teEther: Gnawing at Ethereum to Automatically Exploit Smart Contracts

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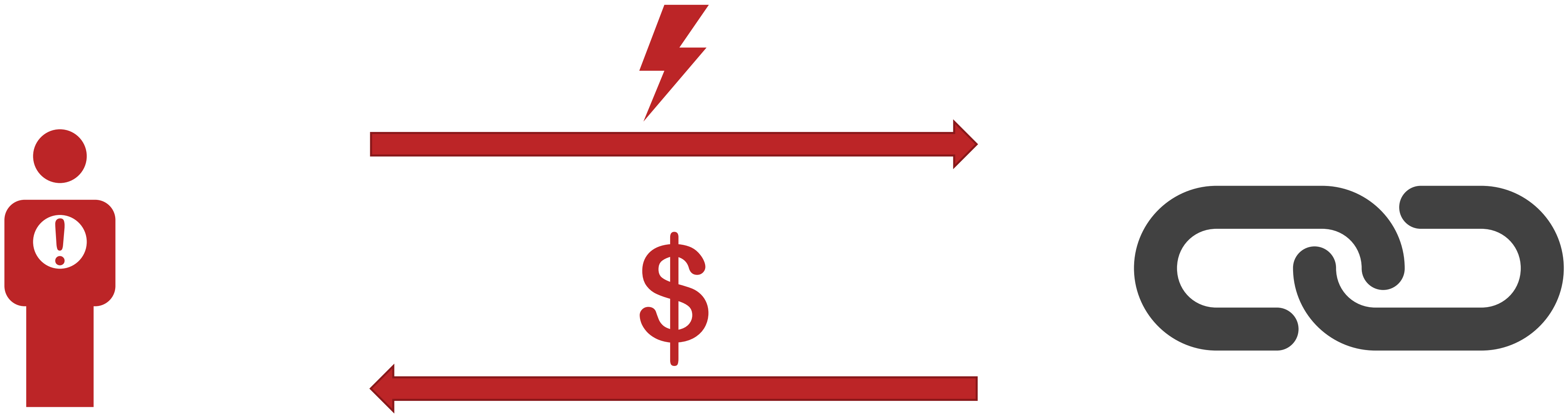
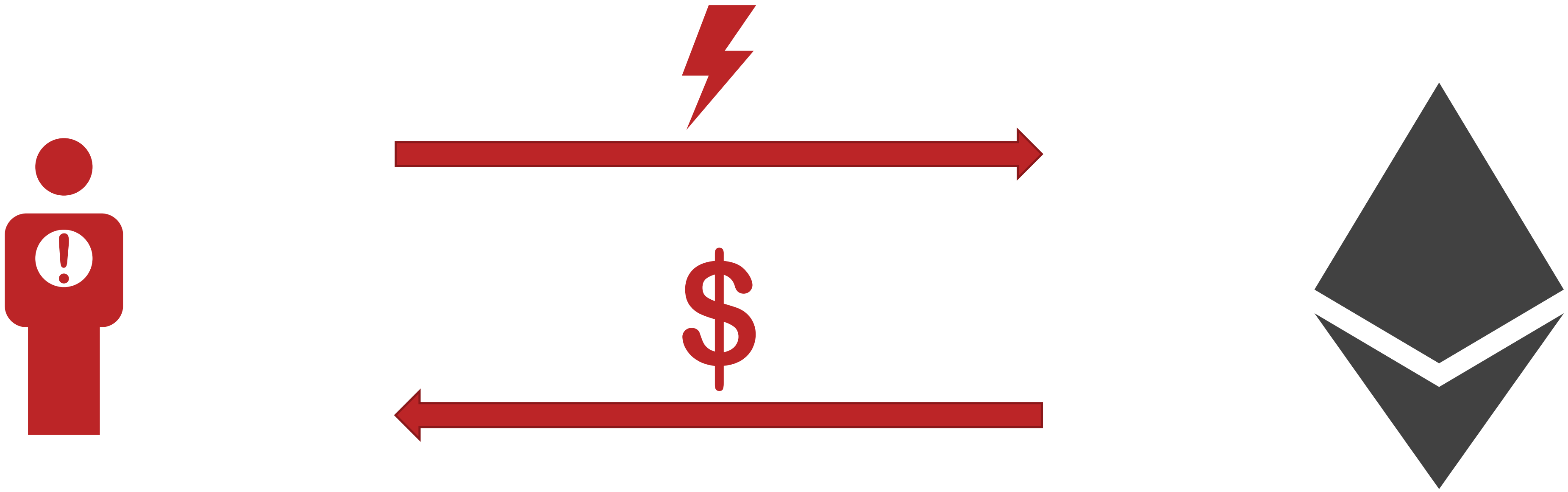
European Commission

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 700176

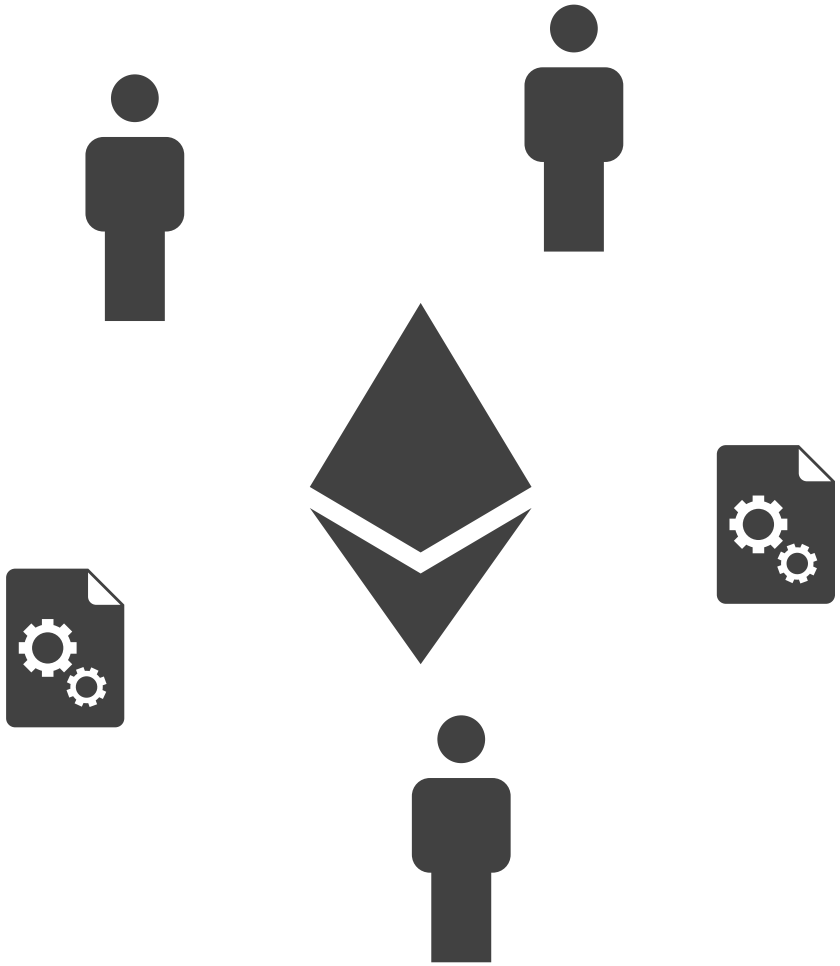
In a nutshell

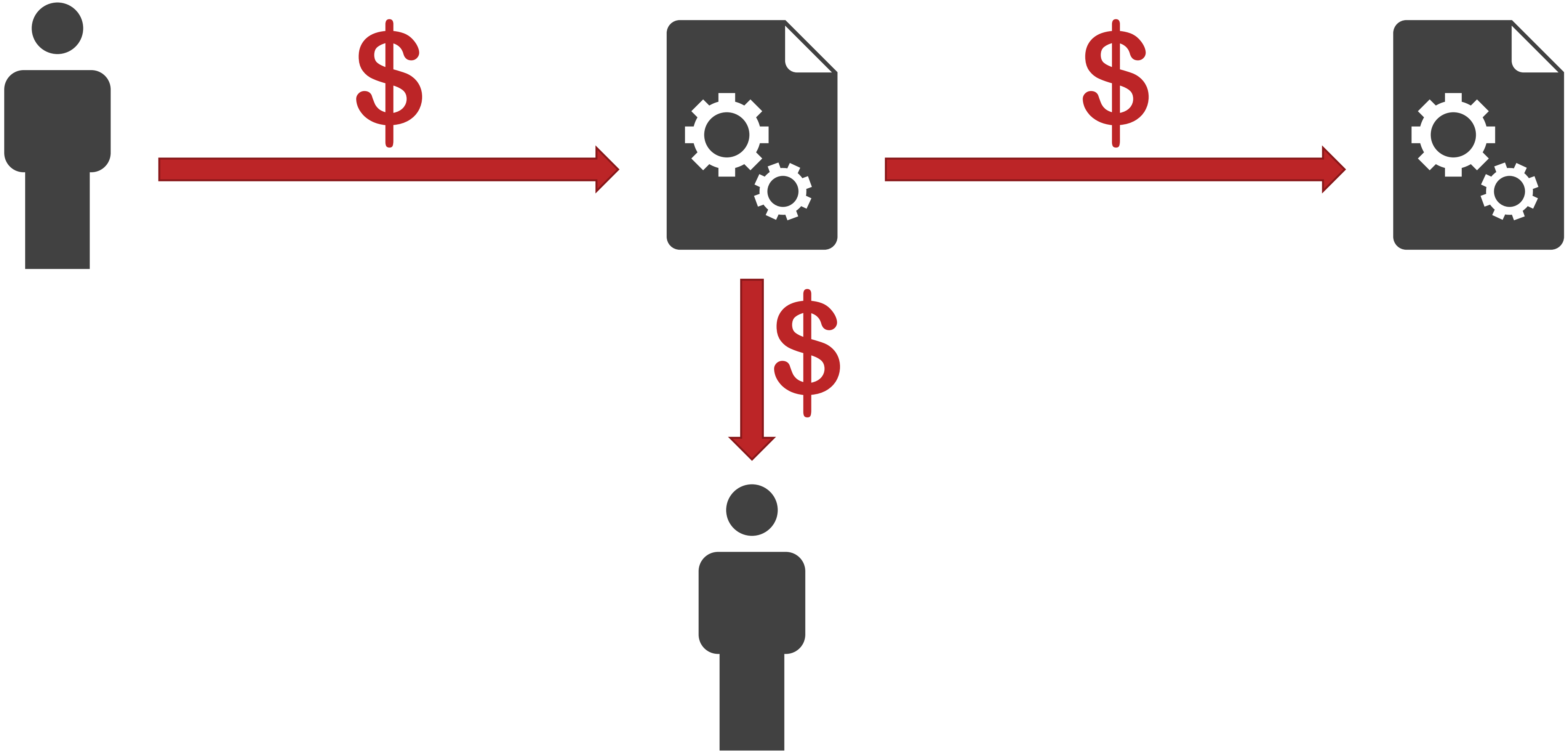


In a nutshell

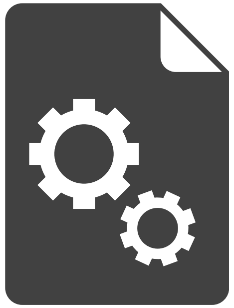


Ethereum

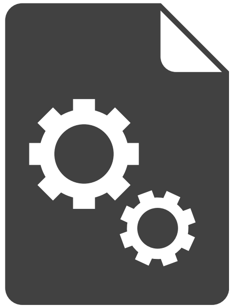




Smart Contracts



- Ethereum Virtual Machine (EVM) bytecode
- executed on incoming transaction
- otherwise like regular account:
  - address
  - balance
- use cases:
  - crowdfunding schemes
  - shared wallets
  - games
  - …



