Property-Based Testing of Smart Contract in Coq using QuickChick

Masters Thesis Defence

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Motivation

- Smart Contracts are typically used for sensitive transaction
- Financial and legislative usage
- Once deployed, impossible to change
- Attacks:
  - The DAO: $50 million worth of ETH lost
  - Parity Wallet: $280 worth of ETH lost
  - UniSwap Microtrading Exploit: 99.5% funds lost (March 2020)

Motivation

Conclusion: need effective methods for finding bugs/vulnerabilities in smart contracts

Existing Methods

- Contract language (type system, compiler, etc.)
- Model Checking
- Formal verification
- Specialized Static Analysis/Symbolic Execution tools

Existing(?) Methods

But what about testing?

(Property-Based) Testing as a Semi-Formal Method

"Program testing can be a very effective way to show the presence of bugs, but it is hopelessly inadequate for showing their absence"[Dij72]

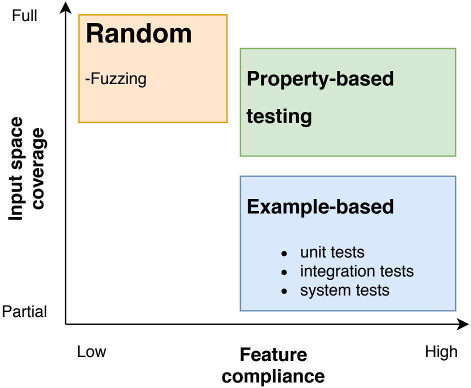
— Edsger W. Dijkstra, The Humble Programmer (1972)

(Property-Based) Testing as a Semi-Formal Method

```
for all inputs x, y, ...
such that precondition(x, y, ...) holds,
P(x, y, ...) is true
```

- P is a mathematical property
- Inputs `x, y, ...` are generated *arbitrarily* (using some generative func)
- Potentially thousands of test cases are generated & executed

PBT versus other testing methods



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Contributions

- A PBT framework for ConCert smart contracts in Coq
- Functional and temporal properties on automatically generated execution traces
- Several case studies of complex contracts
  - ERC20 Tokens, Congress, FA2 Tokens, UniSwap token exchange
  - Successfully tested many safety properties on these
  - Discovered known re-entrancy bugs and other vulnerabilities using testing

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A Brief Introduction to ConCert

- Blockchain & Smart Contract formalisation in Coq
- Certified extraction to Liquidity and Midlang
- Contains a certified, *executable* execution framework
- Functional contracts as Coq terms
- Contracts consist of an `init` and `receive` function

A Brief Introduction to ConCert

Contract Representation

```
Parameter (State Msg Setup : Type).
init :
  Chain →
  ContractCallContext →
  Setup →
  option State;
```

A Brief Introduction to ConCert

Contract Representation

```
Parameter (State Msg Setup : Type).
receive :
  Chain →
  ContractCallContext →
  State →
  option Msg →
  option (State * list ActionBody);
```

A Brief Introduction to ConCert

Execution Model

- Each block holds the states of all deployed contracts
- and a list of `Actions` to execute in this block
- `Actions` can be: contract calls, transfers, contract deployments
- Execution trace: a sequence of blocks where no actions failed

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A Motivating Example: ERC20 Tokens

- Tokens can represent any asset
- Transferable
- Widely used and backbone of many smart contracts
- ERC20: `transfer`, `transfer_from`, `approve`

A Motivating Example: ERC20 Tokens

ConCert Contract Implementation

```
Inductive Msg :=
| transfer : Address → N → Msg
| transfer_from : Address → Address → N → Msg
| approve : Address → N → Msg.

Record State := {
  total_supply : N;
  balances : FMap Address N;
  allowances : FMap Address (FMap Address N)
}.
```

A Motivating Example: ERC20 Tokens

ConCert Contract Implementation

```
Definition receive chain ctx state maybe_msg :=
  ...
  match maybe_msg with
  | Some (transfer to amount) ⇒ try_transfer ...
  | Some (transfer_from from to amount) ⇒ try_transfer_from ...
  | Some (approve delegate amount) ⇒ try_approve ...
  | None ⇒ None
  end.
```

A Motivating Example: ERC20 Tokens

Specification

What is the specification of ERC20?

