TRAIL OF BITS

Before starting

- `git clone https://github.com/crytic/building-secure-contracts`
- `git checkout trust-x`

Building secure contracts: How to fuzz like a pro

Who are we?

- **Josselin Feist (@montyly)**

ToB Twitter list

- **Trail of Bits: trailofbits.com**
  - We help developers to build safer software
  - R&D focused: we use the latest program analysis techniques
  - Slither, Echidna, Tealer, Caracal, solc-select, ..

Agenda

- How to find bugs?
- What is property based testing?
- Exercises: simple and more advanced fuzzing
- How to define good invariants?
- Comparison with similar tools

How to Find Bugs?

```
/// @notice Allow users to buy token. 1 ether = 10 tokens
/// @param tokens The numbers of token to buy
/// @dev Users can send more ether than token to be bought, to give gifts to the
team.
function buy(uint tokens) public payable{
    _valid_buy(tokens, msg.value);
    _mint(msg.sender, tokens);
}


/// @notice Compute the amount of token to be minted. 1 ether = 10 tokens
/// @param desired_tokens The number of tokens to buy
/// @param wei_sent The ether value to be converted into token
function _valid_buy(uint desired_tokens, uint wei_sent) internal view{
    uint required_wei_sent = (desired_tokens / 10) * decimals;
    require(wei_sent >= required_wei_sent);
}
```

How to Find Bugs?

- **4 main techniques**
  - Unit tests
  - Manual analysis
  - Fully automated analysis
  - Semi automated analysis

How to Find Bugs?

- **Unit tests**
  - Benefits
    - Well understood by developers
  - Limitations
    - Mostly cover “happy paths”
    - Might miss edge cases

How to Find Bugs?

```
function test_buy(uint256 tokens_to_receive, uint256 ether_to_send) public {
    uint256 pre_buy_balance = token.balanceOf(address(this));
    mock.buy.call{value: ether_to_send)(tokens_to_receive);
    assert(token.balanceOf(address(this)) == pre_buy_balance + tokens_to_receive)
}
```

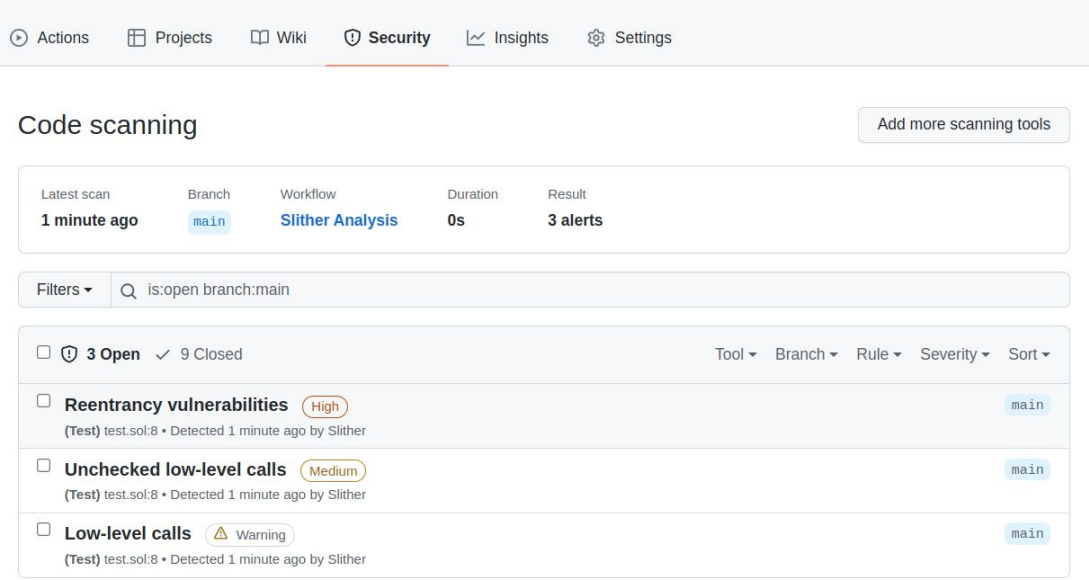
How to Find Bugs?

