Specifying the Ethereum Virtual Machine for Theorem Provers

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Cambridge, Sep. 13, 2017
(FC 2017 + some updates)

Outline

- Problem
    - Motivation
    - EVM as a Machine
    - Wanted Properties
- Current Efforts
    - Writing Specification
    - Testing the Specification
    - Proving Ethereum Contracts Correct
- Outlook

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Ethereum: Program Execution without Trusted Admin

“Server side” computation dictates the society now.
Computers have owners and administrators.

- Will my program be executed unmodified?
- Will my program be available?
- Will my data kept secure from unauthenticated modification?

Ethereum currently uses a Bitcoin-like approach

1. to replicate programs and program states, and
2. to agree on execution traces.

Over 24,000 nodes[1] are running a clone of the Ethereum Virtual Machine (EVM).

[1] According to `ethernodes.org`.

Typical Ethereum Usage: Deposits & Announcements

Ethereum Name Service is a sealed second-price auction. The price is locked while the name is held. Roughly 168,000 ETH ($\approx$ 42,000,000 GBP) locked for 161,000 names.

Voting Protocol McCorry, Shahandashti and Hao [FC 2017] implemented a voting protocol on Ethereum. The protocol requires a public bulletin board; and uses deposit to incentivize participants to perform all steps.

Counterparty risks are now on programs ("smart contracts"). At least you can read the code. Isn't that enough?

The Famous Bug

“The DAO” (an investment club): funds moved out unexpectedly.
17% of total existing ETH affected.
Many miners[2] accepted a protocol change to remedy this particular case; the network split.
The EVM didn’t have a problem; the program on top had.

EVM might be a Good Formalization Target, I Thought

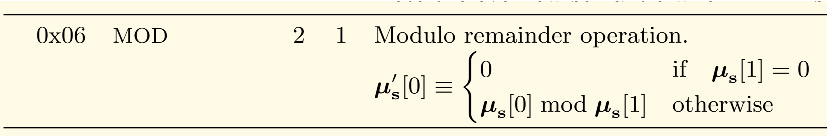
- unstoppable app sounds crazy unless it’s proven correct
- easy machine (deterministic on all inputs)
- test cases for multiple implementations
- a short spec (33 pages).

[2] Miners run GPUs to produce valid blocks.

EVM turns out not too Big to Formalize

The EVM definition in Lem (an ML like specification language) has 2,000 lines.
Most instructions are simply encoded as functions in Lem:

Yellow Paper (original spec):



0x06	MOD	2	1	Modulo remainder operation. $\boldsymbol{\mu}'_{\mathbf{s}}[0] \equiv \begin{cases} 0 & \text{if} \quad \boldsymbol{\mu}_{\mathbf{s}}[1] = 0 \\ \boldsymbol{\mu}_{\mathbf{s}}[0] \bmod \boldsymbol{\mu}_{\mathbf{s}}[1] & \text{otherwise} \end{cases}$

Lem:

```
 | Arith MOD -> stack_2_1_op v c
      (fun a divisor -> (if divisor = 0 then 0 else
           word256FromInteger ((uint a) mod (uint divisor))
       ))
```

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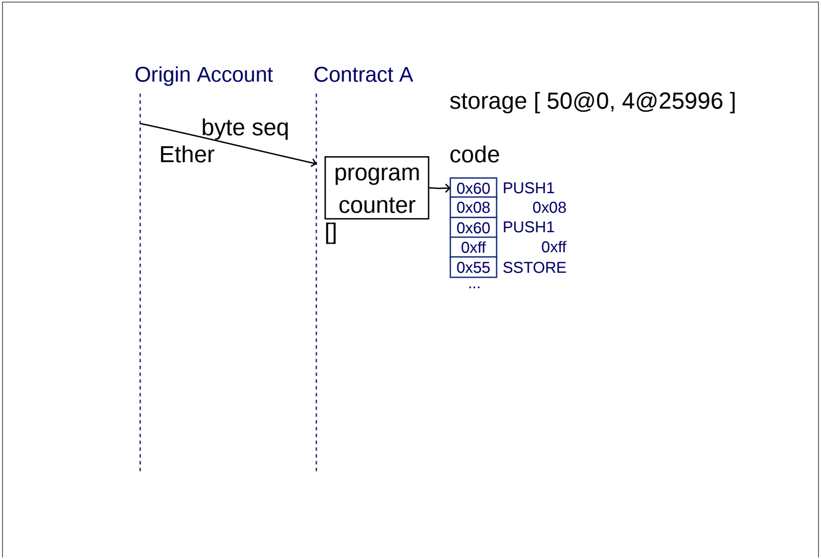
How EVM Works 1



Origin Account

Contract A

storage [50@0, 4@25996]

byte seq

Ether

program counter

[]

code

0x60	PUSH1
0x08	0x08
0x60	PUSH1
0xff	0xff
0x55	SSTORE

...

