Formal Verification with The Certora Prover

certora

Michael George

Product Director, Certora

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The Certora Prover is a tool for finding bugs in smart contracts

- Developers specify the intended behavior of the contract
  - Prover uses specs written in Certora Verification Language (CVL)
  - Specs are like unit tests

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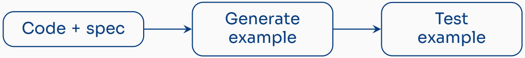
The Prover relies on results of decades of research in formal verification

- Both academic and industrial

Formal Verification vs. Fuzzing

Fuzzing:



Formal Verification vs. Fuzzing

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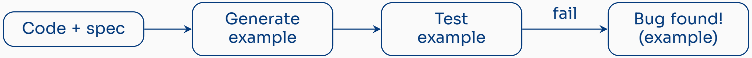

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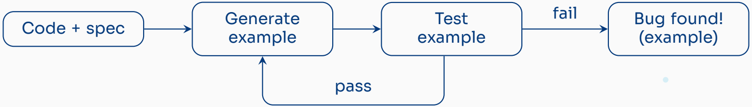

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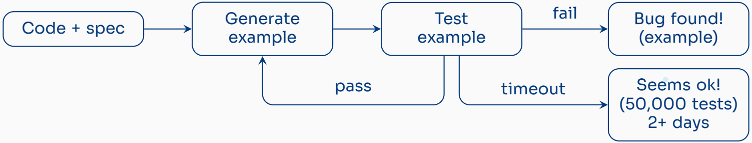

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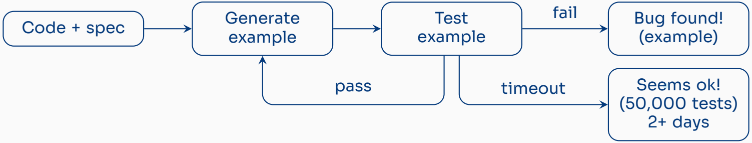


Code + spec

Generate example

Test example

fail

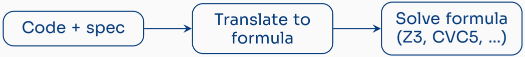
Bug found! (example)

pass

timeout

Seems ok! (50,000 tests) 2+ days

Formal verification (Certora Prover):



Code + spec

Translate to formula

Solve formula (Z3, CVC5, ...)

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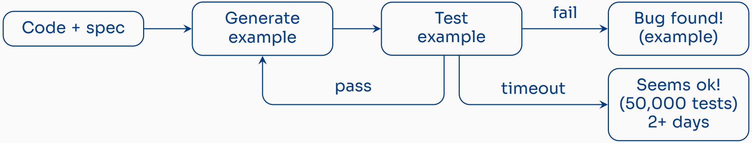

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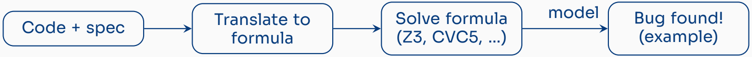

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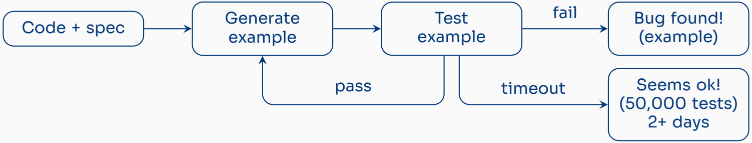

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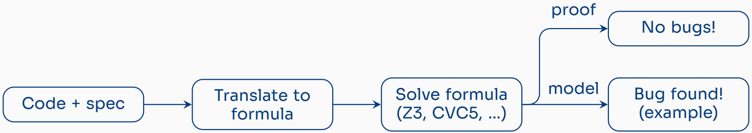

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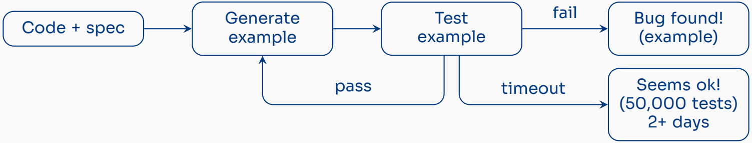

Code + spec

Generate example

Test example

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Bug found! (example)

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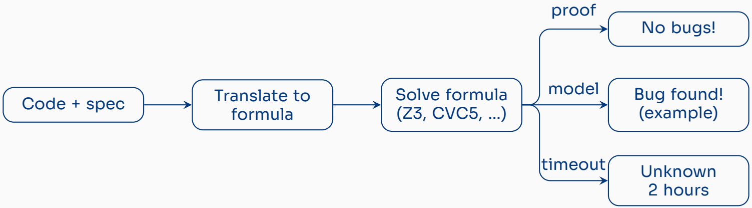

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Translate to formula

Solve formula (Z3, CVC5, ...)

proof

No bugs!

model

Bug found! (example)

timeout

Unknown 2 hours

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- Rewind storage to a previous state
  - e.g. Rerunning with more permissions doesn’t cause revert

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Example / demo

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/// Transfer must move `amount` tokens from
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    transfer(   recip, amount);






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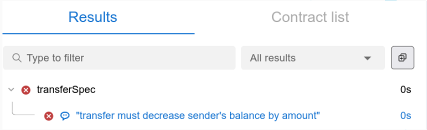

transferSpec 0s

"transfer must decrease sender's balance by amount" 0s

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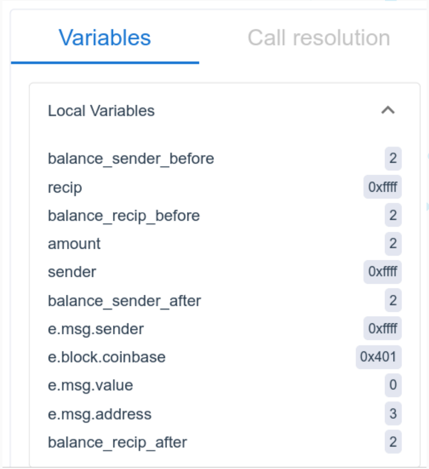

Local Variables

balance_sender_before	2
recip	0xffff
balance_recip_before	2
amount	2
sender	0xffff
balance_sender_after	2
e.msg.sender	0xffff
e.block.coinbase	0x401
e.msg.value	0
e.msg.address	3
balance_recip_after	2

Example / demo

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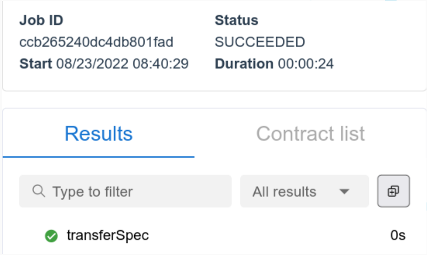

Job ID ccb265240dc4db801fad

Status SUCCEEDED

Start 08/23/2022 08:40:29

Duration 00:00:24

✓ transferSpec 0s

Verification is only as good as the specification

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  - Verifying versions with known bugs against the spec
  - Specs with good coverage should catch them!

Verification is only as good as the specification

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- Bug injection
  - Verifying versions with known bugs against the spec
  - Specs with good coverage should catch them!
- Mututation testing
  - Automatically change the code in ways that probably introduce bugs
  - e.g. remove method decorators, change `require` statements, ...
  - Specs with good coverage should catch them!

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Thank you!

Questions?

