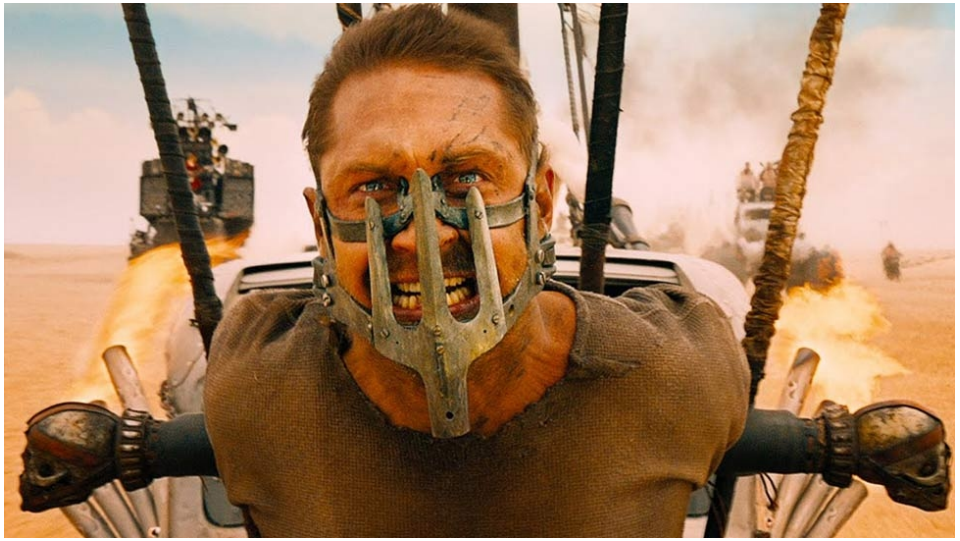

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Smart Contract Static Analysis: Decompilation and Gas Vulnerabilities

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MadMax: Surviving Out-of-Gas Conditions in Ethereum Smart Contracts

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Ethereum is a distributed blockchain platform, serving as an ecosystem for smart contracts: full-fledged inter-communicating programs that capture the transaction logic of an account. Unlike programs in mainstream languages, the execution of an Ethereum smart contract is restricted by a gas limit: execution proceeds as long as gas is available. Thus, gas is a valuable resource that can be manipulated by an attacker to provoke unwanted behavior in a victim's smart contract (e.g., wasting or blocking funds of said victim). Gas-focused vulnerabilities exploit undesired behavior when a contract (directly or through other interacting contracts) runs out of gas. Such vulnerabilities are among the hardest for programmers to protect against, as out-of-gas behavior may be uncommon in non-attack scenarios and reasoning about it is far from trivial.

In this paper, we classify and identify gas-focused vulnerabilities, and present MadMax: a static program analysis technique to automatically detect gas-focused vulnerabilities with very high confidence. Our approach combines a control-flow-analysis-based decompiler and declarative program-structure queries. The combined analysis captures high-level domain-specific concepts (such as "dynamic data structure storage" and "safely reasonable loops") and achieves high precision and scalability. MadMax analyzes the entirety of smart contracts in the current Ethereum blockchain in just 10 hours (with decompilation timeouts in 8% of the cases) and flags contracts with a current (though highly volatile) monetary value of over $5B as vulnerable. Manual inspection of a sample of flagged contracts shows that 81% of the sampled warnings do indeed lead to vulnerabilities, which we report on in our experiment.

Additional Key Words and Phrases: Program Analysis, Smart Contracts, Security

1 INTRODUCTION

Ethereum is a decentralized blockchain platform that can execute arbitrarily-expressive computational *smart contracts*. Developers typically write smart contracts in a high-level language that is translated into immutable low-level bytecode for a persistent distributed virtual machine. Smart contracts handle transactions in ether, a cryptocurrency with a current market capitalization of approximately $50B. Smart contracts (as opposed to non-computational "wallets") hold a considerable portion of the total ether available in circulation, which makes them ripe targets for attackers. Hence, developers and auditors have a strong incentive to make extensive use of various tools and programming techniques that minimize the risk of their contract being attacked.

Analysis and verification of smart contracts is, therefore, a high-value task, possibly more so than in any other programming setting. The combination of monetary value and public availability makes the early detection of vulnerabilities of paramount importance. (Detection may occur after contract deployment. Despite the code immutability which prevents bug fixes, discovering a vulnerability before an attacker could enable a trusted party to move vulnerable funds to safety.)

