DAY 2: DESIGNING SPECIFICATIONS

MICHAEL GEORGE
CERTORA

Certora AAVE Training

DAY 1 RECAP

CERTORA

Prover overview

- Rules are like small programs that call contract functions
- May have undefined variables
- Prover considers every possible combination of value
- Reports counterexamples if there are any

Basic Prover usage

- require, assert, mathint, env, envfree, method, calldataarg, withrevert, and lastReverted
- navigating the call trace and understanding counterexamples

Unit-test style rules

- e.g. "`transfer` must increase recipient's balance by amount"

Parametric rules

- e.g. "`allowance(owner,spender)` can only be increased by `owner`"

DAY 2 PLAN

CERTORA

Part 1: More CVL features

- Goal: totalSupply is sum of balances
- Features: definitions, invariants, ghosts, hooks

Short break

Part 2: Designing specifications

- Rule coverage
- Rule design patterns
  - Unit tests, variable changes, variable relationships, state-transition diagrams, risk assessment, mathematical properties

Demo

DAY 2 PLAN

CERTORA

Part 1: More CVL features

- Goal: totalSupply is sum of balances
- Features: definitions, invariants, ghosts, hooks

Short break

Part 2: Designing specifications

- Rule coverage
- Rule design patterns
  - Unit tests, variable changes, variable relationships, state-transition diagrams, risk assessment, mathematical properties

ASSESSING RULE COVERAGE: WHEN ARE YOU DONE?

CERTORA

Code coverage measures quality of **unit tests**

- number of lines executed during unit tests
- 100% coverage is not a guarantee of correctness

ASSESSING RULE COVERAGE: WHEN ARE YOU DONE?

CERTORA

Code coverage measures quality of **unit tests**

- number of lines executed during unit tests
- 100% coverage is not a guarantee of correctness
  - ...but it gives some assurance that test suite is comprehensive

ASSESSING RULE COVERAGE: WHEN ARE YOU DONE?

CERTORA

Code coverage measures quality of **unit tests**

- number of lines executed during unit tests
- 100% coverage is not a guarantee of correctness
  - ...but it gives some assurance that test suite is comprehensive

What's the right metric for quality of **specifications**?

- Not code coverage: any parametric rule instantly gives 100% code coverage

ASSESSING RULE COVERAGE: WHEN ARE YOU DONE?

Code coverage measures quality of **unit tests**

- number of lines executed during unit tests
- 100% coverage is not a guarantee of correctness
  - ...but it gives some assurance that test suite is comprehensive

What's the right metric for quality of **specifications**?

- Not code coverage: any parametric rule instantly gives 100% code coverage

Certora's QA process:

- Systematic rule design (today's topic)

ASSESSING RULE COVERAGE: WHEN ARE YOU DONE?

Code coverage measures quality of **unit tests**

- number of lines executed during unit tests
- 100% coverage is not a guarantee of correctness
  - …but it gives some assurance that test suite is comprehensive

What's the right metric for quality of **specifications**?

- Not code coverage: any parametric rule instantly gives 100% code coverage

Certora's QA process:

- Systematic rule design (today's topic)
- Bug injection
  - Insert bugs into contracts, check that the rules catch them
  - Best if done by someone other than rule writer

ASSESSING RULE COVERAGE: WHEN ARE YOU DONE?

CERTORA

Code coverage measures quality of **unit tests**

- number of lines executed during unit tests
- 100% coverage is not a guarantee of correctness
  - ...but it gives some assurance that test suite is comprehensive

What's the right metric for quality of **specifications**?

- Not code coverage: any parametric rule instantly gives 100% code coverage

Certora's QA process:

- Systematic rule design (today's topic)
- Bug injection
  - Insert bugs into contracts, check that the rules catch them
  - Best if done by someone other than rule writer
- (Coming soon) randomized mutation testing
  - Automatically inject simple bugs
  - E.g. swap argument order, remove modifiers, drop `require` statements

TYPES OF RULES

- (Most concrete) “Unit test style” / method specification properties
  - Encode the method documentation
  - Consider successful cases and revert conditions

TYPES OF RULES

CERTORA

- (Most concrete) “Unit test style” / method specification properties
  - Encode the method documentation
  - Consider successful cases and revert conditions
- Variable changes
  - For each variable / getter, ask when and how it should change
  - Describe quality of changes and methods that can change

TYPES OF RULES

CERTORA

- (Most concrete) “Unit test style” / method specification properties
  - Encode the method documentation
  - Consider successful cases and revert conditions
- Variable changes
  - For each variable / getter, ask when and how it should change
  - Describe quality of changes and methods that can change
- Variable relationships
  - Ask what variables are related to each other and how