- **Manual review**
  - Benefits
    - Can detect any bug
  - Limitations
    - Time consuming
    - Require specific skills
    - Does not track code changes
  - Example: Security review

How to Find Bugs?

- **Fully automated analysis**
  - Benefits
    - Quick & easy to use
  - Limitations
    - Cover only some class of bugs
  - Example: Slither

Slither Action



https://github.com/crytic/slither-action

How to Find Bugs?

- **Semi automated analysis**
  - Benefits
    - Great for logic-related bugs
  - Limitations
    - Require human in the loop
  - Example: Property based testing with Echidna

What is property based testing?

Fuzzing

- **Stress the program with random inputs**
  - Most basic fuzzer: randomly type on your keyboard
- **Fuzzing is well established in traditional software security**
  - AFL, Libfuzzer, go-fuzz, ..

Property based testing

- **Traditional fuzzers generally detect crashes**
  - Smart contracts don’t (really) have crashes
- **Property based testing**
  - User defines invariants
  - Fuzzer generates random inputs
  - Check whether specified “incorrect” state can be reached
- **“Unit tests on steroids”**

Invariant

- **Something that must always be true**

invariant adjective

Save Word

in·vari·ant | \ (ˌ)in-ˈver-ē-ənt \

Definition of *invariant*

: CONSTANT, UNCHANGING

specifically **:** unchanged by specified mathematical or physical operations or transformations

// invariant factor

Invariant - Token's total supply

User balance never exceeds total supply

Echidna

- **Smart contract fuzzer**
- **Open source: github.com/crytic/echidna**
- **Heavily used in audits & mature codebases**
- **Focused in easy to use**
  - Solidity invariants
  - Github action
  - All compilation frameworks

Public use of Echidna

Property testing suites

This is a partial list of smart contracts projects that use Echidna for testing:

- Uniswap-v3
- Balancer
- MakerDAO vest
- Optimism DAI Bridge
- WETH10
- Yield
- Convexity Protocol
- Aragon Staking
- Centre Token
- Tokencard
- Minimalist USD Stablecoin

Echidna - Overview

Smart Contract Code

```
contract Token {
       uint256 totalSupply;
       mapping (address => uint256) balances;
       function transfer(address to, uint256 amount) {
       }
}
```

Property Invariant

```
function echidna_invariant() public returns(bool)
```

input

Echidna Tests

Can Echidna break the invariant?

Exercises

Exercise 1

- `git clone https://github.com/crytic/building-secure-contracts`
- `git checkout trust-x`
- Open `program-analysis/echidna/exercises/Exercise-1.md`

Goal: check if total supply invariant holds

Notes:

- **Use Solidity 0.8 (see solc-select if needed)**
- **Try without the template!**

Exercise 1 - Target

```
contract Token is Ownable, Pausable {
    mapping(address => uint256) public balances;

    function transfer(address to, uint256 value) public whenNotPaused {
        // unchecked to save gas
        unchecked {
            balances[msg.sender] -= value;
            balances[to] += value;
        }
    }
}
```

Exercise 1 - Template

```
contract TestToken is Token {

    address echidna_caller = msg.sender;



    constructor() public {
        balances[echidna_caller] = 10000;
    }


    // add the property

}
```

Exercise 1 - Solution

```
contract TestToken is Token {

    address echidna_caller = msg.sender;



    constructor() public {
        balances[echidna_caller] = 10000;
    }


    function echidna_test_balance() view public returns(bool) {
        return balances[echidna_caller] <= 10000;
    }
```

Exercise 1 - Solution

```
$ echidna solution.sol
```

```
echidna_test_balance: FAILED! with ReturnFalse

Call sequence:
1.transfer(0x0,10093)
```

Exercise 1 - Solution

```
contract Token is Ownable, Pausable {
    mapping(address => uint256) public balances;

    function transfer(address to, uint256 value) public whenNotPaused {
        // unchecked to save gas
        unchecked {
            balances[msg.sender] -= value;
            balances[to] += value;
        }
    }
}
```

Exercise 2

- `git clone https://github.com/crytic/building-secure-contracts`
- `git checkout trust-x`
- Open `program-analysis/echidna/exercises/Exercise-2.md`

Goal: can you unpause the system?