A broad family of contract vulnerabilities concerns *out-of-gas* behavior. Gas is the fuel of computation in Ethereum. Due to the massively replicated execution platform, wasting the resources of others is prevented by charging users for running a contract. Each instruction executed costs gas,

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OOPSLA '18

What Do I Do?

Static analysis research

- trying to create a model of all possible program behaviors
- mature framework for Java bytecode, less so for LLVM bitcode

This talk: two pieces of recent work, on Ethereum

- MadMax: detector for gas-related vulnerabilities
- Gigahorse: a decompiler for EVM bytecode (and more)

Secret Sauce: Declarative Specifications

All analyses specified declaratively, in the Datalog language

- i.e., logical rules (hundreds of them)

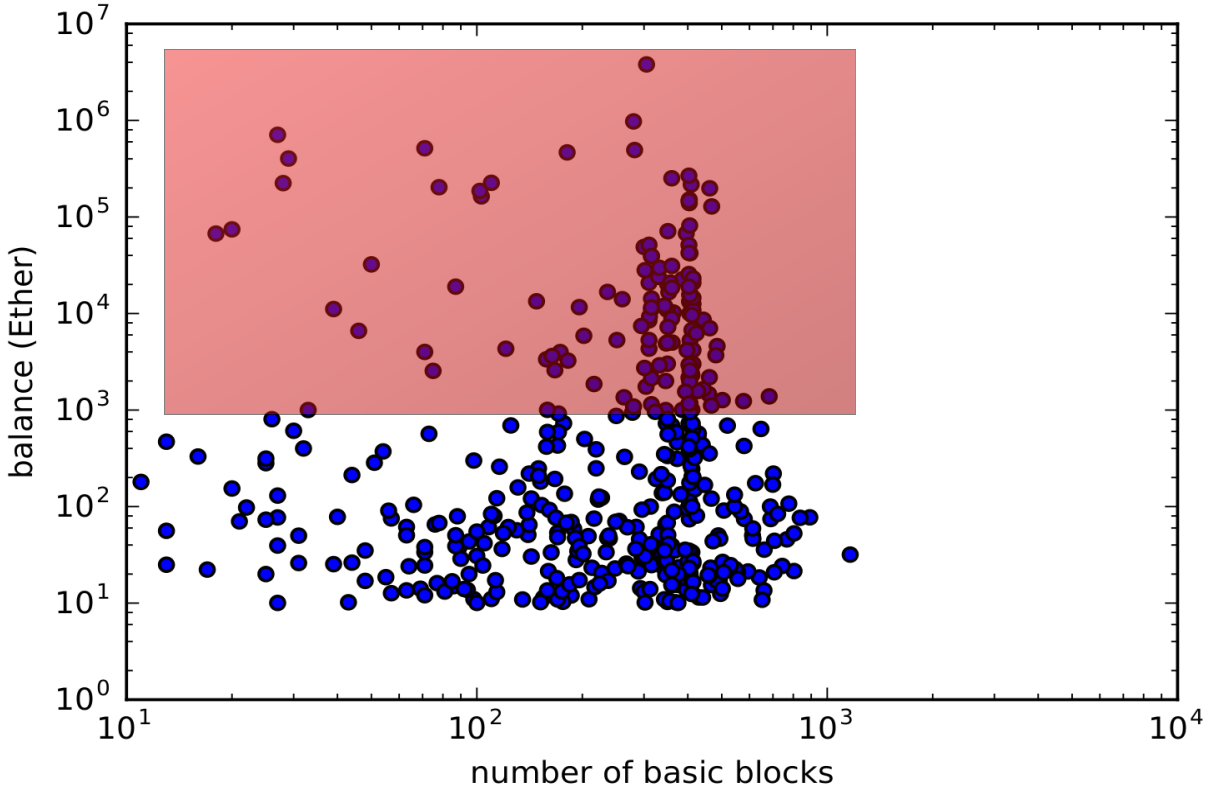
E.g.,

```
LoopBoundBy(loop, var) ←
  InductionVar(i, loop),
  !InductionVar(var, loop),
  Flows(var, condVar),
  Flows(i, condVar),
  LoopExitCond(condVar, loop).
```

Background

- Ethereum: blockchain technology
  - proof of work, mining, the works...
- But also: smart contracts
  - complete programs, persistently on the blockchain
- Gas: fee paid for running them
  - translated in Ether (the Ethereum currency)
  - bounded/hard coded

Complexity, Balance and Risk



Contracts that hold majority of Ether tend to be complex

Gigahorse Decompiler

Go to http://contract-library.com

- sneak preview, release by November

EVM Bytecode Decompilation is Hard!

