uintX x;
        uintY y;
    }
    mapping(uint => Item) items;
    function set(uint i, uintX _x, uintY _y) public {
        items[i].x = _x;
        items[i].y = _y;
    }
    function getX(uint i) public view returns (uintX) {
        return items[i].x;
    }
    function getY(uint i) public view returns (uintY) {
        return items[i].y;
    }
    // more functions omitted
    // ...
}
```

Step 1. Type Declarations

```
struct Item {
    bool activated;
    address owner;
    uintX x;
    uintY y;
}
```




```
struct Point {
    uintX x;
    uintY y;
}
struct Owner {
    bool activated;
    address addr;
}
```

$$
\begin{array}{rcl}
\text{Trans. } \mathcal{T} & ::= & s \mid \mathcal{T};\mathcal{T} \\
\text{Stmt. } s & ::= & S \leftarrow \textbf{Wrap}(\tau, \ldots, \tau) \mid \textbf{Unwrap}(S) \mid (S, S) \leftarrow \textbf{Split}(S, c) \\
& \mid & S \leftarrow \textbf{Merge}(S, S) \mid S \leftarrow \textbf{Reorder}(S, c, c)
\end{array}
$$

$$c \in \textbf{Constant} \quad S \in \textbf{StructName} \quad \tau \in \textbf{Type}$$

Figure. Syntax of the transformation language; see paper for semantics

Step 2. Variable Declarations

```
struct Item {
    bool activated;
    address owner;
    uintX x;
    uintY y;
}
mapping(uint => Item) items;
```

```
Owner, Point = Split(Item, 2)
```

Transformation Program

```
struct Point {
    uintX x;
    uintY y;
}
struct Owner {
    bool activated;
    address addr;
}
mapping(uint => Point) points;
mapping(uint => Owner) owners;
```

Step 3. Code Generation

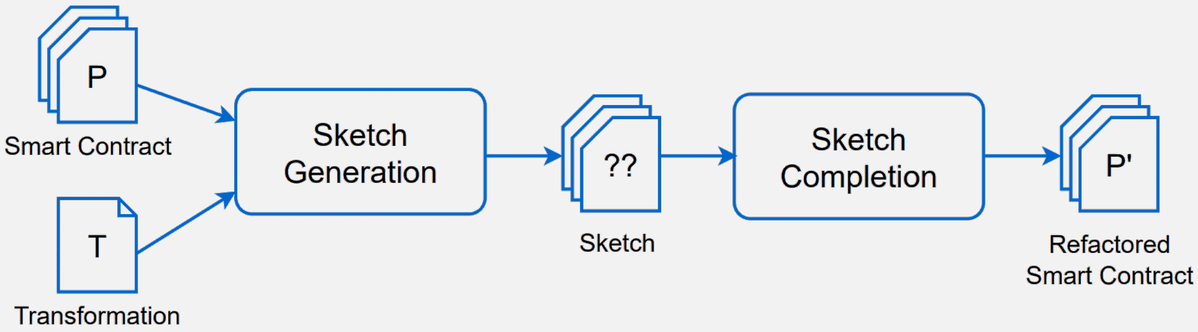


Figure. Workflow of the code generation procedure.

Step 3a. Sketch Generation (Expr.)

```
function set(uint i, uintX _x, uintY _y) public {
    items[i].x = _x;
    items[i].y = _y;
}
```

Stale Expressions

```
Owner, Point = Split(Item, 2)
```

Transformation Program $\mathcal{T} \vdash \Gamma \hookrightarrow \Gamma'$

```
function set(uint i, uintX _x, uintY _y) public {
    if (??1) ??2 = ??3;
    if (??4) ??5 = ??6;
}
```

Each stale expression is replaced with a *hole* whose *domain* includes well-typed expressions.

*Please see the paper for detailed sketch generation rules.

Type Environment Γ

$\Gamma \vdash$ items[i].x : Item.uintX
$\Gamma \vdash$ items[i].y : Item.uintY
$\Gamma \vdash$ _x: Item.uintX
$\Gamma \vdash$ _y: Item.uintY
…

Type Environment Γ'

$\Gamma \vdash$ points[i].x : Point.uintX
$\Gamma \vdash$ points[i].y : Point.uintY
$\Gamma \vdash$ _x: Point.uintX
$\Gamma \vdash$ _y: Point.uintY
…

Step 3a. Sketch Generation (Stmt.)