Note: try without the template!

Exercise 2 - Target

```
contract Ownable {
    address public owner = msg.sender;

    function Owner() public {
        owner = msg.sender;
    }

    modifier onlyOwner() {
        require(owner == msg.sender);
        _;
    }
}
```

```
contract Pausable is Ownable {
    bool private _paused;

    function paused() public view returns
(bool) {
        return _paused;
    }

    function pause() public onlyOwner {
        _paused = true;
    }

    function resume() public onlyOwner {
        _paused = false;
    }
```

Exercise 2 - Solution

```
contract TestToken is Token {

   constructor() {
       paused();
       owner = 0x0; // lose ownership
   }

   // add the property
}
```

Exercise 2 - Solution

```
contract TestToken is Token {

    constructor() {
        paused();
        owner = 0x0; // lose ownership
    }

    function echidna_no_transfer() view returns(bool) {
        return is_paused == true;
    }
}
```

Exercise 2 - Solution

```
$ echidna solution.sol
```

```
echidna_no_transfer: FAILED! with ReturnFalse

Call sequence:
1.Owner()
2.resume()
```

Exercise 2 - Solution

```
contract Ownership{
    address owner = msg.sender;
    function Owner(){
         owner = msg.sender;
     }
     modifier isOwner(){
         require(owner == msg.sender);
         _;
      }
  }
```

```
contract Pausable is Ownership{
    bool is_paused;
    modifier ifNotPaused(){
             require(!is_paused);
             _;
     }

     function paused() isOwner public{
         is_paused = true;
     }

     function resume() isOwner public{
         is_paused = false;
     }
 }
```

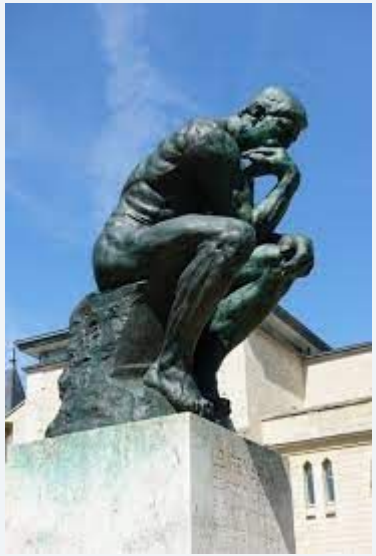
How to define good invariants

Defining good invariants

- **Start small, and iterate**
- **Steps**
  1. Define invariants in English
  2. Write the invariants in Solidity
  3. Run Echidna
     - If invariants broken: investigate
     - Once all the invariants pass, go back to (1)

Identify invariants

- Start early, before starting to code
- Sit down and think about what the contract is supposed to do
- Write the invariant in plain English



Identify invariants: Maths

- **Math library**
  - Commutative property
    - 1 + 2 = 2 + 1
  - Identity property
    - 1 * 2 = 2
  - Inverse property
    - x + (-x) = 0

Identify invariants: tokens

- **ERC20.total_supply**
  - No user should have a balance > total_supply
- **ERC20.transfer:**
  - After calling `transfer`
    - My balance should have decreased by the amount
    - The receiver's balance should have increased by the amount

Identify invariants: tokens

- **ERC20.total_supply**
  - No user should have a balance > total_supply
- **ERC20.transfer:**
  - After calling `transfer`
    - My balance should have decreased by the amount
    - The receiver's balance should have increased by the amount
    - **If the destination is myself, my balance should be the same**