- Ethereum vs. JVM/CIL bytecode
  - No data structures, objects, methods or types
  - Stack depth can be different under different control flow paths
  - All control-flow edges (jumps) are variables, not constants
  - All functions of a contract are fused in one (jumps transfer control)

Decompilation: Stratification Points

Original Bytecode

Whole program 3 address IR + CFG

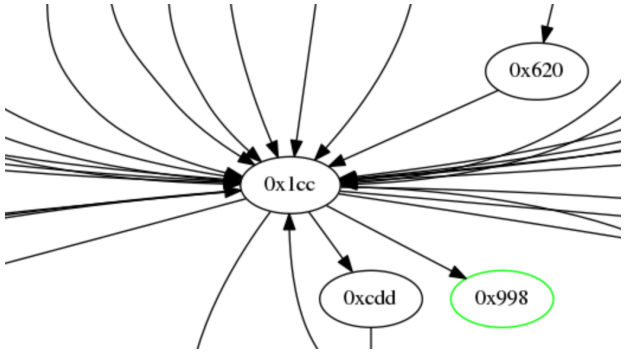
3 address IR + function bounds + local CFGs

Functional 3-address code

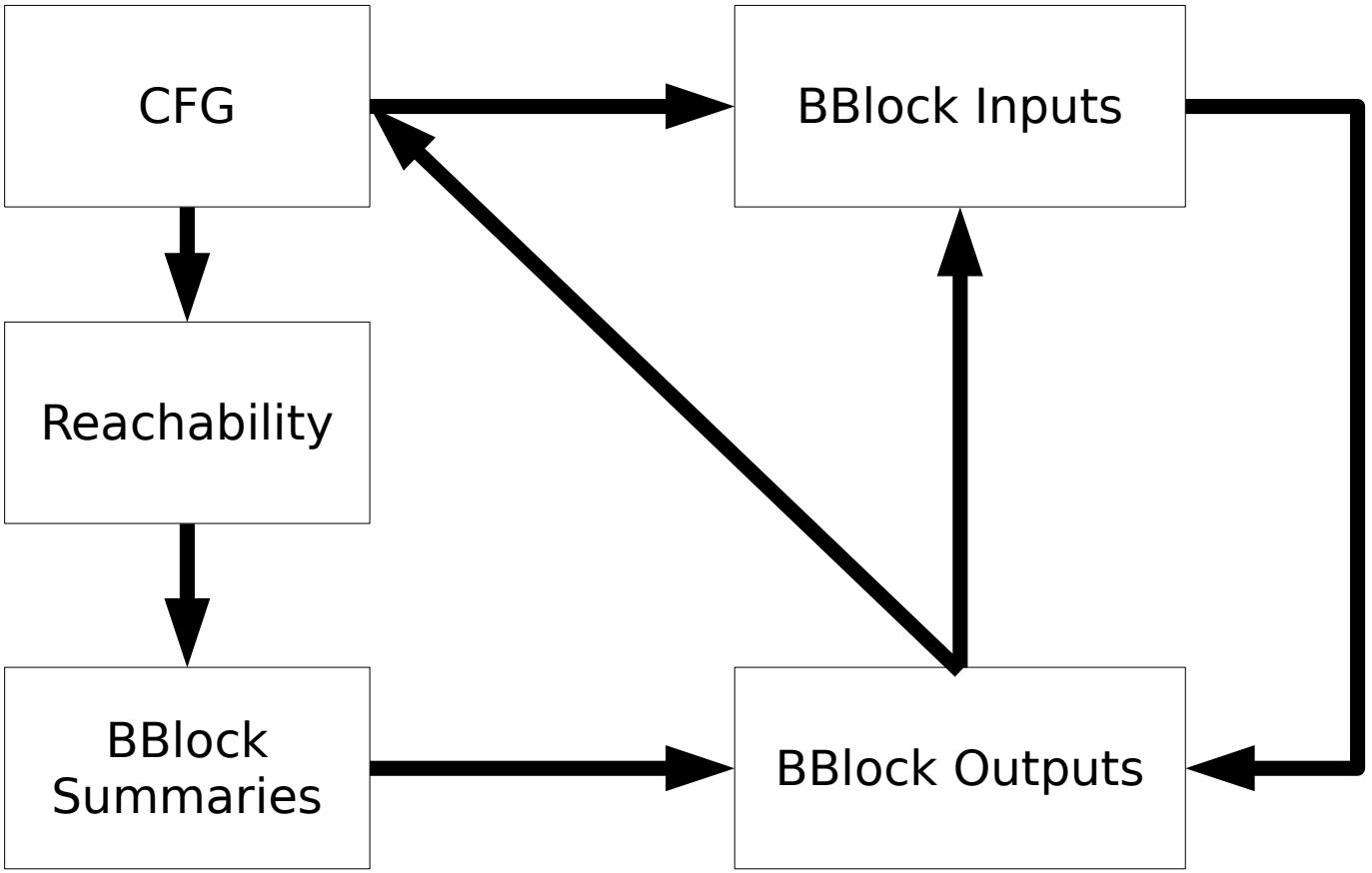
1. Whole contract ctx & flow sensitive analysis