- `transfer` updates balances correctly
- `transfer_from` updates balances correctly, and access control is applied correctly
- `approve` updates the allowances correctly

Can easily be stated as functional properties, and either tested or proved. All is good, then? Not quite...

A Motivating Example: ERC20 Tokens

A Vulnerability

Attack on `approve+transfer_from`:

1. Alice approves Bob for N tokens
2. Alice re-approves Bob for M ($M < N$) tokens
3. Bob notices this and transfers N of Alices tokens somewhere
4. if Bob's transaction is executed *before* Alice's, then he can now transfer another M tokens.

- Thus, Bob can transfer up to $N + M$ tokens, while Alice expected at most M tokens.
- **All ERC20 compliant tokens are vulnerable to this (in Ethereum)**

A Motivating Example: ERC20 Tokens

Safety Property Guarding against the Attack

- What is the safety property?
- Must necessarily be defined over an entire *execution trace*
- Should be able to compare state of ERC20 contract at different steps in execution trace

A Motivating Example: ERC20 Tokens

Safety Property Guarding against the Attack

In "verbatim":

- Let S, S' be ERC20 contract states.
- If S is the result of an `approve` act P for N tokens,
- and if S' is the result of the same `approve` act but with M tokens,
- if $S \rightsquigarrow S'$
- then the delegate has transferred $\leq N$ tokens from the owner in this interval

I have stated and tested this property (QC finds a counterexample just like the attack)

Next: How the testing framework supports this

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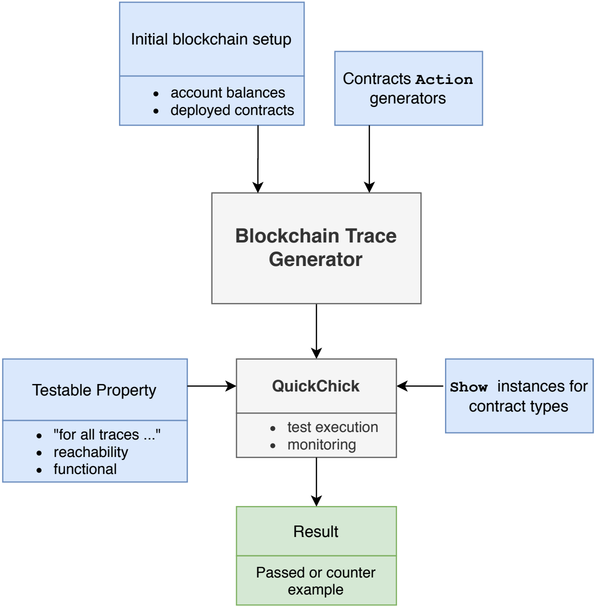
Overview of the Testing Framework



Overview of the Testing Framework

Testable Properties on Execution Traces

Property	Testable interpretation
$\forall t : \mathit{Trace},\ P(t)$	Test P holds on many generated traces
$\exists c : \mathit{Chain}$, $\mathit{reachable}(c) \wedge P(c)$	Assert that the test of $\neg P(c)$ fails in some step of a generated trace. Print counterexample as witness of $P(c)$
Given a contract C, $\forall m : \mathit{Msg}$, $\{P(C,m)\}$ $C.\mathtt{receive}(m)$ $\{Q(C,m)\}$	For each generated trace, check for each step if there are messages to C satisfying P. If so, execute $C.\mathtt{receive}$ and check if Q holds.

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ERC20 Token Example Revisited

Implementing the generator

Composing optional generators with `backtrack`:

```
backtrack [
  (1, gTransfer      token_state) ;;
  (1, gTransfer_from token_state) ;;
  (1, gApprove       token_state) ;;
]
```

ERC20 Token Example Revisited

Implementing the generator

```
Definition gTransfer_from (state : EIP20Token.State)
                              : G (option (Address * Msg)) :=
  (allower, allowance_map) ← sampleFMapOpt state.(allowances) ;;
  (delegate, allowance)   ← sampleFMapOpt allowance_map ;;
  (receiver, _)           ← sampleFMapOpt state.(balances) ;;
  let allower_balance := with_default 0
                           (FMap.find allower state.(balances)) in
  amount ← if allower_balance =? 0
           then returnGen 0
           else choose (0, min allowance allower_balance) ;;
  returnGen (Some
    (delegate, transfer_from allower receiver amount)).
```

ERC20 Token Example Revisited

Testing the Contract

Testing a Functional property:

```
QuickChick (
  {{msg_is_transfer}}
  EIP20Token.contract
  {{post_transfer_correct}}
).
```

Testing a Reachability/Temporal property:

```
QuickChick (
  initial_chain ⇝ transfer_from_is_safe_P
).
```

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Conclusions

- Our approach is based on generating arbitrary blockchain execution traces
- this allows stating both functional and temporal properties
- and test interacting contracts (not shown in this presentation)
- we have sacrificed some automation to obtain the necessary performance...
- we have (re-)discovered many known vulnerabilities/bugs using our testing framework
- hence, the approach is capable, and seems effective at findings bugs
- Since the development is in Coq, we can combine testing and verification efforts (not shown in this presentation)

Future Work

- improve automation of deriving generators, e.g. using Luck[LGWH+16]
- certified generators
- shrinking for minimal counter examples
- align testable execution traces with ConCert's notion of execution traces
- integrate this work into the official ConCert repository (pull request currently under review...)

References I

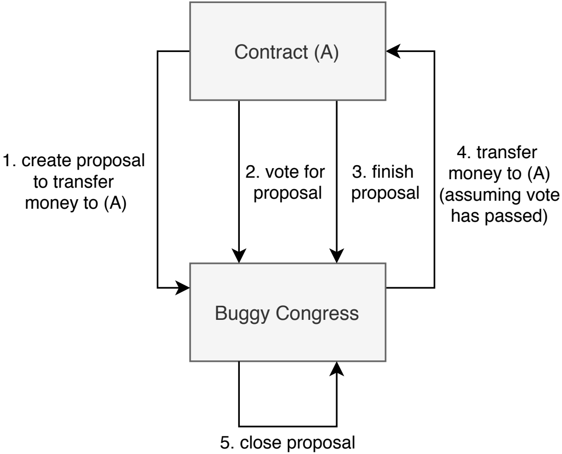
Edsger W. Dijkstra, *The humble programmer*, Commun. ACM **15** (1972), no. 10, 859–866.

Leonidas Lampropoulos, Diane Gallois-Wong, Catalin Hritcu, John Hughes, Benjamin C. Pierce, and Li yao Xia, *Beginner's luck: A language for property-based generators*, 2016.

Extras

Extra Stuff...

Congress/DAO Re-entrancy



Congress/DAO Re-entrancy

Safety Property

```
Definition cacts_preserved new_state resp_acts old_state msg :=
  num_cacts_in_state new_state + length resp_acts <=
  num_cacts_in_state old_state + proposal_cacts msg.

Lemma receive_state_well_behaved
      chain ctx state msg new_state resp_acts :
  receive chain ctx state msg = Some (new_state, resp_acts) →
  cacts_preserved new_state resp_acts old_state msg.

QuickChick (
  {{fun _ _ ⇒ true}}
  Congress_Buggy.contract
  {{receive_state_well_behaved_P}}
).
```

UniSwap Exploit

Exchange Rate Formula

1. calculate the exact exchange rate
2. send corresponding Ether to the caller
3. transfer tokens to the liquidity contract

The exchange rate formula:

$$getInputPrice = \frac{Ts \cdot 997 \cdot ETHr}{Tr \cdot 1000 + Ts \cdot 997}$$

where

$$\begin{aligned} Ts &: \text{nr. of tokens being sold by caller} \\ Tr &: \text{current token reserve held by the liquidity contract} \\ ETHr &: \text{current Ether reserve held by the liquidity contract} \end{aligned}$$

Dexter Exchange Protocol