Identify invariants: tokens

- **ERC20.total_supply**
  - No user should have a balance > total_supply
- **ERC20.transfer:**
  - After calling `transfer`
    - My balance should have decreased by the amount
    - The receiver's balance should have increased by the amount
    - If the destination is myself, my balance should be the same
  - If I don't have enough funds, the transaction should revert/return false

Write invariants in Solidity

- **Identify the target of the invariant**
  - Function-level invariant
    - Ex: arithmetic associativity
    - Usually stateless invariants
    - Can craft scenario to test the invariant
  - System-level invariant
    - Ex: user's balance < total supply
    - Usually stateful invariants
    - All functions must be considered

Function-level invariant

- **Inherit the targets**
- **Create function and call the targeted function**
- **Use assert to check the property**

```
contract TestMath is Math{
    function test_commutative(uint a, uint b) public {
        assert(add(a, b) == add(b, a));
    }
}
```

System level invariant

- **Require initialization**
  - Simple initialization: constructor
  - Complex initialization: leverage your unit tests framework with etheno
- **Echidna will explore all the other functions**

Demo

Demo

```
/// @notice Allow users to buy token. 1 ether = 10 tokens
/// @param tokens The numbers of token to buy
/// @dev Users can send more ether than token to be bought, to give gifts to the
team.
function buy(uint tokens) public payable{
    _valid_buy(tokens, msg.value);
    _mint(msg.sender, tokens);
}


/// @notice Compute the amount of token to be minted. 1 ether = 10 tokens
/// @param desired_tokens The number of tokens to buy
/// @param wei_sent The ether value to be converted into token
function _valid_buy(uint desired_tokens, uint wei_sent) internal view{
    uint required_wei_sent = (desired_tokens / 10) * decimals;
    require(wei_sent >= required_wei_sent);
}
```

Demo

- **buy is stateful**
- **_valid_buy is stateless**
  - Start with it

Demo

- **What invariants?**

```
function _valid_buy(uint desired_tokens, uint wei_sent) internal view{
    uint required_wei_sent = (desired_tokens / 10) * decimals;
    require(wei_sent >= required_wei_sent);
}
```

Demo

- **What invariants?**
  - If `wei_sent` is zero, `desired_tokens` must be zero

```
function _valid_buy(uint desired_tokens, uint wei_sent) internal view{
    uint required_wei_sent = (desired_tokens / 10) * decimals;
    require(wei_sent >= required_wei_sent);
}
```

Demo

```
function assert_no_free_token(uint desired_amount)
public {
      require(desired_amount > 0);
      _valid_buy(desired_amount, 0);
      assert(false); // this should never be reached
}
```

Demo

```
Tests
assertion in assert_no_free_token(uint256): FAILED! with ErrorUnrecognizedOpc

Call sequence:
1.assert_no_free_token(1)
```

Demo

```
function _valid_buy(uint desired_tokens, uint wei_sent) internal view{
    uint required_wei_sent = (desired_tokens / 10) * decimals;
    require(wei_sent >= required_wei_sent);
}
```

Echidna APIs

Echidna APIs

- **Boolean properties**
- **Assertion**
- **Dapp/foundry API**

secure-contracts.com/program-analysis/echidna/basic/testing-modes.html

Boolean properties

- **Most of our examples so far - default mode**
- `echidna_something() returns(bool)`
- **Benefits**
  - Easy to use
  - Invariants easy to find
  - No side effects are kept
- **Limitations**
  - No parameters
  - Revert is a failure
  - No coverage on `echidna_something`

Assertion

- **Solidity** `assert()`
- **Benefits**
  - Simpler for function introspection
  - Code coverage
- **Limitations**
  - Difficult to use if the codebase misuse assert
  - Must be careful where the assert are added to not break the original code

Dapp/foundry

- **setUp() + checking for reverting function**
- **Benefits**
  - Compatible with foundry
- **Limitations**
  - Require to handle reverts (e.g. using FOUNDRY::ASSUME)

Exercise 4(*) - Assertion

- git clone https://github.com/crytic/building-secure-contracts
- git checkout trust-x
- Open program-analysis/echidna/exercises/Exercise-4.md

- Goal: check if total supply invariant holds with assertion

First: try without the template!