- Ethereum Virtual Machine (EVM) bytecode
- executed on incoming transaction
- otherwise like regular account:
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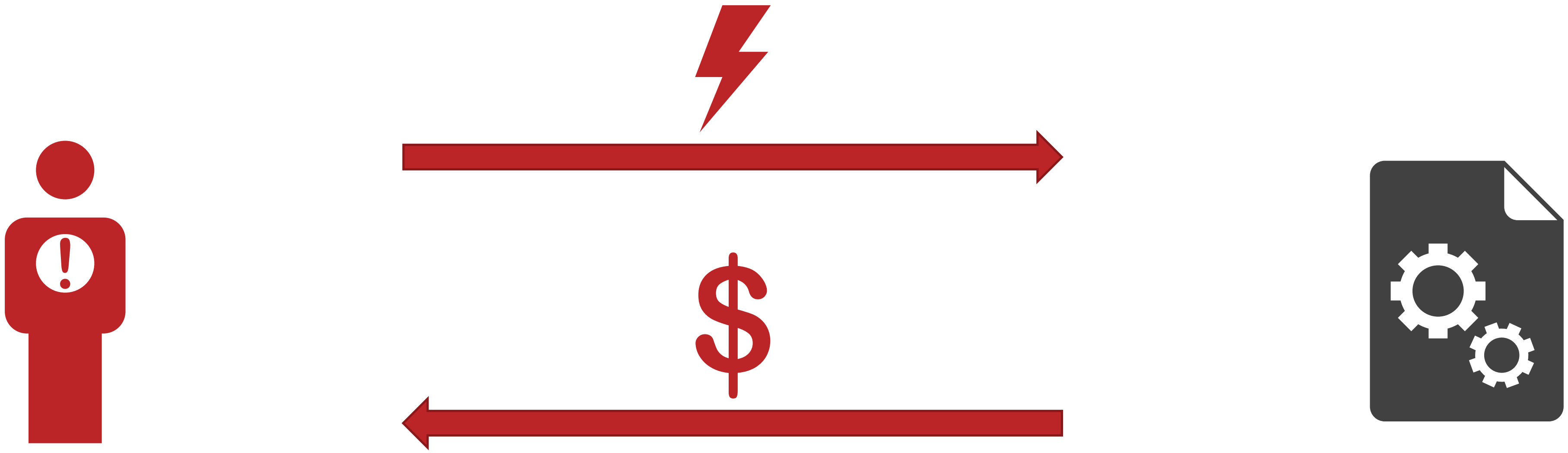
may contain bugs

cannot be updated

goal: find & exploit bugs

Smart Contract Exploitation



Transactions

- `from` sender
- `to` recipient
- `value` transferred amount
  - may also be zero
- `gas` „transaction fee“
- `data` input data
  - may be empty

Ethereum Virtual Machine (EVM)

- stack machine
- 256 bit wordsize
- ~70 instructions
  - arithmetic
  - logic
  - control flow
  - blockchain interaction

Challenges

- control flow graph recovery

Control Flow Instructions

- **`JUMP`**
  - unconditional jump
  - jump to **`target`**

- **`JUMPI`**
  - conditional jump
  - jump to **`target`** if **`test`** is non-zero

- **`JUMPDEST`**
  - marks valid jump target
  - no op

CFG Recovery

600934600757005b565b00

JUMP

JUMPI

JUMPDEST

CFG Recovery

```
0   6009   PUSH1 09
2   34     CALLVALUE
3   6007   PUSH1 07
5   57     JUMPI

6   00     STOP

7   5b     JUMPDEST
8   56     JUMP

9   5b     JUMPDEST
a   00     STOP
```

CFG Recovery

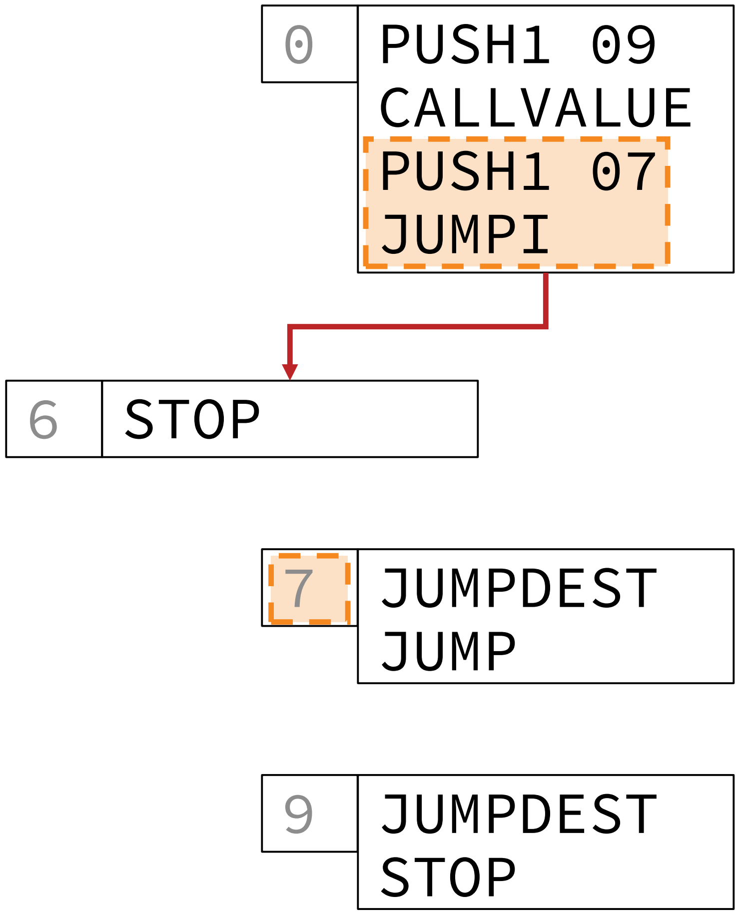
```
0  PUSH1 09
   CALLVALUE
   PUSH1 07
   JUMPI
```

```
6  STOP
```

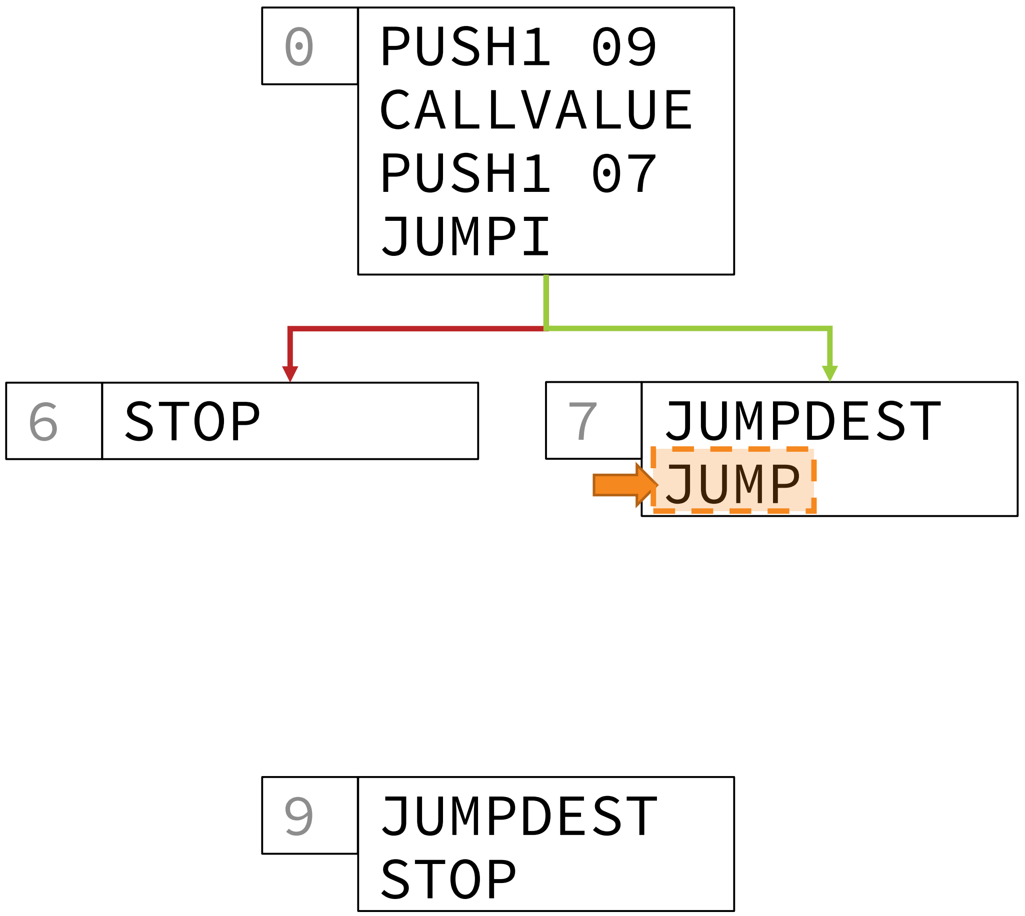
```
7  JUMPDEST
   JUMP
```

```
9  JUMPDEST
   STOP
```