`https://demo.certora.com`

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Setting up the Certora Prover

Michael George

Stanford, August 2022

Workshop overview

Today: using the Certora Prover

- Installation
- Basic rules
- Lunch
- Invariants
- Ghosts

Tomorrow: Background and practical use

- How the Prover works
- Introduction to AAVE Governance token
- Lunch
- Systematic specification design
- Work session
- Closing

Logistics

For synchronous watchers (in person / streaming):

- Ask questions! In person or on our Discord in `#stanford-certora-workshop`
- Slides are dense; we'll post on discord
- Follow along; finished examples are in the repository
- We'll do lots of exercises
- Recordings will be available on Certora youtube channel

For asynchronous watchers:

- Ask questions! On the forum: `https://forum.certora.com/`
- Slides and repository are linked in the comments

Installing the Prover and Examples

1. Clone and update the Examples repo
   - `https://github.com/Certora/Examples`
2. Update the submodules
   - `git submodule update --init`
3. Install the Certora Prover

   Option 1: VSCode + Docker

   3.1 Install VSCode

   3.2 Install Docker Desktop

   3.3 Install “Remote - Containers” VSCode extension

   3.4 Open the ERC20Example folder in VSCode

   3.5 View → Command Palette → Reopen In Container

   Option 2: Local install

   3.1 Install Python

   3.2 Install Java JRE

   3.3 Install solc-select

   3.4 `pip install certora-cli`
4. Set your `CERTORAKEY` to the key we sent you
   - in a terminal, run “`export CERTORAKEY=<key we sent you>`”
5. Verify the ERC20 example
   - in a terminal, change to `ERC20Examples` directory
   - `sh certora/scripts/verifyERC20.spec`
   - view the report link that is printed

CVL: Basic Rules

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Michael George

Stanford, August 2022

Overview for this session

Basic rules for ERC20 contracts

- Presentation: writing and debugging rules
  - `transfer` changes balances appropriately
  - `transfer` reverts when it should
  - `transfer` doesn't revert unexpectedly
- Exercise: similar rules for `transferFrom`

Generalized (parametric) rules

- Presentation: rules that apply to all methods
  - Only the owner can increase their `allowance`
  - The owner only changes their allowance deliberately
- Exercise: similar rules for `balanceOf`

ERC20 transfer and balanceOf

The first properties we’d like to test are described in the interface:

```
//// contracts/IERC20.spec

/**
 * Interface of the ERC20 standard as defined in the EIP.
 */
interface IERC20 {


    /**
     * Moves `amount` tokens from the caller's account to `recipient`.
     */
    function transfer(address recipient, uint256 amount)
        external
        returns(bool);


    /**
     * Returns the amount of tokens owned by `account`.
     */
    function balanceOf(address account)
        external view
        returns(uint256);


    ...
}
```

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Specifying transfer in CVL (unit-test-style rules)

```
//// certora/specs/ERC20.spec




/// Transfer must move `amount` tokens from
/// the caller's account to `recipient`.
rule transferSpec {








    transfer(   recip, amount);







    assert balance_sender_after == balance_sender_before - amount,
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        "transfer must decrease sender's balance by amount";

    assert balance_recip_after  == balance_recip_before  + amount,
        "transfer must increase recipient's balance by amount";
}
```

Specifying transfer in CVL (unit-test-style rules)

```
//// certora/specs/ERC20.spec



/// Transfer must move `amount` tokens from
/// the caller's account to `recipient`.
rule transferSpec {
    address sender; address recip; uint amount;



    mathint balance_sender_before = balanceOf(sender);
    mathint balance_recip_before  = balanceOf(recip);

    transfer(   recip, amount);



    assert balance_sender_after == balance_sender_before - amount,
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certora

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rule transferSpec {
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    env e;


    mathint balance_sender_before = balanceOf(sender);
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    transfer(   recip, amount);

    mathint balance_sender_after = balanceOf(sender);
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certora

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```

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Specifying transfer in CVL (unit-test-style rules)

```
//// certora/specs/ERC20.spec

methods {
    balanceOf(address) returns (uint) envfree
}

/// Transfer must move `amount` tokens from
/// the caller's account to `recipient`.
rule transferSpec {
    address sender; address recip; uint amount;

    env e;
    require e.msg.sender == sender;

    mathint balance_sender_before = balanceOf(sender);
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    transfer(e, recip, amount);

    mathint balance_sender_after = balanceOf(sender);
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    assert balance_sender_after == balance_sender_before - amount,
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    transfer(e, recip, amount);

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    assert balance_sender_after == balance_sender_before - amount,
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}
```

(results link)

Specifying transfer in CVL (unit-test-style rules)

(results link)

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    env e;
    require e.msg.sender == sender;

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    transfer(e, recip, amount);

    mathint balance_sender_after = balanceOf(sender);
    mathint balance_recip_after  = balanceOf(recip);

    require sender != recip;

    assert balance_sender_after == balance_sender_before - amount,
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    require e.msg.sender == sender;

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    mathint balance_recip_before  = balanceOf(recip);

    transfer(e, recip, amount);

    mathint balance_sender_after = balanceOf(sender);
    mathint balance_recip_after  = balanceOf(recip);

    require sender != recip;

    assert balance_sender_after == balance_sender_before - amount,
        "transfer must decrease sender's balance by amount";

    assert balance_recip_after  == balance_recip_before  + amount,
        "transfer must increase recipient's balance by amount";
}
```

(results link)

(second link)

What about revert?

So far:

- Transfer reduces sender’s balance by `amount`
- Transfer increases recipient’s balance by `amount`

What about revert?

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- Transfer increases recipient’s balance by `amount`

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So far:

- Transfer reduces sender’s balance by `amount`
- Transfer increases recipient’s balance by `amount`

What if sender’s balance is less than `amount`?

- Transaction reverts
- No balances change!
- Why doesn’t this violate the rule?

What about revert?

So far:

- Transfer reduces sender’s balance by `amount`
- Transfer increases recipient’s balance by `amount`

What if sender’s balance is less than `amount`?

- Transaction reverts
- No balances change!
- Why doesn’t this violate the rule?

Answer: by default, Prover ignores reverting paths.

- we can override this behavior to reason about reverting

transfer revert conditions

```
//// certora/specs/ERC20.spec

/// Transfer must revert if the sender's balance is too small
rule transferReverts {
    env e; address recip; uint amount;

    require balanceOf(e.msg.sender) < amount;

    transfer@withrevert(e, recip, amount);

    assert lastReverted,
        "transfer(recip,amount) must revert if sender's balance is less than `amount`";
}
```

transfer revert conditions

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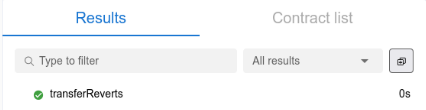
```



✓ transferReverts 0s

(results link)

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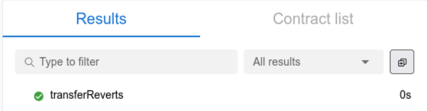

transferReverts 0s

(results link)

Reasoning about reverts:

- Use `f@withrevert(...)` to consider paths where `f` reverts
- Use `lastReverted` to determine whether last call reverted
  - Warning: it is always the last call!
  - save it if you need to make another call

Proving transfer doesn’t revert (liveness rules)

```
//// certora/specs/ERC20.spec

/// Transfer must not revert unless
///    - the sender doesn't have enough funds
///
///
///
///
///
/// @title Transfer doesn't revert
rule transferDoesntRevert {
    env e; address recipient; uint amount;

    require balanceOf(e.msg.sender) > amount;





    transfer@withrevert(e, recipient, amount);
    assert !lastReverted;
}
```

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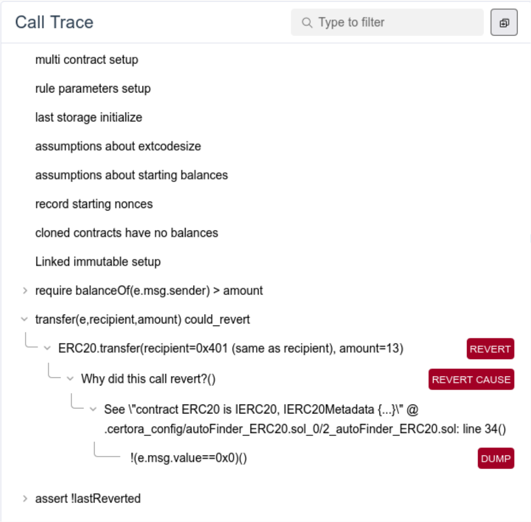

Call Trace