(*) - no exercise 3 today

Exercise 4 - Solution

```
contract TestToken is Token {
    function transfer(address to, uint256 value) public override {
        uint256 oldBalanceFrom = balances[msg.sender];
        uint256 oldBalanceTo = balances[to];

        super.transfer(to, value);

        assert(balances[msg.sender] <= oldBalanceFrom);
        assert(balances[to] >= oldBalanceTo);
    }
}
```

Exercise 4 - Assertion

- **The assertions can be kept in the code**

```
assert(balances[msg.sender] <= oldBalanceFrom);
assert(balances[to] >= oldBalanceTo);
```

- **Benefits**
  - Onchain safeguard
  - Explicit invarians/post condition
- **Drawbacks**
  - Gas
  - Can be complex and have bugs

Composability

All contract

- **By default, Echidna focuses on one contract**
- **Enable the all-contracts allows Echidna to work on composability issue:**
  - Use command-line flag `--all-contracts`
  - Or use `allContracts: true` in the config file

Exercise 5 - Damn-Vulnerable-Defi

- **git clone https://github.com/crytic/building-secure-contracts**
- **git checkout trust-x**
- **Open program-analysis/echidna/exercises/Exercise-5.md**

- **Goal: let echidna solves the NaiveReceiver challenge**

First: try without the hints

Exercise 5 - Description

- **Two contracts**
  - NaiveReceiverLenderPool: allow to take a flash loan for a fee
  - FlashLoanReceiver: user's contract taking flash loan
- **The user deploys a FlashLoanReceiver with 10 eth. Can you drain the funds?**

Exercise 5 - Target (NaiveReceiverLenderPool)

```
function flashLoan(address borrower, uint256 borrowAmount) external nonReentrant {

    uint256 balanceBefore = address(this).balance;
    require(balanceBefore >= borrowAmount, "Not enough ETH in pool");


    require(borrower.isContract(), "Borrower must be a deployed contract");
    // Transfer ETH and handle control to receiver
    borrower.functionCallWithValue(
        abi.encodeWithSignature(
            "receiveEther(uint256)",
            FIXED_FEE
        ),
        borrowAmount
    );

    require(
        address(this).balance >= balanceBefore + FIXED_FEE,
        "Flash loan hasn't been paid back"
    );
```

Exercise 5 - Target (FlashLoanReceiver)

```
// Function called by the pool during flash loan
function receiveEther(uint256 fee) public payable {
    require(msg.sender == pool, "Sender must be pool");

    uint256 amountToBeRepaid = msg.value + fee;

    require(address(this).balance >= amountToBeRepaid, "Cannot borrow that much");

    _executeActionDuringFlashLoan();

    // Return funds to pool
    pool.sendValue(amountToBeRepaid);
}
```

Exercise 5 - Initialization

```
before(async function () {
    /** SETUP SCENARIO - NO NEED TO CHANGE ANYTHING HERE */
    [deployer, user, attacker] = await ethers.getSigners();

    const LenderPoolFactory = await ethers.getContractFactory('NaiveReceiverLenderPool', deployer);
    const FlashLoanReceiverFactory = await ethers.getContractFactory('FlashLoanReceiver', deployer);

    this.pool = await LenderPoolFactory.deploy();
    await deployer.sendTransaction({ to: this.pool.address, value: ETHER_IN_POOL });

    expect(await ethers.provider.getBalance(this.pool.address)).to.be.equal(ETHER_IN_POOL);
    expect(await this.pool.fixedFee()).to.be.equal(ethers.utils.parseEther('1'));

    this.receiver = await FlashLoanReceiverFactory.deploy(this.pool.address);
    await deployer.sendTransaction({ to: this.receiver.address, value: ETHER_IN_RECEIVER });

    expect(await ethers.provider.getBalance(this.receiver.address)).to.be.equal(ETHER_IN_RECEIVER);
});
```