```
function set(uint i, uintX _x, uintY _y) public {
    items[i].x = _x;
    items[i].y = _y;
}
```

```
Owner, Point = Split(Item, 2)
```

Transformation Program $\mathcal{T} \vdash \Gamma \hookrightarrow \Gamma'$

```
function set(uint i, uintX _x, uintY _y) public {
    if (??1) ??2 = ??3;
    if (??4) ??5 = ??6;
}
```

Replace each statement *s* with a stale expression with a conditional statement: **if (??{⊤, ⊥}) then s' else skip**.

*Please see the paper for detailed sketch generation rules.

```
m[0] = Point(x,y);
```

```
Unwrap(Point)
```

```
if (??1) ??2 = ??3; // x
if (??4) ??5 = ??6; // y
```

Some statements become redundant after transformation; removing them saves gas.

Step 3b. Sketch Completion (Alg. & Enc.)

- Max-SAT Encoding
  - Hard Constraints
    - Every hole should be instantiated with ***exactly one*** expression in its domain.
    - Different occurrences of ***same*** source expression are transformed into the ***same*** target expression.
  - Soft Constraints (Proxy Metric of Gas Usage)
    - Minimizing blockchain variables
    - Minimizing statements

Algorithm 1 Sketch Completion

1: **procedure** CompleteSketch($\mathcal{S}, \mathcal{P}$)
Input: Sketch $\mathcal{S}$, Source program $\mathcal{P}$
Output: Target program $\mathcal{P}'$ or $\bot$ to indicate failure
2: $\Phi \leftarrow$ Encode($\mathcal{S}$);
3: **while** SAT(Φ) **do**
4: $\mathcal{M} \leftarrow$ GetModel(Φ);
5: $\mathcal{P}' \leftarrow$ Instantiate($\mathcal{S}, \mathcal{M}$);
6: **if** $\mathcal{P}' \simeq \mathcal{P}$ **then return** $\mathcal{P}'$;
7: $\Phi \leftarrow \Phi \wedge$ Block($\mathcal{P}, \mathcal{S}, \mathcal{M}$);
8: **return** $\bot$;

*Please see the paper for detailed encoding and algorithm.

Step 3b. Sketch Completion (MFS)

- Minimal Failing Sub-Contract

Original Contract P

```
contract SimplePoint {
  uint public x = 0; uint public y = 0;
  function set(uint _x, uint _y) public { x = _x; y = _y; }
  function getX() public returns (uint) { return x; }
  function getY() public returns (uint) { return y; } }
```

Transformed Contract (Incorrect)

Minimal Failing Sub-Contract P^*