```
multi contract setup
rule parameters setup
last storage initialize
assumptions about extcodesize
assumptions about starting balances
record starting nonces
cloned contracts have no balances
Linked immutable setup
› require balanceOf(e.msg.sender) > amount
⌄ transfer(e,recipient,amount) could_revert
  └ ⌄ ERC20.transfer(recipient=0x401 (same as recipient), amount=13)        REVERT
      └ ⌄ Why did this call revert?()                                       REVERT CAUSE
          └ ⌄ See \"contract ERC20 is IERC20, IERC20Metadata {...}\" @
              .certora_config/autoFinder_ERC20.sol_0/2_autoFinder_ERC20.sol: line 34()
              └── !(e.msg.value==0x0)()                                     DUMP
› assert !lastReverted
```

Proving transfer doesn’t revert (liveness rules)

```
//// certora/specs/ERC20.spec

/// Transfer must not revert unless
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///    - or the message value is nonzero,
///
///
///
///
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rule transferDoesntRevert {
    env e; address recipient; uint amount;

    require balanceOf(e.msg.sender) > amount;





    transfer@withrevert(e, recipient, amount);
    assert !lastReverted;
}
```

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rule transferDoesntRevert {
    env e; address recipient; uint amount;

    require balanceOf(e.msg.sender) > amount;
    require e.msg.value == 0;




    transfer@withrevert(e, recipient, amount);
    assert !lastReverted;
}
```

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    transfer@withrevert(e, recipient, amount);
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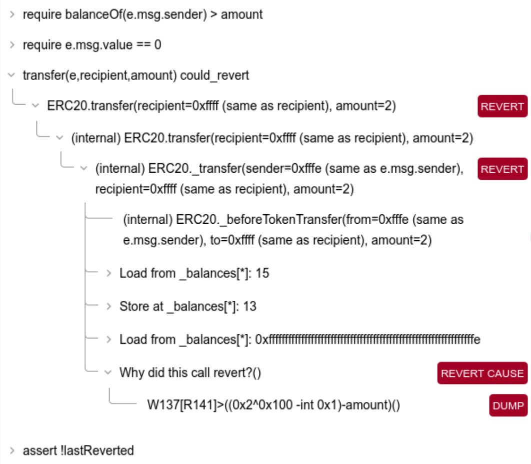
}
```



```
> require balanceOf(e.msg.sender) > amount
> require e.msg.value == 0
v transfer(e,recipient,amount) could_revert
  v ERC20.transfer(recipient=0xffff (same as recipient), amount=2)                          REVERT
    v (internal) ERC20.transfer(recipient=0xffff (same as recipient), amount=2)
      v (internal) ERC20._transfer(sender=0xfffe (same as e.msg.sender),                    REVERT
        recipient=0xffff (same as recipient), amount=2)
          (internal) ERC20._beforeTokenTransfer(from=0xfffe (same as
          e.msg.sender), to=0xffff (same as recipient), amount=2)
        > Load from _balances[*]: 15
        > Store at _balances[*]: 13
        > Load from _balances[*]: 0xfffffffffffffffffffffffffffffffffffffffffffffffffffffffffffffffe
        v Why did this call revert?()                                                 REVERT CAUSE
            W137[R141]>((0x2^0x100 -int 0x1)-amount)()                                      DUMP
> assert !lastReverted
```

Proving transfer doesn’t revert (liveness rules)

```
//// certora/specs/ERC20.spec

/// Transfer must not revert unless
///    - the sender doesn't have enough funds
///    - or the message value is nonzero,
///    - or the recipient's balance would overflow,
///
///
///
/// @title Transfer doesn't revert
rule transferDoesntRevert {
    env e; address recipient; uint amount;

    require balanceOf(e.msg.sender) > amount;
    require e.msg.value == 0;




    transfer@withrevert(e, recipient, amount);
    assert !lastReverted;
}
```

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///
/// @title Transfer doesn't revert
rule transferDoesntRevert {
    env e; address recipient; uint amount;

    require balanceOf(e.msg.sender) > amount;
    require e.msg.value == 0;
    require balanceOf(recipient) + amount < max_uint;



    transfer@withrevert(e, recipient, amount);
    assert !lastReverted;
}
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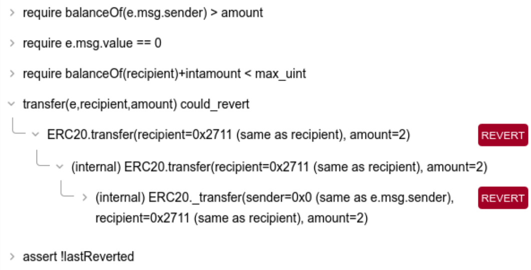

```
> require balanceOf(e.msg.sender) > amount
> require e.msg.value == 0
> require balanceOf(recipient)+intamount < max_uint
v transfer(e,recipient,amount) could_revert
  └ v ERC20.transfer(recipient=0x2711 (same as recipient), amount=2)        REVERT
      └ v (internal) ERC20.transfer(recipient=0x2711 (same as recipient), amount=2)
          └ > (internal) ERC20._transfer(sender=0x0 (same as e.msg.sender),   REVERT
              recipient=0x2711 (same as recipient), amount=2)
> assert !lastReverted
```

Proving transfer doesn't revert (liveness rules)

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/// Transfer must not revert unless
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///    - or the message value is nonzero,
///    - or the recipient's balance would overflow,
///    - or the message sender is 0
///
///
/// @title Transfer doesn't revert
rule transferDoesntRevert {
    env e; address recipient; uint amount;

    require balanceOf(e.msg.sender) > amount;
    require e.msg.value == 0;
    require balanceOf(recipient) + amount < max_uint;



    transfer@withrevert(e, recipient, amount);
    assert !lastReverted;
}
```

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    env e; address recipient; uint amount;

    require balanceOf(e.msg.sender) > amount;
    require e.msg.value == 0;
    require balanceOf(recipient) + amount < max_uint;
    require e.msg.sender != 0;


    transfer@withrevert(e, recipient, amount);
    assert !lastReverted;
}
```

Proving transfer doesn’t revert (liveness rules)

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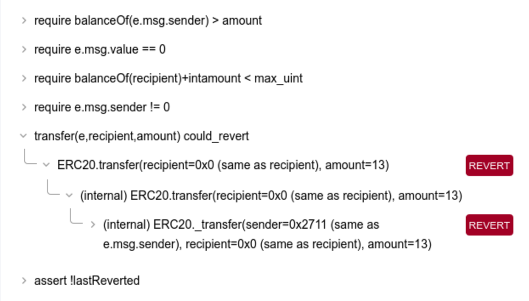

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              e.msg.sender), recipient=0x0 (same as recipient), amount=13)
> assert !lastReverted
```

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rule transferDoesntRevert {
    env e; address recipient; uint amount;

    require balanceOf(e.msg.sender) > amount;
    require e.msg.value == 0;
    require balanceOf(recipient) + amount < max_uint;
    require e.msg.sender != 0;
    require recipient != 0;

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certora

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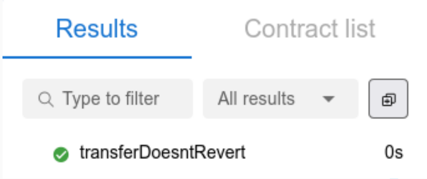
    require e.msg.value == 0;
    require balanceOf(recipient) + amount < max_uint;
    require e.msg.sender != 0;
    require recipient != 0;

    transfer@withrevert(e, recipient, amount);
    assert !lastReverted;
}
```



✓ transferDoesntRevert 0s

(results link)

Summary

- Writing rules is like writing unit tests
  - But you can let the prover choose the values!

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- Pass `env` as first argument to specify `msg.sender` and other variables
    - Use `envfree` declaration in `methods` block to avoid passing `env`

Summary

- Writing rules is like writing unit tests
  - But you can let the prover choose the values!
- Use `mathint` variables to avoid overflow in spec
- Pass `env` as first argument to specify `msg.sender` and other variables
  - Use `envfree` declaration in `methods` block to avoid passing `env`
- By default, reverting paths are ignored
  - Use `@withrevert` and `lastReverted` to reason about reverting paths
  - Writing “liveness properties” is hard (but possible!)

Exercise (∼15 minutes)

So far (certora/specs/ERC20.spec):

- transferSpec
- transferReverts
- transferDoesntRevert

Exercise:

- Write transferFromSpec
    - ...get it to pass
- Try transferFromReverts
- Try transferFromSucceeds

To run:
sh certora/scripts/verifyERC20.sh

Ask for help!