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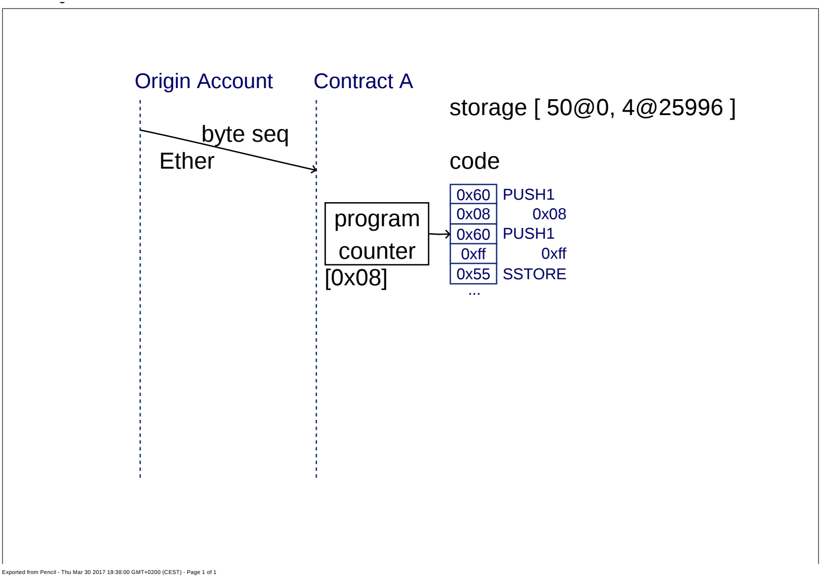
How EVM Works 2



Origin Account

Contract A

byte seq

Ether

storage [50@0, 4@25996]

code

program counter

[0x08]

0x60	PUSH1
0x08	0x08
0x60	PUSH1
0xff	0xff
0x55	SSTORE
...	

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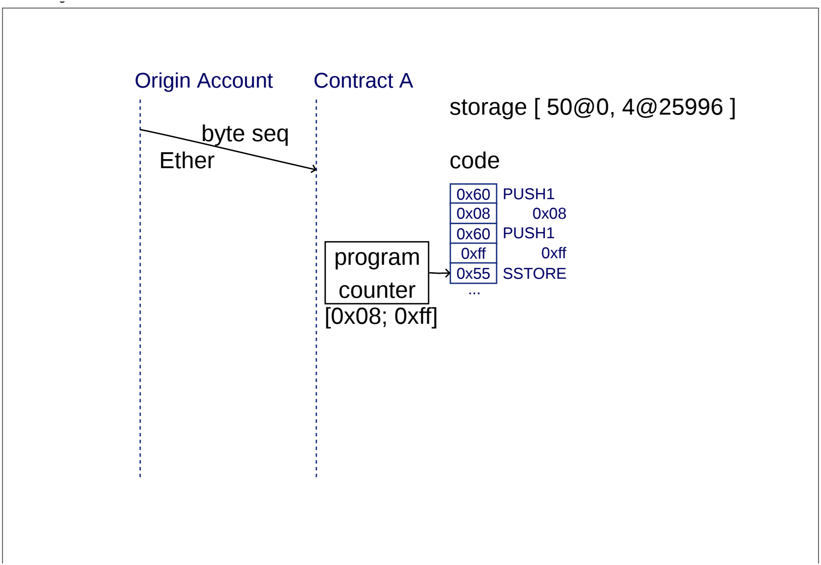
How EVM Works 3



0x60	PUSH1
0x08	0x08
0x60	PUSH1
0xff	0xff
0x55	SSTORE
...	