```
contract SimplePoint {
  uint public x = 0; uint public y = 0;
  function set(uint _x, uint _y) public { x = _x; y = _y; }
  function getX() public returns (uint) { return y; } }
  function getY() public returns (uint) { return y; } }
```

1. P^* only contains a subset of functions in P
2. P^* is not equivalent to P with respect to functions it implements
3. P^* is minimal – removing any functions would make P^* and P equivalent with respect to functions P^* implemented

*Please see the paper for more details.

The key idea is to generalize model $\mathcal{M}$ and add a blocking clause that prevents *many* incorrect programs at the same time.

Evaluation

- SOLIDARE is implemented in a combination of Java and Kotlin, with Sat4J[1] as backend.
- Benchmarks
  - **Etherscan**: 20
    - Contains rich data structures, complicated control flows
    - Wide coverage: auctions, crowd sourcing, decentralized autonomous organizations (DAOs), etc.
  - **GasStation**: 10
    - Most frequently used smart contracts / gas burners
- Experimental Settings
  - Two usage modes: manual + auto-tuner transformations
  - Intel® Xeon® E5-2640@2.60GHz CPU, 128GB Physical Memory
  - Ubuntu 18.04@Docker
  - For more implementation details, please refer to the paper

[1] The sat4j library, release 2.2, system description. *Daniel Le Berre, Anne Parrain*. In Journal on Satisfiability, Boolean Modeling and Computation 7. 2010

Evaluation

RQ1: Is SOLIDARE able to generate equivalent code for different data layouts?

Yes.

Averaged running time: 21.1s
Medium running time: 0.9s

Major time cost: sketch completion (including equivalence checking)

	ID	Contract	LOC	# Funcs	# Trans	Sketch Time (s)	Completion Time (s)	Max Diff	Avg Diff
Etherscan	1	Announcement	112	7	2	0.2	0.2	23	17.5
	2	Auction	964	70	1	3.7	7.7	34	34.0
	3	BdpImageStorage	258	27	2	0.1	0.4	32	32.0
	4	BinaryOption	916	20	1	0.4	1.4	31	31.0
