Fully Automated Formal Verification: How far can we go?

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```solidity
contract Token {
    mapping (address => uint) balance;
    address immutable owner;

    constructor(uint _amt) {
        owner = msg.sender;
        balance[msg.sender] = _amt;
    }

    function balanceOf(address _user) public view returns (uint) {
        return balance[_user];
    }

    function transfer(address _to, uint _amt) public {
        require(msg.sender != _to);
        require(balance[msg.sender] >= _amt);

        uint prevBal = balance[msg.sender] + balance[_to];

        balance[msg.sender] -= _amt;
        balance[_to] += _amt;

        uint postBal = balance[msg.sender] + balance[_to];

        assert(prevBal == postBal);
    }
}
```

```
contract AMM is ERC20 {
    ERC20 token0;
    ERC20 token1;

    constructor(address _token0, address _token1) {
        token0 = ERC20(_token0);
        token1 = ERC20(_token1);
    }

    // swap allows the caller to exchange amt of src for dst at a price given
    // by the constant product formula: x * y == k.
    function swap(address src, address dst, uint amt) external {
        require(src != dst, "no self swap");
        require(src == address(token0) || src == address(token1), "src not in pair");
        require(dst == address(token0) || dst == address(token1), "dst not in pair");

        uint k = token0.balanceOf(address(this)) * token1.balanceOf(address(this));

        ERC20(src).transferFrom(msg.sender, address(this), amt);

        uint out =
            ERC20(dst).balanceOf(address(this)) -
            (k / ERC20(src).balanceOf(address(this)));

        ERC20(dst).transfer(msg.sender, out);

        uint kpost = token0.balanceOf(address(this)) * token1.balanceOf(address(this));

        assert(kpost >= k);
    }
```

```
function deposit(bytes calldata pubkey,
    bytes calldata withdrawal_credentials,
    bytes calldata signature,
    bytes32 deposit_data_root
) override external payable {
    // Extended ABI length checks since dynamic types are used.
    require(pubkey.length == 48, "DepositContract: invalid pubkey length");
    require(withdrawal_credentials.length == 32, "DepositContract: invalid withdrawal_credentials length");
    require(signature.length == 96, "DepositContract: invalid signature length");
    // Check deposit amount
    require(msg.value >= 1 ether, "DepositContract: deposit value too low");
    require(msg.value % 1 gwei == 0, "DepositContract: deposit value not multiple of gwei");
    uint deposit_amount = msg.value / 1 gwei;
    require(deposit_amount <= type(uint64).max, "DepositContract: deposit value too high");

    // Emit `DepositEvent` log
    bytes memory amount = to_little_endian_64(uint64(deposit_amount));
    emit DepositEvent(
        pubkey,
        withdrawal_credentials,
        amount,
        signature,
        to_little_endian_64(uint64(deposit_count))
    );
    // Compute deposit data root (`DepositData` hash tree root)
    bytes32 pubkey_root = sha256(abi.encodePacked(pubkey, bytes16(0)));
    bytes32 signature_root = sha256(abi.encodePacked(
        sha256(abi.encodePacked(signature[:64])),
        sha256(abi.encodePacked(signature[64:], bytes32(0)))
    ));
    bytes32 node = sha256(abi.encodePacked(
        sha256(abi.encodePacked(pubkey_root, withdrawal_credentials)),
        sha256(abi.encodePacked(amount, bytes24(0), signature_root))
    ));
    // Verify computed and expected deposit data roots match
    require(node == deposit_data_root, "DepositContract: reconstructed DepositData does not match supplied deposit_data_root");
    // Avoid overflowing the Merkle tree (and prevent edge case in computing `branch`)
    require(deposit_count < MAX_DEPOSIT_COUNT, "DepositContract: merkle tree full");
    // Add deposit data root to Merkle tree (update a single `branch` node)
    deposit_count += 1;
    uint size = deposit_count;
    for (uint height = 0; height < DEPOSIT_CONTRACT_TREE_DEPTH; height++) {
        if ((size & 1) == 1) {
            branch[height] = node;
            return;
        }
        node = sha256(abi.encodePacked(branch[height], node));
        size /= 2;
    }
    // As the loop should always end prematurely with the `return` statement,
    // this code should be unreachable. We assert `false` just to be safe.
    assert(false);
}
```

```solidity
function transfer(address recipient, uint256 amount) public virtual override returns (bool) {
    require(recipient != address(0), "ERC777: transfer to the zero address");
    address from = _msgSender();
    _callTokensToSend(from, from, recipient, amount);
    _move(from, from, recipient, amount);
    _callTokensReceived(from, from, recipient, amount);
    return true;
}

/**
 * @dev Call from.tokensToSend() if the interface is registered
 * @param operator address operator requesting the transfer
 * @param from address token holder address
 * @param to address recipient address
 * @param amount uint256 amount of tokens to transfer
 */
function _callTokensToSend(address operator, address from, address to, uint256 amount) private {
    uint prevTotal = _totalSupply;
    IERC777Sender(from).tokensToSend(operator, from, to, amount);
    assert(prevTotal == _totalSupply);
}