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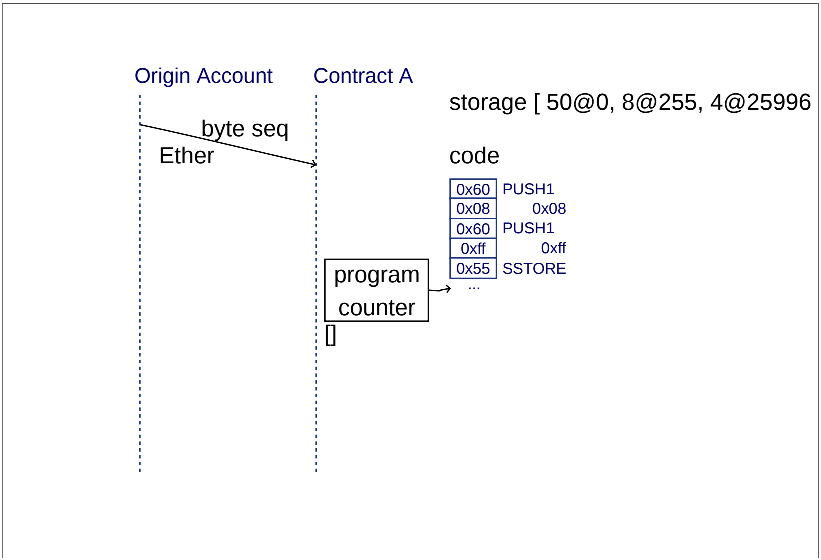
How EVM Works 4



Origin Account

Contract A

storage [50@0, 8@255, 4@25996

byte seq

Ether

code

0x60	PUSH1
0x08	0x08
0x60	PUSH1
0xff	0xff
0x55	SSTORE
...	

program counter

[]

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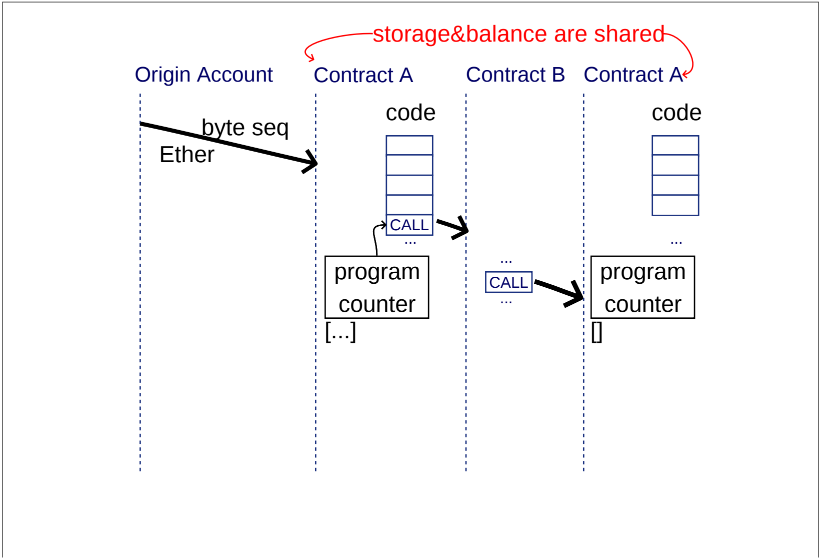
An Annoying Phenomenon Called Reentrancy (Transaction's View)



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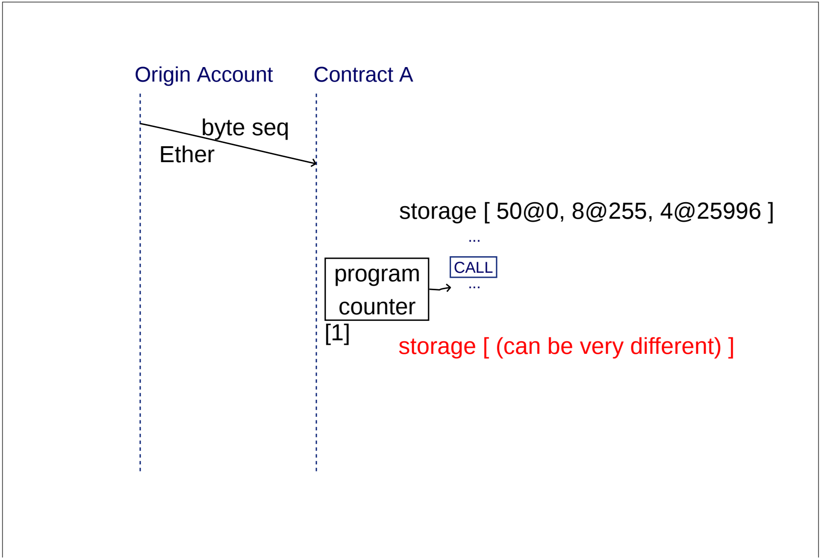
An Annoying Phenomenon Called Reentrancy (Invocation’s View)


Origin Account
Contract A
byte seq
Ether
storage [50@0, 8@255, 4@25996]
...
CALL
...
program counter
[1]
storage [(can be very different)]

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Properties Wanted about a Contract

Safety Properties

- only this kind of callers can alter storage
- only this kind of callers can decrease the balance[3]
- the invalid opcode `0xfd` is never hit
  (Some compilers encode safety properties using 0xfd)

Game Theoretic / Cryptographic Properties

“bidding honestly” should be a dominant strategy

if a contract implements a second-price sealed auction correctly.

[3] Anyone can add balance to any account ☹

Phases of EVM Modeling

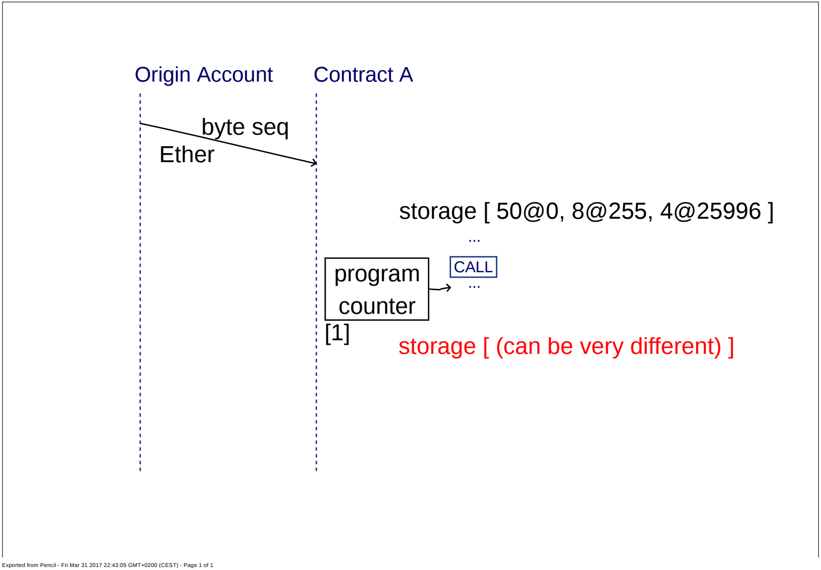
Phase 1 single call—done

Phase 2 caller-callee interaction—in testing & debugging

Phase 3 follow the blockchain—not started

Phase 1: Take the Single Invocation's View

Involves some artificial nondeterminism.



Origin Account

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...

CALL

...

program counter

[1]

storage [(can be very different)]

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Special Treatment of CALL

During CALL instruction, nested calls can enter our program.
Our black box treatment of CALL during phase 1

- by default, the storage and the balance change arbitrarily during a CALL.
- optionally, you can impose an invariant of the contract,
  which is assumed to be kept during a CALL
  but you are supposed to prove the invariant.

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Lem

- a specification language
- translates into HOL4, Isabelle/HOL, OCaml (and Coq)

How I started using Lem

1. I started this project in 2015 in Coq.
2. I tried Isabelle/HOL and my proofs got shorter.
3. Sami Mäkelä saw this and started the Lem version.

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OCaml for Testing

- Lem to OCaml extraction
- OCaml code to parse test cases (simplest “VMTest” format)

- Luckily, EVM has test suites
  - for implementations in Python, Go, Rust, C++, . . . need to match exactly
- VM Test suite: 40,617 cases (24 cases skipped; they involve multiple calls)

Need to run other formats.

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Isabelle/HOL for Proving

Lem to Isabelle/HOL translation seems to be working.

As an off-the-shelf symbolic executor

Keeping the input *x*, without making it concrete.
Just watching the states evolve after each instruction.
Soon we see one stack element
"¬ (the first four bytes of *x* == 0x44552211)"

Number & size of the cases explode.
One instruction takes 15 seconds for a realistic code.

Separation logic

Amani Sidney and Maksym Bortin ported a separation logic library onto EVM.
Compositional reasoning.

Proving Theorems about Ethereum Programs in Isabelle/HOL

With symbolic execution

One theorem about a program (501 instructions) says:

- If the caller's address is not at the storage index 1, the call cannot decrease the balance
- On the same condition, the call cannot change the storage

With separation logic

I deployed a proven wallet as a bounty program (since closed).

Way Ahead

Ongoing

- testing the formalization of a whole transaction, containing transactions containing calls
- verified compiler for a simple language (by Sami Mäkelä)

Not started

- implementing the next protocol change
- common Ethereum contract method/argument encoding
- connect to test/main network

A Competitor

- KEVM by Grigore Rosu and his team: EVM definition in K-framework, gets some tools “for free”.

Summary

- We defined EVM for proof assistants Isabelle/HOL, Coq and HOL4
- The EVM definition is usable for proving Ethereum contracts against a specification
- We found mistakes in the LaTeX spec while writing and testing our definition.

- Proof/tool/language/protocol developments in the proof assistants welcome
  `https://github.com/pirapira/eth-isabelle`
  (Apache License ver. 2 except material from Lem)