2. Function extraction algorithms

3. Function argument inference with flow sensitive analysis

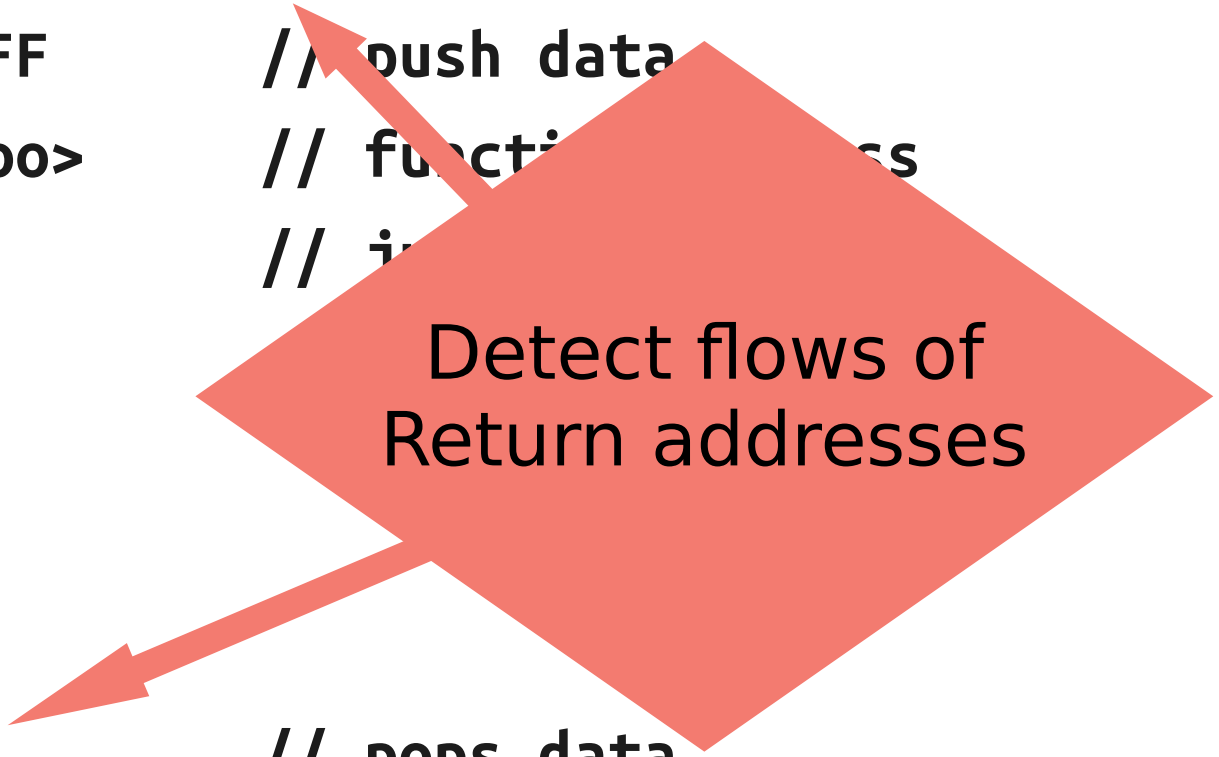


Large-Scale Recursion



Heuristics: Functions That Return

```
          PUSH4 <return>   // return address
          PUSH4 0xFF       // push data
          PUSH4 <foo>      // functi      ss
          JUMP             // j
return:   JUMPDEST
          ...
          ...
foo:      JUMPDEST
          POP              // pops data
          JUMP             // jumps to 'return'
```



Heuristics: Finding More Functions

```
i = 1.
do {
  InFunction_i(block, block) ←  FunctionEntry_i-1(block).
  InFunction_i(next, func) ←
    InFunction_i(block, func),BlockEdge(block, next),
    !FunctionCall_i-1(block, next), !Function_Exit(block).

  FunctionCall_i(prev, block), FunctionEntry_i(block) ←
    InFunction_i(block, f1), InFunction_i(block, f2), f1 != f2,
    BlockEdge(prev, block), !FunctionExit(prev),
    !InFunction_i(prev, f1), !InFunction_i(prev, f2).

  i = i + 1.
} until fixpoint(FunctionEntry)
```

Output IR After Function Arg Inference

```
private 0xa3b (va1, va2, va3) → (int4, int16)
    f1 := CONST 0xa4b
    ret := CONST 0x3f
    v1, v2 := CALLPRIVATE(f1, ret, va2)
    r1 := SHA3(va2, va3)
    RETURNPRIVATE va1, r1, v1;
}
private 0xa4b(va1, va2) → (int4, int16)
...
}
```

Implementation

- A few (<5) KLoC of Datalog
- Decompiles 99.9% of entire Ethereum blockchain in 2 hours

MadMax: Gas-Focused Vulnerability Detection

What is MadMax? [OOPSLA'18]

Cutting-edge (exhaustive) *static analysis*

- Abstract Interpretation, CFA Flow Analysis, memory modeling

Performs analysis directly on the bytecode

- Source code only available for 0.34% of contracts (Etherscan)

Evaluated on the entire Ethereum blockchain

- Found $5B on vulnerable contracts (81% estimated precision)

Gas-focused vulnerabilities

Gas Focused Vulnerabilities

- **Gas is needed to execute contracts:**
  - Paid for by the account that calls the smart contract.
  - Has monetary value - prevents wasting of resources.
  - If not enough gas is budgeted, transaction is reverted.
  - Possibly blocking forever due to lack of progress.
- **Contract susceptible to DoS attacks if attacker can cause it to require unbounded gas.**

Vulnerability 1: Unbounded Mass Ops

```
contract NaiveBank {
  struct Account {
    address addr;
    uint balance;
  }
  Account accounts[];
  function applyInterest() returns (uint) {
    for (uint i = 0; i < accounts.length; i++) {
      // apply 5 percent interest
      accounts[i].balance = accounts[i].balance * 105 / 100;
    }
    return accounts.length;
  }
  function openAccount() returns (uint) { … }
}
```

Vulnerability 2: Wallet Griefing

```
for (uint i = 0; i < investors.length; i++) {
  if (investors[i].invested < min_investment) {
    // Refund, and check for failure.
    // Looks benign but locks entire contract
    // if attacked by a griefing wallet.
    if (!(investors[i].addr.send(investors[i].dividendAmount))) {
        throw;
    }
    investors[i] = newInvestor;
  }
}
```

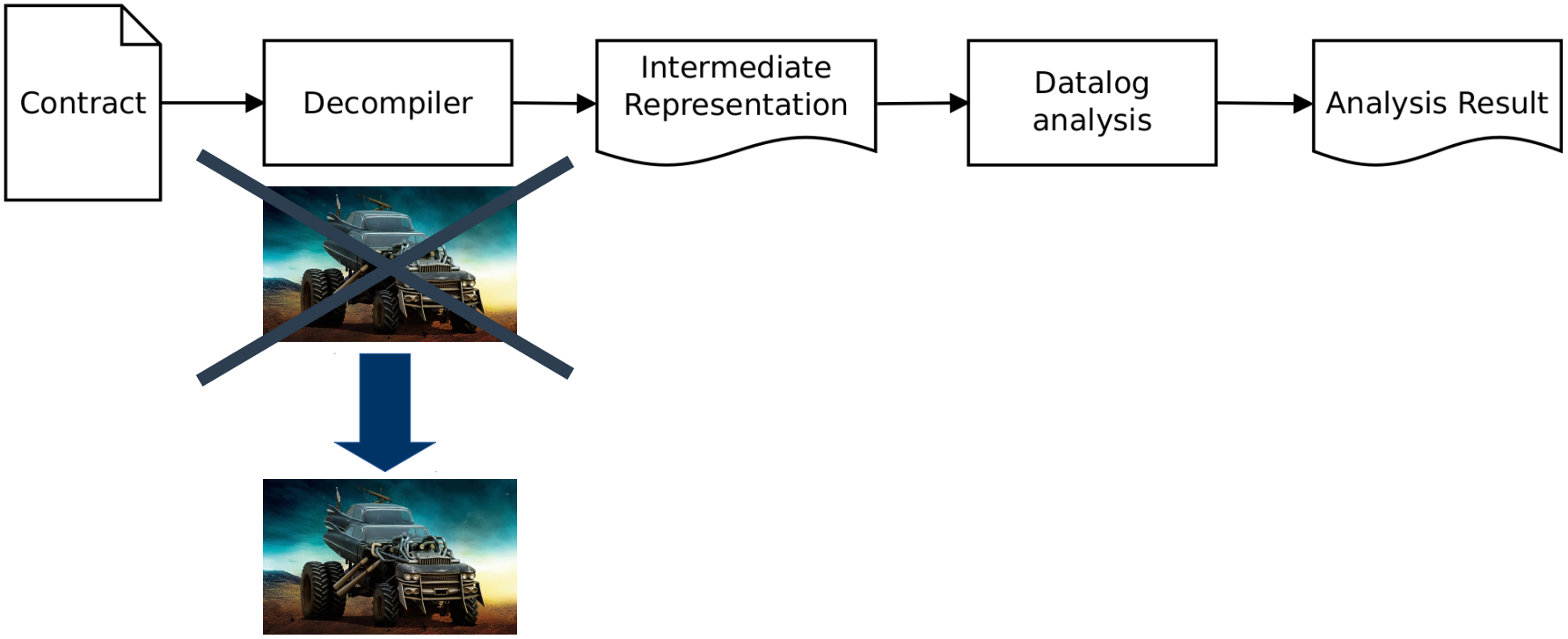
Vulnerability 3: Integer Overflow

```
contract Overflow {
  Payee payees[];

  function goOverAll() {
    for (var i = 0; i < payees.length; i++) {
    ...
    }
  }
  ...
}
```

Higher level analyses

Overview of MadMax



Higher Level Analyses

Structured loop reconstruction:

- Induction Variables & Loop Exit Conditions

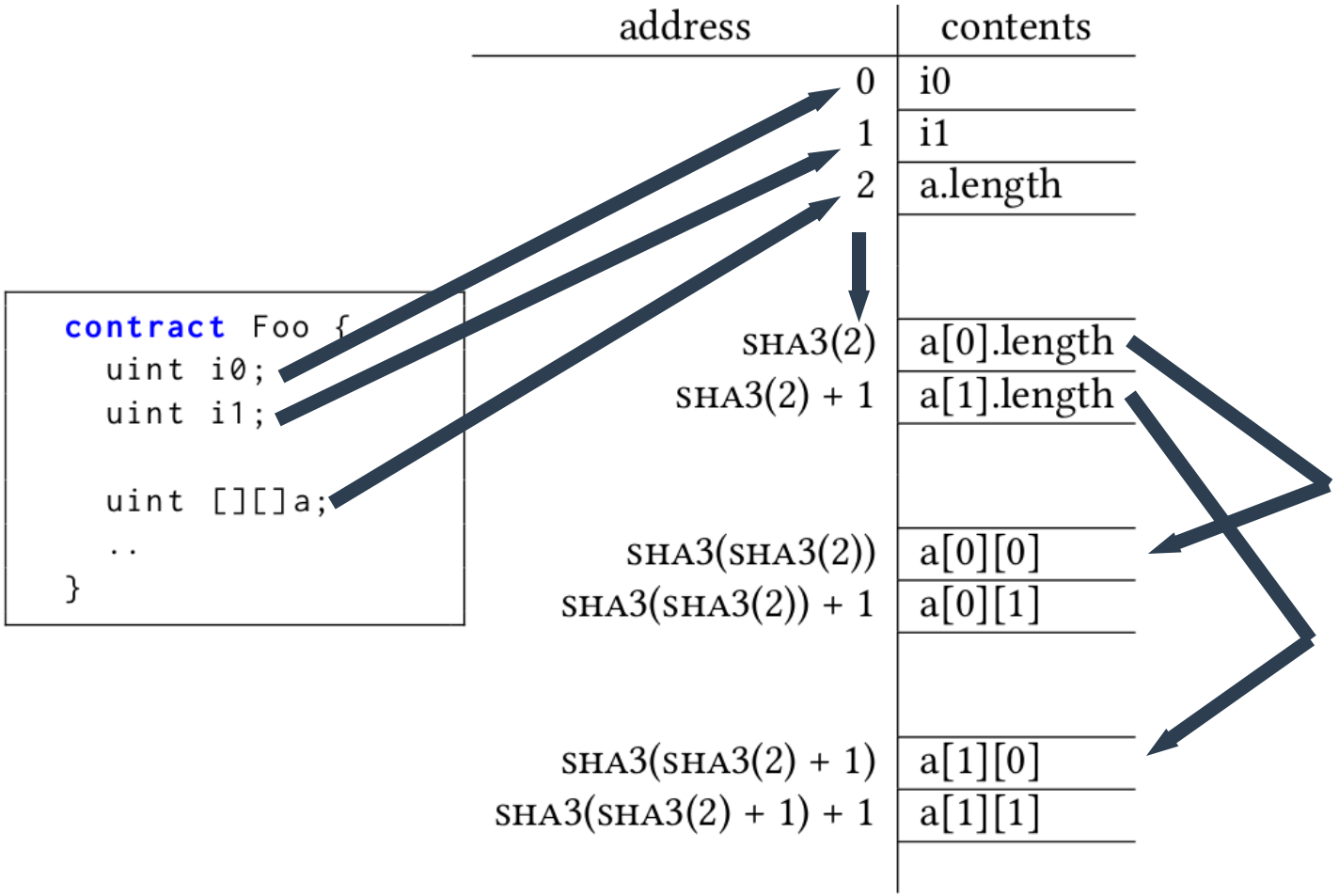
Alias Analyses

High level data structure semantic analysis

Cool concepts such as:

- `IncreasedStorageOnPublicFunction`
- `PossiblyResumableLoop`

Modeling Storage & Data Structures



Example top-level query

```
UnboundedMassOp(loop) ←
  IncreasedStorageOnPublicFunction(arrayId),
  ArrayIdToStorageIndex(arrayId, storeOffsetVar),
  Flows(storeOffsetVar, index),
  VarIndexesStorage(storeOrLoadStmt, index),
  InLoop(storeOrLoadStmt, loop),
  ArrayIterator(loop, arrayId),
  InductionVar(i, loop),
  Flows(i, index),
  !PossiblyResumableLoop(loop).
```

Experimental Evaluation

Results: Effectiveness

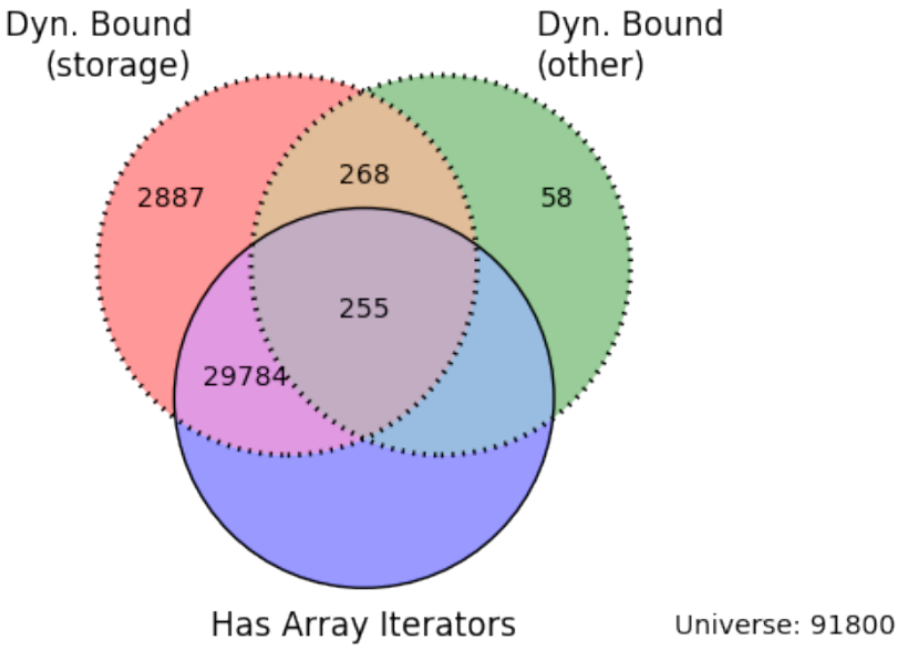
Analysed entire blockchain:

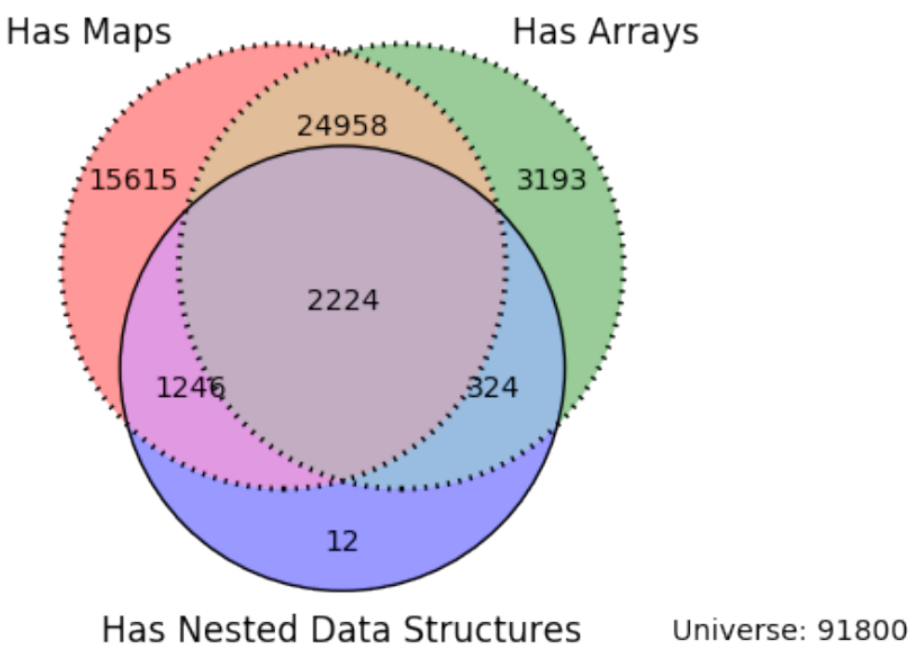
- 6.33M contracts (90k unique) in 10 hours
- 4.1% susceptible to unbounded iteration.
- 0.12% susceptible to wallet griefing.
- 1.2% susceptible to loop overflows.

Combined holding of 7.07 million ETH

81% estimated precision

Insights: Iteration and Data Structures





Reconstructing high level data structure semantics critical for low false positive rate.

Related work

Approach	Works	Soundy	Automated	Bytecode	General
Symbolic Execution	- Oyente by Luu et al. (2016) - Maian by Nikolic et al. (2018) - gasper by Chen et al. (2017) - Grossman et al. (2017)				
Formal Verification	- Proofs in Isabelle/HOL by Hirai (2017) & Amani et al. (2018) - Proofs in the K framework by Hildenbrandt et al. (2017) - Formalism of EVM in F* by Bhargavan et al. (2016)				
Abstract interpretation on Solidity	- Zeus by Kalra et al. (2018) - FSolidM by Mavridou and Laszka (2018)				
Abstract interpretation on EVM bytecode	MadMax (OOPSLA'18) (**Our Approach)**				

Conclusions

Datalog lends itself well to:

- Program analyzers (even flow-sensitive ones)
- High level decompilers

MadMax, a vulnerability detection tool:

- Scales to the entire Blockchain
- Interesting results, practical impact

Decompilation a very important step

- Current work focuses on this