```
//// contracts/IERC20.sol

/// Interface of the ERC20 standard as defined in the EIP.
interface IERC20 {

    /// Moves `amount` tokens from `sender` to `recipient` using
    /// the allowance mechanism. `amount` is then deducted from
    /// the caller's allowance.
    ///
    function transferFrom(
        address sender,
        address recipient,
        uint256 amount
    ) external returns (bool);


    /// Returns the remaining number of tokens that `spender`
    /// will be allowed to spend on behalf of `owner` through
    /// {transferFrom}.
    ///
    /// This value changes when {approve} or {transferFrom} are
    /// called.
    ///
    function allowance(address owner, address spender)
        external
        view
        returns(uint256);

}
```

CVL: Parametric Rules

certora

Michael George

Stanford, August 2022

Are my funds safe?

So far:

- `transfer` spends the sender's funds
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Only token holder can approve (stakeholder rule)

We want to show that the token holder controls their allowances

- Allowances are controlled by `approve`:

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//// contracts/IERC20.sol

/// Sets `amount` as the allowance of `spender` over the caller's tokens.
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    env e; uint256 amount;
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    // note: P => Q means "if P then Q" or "P implies Q"
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  - “Variable change rules”: describe conditions of variable changes
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  - More on rule patterns tomorrow!

Exercise (∼15 minutes)

We just wrote rules for allowance changes

- In certora/specs/ERC20.spec
- If allowance increases, then the sender was the holder, and the method was appropriate

Now, write rules for balance changes

- In certora/specs/ERC20.spec
- If my balance goes down, what should I know?

Invariants

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Michael George

Stanford, August 2022

Invariants

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Invariants in CVL

Writing an invariant in CVL:

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/// The address 0x0 always has a balance of 0
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Invariants in CVL

Writing an invariant in CVL:

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/// The address 0x0 always has a balance of 0
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/// The balance of a single user is always less than the total supply
invariant balanceBoundedBySupply(address a)
    balanceOf(a) <= totalSupply()
```

Checking invariants

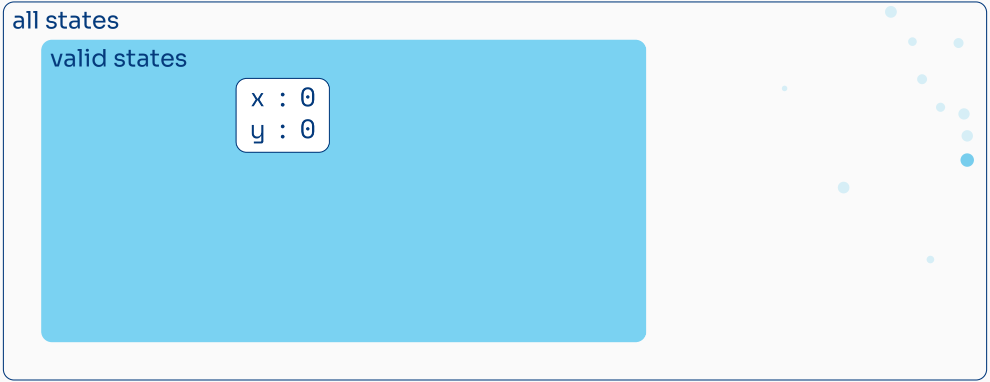
- Invariant: $x \geq y$

all states

valid states

Checking invariants

- Invariant: `x ≥ y`



all states

valid states

x : 0
y : 0

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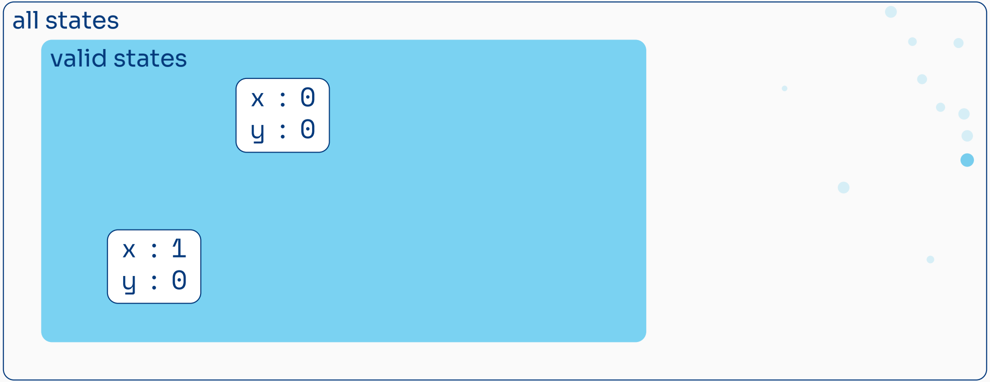