TYPES OF RULES

CERTORA

- (Most concrete) “Unit test style” / method specification properties
  - Encode the method documentation
  - Consider successful cases and revert conditions
- Variable changes
  - For each variable / getter, ask when and how it should change
  - Describe quality of changes and methods that can change
- Variable relationships
  - Ask what variables are related to each other and how
- State-transition diagrams
  - Ask how a contract (or part of the state) can evolve

TYPES OF RULES

- (Most concrete) “Unit test style” / method specification properties
  - Encode the method documentation
  - Consider successful cases and revert conditions
- Variable changes
  - For each variable / getter, ask when and how it should change
  - Describe quality of changes and methods that can change
- Variable relationships
  - Ask what variables are related to each other and how
- State-transition diagrams
  - Ask how a contract (or part of the state) can evolve
- Risk assessment
  - Take perspective of different stakeholders

TYPES OF RULES

- (Most concrete) “Unit test style” / method specification properties
  - Encode the method documentation
  - Consider successful cases and revert conditions
- Variable changes
  - For each variable / getter, ask when and how it should change
  - Describe quality of changes and methods that can change
- Variable relationships
  - Ask what variables are related to each other and how
- State-transition diagrams
  - Ask how a contract (or part of the state) can evolve
- Risk assessment
  - Take perspective of different stakeholders
- (Most abstract) Mathematical properties
  - Abstract away from details (e.g. monotonicity, additivity, commutativity)

UNIT-TEST STYLE RULES (SINGLE-METHOD SPECS)

CERTORA

Writing method spec rules:

- Describe expected output
- Describe expected state changes
- Describe revert conditions

Example from demo: `transferSpec` and `transferRevertSpec`

```
rule methodSpec {
    env e; address ...;          // declare arguments
    require ...;                 // preconditions

    mathint value_before = ...;  // saved pre-state

    mathint result = f(args);    // call method

    assert ...;                  // check post-state
}
```

Good coverage: a spec for every method

- Except for fiat methods like `balanceOf`

VARIABLE CHANGES

CERTORA

Writing variable change rules:

- Describe how a variable should evolve (e.g. only increasing, ...)
- Describe methods that are allowed to change a variable

Example from demo: `onlyOwnerCanDecreaseBalance`

```
rule varChanges {
    mathint value_before = var();          // save old value

    env e; method f; calldataarg args;     // call arbitrary method
    f(e, args);

    mathint value_after = var();           // save new value

    assert value_before != value_after =>  // if changed then ...
        ...,
        "var must only change if ...";

    assert value_before != value_after =>  // only changed by ...
        f.selector == mint(uint).selector,
        "only mint can change var";
}
```

Good coverage: changes for every variable

- Except unconstrained variables

VARIABLE RELATIONSHIPS (INVARIANTS)

CERTORA

Writing variable relationships:

- Identify groups of related variables
  - Including variables of related contracts (e.g. `underlying.balanceOf(currentContract)`)
- Ask "how could I tell if state is valid by looking at these variables?"
- Often good to write these early so you can use `requireInvariant`

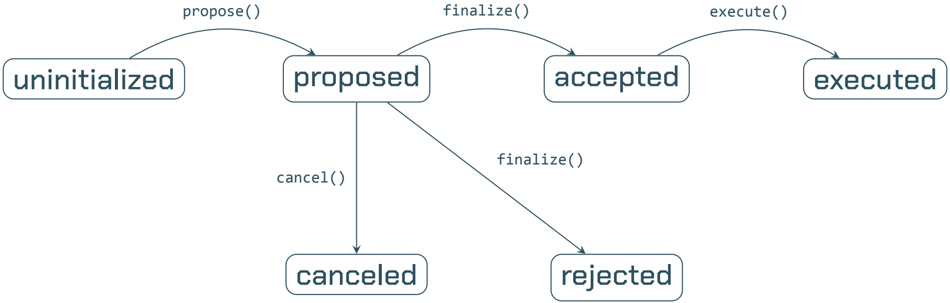
Example from demo: `totalSupplyBounded`

```
invariant x_and_y_correlation()
    ...                         // describe desired relationship
```

Good coverage: groups of related variables have invariants

STATE-TRANSITION SYSTEMS

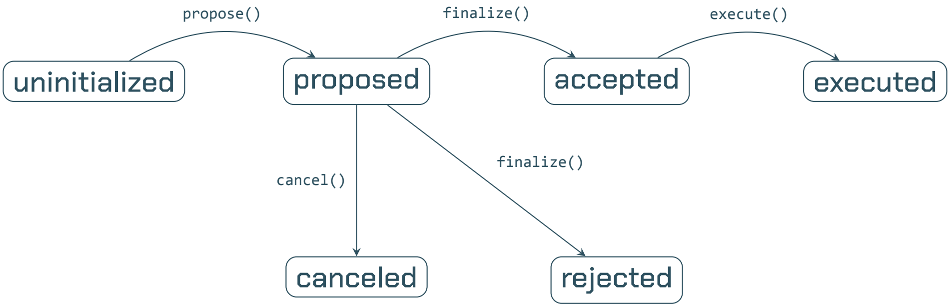
Example: Governance system



STATE-TRANSITION SYSTEMS

CERTORA

Example: Governance system



Definitions:

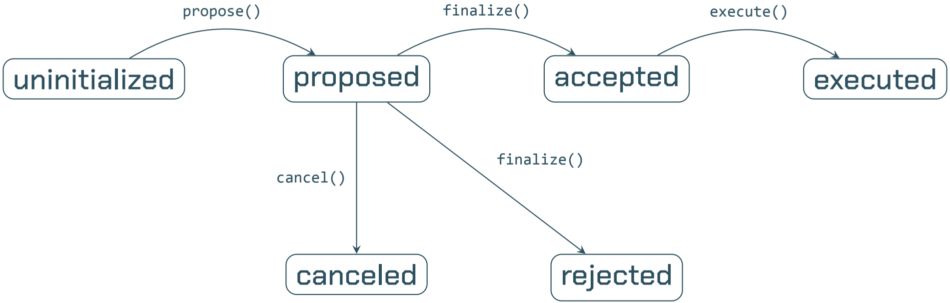
- uninitialized: `id() == 0`
- executed:

  `isClosed() && votesFor() > threshold()`
- ...

STATE-TRANSITION SYSTEMS

CERTORA

Example: Governance system



Definitions:

- uninitialized: `id() == 0`
- executed:

  `isClosed() && votesFor() > threshold()`
- ...

Properties:

- Can only vote in proposed state
- Once canceled always canceled
- ...

STATE-TRANSITION RULES

CERTORA

Writing state-transition rules:

```
definition state1() returns bool = ...;        // define states
definition state2() returns bool = ...;
definition state3() returns bool = ...;

invariant inSomeState()                         // ensure states cover possibilities
    state1() || state2() || state3()

invariant inOneState()                          // if necessary, check state disjointness
    (state1() => !state2() && !state3())
    && ...

rule state1ToState2 {                           // check state transitions
    ...
    require state1_before && state2_after;
    assert ...;
}

invariant varValid()                            // use definitions in rules and invariants
    state1() => ...

rule methodSpec {
    ...
    if (state1()) {
        ...
    } else if (state2()) {
        ...
    } else {
        ...
    }
}
```

RISK ASSESSMENT

CERTORA

Using risk assessment to define rules:

- Identify stakeholders
  - e.g. traders, liquidity providers, owners, voters, ...
- Ask what would make them most unhappy
  - e.g. fees too high, insolvency, DOS, front-running, ...
- Rule those things out

Example:

```
definition assets()      returns uint256 = underlyingBalance(currentContract);
definition liabilities() returns uint256 = totalSupply() * conversion_factor();

invariant solvency()
    assets() >= liabilities()
```

Good coverage: All stakeholders are happy

MATHEMATICAL ABSTRACTIONS

CERTORA

Abstract properties of functions as mathematical functions can reveal bugs

- Monotonicity: a function is only increasing or only decreasing
- Correlation: if one function increases, so does another
- Commutativity: it doesn’t matter which order two operations happen in
- Additivity: the effect of two operations is the sum of their individual effects

Example:

```
rule depositAdditivity {
    uint amountA; uint amountB; env e;

    storage init = lastStorage;                             // save state of storage for replay

    deposit(e, amountA);                                    // deposit two smaller amounts
    deposit(e, amountB);

    uint separate_balance = balanceOf(e.msg.sender);        // save resulting balance

    deposit(e, amountA + amountB) at init;                  // reset storage to init and deposit sum

    uint together_balance = balanceOf(e.msg.sender);        // save resulting balance

    assert separate_balance == together_balance,            // compare

        "splitting a deposit into two smaller deposits must have the same effect on user's balance";
}
```

TYPES OF RULES

CERTORA

- (Most concrete) "Unit test style" / method specification properties
  - Encode the method documentation
  - Consider successful cases and revert conditions
- Variable changes
  - For each variable / getter, ask when and how it should change
  - Describe quality of changes and methods that can change
- Variable relationships
  - Ask what variables are related to each other and how
- State-transition diagrams
  - Ask how a contract (or part of the state) can evolve
- Risk assessment
  - Take perspective of different stakeholders
- (Most abstract) Mathematical properties
  - Abstract away from details (e.g. monotonicity, additivity, commutativity)

HOMEWORK

CERTORA

For next time:

- Design rule set for SymbolicPool (checked in soon)