	5	Congress	163	9	3	1.2	1.6	66	34.7
	6	CreditDAO	111	14	2	0.4	0.4	54	50.0
	7	CryptoTask	255	17	3	0.3	0.3	12	8.3
	8	DAOG2X	319	19	3	0.7	1.9	24	23.0
	9	EMPresale	306	30	3	0.7	551.1	57	38.0
	10	EthLottery	132	6	2	0.3	0.2	22	21.5
	11	EtherRacing	250	20	2	1.2	6.2	32	32.0
	12	FTICrowdsale	553	17	1	0.1	0.3	9	9.0
	13	JanKenPon	510	40	1	17.0	2.7	47	47.0
	14	Kingdom	189	13	3	0.6	3.5	64	44.7
	15	Oryza	152	7	2	1.0	1.4	21	20.0
	16	PollManager	473	12	2	3.0	3.1	17	17.0
	17	Slaughter3D	287	26	1	0.7	2.2	22	22.0
	18	SplitStealContract	465	28	2	5.0	3.9	24	23.5
	19	TwoXJackpot	222	15	1	0.4	1.3	14	14.0
	20	moduleToken	392	21	2	0.6	0.8	18	18.0
GasStation	21	MetaMasks	597	88	1	0.1	0.2	18	18.0
	22	MoonStaking	525	65	1	0.1	0.4	19	19.0
	23	MoonStakingForTax	842	120	1	0.1	0.3	24	24.0
	24	MASTERPLAN	494	57	1	0.1	0.4	21	21.0
	25	MasterInu	758	149	1	0.1	0.9	15	15.0
	26	MetaPunkController2022	1586	446	1	0.2	0.2	14	14.0
	27	KaijuFrenz	924	99	1	0.1	0.2	25	25.0
	28	EMOBUDDIES	852	101	1	0.1	0.2	15	15.0
	29	GemSwap	528	76	1	0.1	0.3	16	16.0
	30	LL420Reveal	131	16	1	0.1	0.1	10	10.0

Table. Statistics about benchmarks and results of running time.

Evaluation

RQ2: Can we reduce the gas usage of real-world smart contracts through data type refactoring?

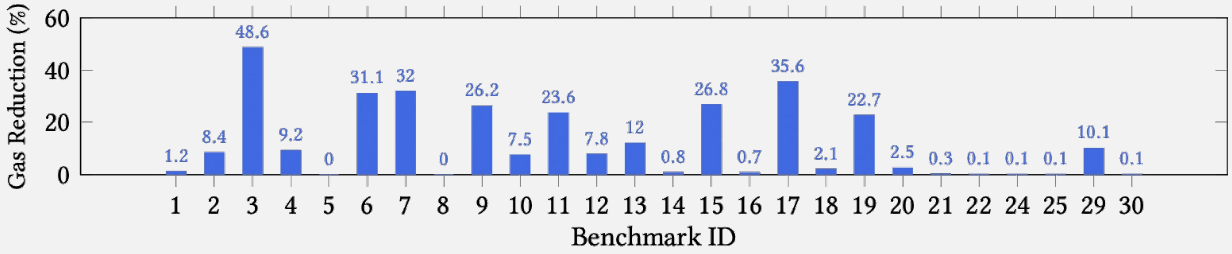


Figure. Gas reduction in benchmarks.

Yes.

Etherscan Dataset: 18/20 have improvement, avg. gas saving is 16%.

GasStation Dataset: 6/10 have improvement, gas saving is 0.1% ~ 10%.

Most benchmarks in GasStation are digital tokens, which require more complex program logic and less complicated data layout.

Evaluation

RQ3: How much manual effort does SOLIDARE save developers?

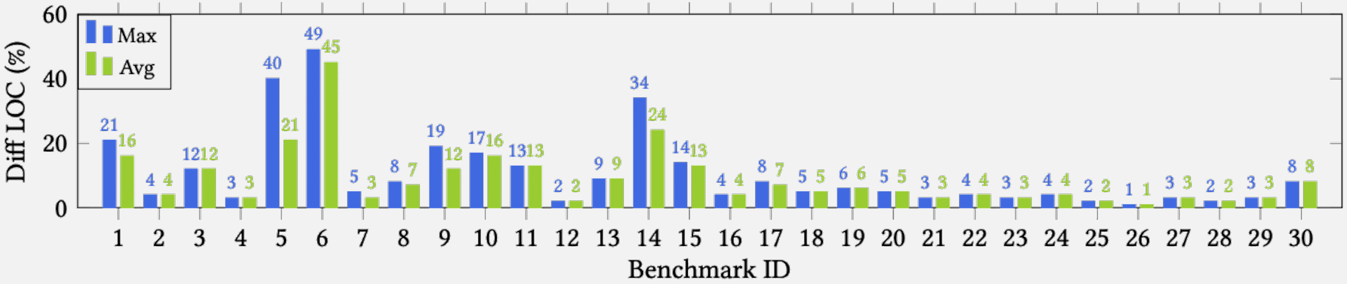


Figure. Diff size as percentage of the lines of code in original contracts. **Max**: Statistics of transformation the requires the most changes; **Avg**: Averaged diff ratio per benchmark across all transformations.