/**
 * @dev Call to.tokensReceived() if the interface is registered. Reverts if the recipient is a contract but
 * tokensReceived() was not registered for the recipient
 * @param operator address operator requesting the transfer
 * @param from address token holder address
 * @param to address recipient address
 * @param amount uint256 amount of tokens to transfer
 */
function _callTokensReceived(address operator, address from, address to, uint256 amount) private {
    uint prevTotal = _totalSupply;
    IERC777Recipient(to).tokensReceived(operator, from, to, amount);
    assert(prevTotal == _totalSupply);
}
```

- Mythril - symbolic execution
- hevm - symbolic execution, invariant fuzzing
- Echidna - invariant fuzzing
- SMTChecker - model checking
- solc-verify - model checking
- VeriSmart - model checking

Tools that claim to try to prove/break properties automatically and are publicly available.

Which tool can either prove correctness or find bugs in all the examples?

None

Automated formal verification is undecidable

Target Solidity

Cons

- A lot to encode: high level features, various data types, pointers, inheritance.
- Results rely on compiler correctness.

Pros

- Gives more structure information, for example, loops, external calls, functions.
- Can try harder problems, involving loop/contract invariants.

Model checking: SMTChecker, solc-verify, VeriSmart

Target EVM bytecode

Cons

- Not a lot of structure.
- Hard to track storage, external calls, functions.
- Needs to verify ABI encoding/decoding.

Pros

- Easier to encode.
- Results are closer to the deployed object.

Symbolic execution and fuzzing: Mythril, hevm, Echidna

Experiment:

Use each tool on each example, first automatically then tweaking parameters and writing specs taylored to the tool.

Prove functional correctness of transfer function

```
contract Token {
    mapping (address => uint) balance;
    address immutable owner;

    constructor(uint _amt) {
        owner = msg.sender;
        balance[msg.sender] = _amt;
    }

    function balanceOf(address _user) public view returns (uint) {
        return balance[_user];
    }

    function transfer(address _to, uint _amt) public {
        require(msg.sender != _to);
        require(balance[msg.sender] >= _amt);

        uint prevBal = balance[msg.sender] + balance[_to];

        balance[msg.sender] -= _amt;
        balance[_to] += _amt;

        uint postBal = balance[msg.sender] + balance[_to];

        assert(prevBal == postBal);
    }
}
```

Prove functional correctness of transfer function

- Mythril - OK
- hevm - OK
- Echidna - OK (no bugs found)
- SMTChecker - OK
- solc-verify - OK
- VeriSmart - OK

Find bug in buggy transfer function

```
contract Token {
    mapping (address => uint) balance;
    address immutable owner;

    constructor(uint _amt) {
        owner = msg.sender;
        balance[msg.sender] = _amt;
    }

    function balanceOf(address _user) public view returns (uint) {
        return balance[_user];
    }

    function transfer(address _to, uint _amt) public {
        require(msg.sender != _to);
        require(balance[msg.sender] >= _amt);

        uint prevBal = balance[msg.sender] + balance[_to];

        balance[msg.sender] += _amt;
        balance[_to] += _amt;

        uint postBal = balance[msg.sender] + balance[_to];

        assert(prevBal == postBal);
    }
}
```

Find bug in buggy transfer function

- Mythril - OK, with counterexample
- hevm - OK, with counterexample
- Echidna - OK, with counterexample
- SMTChecker - OK, with counterexample
- solc-verify - OK, no counterexample
- VeriSmart - No

AMM swap functional correctness (?)

```
contract AMM is ERC20 {
    ERC20 token0;
    ERC20 token1;

    constructor(address _token0, address _token1) {
        token0 = ERC20(_token0);
        token1 = ERC20(_token1);
    }

    // swap allows the caller to exchange amt of src for dst at a price given
    // by the constant product formula: x * y == k.
    function swap(address src, address dst, uint amt) external {
        require(src != dst, "no self swap");
        require(src == address(token0) || src == address(token1), "src not in pair");
        require(dst == address(token0) || dst == address(token1), "dst not in pair");

        uint k = token0.balanceOf(address(this)) * token1.balanceOf(address(this));

        ERC20(src).transferFrom(msg.sender, address(this), amt);

        uint out =
            ERC20(dst).balanceOf(address(this)) -
            (k / ERC20(src).balanceOf(address(this)));

        ERC20(dst).transfer(msg.sender, out);

        uint kpost = token0.balanceOf(address(this)) * token1.balanceOf(address(this));

        assert(kpost >= k);
    }
```

AMM swap functional correctness (?)

Symbolic execution and model checking tools could not prove/disprove the assertion

AMM swap functional correctness (?)

Fuzzing?

```
Fuzzing invariant
Running 1 tests for src/Amm.t.sol:TestAMM
[FAIL] invariant_k()
Replay data: '("invariant_k()", "0xf90105f870940000000000000000000000000000000
0000ff6469442997ac9251e5bb0a61f4ff790e5b991ea07fd9ba4d34e53a000000000000000000
0000000000000000000000000000000000000000000009ca000000000000000000000000000000
0000000000000000000000000000000000cf8919400000000000000000000000000000000000000
99c940b7108e278c2e77e4e4f5c93d9e5e9a11ac837fcb844ac155247000000000000000000000
00000000000000000000000000000000000000000490000000000000000000000000000000000
0000000000000000000000000000071a0000000000000000000000000000000000000000000000
000000000000000c")'

Failure: invariant_k
```

```
Echidna 1.7.1
Tests found: 1
Seed: -4482172574130288672
Unique instructions: 4673
Unique codehashes: 4
Corpus size: 1
Tests
echidna_k: FAILED!

Call sequence:
1.join(0,1,1)
2.swap1(0,1)

Campaign complete, C-c or esc to exit
```

AMM swap functional correctness

Fuzzing with hevm

```
// swap allows the caller to exchange amt of src for dst at a price given
// by the constant product formula: x * y == k.
function swap(address src, address dst, uint amt) external {
    require(src != dst, "no self swap");
    require(src == address(token0) || src == address(token1), "src not in pair");
    require(dst == address(token0) || dst == address(token1), "dst not in pair");

    KPrev = token0.balanceOf(address(this)) * token1.balanceOf(address(this));

    ERC20(src).transferFrom(msg.sender, address(this), amt);

    uint out =
        ERC20(dst).balanceOf(address(this)) -
        (KPrev / ERC20(src).balanceOf(address(this)));

    ERC20(dst).transfer(msg.sender, out);

    KPost = token0.balanceOf(address(this)) * token1.balanceOf(address(this));
}

function invariant_k() public view {
    assert(KPost >= KPrev);
}

function kprev() public view returns (uint) {
    return KPrev;
}

function kpost() public view returns (uint) {
    return KPost;
}
```

```
contract TestAMM is DSTest {
    MintableERC20 token0;
    MintableERC20 token1;
    AMM pair;

    User user0;
    User user1;
    User user2;

    function targetContracts() public view returns (address[] memory) {
        address[] memory addrs = new address[](3);
        addrs[0] = address(user0);
        addrs[1] = address(user1);
        addrs[2] = address(user2);
        return addrs;
    }

    function setUp() public {
        token0 = new MintableERC20();
        token1 = new MintableERC20();
        pair = new AMM(address(token0), address(token1));

        user0 = new User(token0, token1, pair);
        user1 = new User(token0, token1, pair);
        user2 = new User(token0, token1, pair);

        token0.approve(address(pair), type(uint).max);
        token1.approve(address(pair), type(uint).max);

        uint amt = type(uint).max / 24;

        token0.mint(address(user0), amt);
        token0.mint(address(user1), amt);
        token0.mint(address(user2), amt);

        token1.mint(address(user0), amt);
        token1.mint(address(user1), amt);
        token1.mint(address(user2), amt);
    }

   function invariant_k() public view {
       pair.invariant_k();
   }
}
```

AMM swap functional correctness

Fuzzing with Echidna

```
contract TestAMM {
    MintableERC20 token0;
    MintableERC20 token1;
    AMM pair;

    User[3] users;

    constructor() {
        token0 = new MintableERC20();
        token1 = new MintableERC20();
        pair = new AMM(address(token0), address(token1));

        users[0] = new User(token0, token1, pair);
        users[1] = new User(token0, token1, pair);
        users[2] = new User(token0, token1, pair);

        token0.approve(address(pair), type(uint).max);
        token1.approve(address(pair), type(uint).max);

        uint amt = type(uint).max / 24;

        token0.mint(address(users[0]), amt);
        token0.mint(address(users[1]), amt);
        token0.mint(address(users[2]), amt);

        token1.mint(address(users[0]), amt);
        token1.mint(address(users[1]), amt);
        token1.mint(address(users[2]), amt);
    }

    function echidna_k() public returns (bool) {
        return pair.kpost() >= pair.kprev();
    }
```

AMM swap functional correctness

```
function swap(address src, address dst, uint amt) external {
    require(src != dst, "no self swap");
    require(src == address(token0) || src == address(token1), "src not in pair");
    require(dst == address(token0) || dst == address(token1), "dst not in pair");

    KPrev = token0.balanceOf(address(this)) * token1.balanceOf(address(this));

    ERC20(src).transferFrom(msg.sender, address(this), amt);

    uint out =
        ERC20(dst).balanceOf(address(this)) -
        (KPrev / ERC20(src).balanceOf(address(this)) + 1);

    ERC20(dst).transfer(msg.sender, out);

    KPost = token0.balanceOf(address(this)) * token1.balanceOf(address(this));
}
```

Model checkers still cannot prove correctness, but fuzzers could not find any other problems.

```
Fuzzing invariant
Running 1 tests for src/Amm.t.sol:TestAMM
[PASS] invariant_k() (runs: 100, depth: 20)
```

```
Echidna 1.7.1
Tests found: 1
Seed: 880666784831901063
Unique instructions: 4724
Unique codehashes: 4
Corpus size: 2
Tests
echidna_k: fuzzing (1280/50000)
```

Prove function correctness of deposit

```
function deposit(bytes calldata pubkey,
    bytes calldata withdrawal_credentials,
    bytes calldata signature,
    bytes32 deposit_data_root
) override external payable {
    // Extended ABI length checks since dynamic types are used.
    require(pubkey.length == 48, "DepositContract: invalid pubkey length");
    require(withdrawal_credentials.length == 32, "DepositContract: invalid withdrawal_credentials length");
    require(signature.length == 96, "DepositContract: invalid signature length");
    // Check deposit amount
    require(msg.value >= 1 ether, "DepositContract: deposit value too low");
    require(msg.value % 1 gwei == 0, "DepositContract: deposit value not multiple of gwei");
    uint deposit_amount = msg.value / 1 gwei;
    require(deposit_amount <= type(uint64).max, "DepositContract: deposit value too high");

    // Emit `DepositEvent` log
    bytes memory amount = to_little_endian_64(uint64(deposit_amount));
    emit DepositEvent(
        pubkey,
        withdrawal_credentials,
        amount,
        signature,
        to_little_endian_64(uint64(deposit_count))
    );
    // Compute deposit data root (`DepositData` hash tree root)
    bytes32 pubkey_root = sha256(abi.encodePacked(pubkey, bytes16(0)));
    bytes32 signature_root = sha256(abi.encodePacked(
        sha256(abi.encodePacked(signature[:64])),
        sha256(abi.encodePacked(signature[64:], bytes32(0)))
    ));
    bytes32 node = sha256(abi.encodePacked(
        sha256(abi.encodePacked(pubkey_root, withdrawal_credentials)),
        sha256(abi.encodePacked(amount, bytes24(0), signature_root))
    ));
    // Verify computed and expected deposit data roots match
    require(node == deposit_data_root, "DepositContract: reconstructed DepositData does not match supplied deposit_data_root");
    // Avoid overflowing the Merkle tree (and prevent edge case in computing `branch`)
    require(deposit_count < MAX_DEPOSIT_COUNT, "DepositContract: merkle tree full");
    // Add deposit data root to Merkle tree (update a single `branch` node)
    deposit_count += 1;
    uint size = deposit_count;
    for (uint height = 0; height < DEPOSIT_CONTRACT_TREE_DEPTH; height++) {
        if ((size & 1) == 1) {
            branch[height] = node;
            return;
        }
        node = sha256(abi.encodePacked(branch[height], node));
        size /= 2;
    }
    // As the loop should always end prematurely with the `return` statement,
    // this code should be unreachable. We assert `false` just to be safe.
    assert(false);
```

Prove function correctness of deposit:

No tool could prove that the assertion is not reachable automatically.

Modified version for hevm

```solidity
function deposit(
    bytes16 pubkey_0, bytes16 pubkey_1, bytes16 pubkey_2,
    bytes32 withdrawal_credentials,
    bytes32 signature_0, bytes32 signature_1, bytes32 signature_2,
    bytes32 deposit_data_root
) override external payable {
    // Check deposit amount
    require(msg.value >= 1 ether, "DepositContract: deposit value too low");
    require(msg.value % 1 gwei == 0, "DepositContract: deposit value not multiple of gwei");
    uint deposit_amount = msg.value / 1 gwei;
    require(deposit_amount <= type(uint64).max, "DepositContract: deposit value too high");

    // Emit `DepositEvent` log
    bytes memory amount = to_little_endian_64(uint64(deposit_amount));
    emit DepositEvent(
        pubkey_0, pubkey_1, pubkey_2,
        withdrawal_credentials,
        amount,
        signature_0, signature_1, signature_2,
        to_little_endian_64(uint64(deposit_count))
    );

    // Compute deposit data root (`DepositData` hash tree root)
    bytes32 pubkey_root = sha256(abi.encodePacked(pubkey_0, pubkey_1, pubkey_2, bytes16(0)));
    bytes32 signature_root = sha256(abi.encodePacked(
        signature_0, signature_1, signature_2, bytes32(0)
    ));
    bytes32 node = sha256(abi.encodePacked(
        sha256(abi.encodePacked(pubkey_root, withdrawal_credentials)),
        sha256(abi.encodePacked(amount, bytes24(0), signature_root))
    ));

    // Verify computed and expected deposit data roots match
    require(node == deposit_data_root, "DepositContract: reconstructed DepositData does not match supplied deposit_data_root");
    // Avoid overflowing the Merkle tree (and prevent edge case in computing `branch`)
    require(deposit_count < MAX_DEPOSIT_COUNT, "DepositContract: merkle tree full");

    // Add deposit data root to Merkle tree (update a single `branch` node)
    deposit_count += 1;
    uint size = deposit_count;
    for (uint height = 0; height < DEPOSIT_CONTRACT_TREE_DEPTH; height++) {
        if ((size & 1) == 1) {
            branch[height] = node;
            return;
        }
        node = sha256(abi.encodePacked(branch[height], node));
        size /= 2;
    }
    // As the loop should always end prematurely with the `return` statement,
    // this code should be unreachable. We assert `false` just to be safe.
    assert(false);
}
```

hevm results

```
Running Deposit contract
checking postcondition...
Q.E.D.
Explored: 295 branches without assertion violations
```

Modified version for SMTChecker

```
// Add deposit data root to Merkle tree (update a single `branch` node)
deposit_count += 1;
uint size = deposit_count;
for (uint height = 0; height < DEPOSIT_CONTRACT_TREE_DEPTH; height++) {
    //if ((size & 1) == 1) {
    if ((size % 2) == 1) {
        branch[height] = node;
        return;
    }
    node = sha256(abi.encodePacked(branch[height], node));
    size /= 2;
}
// As the loop should always end prematurely with the `return` statement,
// this code should be unreachable. We assert `false` just to be safe.
assert(false);
```

+ use non default Horn solver Eldarica via solc-js' SMT callback

+ use Eldarica's abstract:off option

SMTChecker's inductive invariant for the loop before the assertion

```
(define-fun block_54_for_header_deposit_367_406_0 ((A Int) (B Int) (C abi_type) (D crypto_type) (E tx_type) (F state_type) (G Int) (H Int) (I fixedbytes_array_tuple) (J Int) (K fixedbytes_array_tuple) (L bytes_tuple) (M bytes_tuple) (N bytes_tuple) (O Int) (P state_type) (Q Int) (R Int) (S fixedbytes_array_tuple) (T Int) (U fixedbytes_array_tuple) (V bytes_tuple) (W bytes_tuple) (X bytes_tuple) (Y Int) (Z Int) (A1 bytes_tuple) (B1 Int) (C1 Int) (D1 Int) (E1 Int) (F1 Int)) Bool (and (and (and (and (and (and (and (and (= P F) (= Q G)) (= R H)) (= S I)) (= U K)) (= V L)) (= W M)) (= X N)) (and (and (and (and (and (= A 0) (= O 0)) (= Y 0)) (= B1 0)) (= C1 0)) (and (and (and (= (bytes_tuple_accessor_length L) 48) (= (bytes_tuple_accessor_length M) 32)) (= (bytes_tuple_accessor_length N) 96)) (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or (or
(and (and (= (+ J (* (- 2147483648) E1)) (- 1)) (= F1 31)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0)))
(and (and (= (+ J (* (- 1073741824) E1)) (- 1)) (= F1 30)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 536870912) E1)) (- 1)) (= F1 29)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 268435456) E1)) (- 1)) (= F1 28)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 134217728) E1)) (- 1)) (= F1 27)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 67108864) E1)) (- 1)) (= F1 26)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 33554432) E1)) (- 1)) (= F1 25)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 16777216) E1)) (- 1)) (= F1 24)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 8388608) E1)) (- 1)) (= F1 23)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 4194304) E1)) (- 1)) (= F1 22)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 2097152) E1)) (- 1)) (= F1 21)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 1048576) E1)) (- 1)) (= F1 20)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 524288) E1)) (- 1)) (= F1 19)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 262144) E1)) (- 1)) (= F1 18)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 131072) E1)) (- 1)) (= F1 17)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 65536) E1)) (- 1)) (= F1 16)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 32768) E1)) (- 1)) (= F1 15)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 16384) E1)) (- 1)) (= F1 14)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 8192) E1)) (- 1)) (= F1 13)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 4096) E1)) (- 1)) (= F1 12)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 2048) E1)) (- 1)) (= F1 11)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 1024) E1)) (- 1)) (= F1 10)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 512) E1)) (- 1)) (= F1 9)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 256) E1)) (- 1)) (= F1 8)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 128) E1)) (- 1)) (= F1 7)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 64) E1)) (- 1)) (= F1 6)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 32) E1)) (- 1)) (= F1 5)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 16) E1)) (- 1)) (= F1 4)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 8) E1)) (- 1)) (= F1 3)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 4) E1)) (- 1)) (= F1 2)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (<= E1 4294967295)) (>= E1 0))))
(and (and (= (+ J (* (- 2) E1)) (- 1)) (= F1 1)) (and (and (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (>= (- E1 J) (- 4294967294))) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0)) (>= E1 0))))
(and (and (= (- J E1) (- 1)) (= F1 0)) (and (and (and (and (and (and (and (<= (msg.value E) 18446744073709551615999999999) (>= (msg.value E) 1000000000000000000)) (<= J 4294967294)) (>= J 0)) (<= T 4294967295)) (>= T 1)) (<= D1 115792089237316195423570985008687907853269984665640564039457584007913129639935)) (>= D1 0))))))))
```

Prove ERC777 property in the presence of external calls

```solidity
function transfer(address recipient, uint256 amount) public virtual override returns (bool) {
    require(recipient != address(0), "ERC777: transfer to the zero address");
    address from = _msgSender();
    _callTokensToSend(from, from, recipient, amount);
    _move(from, from, recipient, amount);
    _callTokensReceived(from, from, recipient, amount);
    return true;
}

/**
 * @dev Call from.tokensToSend() if the interface is registered
 * @param operator address operator requesting the transfer
 * @param from address token holder address
 * @param to address recipient address
 * @param amount uint256 amount of tokens to transfer
 */
function _callTokensToSend(address operator, address from, address to, uint256 amount) private {
    uint prevTotal = _totalSupply;
    IERC777Sender(from).tokensToSend(operator, from, to, amount);
    assert(prevTotal == _totalSupply);
}

/**
 * @dev Call to.tokensReceived() if the interface is registered. Reverts if the recipient is a contract but
 * tokensReceived() was not registered for the recipient
 * @param operator address operator requesting the transfer
 * @param from address token holder address
 * @param to address recipient address
 * @param amount uint256 amount of tokens to transfer
 */
function _callTokensReceived(address operator, address from, address to, uint256 amount) private {
    uint prevTotal = _totalSupply;
    IERC777Recipient(to).tokensReceived(operator, from, to, amount);
    assert(prevTotal == _totalSupply);
}
```

SMTChecker says that the property does not hold

```
Warning: CHC: Assertion violation happens here.
Counterexample:
_totalSupply = 0
amount = 1
prevTotal = 115792089237316195423570985008687907853269984665640564039457584007913129639897

Transaction trace:
ERC777.constructor(115792089237316195423570985008687907853269984665640564039457584007913129639897)
State: _totalSupply = 115792089237316195423570985008687907853269984665640564039457584007913129639897
ERC777.burn(1)
    Context._msgSender() -- internal call
    ERC777._burn(7720, 1) -- internal call
        Context._msgSender() -- internal call
        ERC777._callTokensToSend(7720, 7720, 0, 1) -- internal call
            IERC777Sender(from).tokensToSend(operator, from, to, amount) -- untrusted external call, synthesized as:
                ERC777.burn(115792089237316195423570985008687907853269984665640564039457584007913129639897){ value: 14 } -- reentrant call
                    Context._msgSender(){ value: 14 } -- internal call
                    ERC777._burn(3565, 115792089237316195423570985008687907853269984665640564039457584007913129639897){ value: 14 } -- internal call
                        Context._msgSender(){ value: 14 } -- internal call
                        ERC777._callTokensToSend(3565, 3565, 0, 115792089237316195423570985008687907853269984665640564039457584007913129639897){ value: 14 } -- internal call
                            IERC777Sender(from).tokensToSend(operator, from, to, amount) -- untrusted external call
  --> ERC777.sol:61:3:
   |
61 |            assert(prevTotal == _totalSupply);
   |            ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
```

- Remove strings (hard for counterexamples)

Let's test that

```
contract Rec is IERC777Sender, IERC777Recipient {
    IERC777 immutable erc;

    constructor(IERC777 _erc) {
        erc = _erc;
    }

    function tokensReceived(address, address, address, uint256 amount) public override
        erc.burn(amount);
    }

    function tokensToSend(address, address, address, uint256 amount) public override {}
}

contract ERC777Test is DSTest, IERC777Sender {
    ERC777 erc;
    Rec rec;

    uint constant AMT = 10000;

    function setUp() public {
        erc = new ERC777("", "", AMT);
        rec = new Rec(erc);
    }

    function test_totalSupply() public {
        erc.transfer(address(rec), 100);
    }

    function tokensToSend(address, address, address, uint256 amount) public override {}
}
```

Property is indeed broken

```
dapp: Predeploying test library src/Address.sol:Address at 0x0DdeDfFe2789df61F5f76479464F568334414389
Running 1 tests for src/ERC777.t.sol:ERC777Test
[BAIL] test_totalSupply()

Failure: test_totalSupply
  src/ERC777.t.sol:ERC777Test
   ├ constructor
   ├ setUp()
   │  ├ create ERC777@0xCe71065D4017F316EC606Fe4422e11eB2c47c246 (src/ERC777.t.sol:29)
   │  │  └ ← 6856 bytes of code
   │  └ create Rec@0x185a4dc360CE69bDCceE33b3784B0282f7961aea (src/ERC777.t.sol:30)
   │     └ ← 618 bytes of code
   └ test_totalSupply()
      ├ call ERC777::transfer(address,uint256)(@0x185a4dc360CE69bDCceE33b3784B0282f7961aea, 100) (src/ERC777.t.sol:34)
      │  ├ call ERC777Test::tokensToSend(address,address,address,uint256)(ERC777Test@0xb4c79daB8f259C7Aee6E5b2Aa729821864227e84, ERC777Test@0xb4c79daB8f259C7A
ee6E5b2Aa729821864227e84, @0x185a4dc360CE69bDCceE33b3784B0282f7961aea, 100) (src/ERC777.sol:67)
      │  │  └ ← 0x
      │  ├ Sent(100) (src/ERC777.sol:323)
      │  ├ Transfer(100) (src/ERC777.sol:324)
      │  ├ call 0x185a4dc360CE69bDCceE33b3784B0282f7961aea::tokensReceived(ERC777Test@0xb4c79daB8f259C7Aee6E5b2Aa729821864227e84, ERC777Test@0xb4c79daB8f259C7
Aee6E5b2Aa729821864227e84, @0x185a4dc360CE69bDCceE33b3784B0282f7961aea, 100) (src/ERC777.sol:84)
      │  │  ├ call ERC777::burn(uint256)(100) (src/ERC777.t.sol:16)
      │  │  │  ├ call 0x185a4dc360CE69bDCceE33b3784B0282f7961aea::tokensToSend(@0x185a4dc360CE69bDCceE33b3784B0282f7961aea, @0x185a4dc360CE69bDCceE33b3784B028
2f7961aea, IERC777Sender@0x0000000000000000000000000000000000000000, 100) (src/ERC777.sol:67)
      │  │  │  │  └ ← 0x
      │  │  │  ├ Burned(100) (src/ERC777.sol:306)
      │  │  │  ├ Transfer(100) (src/ERC777.sol:307)
      │  │  │  └ ← 0x
      │  │  └ ← 0x
      │  └ error Revert 0x4e487b710000000000000000000000000000000000000000000000000000000000000001 <source not found>
      └ error Revert 0x4e487b710000000000000000000000000000000000000000000000000000000000000001 (src/ERC777.t.sol:34)
```

We can forbid reentrancy

```
bool lock;
modifier mutex {
    require(!lock);
    lock = true;
    _;
    lock = false;
}

/**
 * @dev See {IERC20-transfer}.
 *
 * Unlike `send`, `recipient` is _not_ required to implement the {IERC777Recipient}
 * interface if it is a contract.
 *
 * Also emits a {Sent} event.
 */
function transfer(address recipient, uint256 amount) public virtual override mutex returns (bool) {
    require(recipient != address(0), "ERC777: transfer to the zero address");
    address from = _msgSender();
    _callTokensToSend(from, from, recipient, amount);
    _move(from, from, recipient, amount);
    _callTokensReceived(from, from, recipient, amount);
    return true;
}

/**
 * @dev Call from.tokensToSend() if the interface is registered
 * @param operator address operator requesting the transfer
 * @param from address token holder address
 * @param to address recipient address
 * @param amount uint256 amount of tokens to transfer
 */
function _callTokensToSend(address operator, address from, address to, uint256 amount) private {
    uint prevTotal = _totalSupply;
    IERC777Sender(from).tokensToSend(operator, from, to, amount);
    assert(prevTotal == _totalSupply);
}

/**
 * @dev Call to.tokensReceived() if the interface is registered. Reverts if the recipient is a contract but
 * tokensReceived() was not registered for the recipient
 * @param operator address operator requesting the transfer
 * @param from address token holder address
 * @param to address recipient address
 * @param amount uint256 amount of tokens to transfer
 */
function _callTokensReceived(address operator, address from, address to, uint256 amount) private {
    uint prevTotal = _totalSupply;
    IERC777Recipient(to).tokensReceived(operator, from, to, amount);
    assert(prevTotal == _totalSupply);
}
```

Are we safe now? Reentrancy guard blocks the tx before the assertion failure

```
dapp: Predeploying test library src/Address.sol:Address at 0x0DdeDfFe2789df61F5f76479464F568334414389
Running 1 tests for src/ERC777.t.sol:ERC777Test
[BAIL] test_totalSupply()

Failure: test_totalSupply
  src/ERC777.t.sol:ERC777Test
   ├ constructor
   ├ setUp()
   │  ├ create ERC777Mutex@0xCe71065D4017F316EC606Fe4422e11eB2c47c246 (src/ERC777.t.sol:40)
   │  │  └ ← 7124 bytes of code
   │  └ create Rec@0x185a4dc360CE69bDCceE33b3784B0282f7961aea (src/ERC777.t.sol:41)
   │     └ ← 618 bytes of code
   └ test_totalSupply()
      ├ call ERC777Mutex::transfer(address,uint256)(@0x185a4dc360CE69bDCceE33b3784B0282f7961aea, 100) (src/ERC777.t.sol:45)
      │  ├ call ERC777Test::tokensToSend(address,address,address,uint256)(ERC777Test@0xb4c79daB8f259C7Aee6E5b2Aa729821864227e84, ERC777Test@0xb4c79daB8f259C7Aee6E5b2Aa72982
1864227e84, @0x185a4dc360CE69bDCceE33b3784B0282f7961aea, 100) (src/ERC777Mutex.sol:74)
      │  │  └ ← 0x
      │  ├ Sent(100) (src/ERC777Mutex.sol:327)
      │  ├ Transfer(100) (src/ERC777Mutex.sol:328)
      │  ├ call 0x185a4dc360CE69bDCceE33b3784B0282f7961aea::tokensReceived(ERC777Test@0xb4c79daB8f259C7Aee6E5b2Aa729821864227e84, ERC777Test@0xb4c79daB8f259C7Aee6E5b2Aa7298
21864227e84, @0x185a4dc360CE69bDCceE33b3784B0282f7961aea, 100) (src/ERC777Mutex.sol:88)
      │  │  ├ call ERC777Mutex::burn(uint256)(100) (src/ERC777.t.sol:21)
      │  │  │  └ error Revert 0x (src/ERC777Mutex.sol:42)
      │  │  └ error Revert 0x (src/ERC777.t.sol:21)
      │  └ error Revert 0x (src/ERC777Mutex.sol:88)
      └ error Revert 0x (src/ERC777.t.sol:45)
```

SMTChecker proves that now the assertions are safe

```
Contract invariants and external call properties for ERC777Mutex.sol:ERC777Mutex:
(!(<errorCode> >= 2) && (!lock || ((_totalSupply + ((- 1) * _totalSupply')) <= 0)) && (lock' || !lock) && (!lock || ((_totalSupply + ((- 1) * _totalSupply')) >= 0)))
((!lock || !(<errorCode> >= 2)) && (!lock || ((_totalSupply + ((- 1) * _totalSupply')) <= 0)) && (lock' || !lock) && (!lock || ((_totalSupply + ((- 1) * _totalSupply')) >= 0)))
```

$$\textbf{lock} \implies (\textbf{\_totalSupply} = \textbf{\_totalSupply}')$$

SMTChecker internals

```
contract BinaryMachine {
    uint x = 0;

    function setOne() public {
        x = 1;
    }

    function setZero() public {
        x = 0;
    }

    function invariant() public view {
        assert(x < 1);
    }
}
```

$$\text{error} = 0 \land x = 0 \implies \text{constructor}(\text{error}, x)$$

$$\text{error} = 0 \land x = x' \implies \text{setOneEntry}(\text{error}, x, x')$$

$$\text{setOneEntry}(\text{error}, x, x') \implies \text{setOneSummary}(\text{error}, x, 1)$$

$$\text{error} = 0 \land x = x' \implies \text{setZeroEntry}(\text{error}, x, x')$$

$$\text{setZeroEntry}(\text{error}, x, x') \implies \text{setZeroSummary}(\text{error}, x, 0)$$

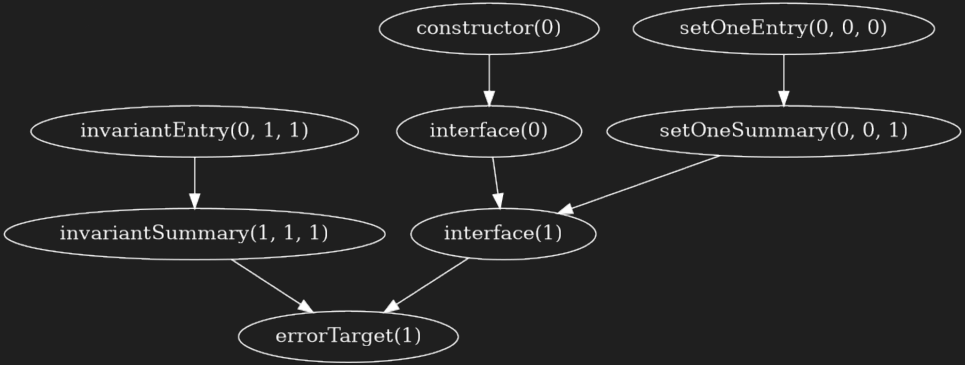
$$\text{error} = 0 \land x = x' \implies \text{invariantEntry}(\text{error}, x, x')$$

$$\text{invariantEntry}(\text{error}, x, x') \land x \geq 2 \land \text{errorCode} = 1 \implies \text{invariantSummary}(\text{errorCode}, x, x')$$

$$\text{invariantEntry}(\text{error}, x, x') \land x < 2 \implies \text{invariantSummary}(\text{error}, x, 1)$$

$$\begin{aligned}
\text{error} = 0 \land \text{constructor}(\text{error}, \text{x}) &\implies \text{interface}(\text{x}) \\
\text{interface}(\text{x}) \land \text{setOneSummary}(\text{error}, \text{x}, \text{x}') \land \text{error} = 0 &\implies \text{interface}(\text{x}') \\
\text{interface}(\text{x}) \land \text{setOneSummary}(\text{error}, \text{x}, \text{x}') \land \text{error} > 0 &\implies \text{errorTarget}(\text{error}) \\
\text{interface}(\text{x}) \land \text{setZeroSummary}(\text{error}, \text{x}, \text{x}') \land \text{error} = 0 &\implies \text{interface}(\text{x}') \\
\text{interface}(\text{x}) \land \text{setZeroSummary}(\text{error}, \text{x}, \text{x}') \land \text{error} > 0 &\implies \text{errorTarget}(\text{error}) \\
\text{interface}(\text{x}) \land \text{invariantSummary}(\text{error}, \text{x}, \text{x}') \land \text{error} = 0 &\implies \text{interface}(\text{x}') \\
\text{interface}(\text{x}) \land \text{invariantSummary}(\text{error}, \text{x}, \text{x}') \land \text{error} > 0 &\implies \text{errorTarget}(\text{error})
\end{aligned}$$

Counterexample graph



Correct code

```
contract BinaryMachine {
    uint x = 0;

    function setOne() public {
        x = 1;
    }

    function setZero() public {
        x = 0;
    }

    function invariant() public view {
        assert(x <= 2);
    }
}
```

Inductive invariants

$$\mathbf{interface}(e, x) = x < 2$$

$$\mathbf{invariantSummary}(e, x, x') = x' = 0 \lor x' = 1$$

$$\mathbf{constructorSummary}(e, x) = e = 0 \land x' = 0$$

$$\mathbf{setOneSummary}(e, x, x') = e = 0 \land x' = 1$$

$$\mathbf{setZeroSummary}(e, x, x') = e = 0 \land x' = 0$$

SMTChecker internals - External calls

```
interface Unknown {
    function callMe() external;
}

contract ExtCall {
    uint x;
    function setX(uint _x) public { x = _x; }
    function xMut(Unknown _u) public {
        uint xPrev = x;
        _u.callMe();
        assert(xPrev == x);
    }
}
```

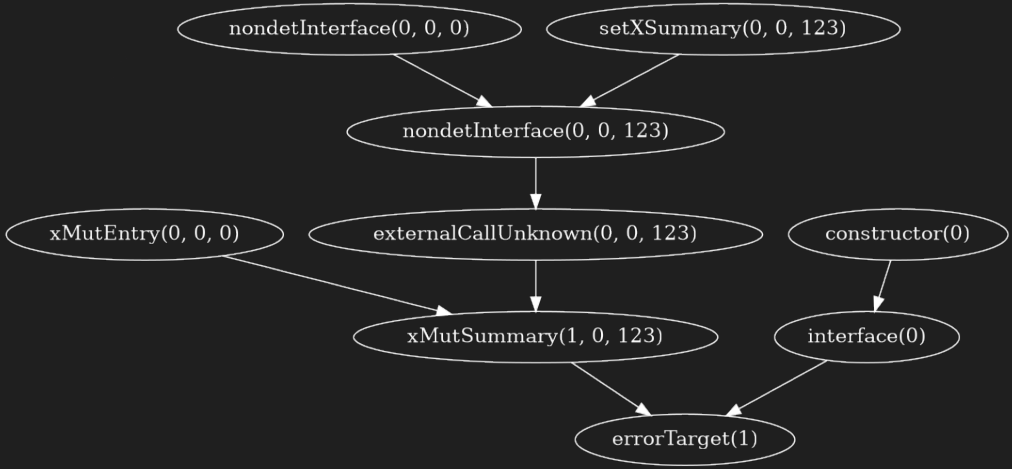
New rules help with synthesis of externally called unknown functions

$$\mathsf{error} = 0 \implies \mathsf{nondetInterface}(\mathsf{error}, \mathsf{x}, \mathsf{x}')$$

$$\mathsf{error} = 0 \land \mathsf{nondetInterface}(\mathsf{error}, \mathsf{x}, \mathsf{x}') \land \mathsf{setX}(\mathsf{error}', \mathsf{x}', \mathsf{x}'') \implies \mathsf{nondetInterface}(\mathsf{error}', \mathsf{x}, \mathsf{x}'')$$

$$\mathsf{error} = 0 \land \mathsf{nondetInterface}(\mathsf{error}, \mathsf{x}, \mathsf{x}') \land \mathsf{xMut}(\mathsf{error}', \mathsf{x}', \mathsf{x}'') \implies \mathsf{nondetInterface}(\mathsf{error}', \mathsf{x}, \mathsf{x}'')$$

Counterexample graph synthesizing external calls



SMTChecker internals - External calls

```
interface Unknown {
    function callMe() external;
}

contract ExtCall {
    uint x;

    function xMut(Unknown _u) public {
        uint xPrev = x;
        _u.callMe();
        assert(xPrev == x);
    }
}
```

Inductive invariants and external call properties

$$\mathbf{externalCallUnknown}(\mathbf{e}, \mathbf{x}, \mathbf{x}') = (\mathbf{x} = \mathbf{0} \implies \mathbf{e} = \mathbf{0}) \land (\mathbf{x} = \mathbf{0} \implies \mathbf{x}' = \mathbf{0})$$

$$\mathbf{interface}(\mathbf{x}) = \mathbf{x} = \mathbf{0}$$

Conclusions

- Automated FV tools can be quite powerful but...
- No automated tool will do the job everytime
- FV is still an expert domain
- Specific tool knowledge is required to extract full potential
- Playing with the tool is essential to get good results

Thank you!