all states

valid states

```
x : 0
y : 0
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```
x : 1
y : 0
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Checking invariants

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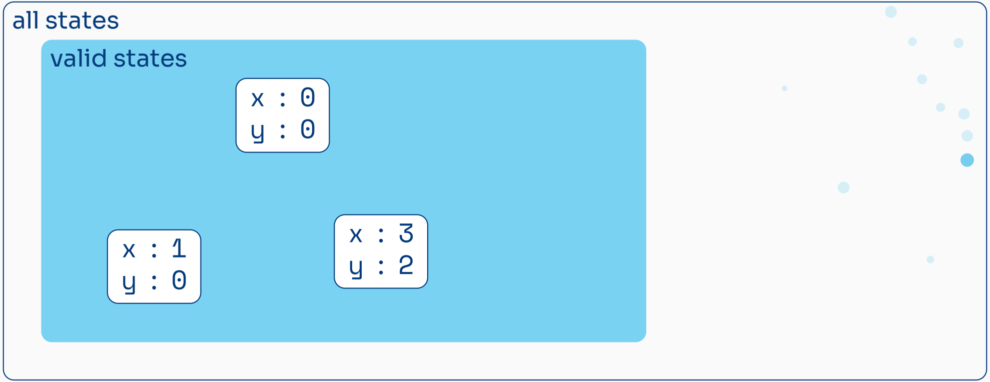

all states

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x : 0
y : 0

x : 1
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y : 2

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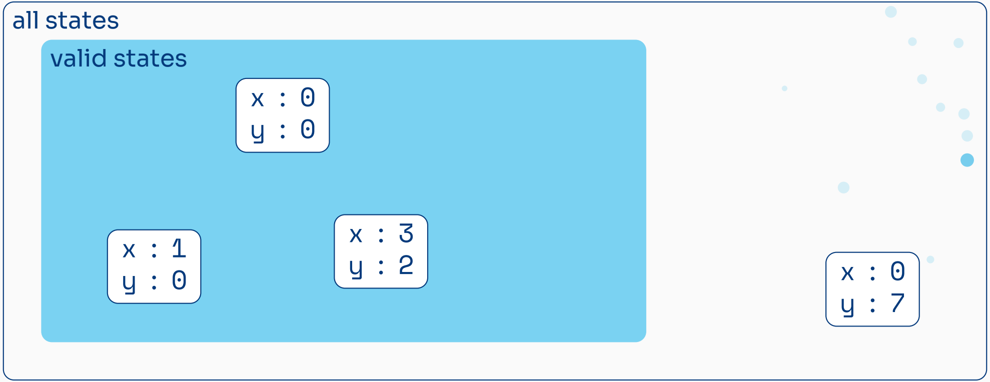

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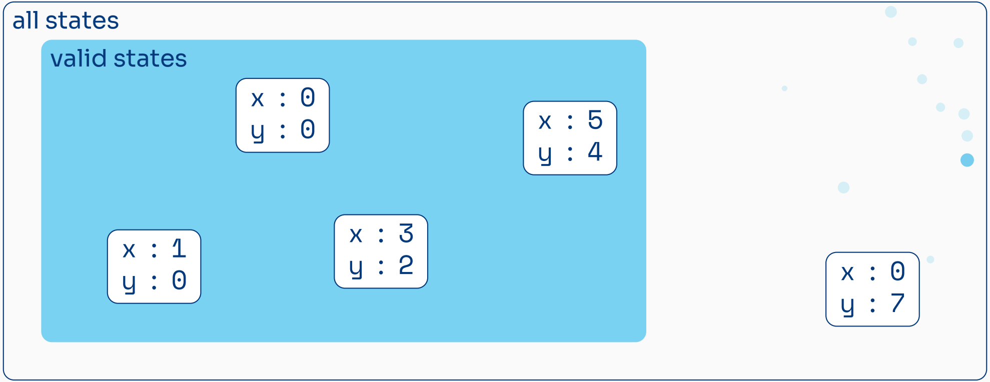

all states

valid states

x : 0
y : 0

x : 5
y : 4

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y : 0

x : 3
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Checking invariants

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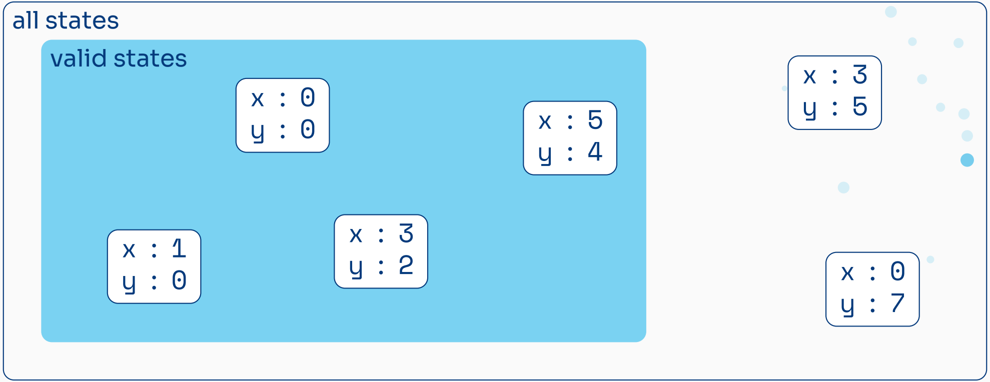

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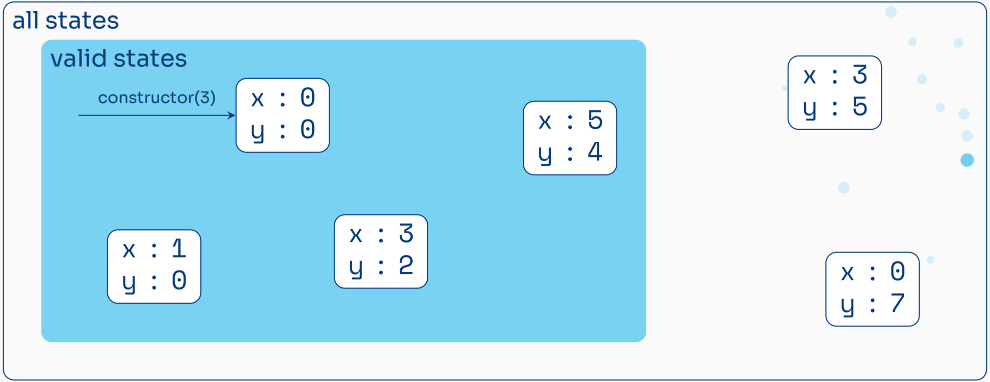

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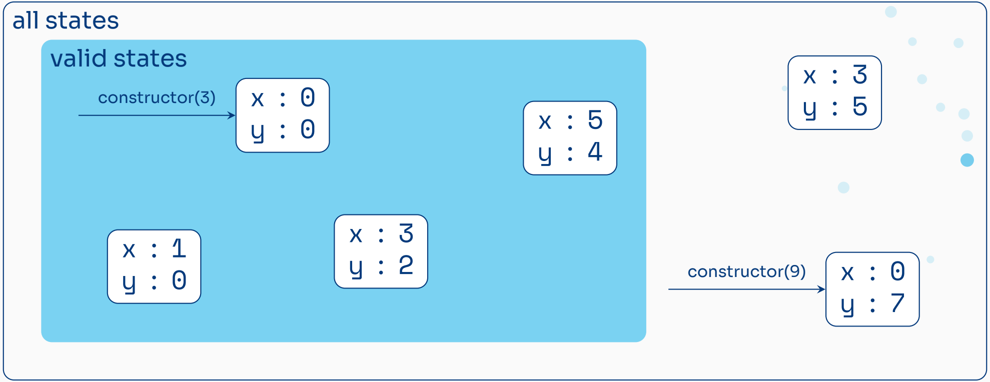

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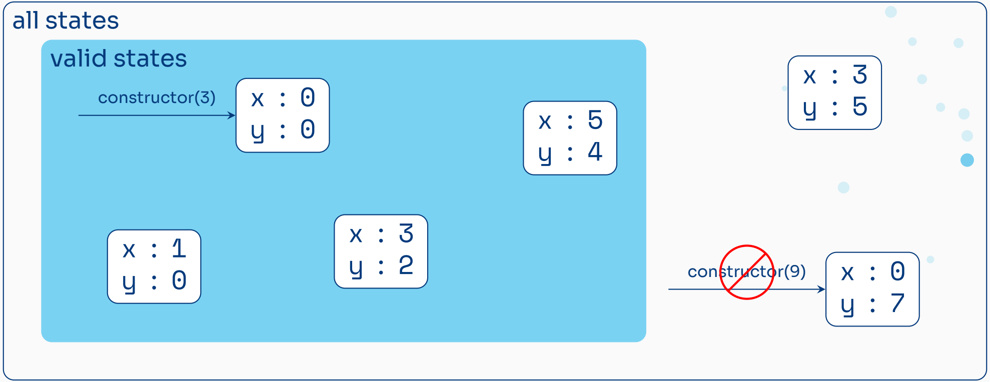

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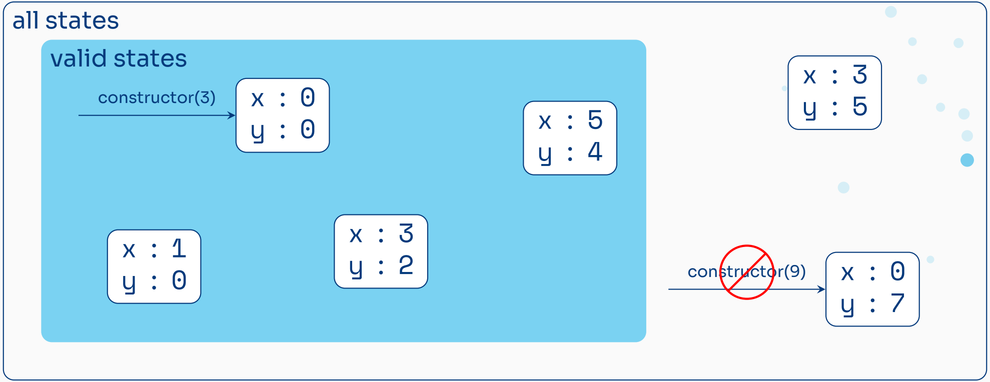

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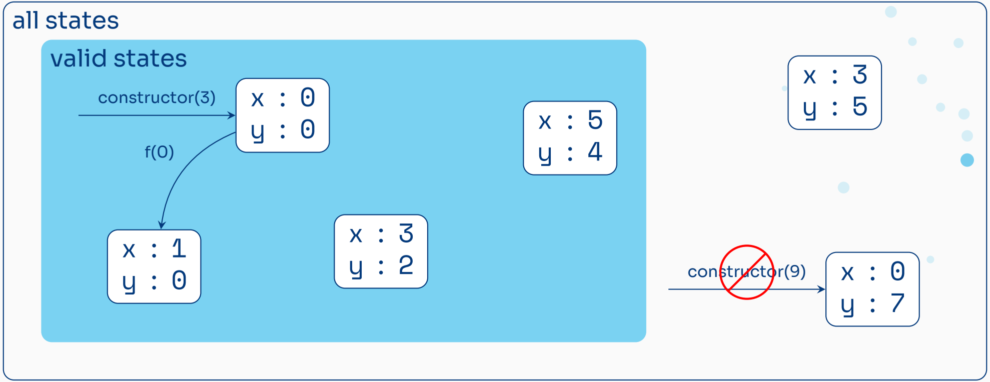

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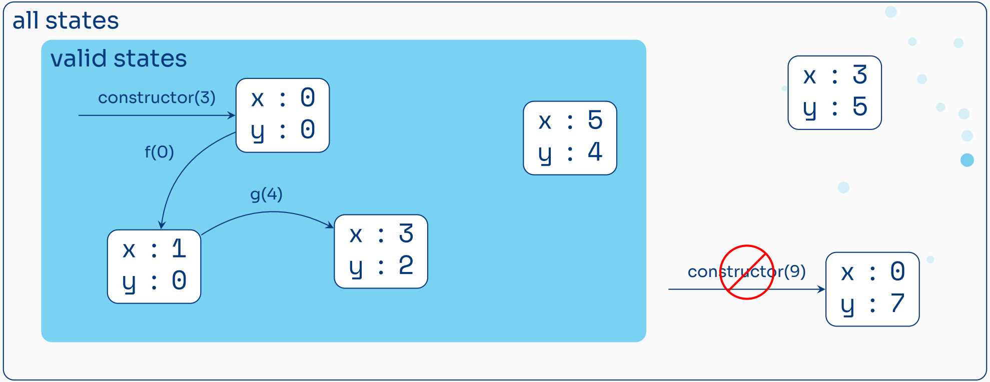

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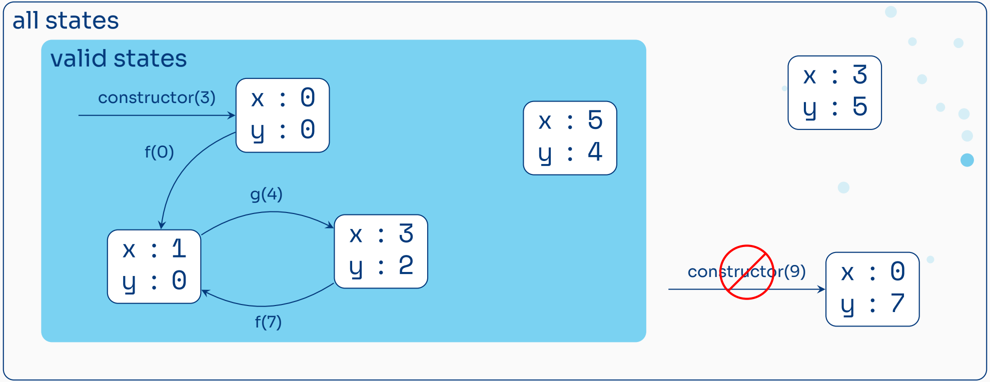