On average, 25% of the lines of code (~avg. 53 lines) need to be modified.

The largest diff size could be 49% and 40%.

Evaluation

RQ4: How does our sketch completion method compare with simpler baselines?

Timeout: 20min

Ablative Variants:

- SOLIDARE solves **100%**
- SOLIDARE-NOMFS solves 22% less
- SOLIDARE-NOSOFT solves 10% less
- SOLIDARE-BASELINE solves 24% less

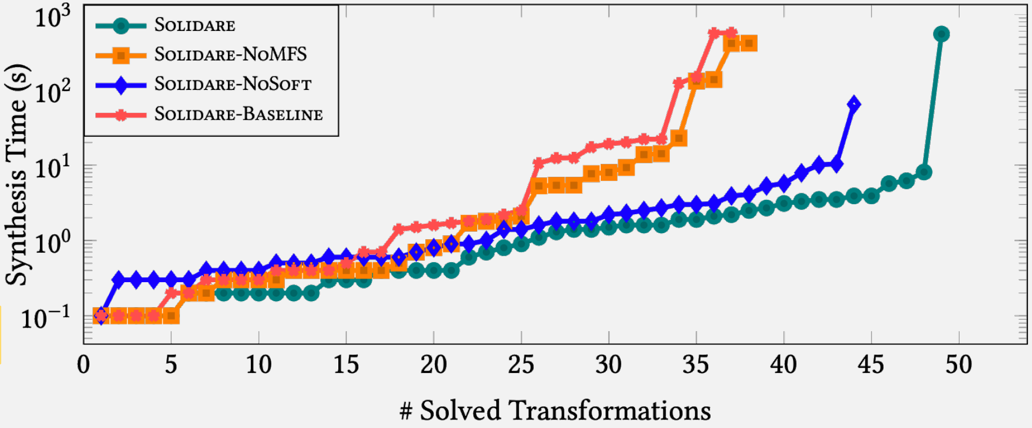


Figure. Comparing SOLIDARE against baselines. y-axis is on log-scale.

Our MaxSAT-based sketch solver that utilizes minimal failing sub-contracts significantly outperforms other baselines.

Evaluation

RQ5: Is SOLIDARE's auto-tuner able to automatically find gas-saving refactorings?

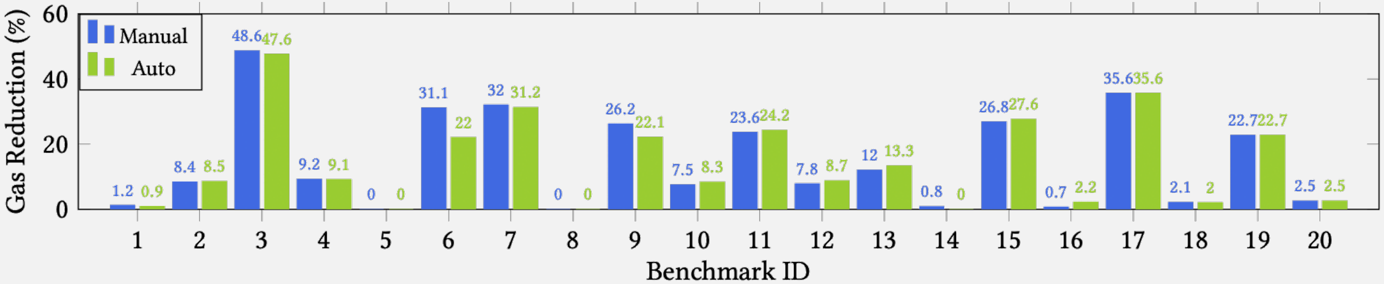


Figure. Comparison of gas reduction between manual refactoring and autotuning.

Yes.

The auto-tuner can automatically reduce gas usage for 17/20 (85%) benchmarks.

For 13/20 (65%), the reduction is >5%.

For 9/20 (45%), the reduction is >10%.

For 7/20 (65%), auto-tuner is better than manual refactoring.

Evaluation

RQ6: How does SOLIDARE compare with other gas optimization tools?

- SYRUP[1]: Bytecode Superoptimization

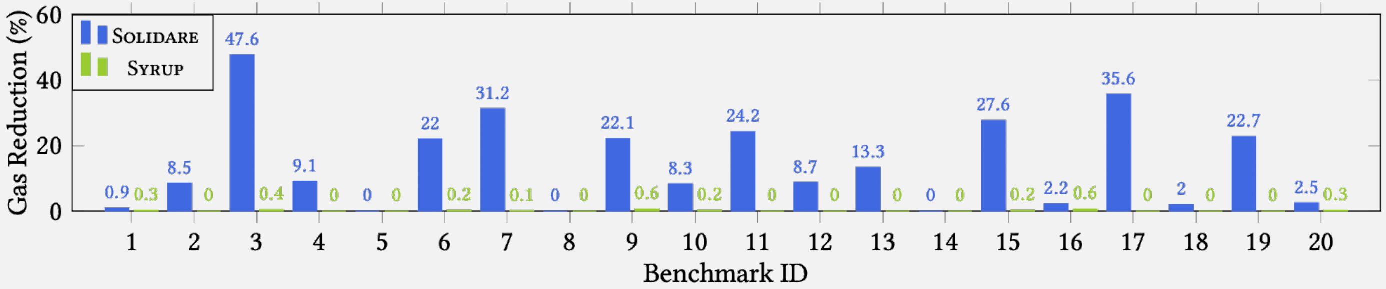


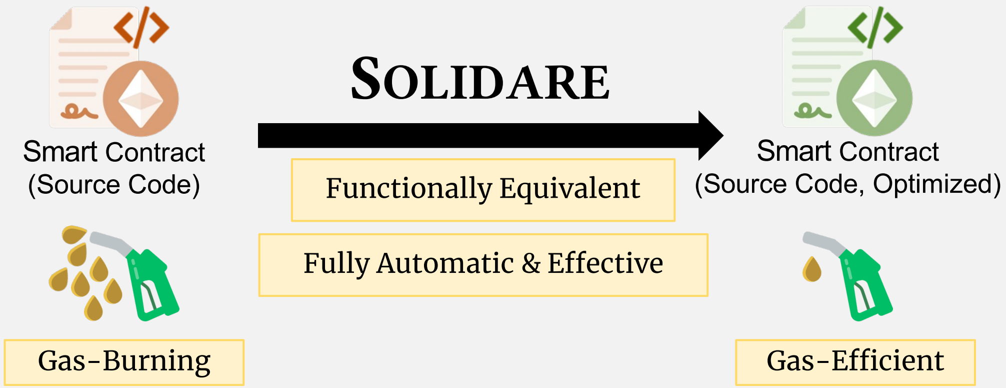
Figure. Comparing SOLIDARE and SYRUP.

SYRUP focuses on optimizing arithmetic operations within a basic block, but more significant gas savings require changing in data layout.

Nonetheless, we believe the types of optimizations performed by SYRUP are complementary SOLIDARE's.

[1] Synthesis of Super-Optimized Smart Contracts Using Max-SMT. *Elvira Albert, Pablo Gordillo, Albert Rubio, Maria A. Schett.* In CAV'20.

Conclusion


Smart Contract
(Source Code)
Gas-Burning
SOLIDARE
Functionally Equivalent
Fully Automatic & Effective
Smart Contract
(Source Code, Optimized)
Gas-Efficient