Exercise 5 - Solution

- **Config file**

```
# 10,000 ether is placed in the NaiveReceiverEchidna
contract.
balanceContract: 10000000000000000000000
# Allow for multi-abi use
allContracts: true
```

Exercise 5 - Solution

```
    // We will send ETHER_IN_POOL to the flash loan pool.
    uint256 constant ETHER_IN_POOL = 1000e18;
    // We will send ETHER_IN_RECEIVER to the flash loan receiver.
    uint256 constant ETHER_IN_RECEIVER = 10e18;

    // Setup echidna test by deploying the flash loan pool and receiver and sending them
some ether.
    constructor() payable {
        pool = new NaiveReceiverLenderPool();
        receiver = new FlashLoanReceiver(payable(address(pool)));
        payable(address(pool)).sendValue(ETHER_IN_POOL);
        payable(address(receiver)).sendValue(ETHER_IN_RECEIVER);
    }

    // We want to test whether the balance of the receiver contract can be decreased.
    function echidna_test_contract_balance() public view returns (bool) {
        return address(receiver).balance >= 10 ether;
    }
```

Exercise 5 - Solution

```
Tests
echidna_test_contract_balance: FAILED! with ReturnFalse

Call sequence:
1.flashLoan(0x62d69f6867a0a084c6d313943dc22023bc263691,10000000000000001)
```

Exercise 5 - Solution

- **Access controls issue**
  - **Anyone** can trigger the flash loan on the user contract
  - An attacker can do flash loans on behalf of the receiver's owner and drain the funds through the fees

Exercise 6 - Damn-Vulnerable-Defi

- **git clone https://github.com/crytic/building-secure-contracts**
- **git checkout `trust-x`**
- **Open program-analysis/echidna/exercises/Exercise-6.md**

- **Goal: let echidna solves the Unstoppable challenge**

First: try without the hints

Exercise 6 - Description

- **Two contracts**
  - UnstoppableLender: allow to take a flash loan and do a callback on the caller
  - ReceiverUnstoppable: user callback example
- **Can you prevent UnstoppableLender from working?**

Exercise 6 - Target (UnstoppableLender)

```
function flashLoan(uint256 borrowAmount) external nonReentrant {
    require(borrowAmount > 0, "Must borrow at least one token");

    uint256 balanceBefore = damnValuableToken.balanceOf(address(this));
    require(balanceBefore >= borrowAmount, "Not enough tokens in pool");

    // Ensured by the protocol via the `depositTokens` function
    assert(poolBalance == balanceBefore);

    damnValuableToken.transfer(msg.sender, borrowAmount);

    IReceiver(msg.sender).receiveTokens(address(damnValuableToken), borrowAmount);

    uint256 balanceAfter = damnValuableToken.balanceOf(address(this));
    require(balanceAfter >= balanceBefore, "Flash loan hasn't been paid back");
}
```

Exercise 6 - Initialization

```
before(async function () {
    /** SETUP SCENARIO - NO NEED TO CHANGE ANYTHING HERE */

    [deployer, attacker, someUser] = await ethers.getSigners();

    const DamnValuableTokenFactory = await ethers.getContractFactory('DamnValuableToken', deployer);
    const UnstoppableLenderFactory = await ethers.getContractFactory('UnstoppableLender', deployer);

    this.token = await DamnValuableTokenFactory.deploy();
    this.pool = await UnstoppableLenderFactory.deploy(this.token.address);

    await this.token.approve(this.pool.address, TOKENS_IN_POOL);
    await this.pool.depositTokens(TOKENS_IN_POOL);

    await this.token.transfer(attacker.address, INITIAL_ATTACKER_TOKEN_BALANCE);
```