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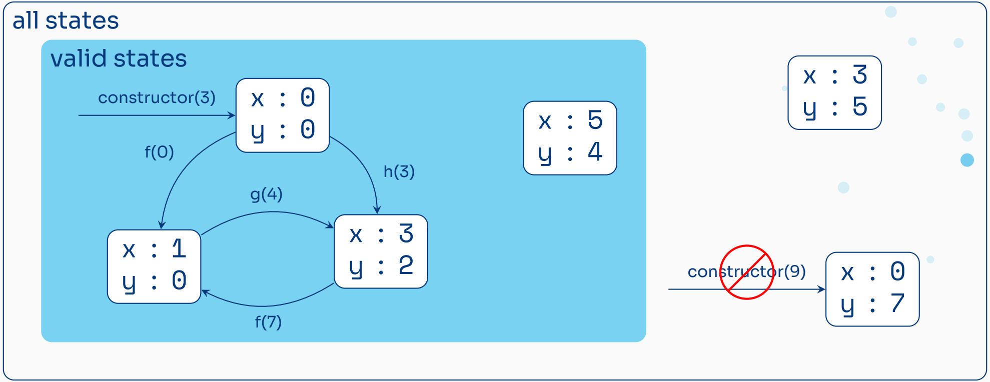

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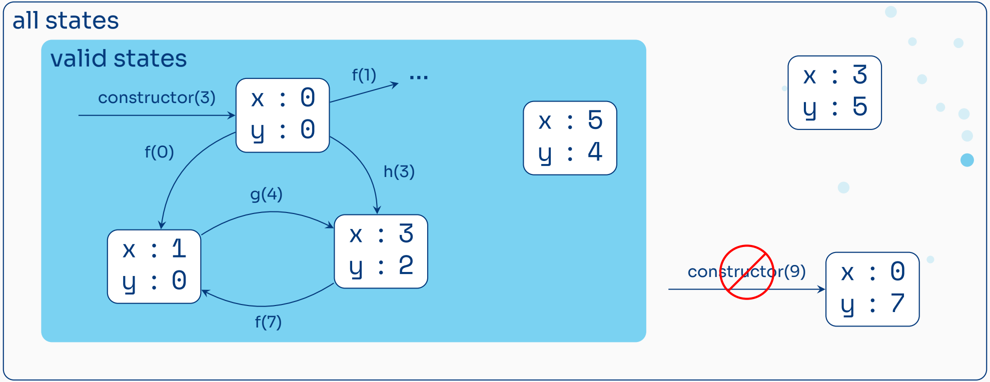

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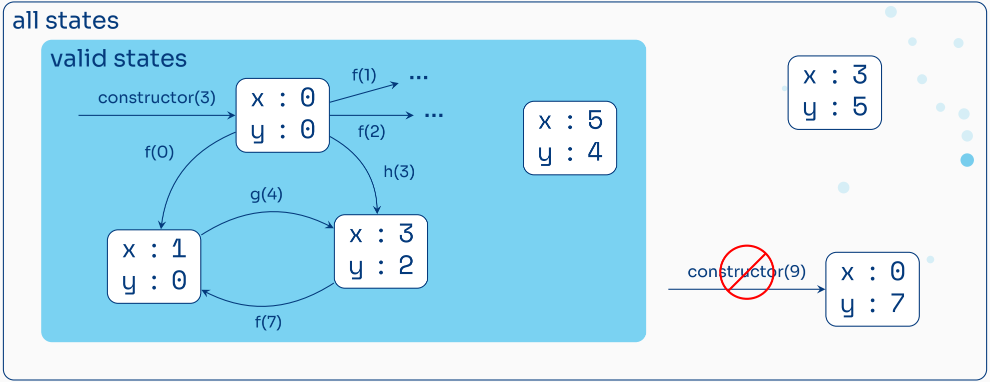

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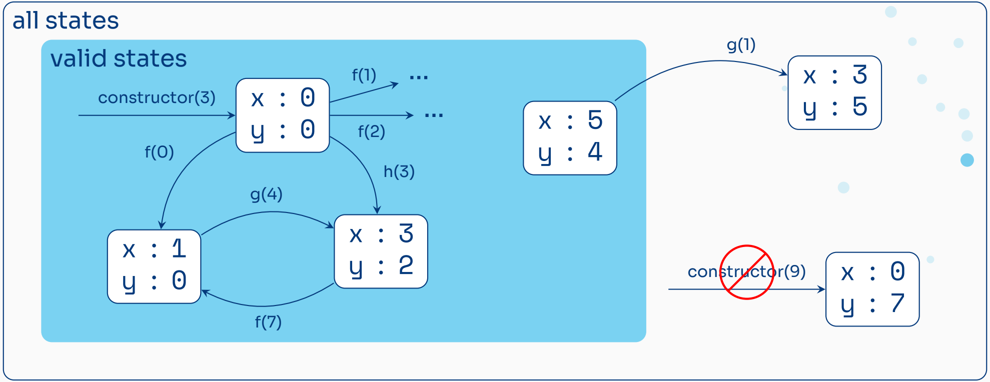

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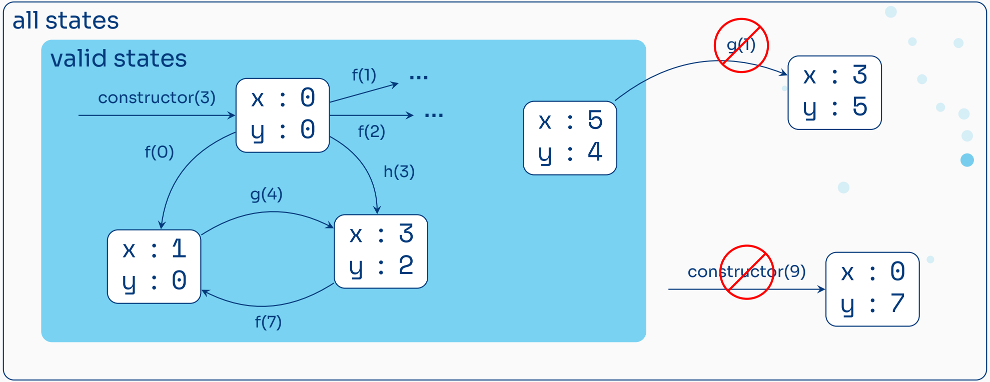

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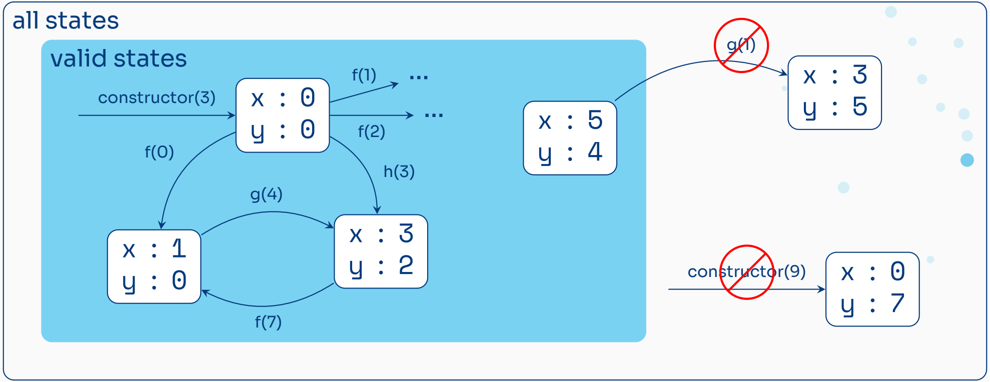

- Need to check that initial state (after any constructor call) is valid
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Verifying an invariant

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(results with preserved block)

- `preserved` blocks allow adding requirements to preservation checks
- WARNING: only use these for things that are always true!
    - ...examples of danger soon

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BallGame Exercise (∼10 minutes)

`BallGame` is a simple implementation of keep away:

- Player 1 always passes to player 3
- Player 3 always passes to player 1
- Everyone else passes to player 2
- Ball starts with player 1
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- Exercise: Prove it!
- In `BallGame` directory:
  - Contract in `contracts/BallGame.sol`
  - Spec in `certora/specs/BallGame.spec`
  - Run using `sh certora/scripts/verifyBallGame.sh`

Solution walkthrough

Goal: player 2 never gets the ball

- First attempt:

```
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  Fails with a different bad case! (results link)

Third attempt: rule out more bad cases

```
invariant playerTwoNeverWins()
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Passes! (results link)

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```
//// contracts/BallGameBroken.sol

/// Move the ball to the next player,
/// based on who is currently holding it:
///   - player 1 will pass to player 3
///   - player 3 will pass to player 1
///   - everyone else will pass to player 2
///
/// @dev this version has a known bug
function pass() external {
    if (ballPosition == 1)
        ballPosition = 4;
    else if (ballPosition == 3)
        ballPosition = 1;
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        ballPosition = 2;
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The rule still passes on the buggy code (results link)! Why?

- We ruled out the counterexample!
- We assumed something that we didn’t prove

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- Fails on our broken code (results link)
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- Still passes on buggy version too (link)
- ...but it is much safer because we separately proved the requirement
- `requireInvariant` can be used anywhere `require` can, use it!

Back to ERC20

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Back to ERC20: Invariants about total supply

Let’s prove invariants relating balances to total supply

- Individual user balances can’t be larger than the total supply
- Total supply is the sum of user balances (next session)

Proving that each user balance is bounded by total supply

- First attempt (results link):

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- Fourth attempt: exercise (in 2 slides)
- Fifth (correct) attempt: next session

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Next session: strengthening bounded balance more and proving it

Exercise: Exploit the buggy rule

- Fourth attempt: use `preserved` blocks:

```
invariant balancesBoundedByTotalSupply(address alice, address bob)
    balanceOf(alice) + balanceOf(bob) <= totalSupply()
{
    preserved transfer(address recip, uint256 amount) with (env e) {
        require recip        == alice || recip        == bob;
        require e.msg.sender == alice || e.msg.sender == bob;
    }

    preserved transferFrom(address from, address to, uint256 amount) {
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  - Here `preserved` blocks apply to specific methods

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  - Here preserved blocks apply to specific methods
- Rule passes (results link)

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        require to   == alice || to   == bob;
    }
}
```

  - Here `preserved` blocks apply to specific methods
- Rule passes (results link)
- Exercise: modify `ERC20.sol` to pass rule but violate invariant

Exercise: Exploit the buggy rule

- Fourth attempt: use `preserved` blocks:

```
invariant balancesBoundedByTotalSupply(address alice, address bob)
    balanceOf(alice) + balanceOf(bob) <= totalSupply()
{
    preserved transfer(address recip, uint256 amount) with (env e) {
        require recip        == alice || recip        == bob;
        require e.msg.sender == alice || e.msg.sender == bob;
    }

    preserved transferFrom(address from, address to, uint256 amount) {
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```

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- Rule passes (results link)
- Exercise: modify `ERC20.sol` to pass rule but violate invariant
- Note: I forgot to push this before we started!
  - In `ERC20Examples`:

```
git switch main
git pull
```

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Ghosts

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Michael George

Stanford, August 2022

A (much) stronger invariant

Before the break:

- Tried to show that each user balance is at most the total supply

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- Pattern is a field followed by any number of:
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- Hook can update our tracked sum of balances

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Prover considers every possible value of ghost (just like storage)

Putting ghost and hook together

Example (results link):

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hook Sstore _balances[KEY address a] uint new_value (uint old_value) STORAGE {
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    sum_of_balances = sum_of_balances + new_value - old_value;
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invariant totalSupplyIsSumOfBalances()
    totalSupply() == sum_of_balances
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Rule passes on preservation but fails on initialization

- Prover chooses non-zero initial value for the ghost

Putting ghost and hook together

Example (results link):

```
ghost mathint sum_of_balances {
    init_state axiom sum_of_balances == 0;
}

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Rule passes on preservation but fails on initialization

- Prover chooses non-zero initial value for the ghost

Initial state axiom tells prover to make assumptions about the intial value of the ghost (before the constructor)

Exercise

- Create a ghost to track the number of changes to users’ balances
- Use it to prove that no method changes more than two balances

Hyperproperties

Michael George

Stanford, August 2022

Comparing hypothetical executions

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CVL allows saving and restoring the state of the world

- `storage` type represents a snapshot of storage
- `lastStorage` gives the current state of storage
- `f(...) at s` resets the storage before executing `f`

Example

- Want to show that transferring a and the b is the same as transferring a + b

```
//// certora/specs/ERC20.spec

/// transferring `a` tokens and then then `b` tokens has the same effect as
/// transferring `a+b` tokens
rule transferFromAdditive {
    address sender; address recipient;
    uint amount_a; uint amount_b;

    storage init = lastStorage;                                   // save storage

    transferFrom(sender, recipient, amount_a);
    transferFrom(sender, recipient, amount_b);

    mathint balance_sender_1 = balanceOf(sender);
    mathint balance_recip_1  = balanceOf(recipient);

    transferFrom(sender, recipient, amount_a + amount_b) at init; // restore storage

    mathint balance_sender_2    = balanceOf(sender);
    mathint balance_recipient_2 = balanceOf(recipient);

    assert balance_sender_1 == balance_sender_2,
        "two small transfers must change the sender's balance by the same amount as one large transfer";

    assert balance_recip_1 == balance_recip_2,
        "two small transfers must change the recipient's balance by the same amount as one large transfer";
}
```

The Art and Science of Designing Specifications

certora

Types of properties

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So far: how to write specs

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Now: what specs to write?

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When designing specifications, it helps to work systematically

- Unit-test-style rules
- Variable relationships and changes
- State transition diagrams
- Stakeholder rules
- High-level properties

Unit-test style rules

- Public functions and interfaces should have documentation
  - Describe what their arguments are
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  - Example: transfer decreases sender’s balance by amount
- Note: you can get a list of public functions from the Prover (example)
- In practice, the documentation is often incomplete
  - Think about the documentation you’d write
  - Maybe submit a PR!

Variable relationships and changes

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Variable changes

- For each variable, ask “how can it change, and when?”
- Each variable has one or more parametric rules:

```
rule variableChange {
    mathint value_before = getValue();

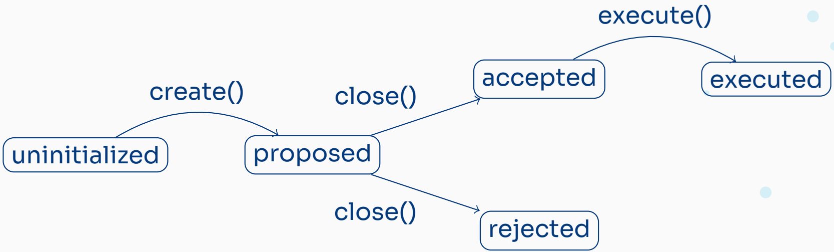
    method f; env e; calldataarg args;
    f(e,args);

    mathint value_after = getValue();

    assert value_before != value_after => ...;
}
```

State transition diagrams

Often contracts have a natural “flow-chart” feel:



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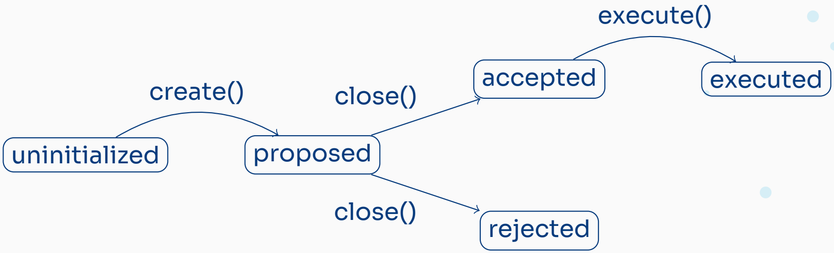

These can naturally be turned into rules:

- Define properties of each state

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definition accepted_state (env e) returns bool =
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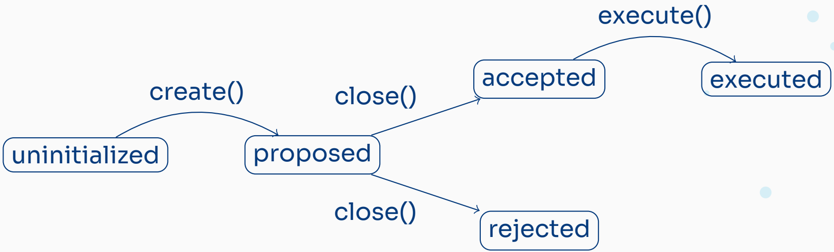

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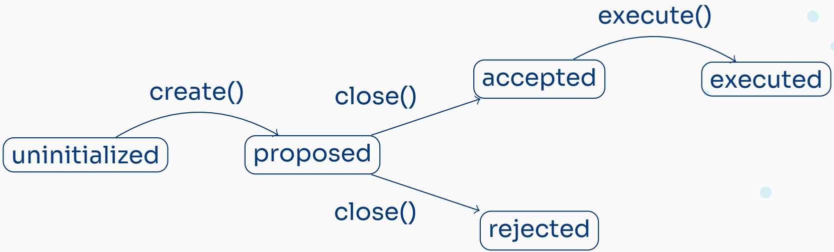

execute()

accepted

executed

create()

close()

uninitialized

proposed

close()

rejected

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- Invariant: contract is always in one and only one state
- Each transition can have one or more rules, like variable changes

Stakeholder rules

Think about what can go wrong from stakeholders' perspectives

- User: I deposit funds and can't get them back
- Bank: Someone removes all the funds

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Each "user (horror) story" can be turned into properties

Often multiple rules: e.g. to show "after deposit I can reclaim funds"

- If I deposit, I get a balance
- My balance doesn't go down unless I withdraw
- I can always withdraw without revert
- When I withdraw, the contract transfers tokens to me

High-level properties

There are some simple properties that can often get good coverage

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- Different ways to do the same thing have the same effect

Sometimes, more abstract properties are useful

- Get good coverage quickly
- Help us think in a different way, avoiding spec bugs

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- High-level properties
  - Think abstractly about your functions and their relationships

AAVE Token Example

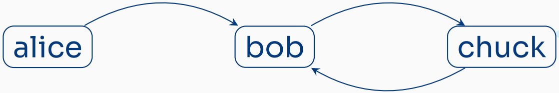
Voting and delegation

The AAVE token is used for voting on proposals

- The more tokens you hold, the more votes you get

You can delegate your vote to another address:

- Delegation is all-or-nothing
- You can't redelegate tokens



Delegation:	alice	bob	chuck
Token balance:	10	7	5
Voting power:	0	15	7

A few more details

- The token manages two types of voting power: `VOTING` and `PROPOSITION`

- The contract supports “meta-delegation”
  - Allows delegation for someone other than `msg.sender`
  - Requires a digital certificate

- The contract is also an ERC20

Exercise: write (English) properties for governance

1. Fetch the code: in the `Examples` repo,
   - `git pull`
   - `git submodule update --init`
   - Alternately, get directly at `https://github.com/Certora/aave-token-v3`
2. Review the interfaces
   - Main interface is in `src/interfaces/IGovernancePowerDelegationToken.sol`
   - The token also implements the ERC20 interface
3. Start writing down properties!
   - `https://bit.ly/certora-stanford/`

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