CFG Recovery



CFG Recovery



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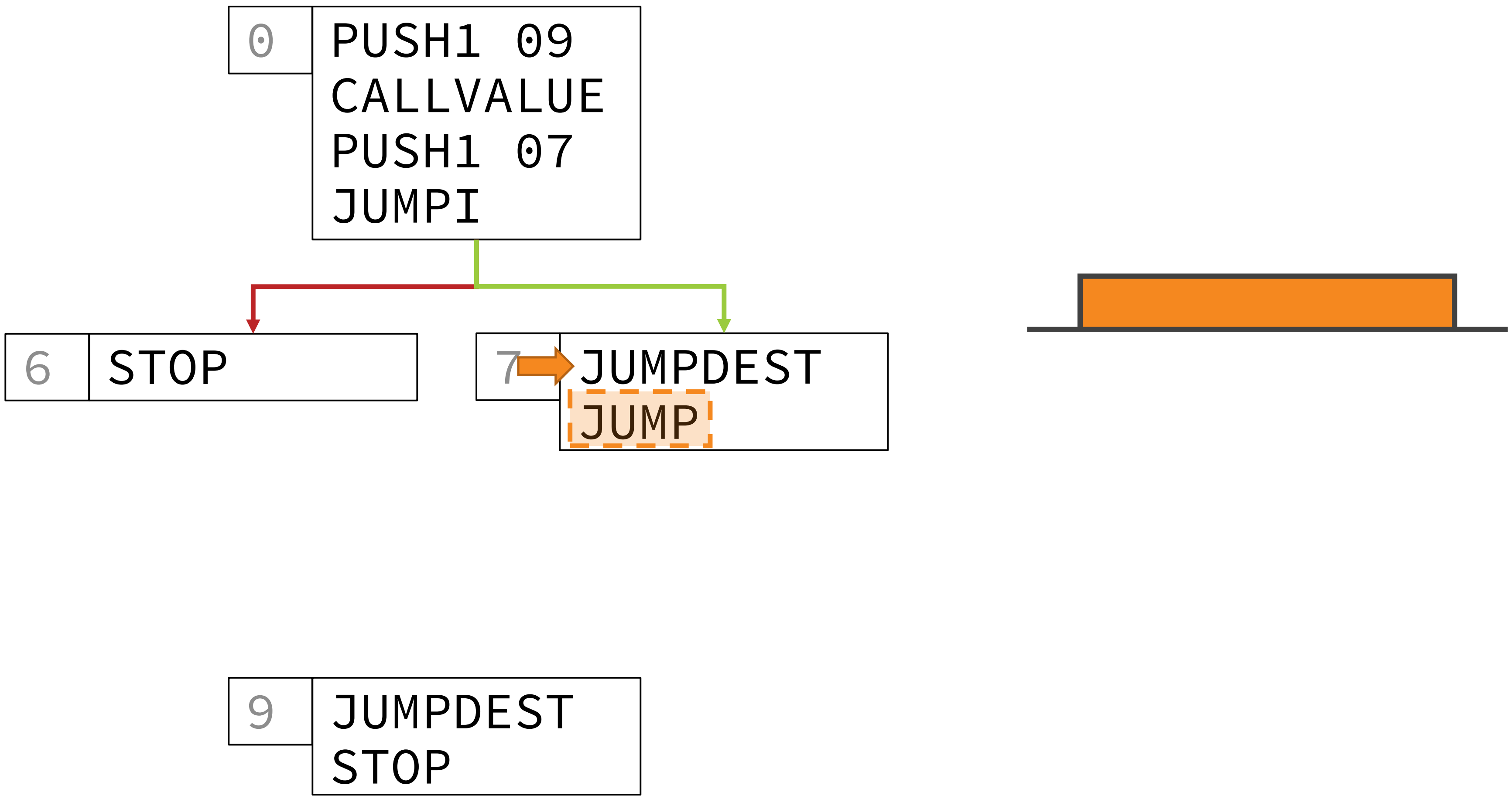

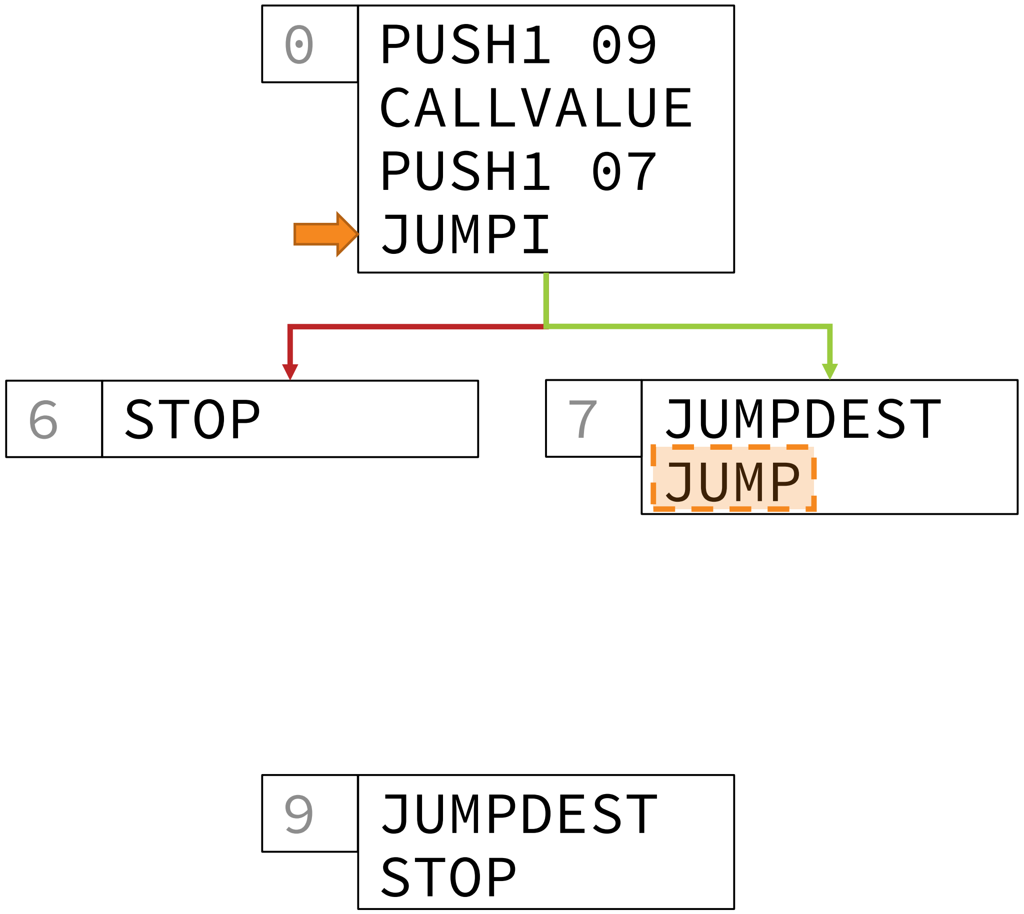
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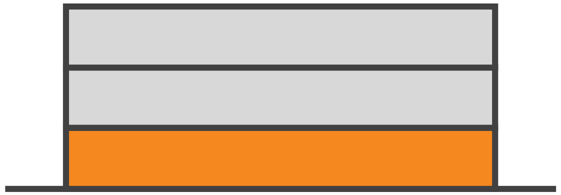

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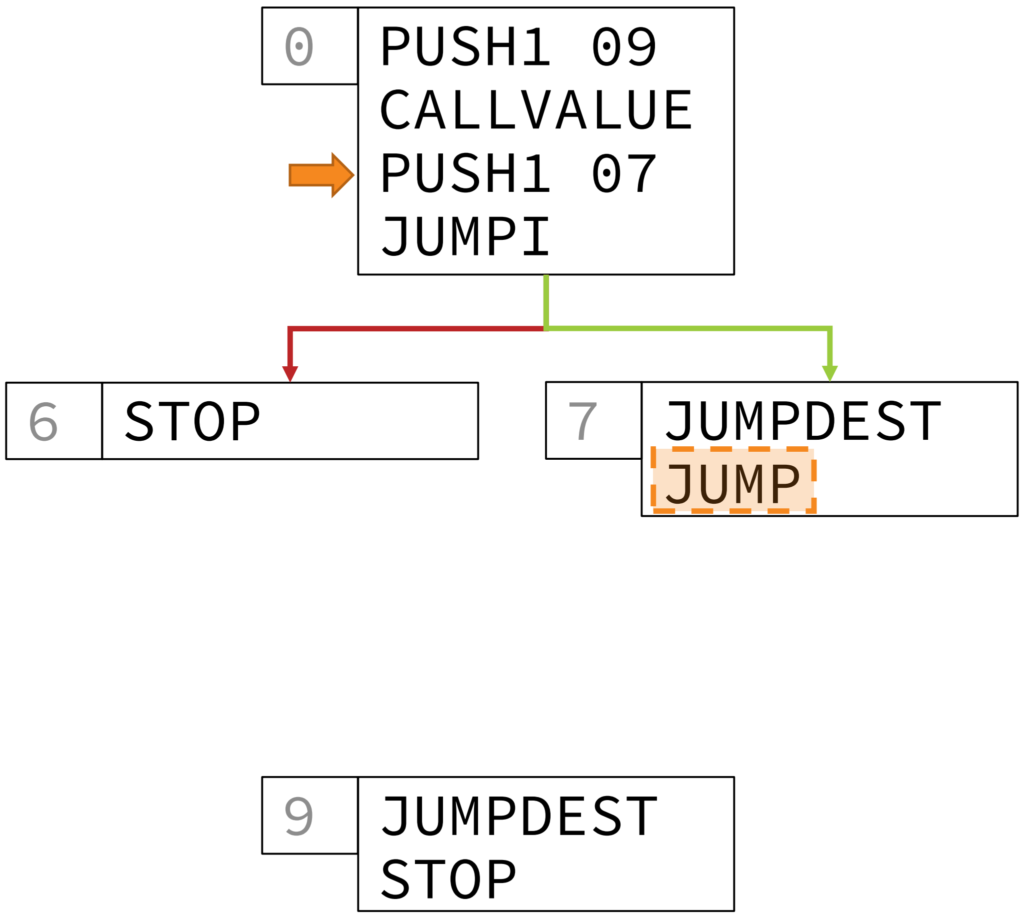
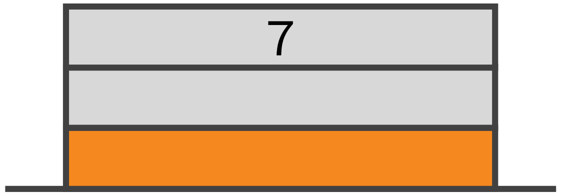
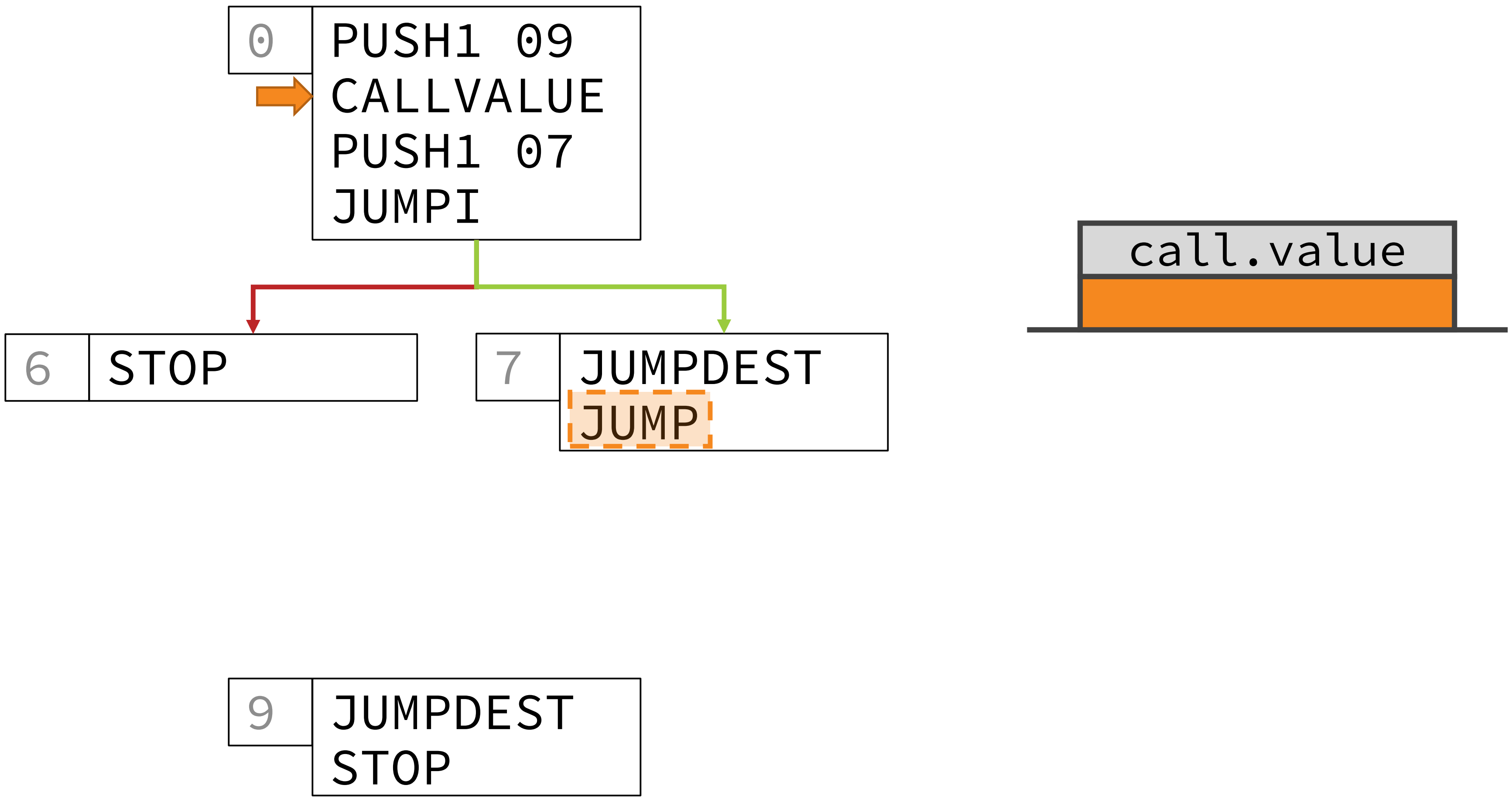
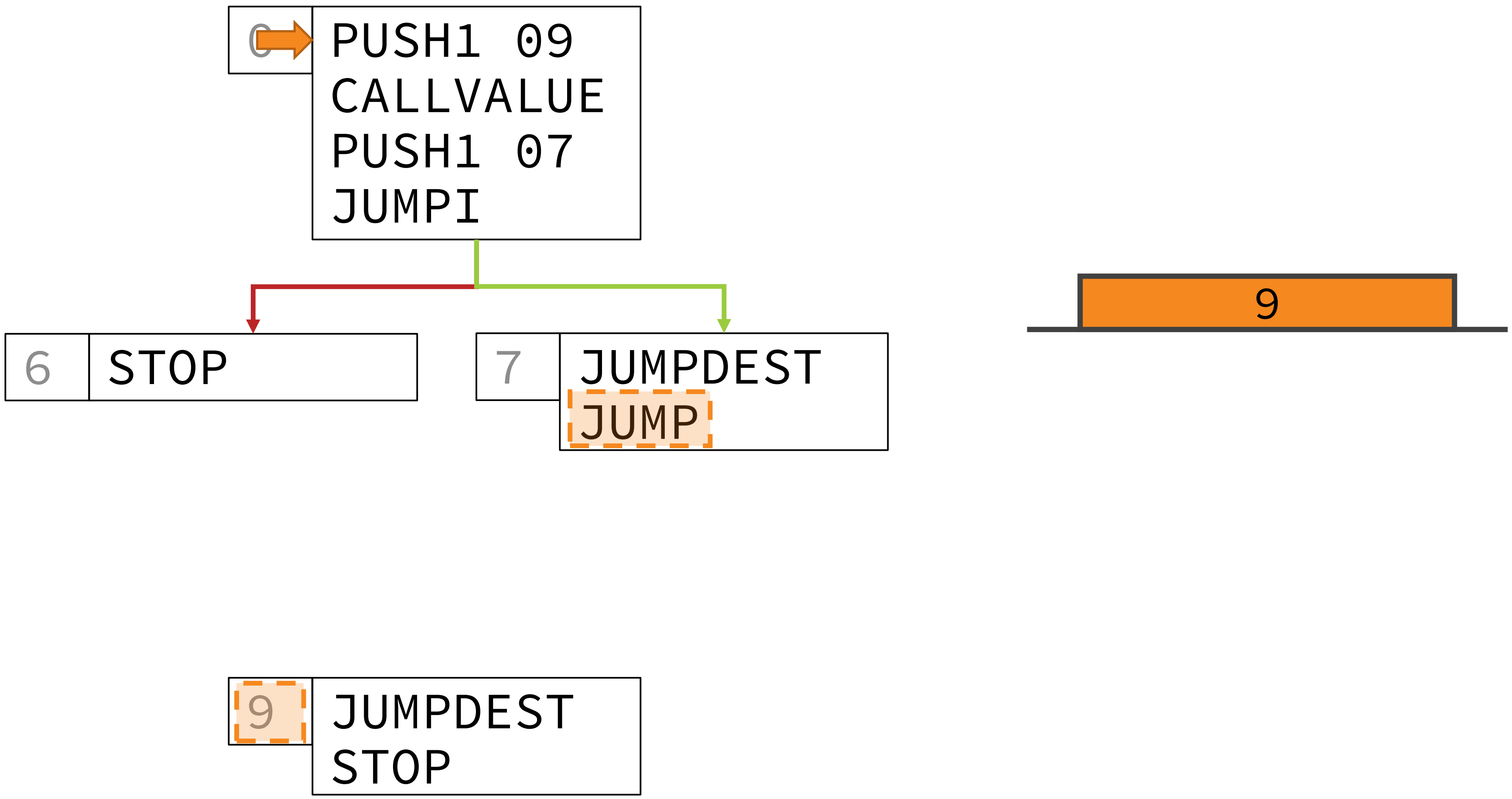




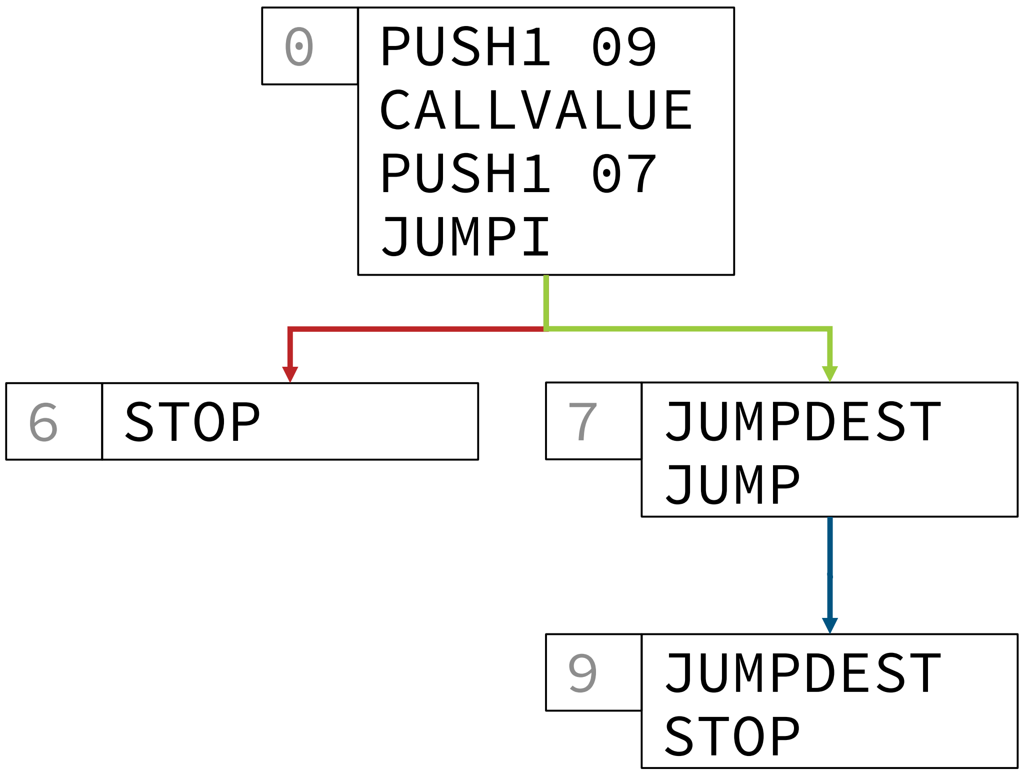
CFG Recovery



CFG Recovery



CFG Recovery



Challenges

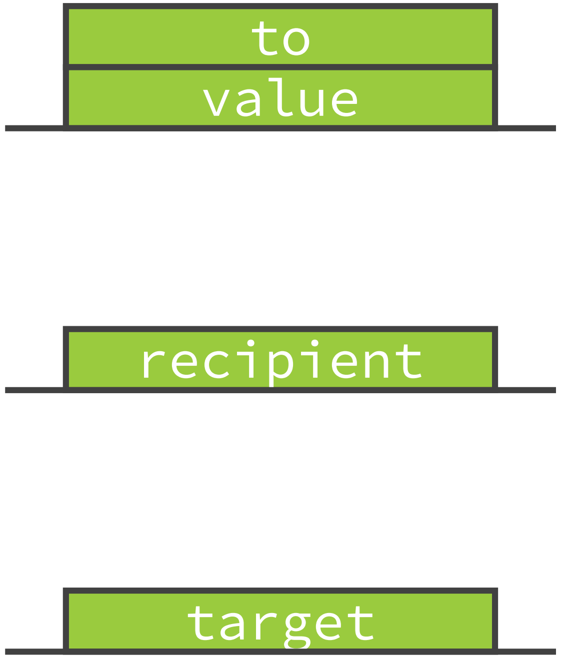
- control flow graph recovery ✓

how can we get money from a contract?

Ethereum Virtual Machine (EVM)

- stack machine
- 256 bit wordsize
- ~70 instructions
  - arithmetic
  - logic
  - control flow
  - **blockchain interaction**

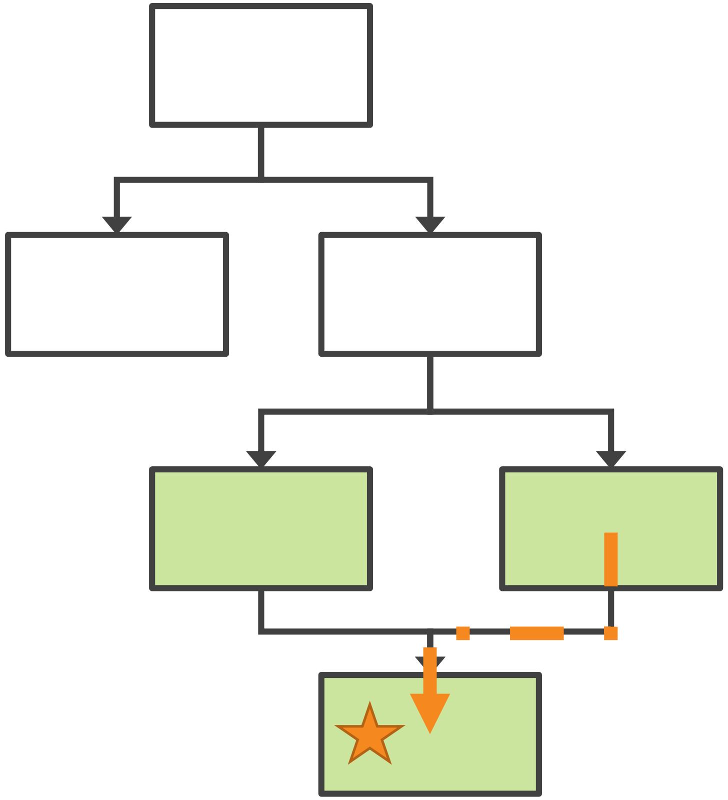
Critical Instructions



- **`CALL`**
  - regular transaction
  - transfer **`value`** to **`to`**
- **`SELFDESTRUCT`**
  - contract destruction
  - transfer funds to **`recipient`**
- **`CALLCODE`** / **`DELEGATECALL`**
  - execute code of **`target`**
  - „code injection“

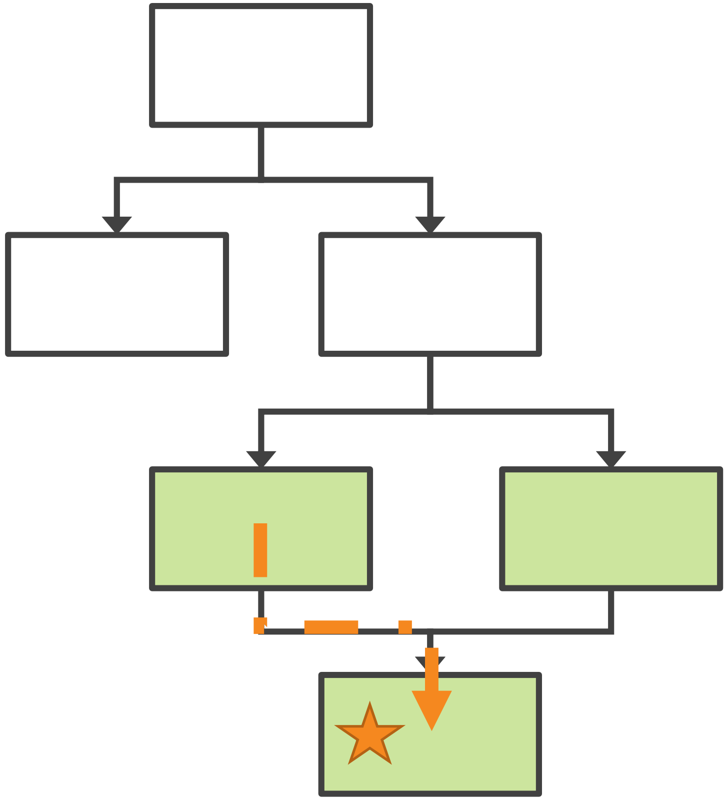
must execute one of these

Critical Paths



1. locate critical instructions
2. compute backward slices of argument(s)
3. filter for attacker controlled slices

Critical Paths



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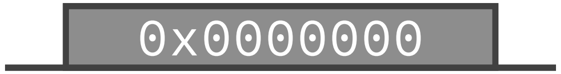
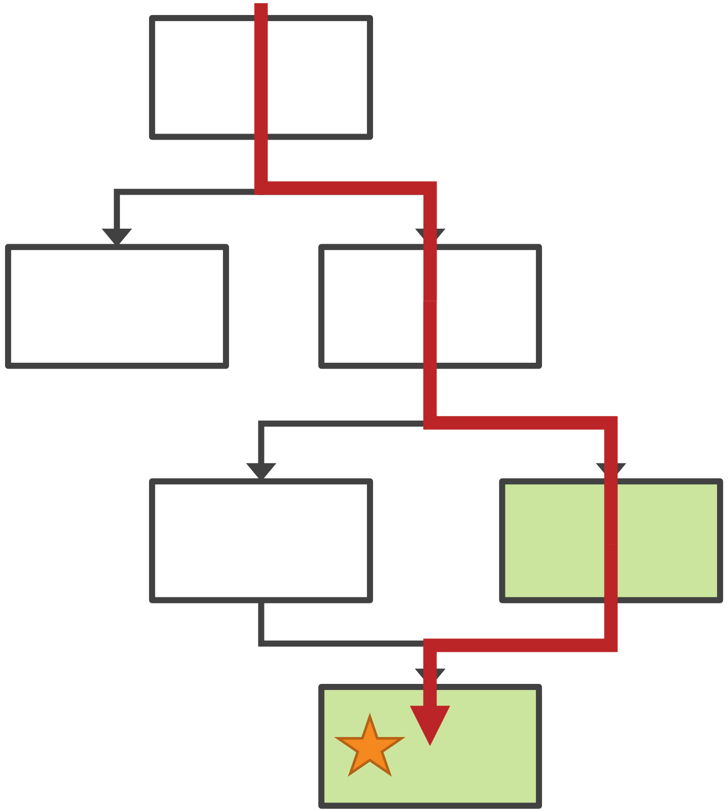


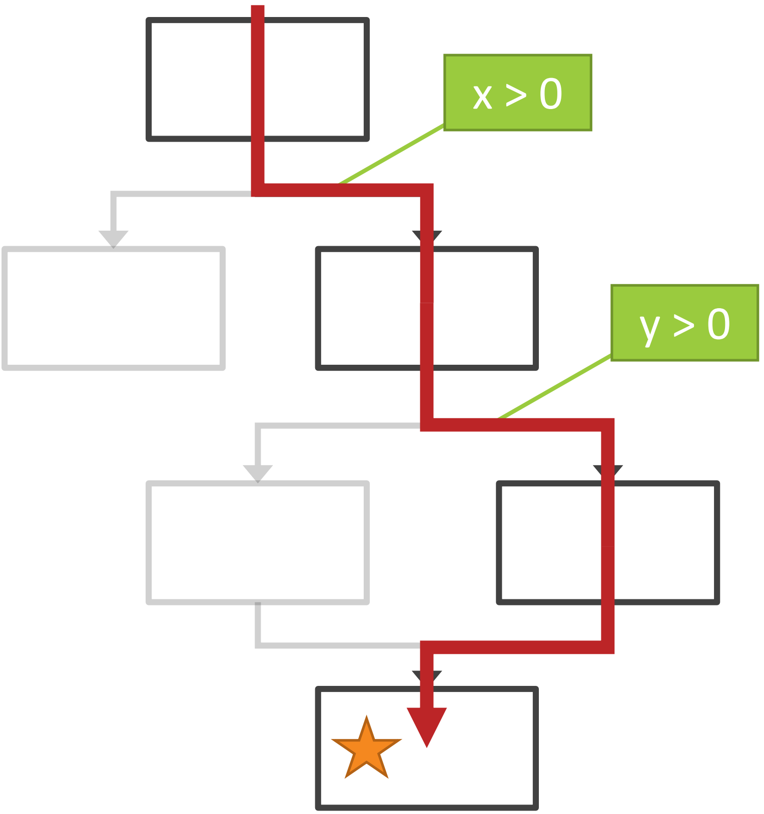
Critical Paths

CISPA HELMHOLTZ-ZENTRUM i. G.



1. locate critical instructions
2. compute backward slices of argument(s)
3. filter for attacker controlled slices
4. generate path through a slice

Exploit Generation – General Approach



1. locate critical instructions
2. compute backward slices of argument(s)
3. filter for attacker controlled slices
4. generate path through a slice
5. execute path symbolically
    - collect path constraints
6. use constraint solver
    - unsatisfiable: generate next path
    - satisfiable: done

Challenges

- control flow graph recovery ✓
- contract state
- **SHA3** instruction

Contract State

```
contract Stateful{

  bool vulnerable = false;

  function exploit(address attacker){
    require(vulnerable);
    attacker.transfer(this.balance);
  }

  function makeVulnerable(){
    vulnerable = true;
  }

}
```

state at bytecode level?

EVM – Memory Model

CISPA HELMHOLTZ-ZENTRUM i. G.

Stack

- stack
- 256 bit words
- volatile

Memory

- array
- byte-addressable
- volatile

Storage

- map/dictionary
- 256 bit keys, 256 bit values
- persistent

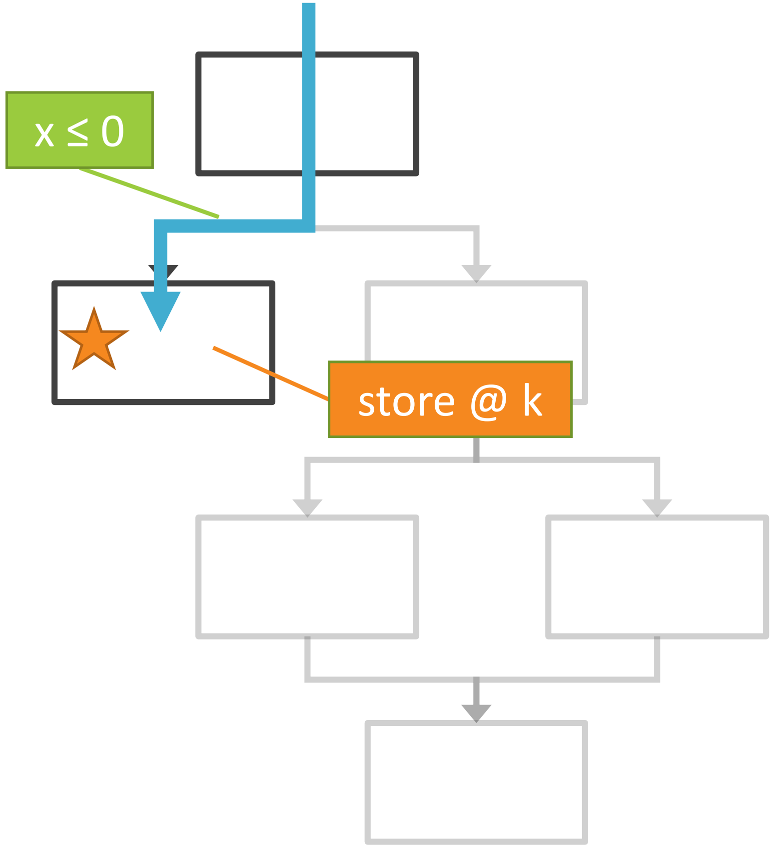
state change = storage change

Storage Instructions

- **`SLOAD`**
  - load value for **`key`**

- **`SSTORE`**
  - store **`value`** at **`key`**

State Changing Paths



1. locate **SSTORE** instructions
2. compute backward slices of argument(s)
3. generate path through a slice
4. execute path symbolically
   - collect path constraints C
   - collect storage reads R & writes W

$$C = \{x \leq 0\}$$

$$R = \emptyset$$

$$W = \{k\}$$

Path Stitching

- combine n state changing paths + 1 critical path

$$C_{\color{blue}\rightarrow} = \{x \leq 0\}$$

$$R_{\color{blue}\rightarrow} = \emptyset$$

$$W_{\color{blue}\rightarrow} = \{k\}$$

$$C_{\color{red}\rightarrow} = \{x > 0, y > 0\}$$

$$R_{\color{red}\rightarrow} = \{k\}$$

$$W_{\color{red}\rightarrow} = \emptyset$$

$$C_{\color{blue}\rightarrow\color{red}\rightarrow} = C^*_{\color{blue}\rightarrow} \cup C^*_{\color{red}\rightarrow} = \{x_0 \leq 0, x_1 > 0, y_1 > 0\}$$

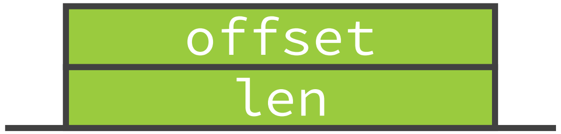
$$R_{\color{blue}\rightarrow\color{red}\rightarrow} = R_{\color{red}\rightarrow} \setminus W_{\color{blue}\rightarrow} \cup R_{\color{blue}\rightarrow} = \emptyset$$

$$W_{\color{blue}\rightarrow\color{red}\rightarrow} = W_{\color{blue}\rightarrow} \cup W_{\color{red}\rightarrow} = \{k\}$$

Challenges

- control flow graph recovery ✓
- contract state ✓
- **SHA3** instruction

SHA3 Instruction



- **SHA3**
  - compute Keccak-256 hash over `memory[offset : offset + len]`
  - used to implement Solidity's `mapping` type

```
function check(bytes32 data, bytes32 check){
   require(data == "1337" && sha3(data) == check)
   //…
```

$$C = \{data = \text{"1337"}, sha3(data) \ = \ check\}$$

How to solve $sha3(data) \ = \ check$?

SHA3 Instruction

dependent expression

$$C = \{data = "1337", sha3(data) = check\}$$

dependent constraint

---

1. remove dependent constraints
2. solve reduced set
3. compute hash values
4. replace dependent constraints
5. repeat

$$C' = \{data = "1337"\}$$

$$sha3(data) \rightarrow 0x985d..$$

$$C' = \{data = "1337", 0x985d.. = check\}$$

independent

Challenges

- control flow graph recovery ✓
- contract state ✓
- **SHA3** instruction ✓

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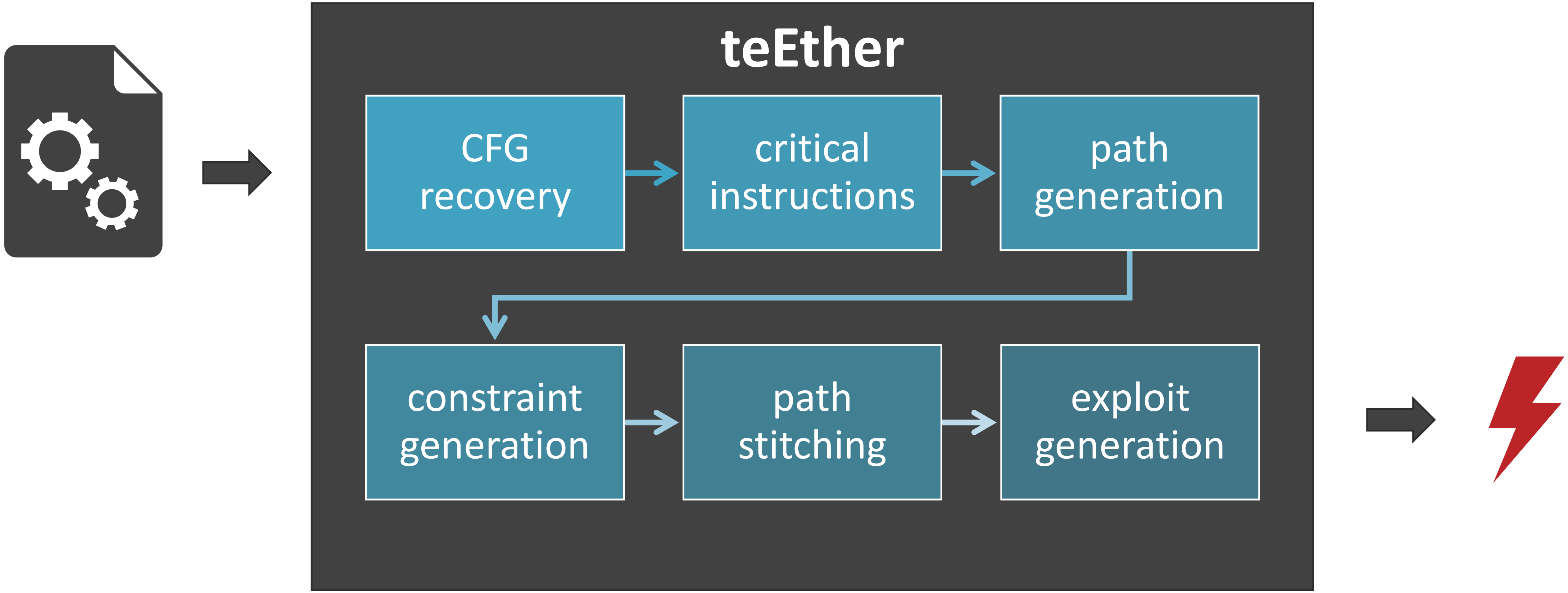
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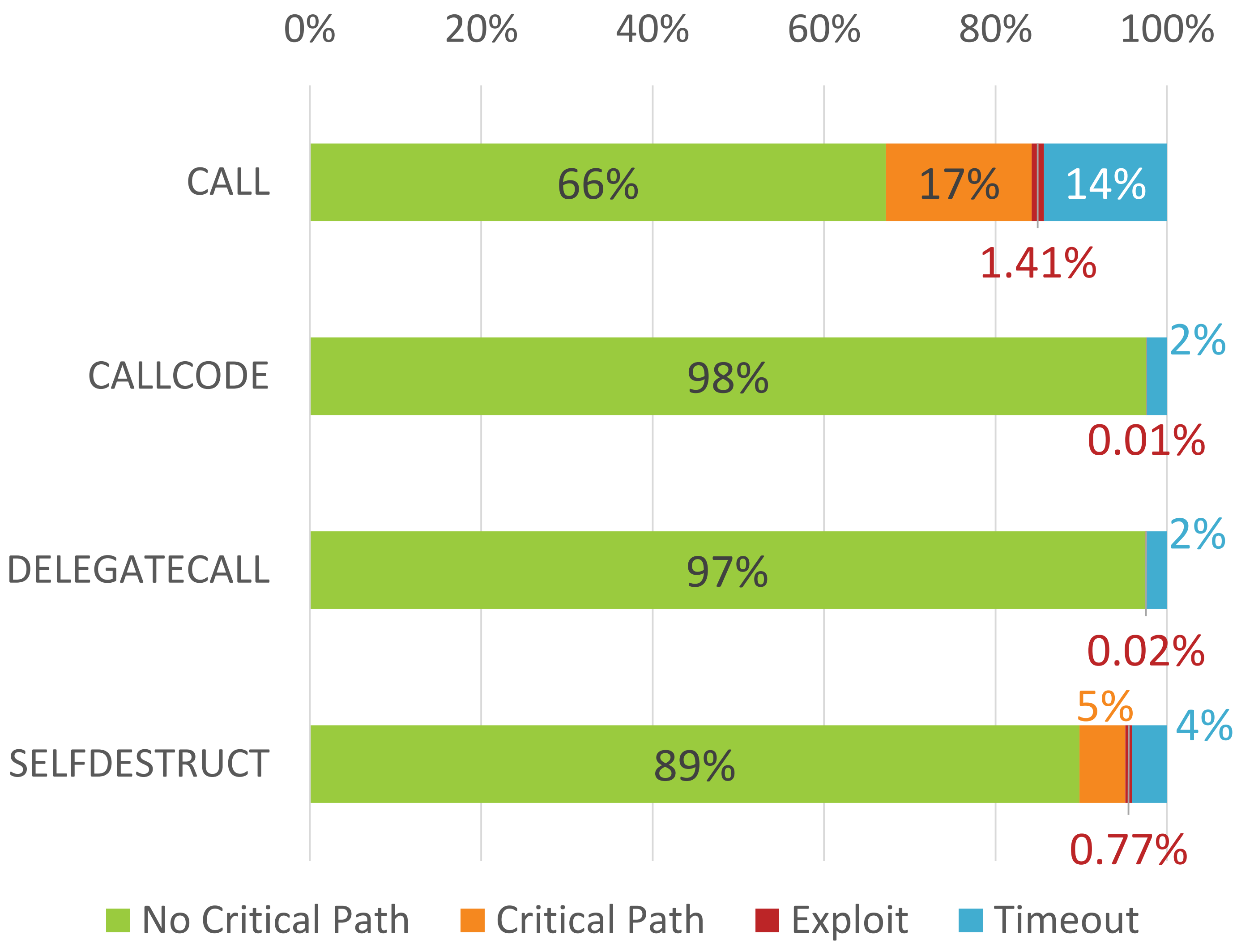
CFG recovery
critical instructions
path generation
constraint generation
path stitching
exploit generation

Evaluation

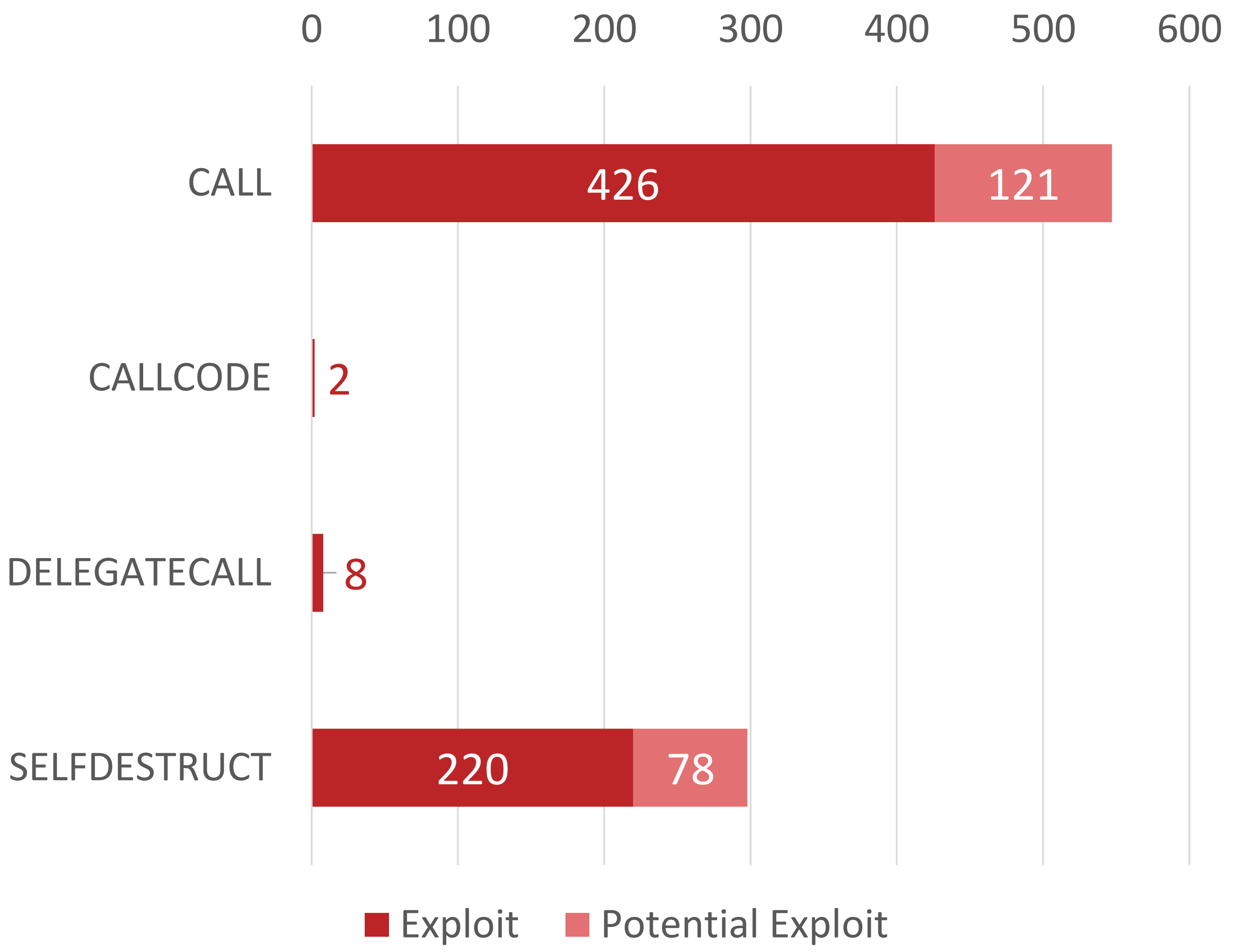
- contracts from blockchain
- 784,344 total
- 38,757 unique
- 30 min CFG recovery +
  30 min exploit generation



Evaluation - Exploits

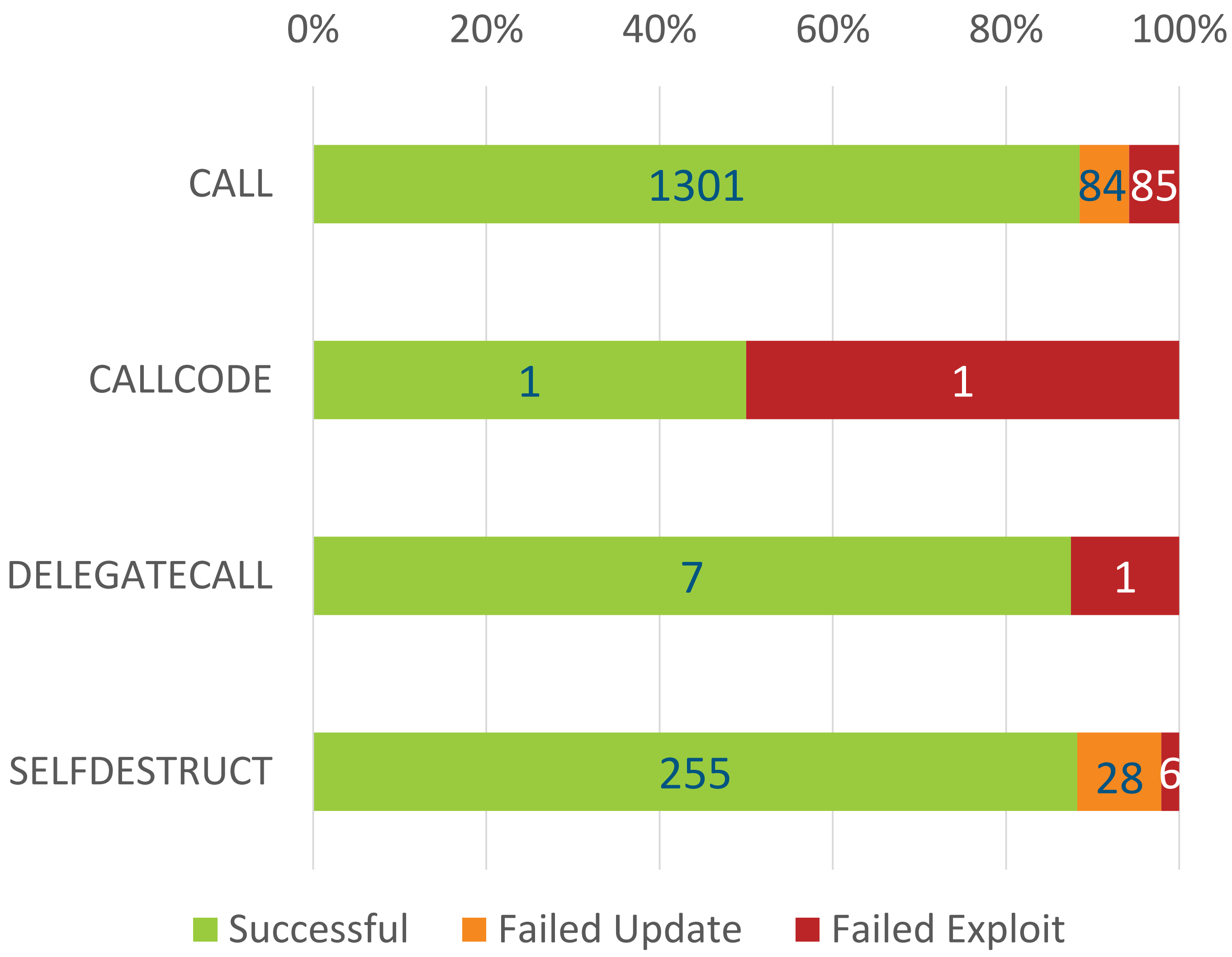
- contracts from blockchain
- 784,344 total
- 38,757 unique
- 30 min CFG recovery +
  30 min exploit generation

- 630 unique exploits
- 1,731 affected contracts
- 1,769 total exploits



Validation

- local test network
- three accounts:
  - target contract
  - attacker
  - „shellcode“ contract
- two step validation:
  - update exploit to reflect target storage
  - replay exploit



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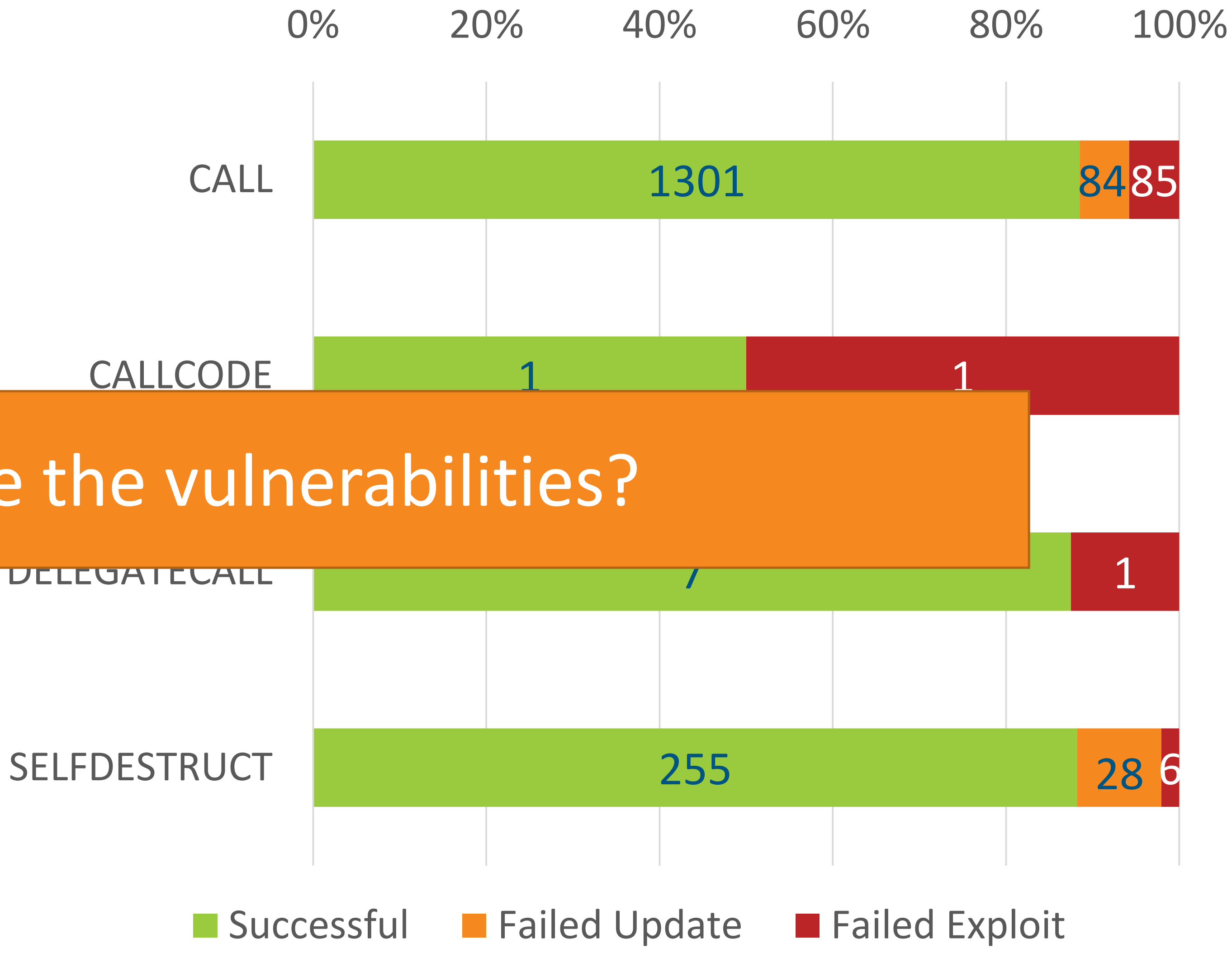
- two ste[...]
  - upd[...] target storage
  - replay exploit

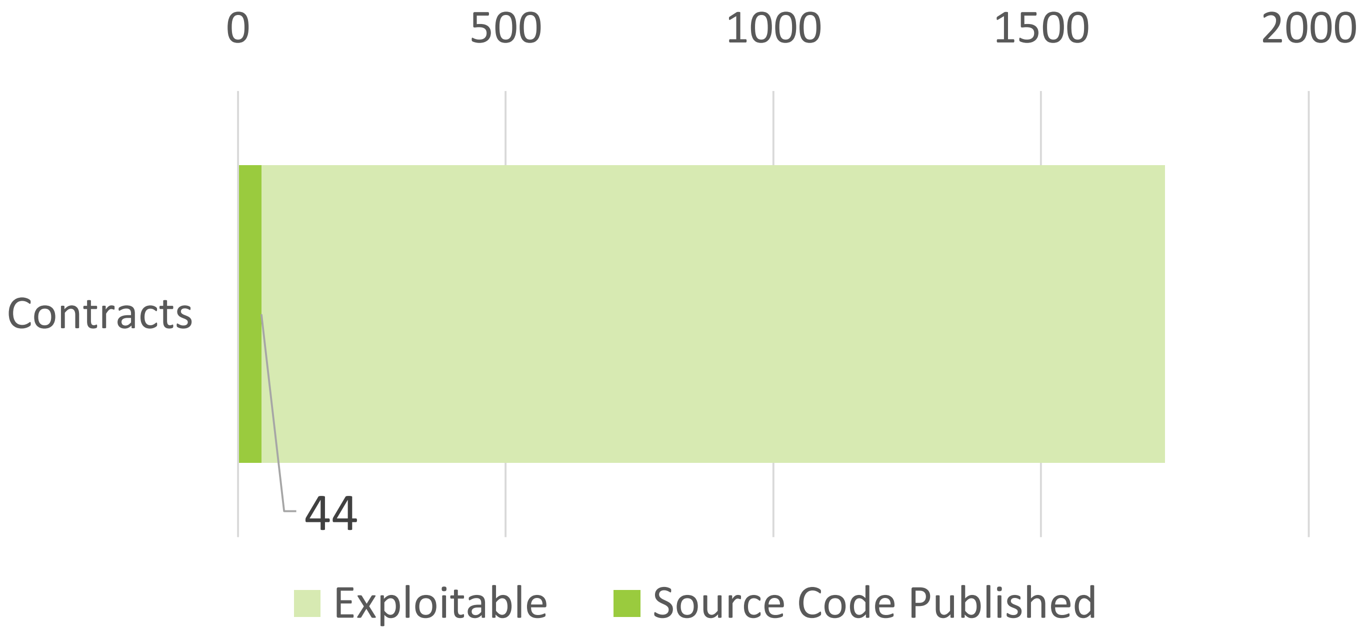


What are the vulnerabilities?

Vulnerabilities

- reverse engineering infeasible
- ~~source code unavailable~~
- OSINT: „publish & verify“ on etherscan.io
- manual analysis

ETHERSCAN
The Ethereum Block Explorer



Vulnerabilities

- logic bugs

```
modifier onlyowner() {
  require(msg.sender != owner);
  _;
}
```

Vulnerabilities

- logic bugs
- semantic confusion

`msg.value`	value of current transaction
`this.balance`	balance of account

Vulnerabilities

- logic bugs
- semantic confusion
- visibility errors

Vulnerabilities – Visibility

```
contract Bet{
  function play() {
    if(bet1 > bet2){
      win(player1);
    }else if(bet2 > bet1){
      win(player2);
    }else{
      draw(player1, player2);
    }
  }
  …
}
```

Vulnerabilities – Visibility

CISPA HELMHOLTZ-ZENTRUM i.G.

```
contract Bet{

  …

  function win(address winner) internal {
    winner.transfer(AMOUNT_WIN);
  }

  function draw(address player1, address player2) {
    player1.transfer(AMOUNT_DRAW);
    player2.transfer(AMOUNT_DRAW);
  }

}
```

default visibility: **public**

call **draw(attacker, attacker)**

Vulnerabilities

- logic bugs
- semantic confusion
- visibility errors
- constructor errors

Vulnerabilities – Constructor

```
contract Owned{
  function Owned() {
    owner = msg.sender;
  }

  ...

}
```

- constructor
- executed only once
- `msg.sender` = contract creator

```
contract Owned{
  function owned() {
    owner = msg.sender;
  }

  ...

}
```

- regular function
- can be called by anyone
- `msg.sender` = anyone

Vulnerabilities

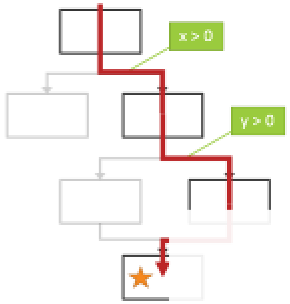
- logic bugs
- semantic confusion
- visibility errors
- constructor errors

caused by Solidity syntax? (semantic confusion, visibility errors, constructor errors)

Solidity partially at fault

Conclusion

Exploit Generation – General Approach



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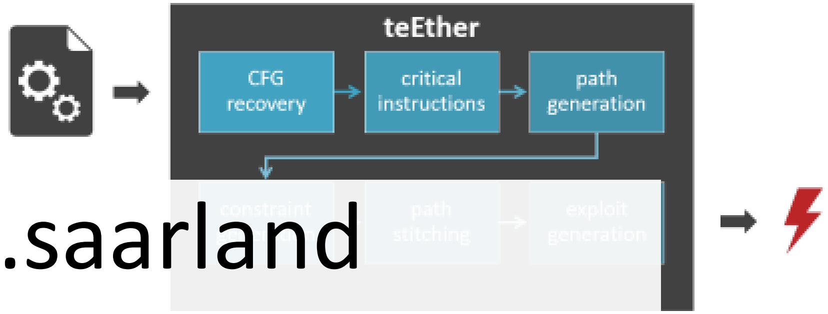

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@KruppJohannes

teEther will be open sourced!

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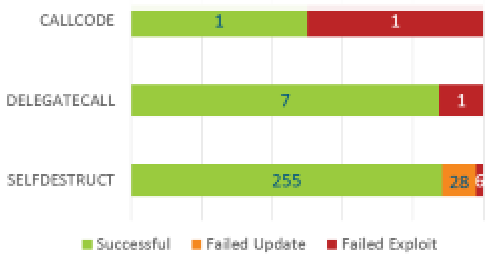

Solidity partially at fault