Exercise 6 - Initialization

```
    expect(
        await this.token.balanceOf(this.pool.address)
    ).to.equal(TOKENS_IN_POOL);

    expect(
        await this.token.balanceOf(attacker.address)
    ).to.equal(INITIAL_ATTACKER_TOKEN_BALANCE);

     // Show it's possible for someUser to take out a flash loan
     const ReceiverContractFactory = await ethers.getContractFactory('ReceiverUnstoppable', someUser);
     this.receiverContract = await ReceiverContractFactory.deploy(this.pool.address);
     await this.receiverContract.executeFlashLoan(10);
});
```

Exercise 6 - Solution

- **Config file**

```
# The deployer and sender must be the same for this example.
# The deployer is the 'attacker' and is sent INITIAL_ATTACKER_BALANCE
# The actual value does not matter, as long as they are the same
deployer: '0x30000'
# Sender must be the same so that it can use the attacker balance to try to break
the invariant.
sender: ['0x30000']
# Allow for multi-abi use
allContracts: true
```

Exercise 6 - Solution

```
// We will send ETHER_IN_POOL to the flash loan pool.
uint256 constant ETHER_IN_POOL = 1000000e18;
// We will send INITIAL_ATTACKER_BALANCE to the attacker (which is the deployer)
of this contract.
uint256 constant INITIAL_ATTACKER_BALANCE = 100e18;

DamnValuableToken token;
UnstoppableLender pool;

// Setup echidna test by deploying the flash loan pool, approving it for token
transfers, sending it tokens, and sending the attacker some tokens.
constructor() public payable {
    token = new DamnValuableToken();
    pool = new UnstoppableLender(address(token));
    token.approve(address(pool), ETHER_IN_POOL);
    pool.depositTokens(ETHER_IN_POOL);
    token.transfer(msg.sender, INITIAL_ATTACKER_BALANCE);
}
```

Exercise 6 - Solution

```
// This is the callback function for flash loan receivers.
function receiveTokens(address tokenAddress, uint256 amount) external {
    require(msg.sender == address(pool), "Sender must be pool");
    // Return all tokens to the pool
    require(
        IERC20(tokenAddress).transfer(msg.sender, amount),
        "Transfer of tokens failed"
    );
}

// This is the Echidna property entrypoint.
// We want to test whether flash loans can always be made.
function echidna_testFlashLoan() public returns (bool) {
    pool.flashLoan(10);
    return true;
}
```

Exercise 6 - Solution

```
echidna_testFlashLoan: FAILED! with ErrorRevert

Call sequence:
1.transfer(0x62d69f6867a0a084c6d313943dc22023bc263691,10001)
Event sequence:
Panic(1)
merror Revert 0x4e487b7100000000000000000000000000000000000000000000000000000000000000001
```

Exercise 6 - Solution

- **The pool require an exact balance equality - sending token to directly to the pool will break this requirements**

```
// Ensured by the protocol via the `depositTokens` function
assert(poolBalance == balanceBefore);
```

Comparison with similar tools

Other fuzzers

- **Inbuilt in dapp, brownie, foundry, ..**
- **Might be easier for simple test, however**
  - Less powerful
  - Require specific compilation framework

Formal methods based approach

- **Manticore, KEVM, Certora, ..**
- **Provide proofs, however**
  - More difficult to use
  - Return on investment is significantly higher with fuzzing

Echidna's advantages

- **Echidna has unique additional advanced features**
  - Can target high gas consumption functions
  - Differential fuzzing
  - Works with any compilation framework
  - Different APIs
    - Boolean property, assertion, dapptest/foundry mode, ...
- **Free & open source**

Medusa

- https://github.com/crytic/medusa
- **Rewrite of Echidna in Go**
- **Still experimental, but we are looking for feedback**

Conclusion

Conclusion

- **To learn more**
  - Secure-contracts.com
  - github.com/crytic/properties
- **Start with invariants in English, then Solidity**
  - Start simple and iterate
  - Try Echidna on your current project

Do you want help? Invariant as a service: