CASA
CYBER SECURITY IN THE AGE OF LARGE-SCALE ADVERSARIES

Heinz Nixdorf Stiftung

MAX PLANCK INSTITUTE
FOR SECURITY AND PRIVACY

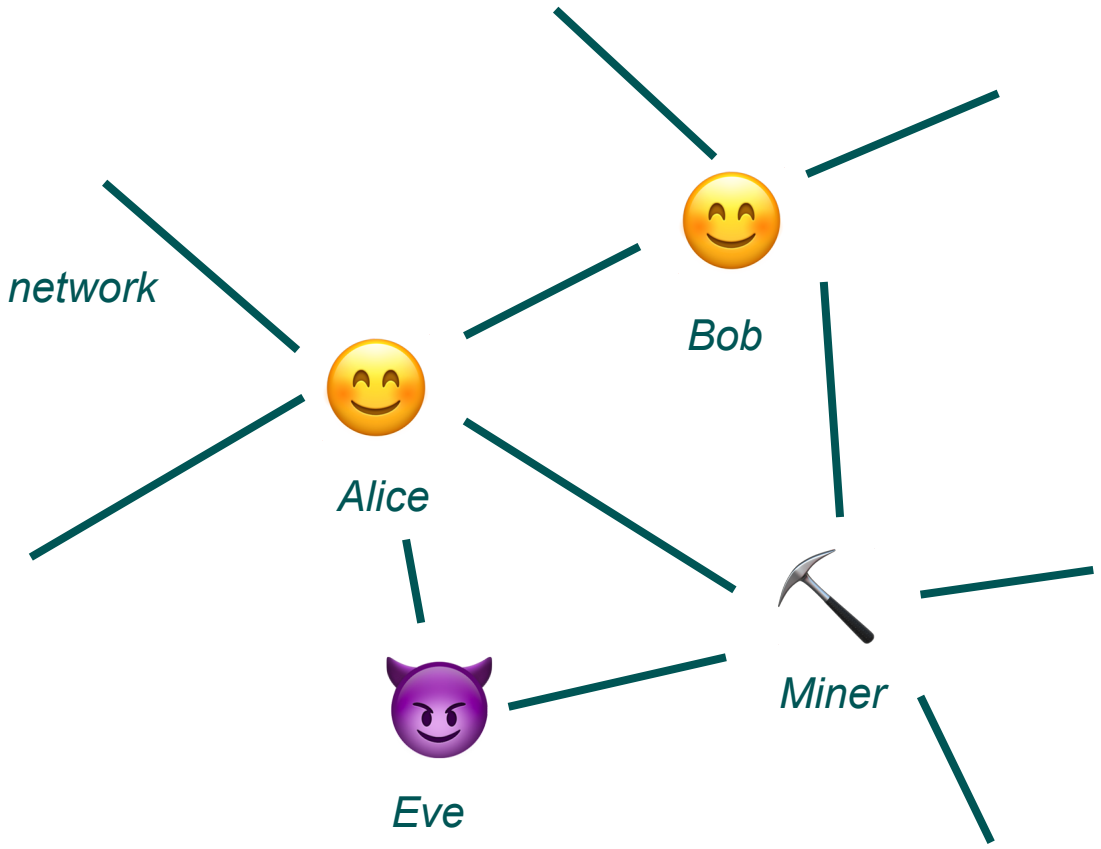
Combining Program and Protocol Analysis for Frontrunning Resistance in Smart Contracts

FCS 2026

Sebastian Holler, **Yan Farba**, Clara Schneidewind

Introduction

Blockchain 101



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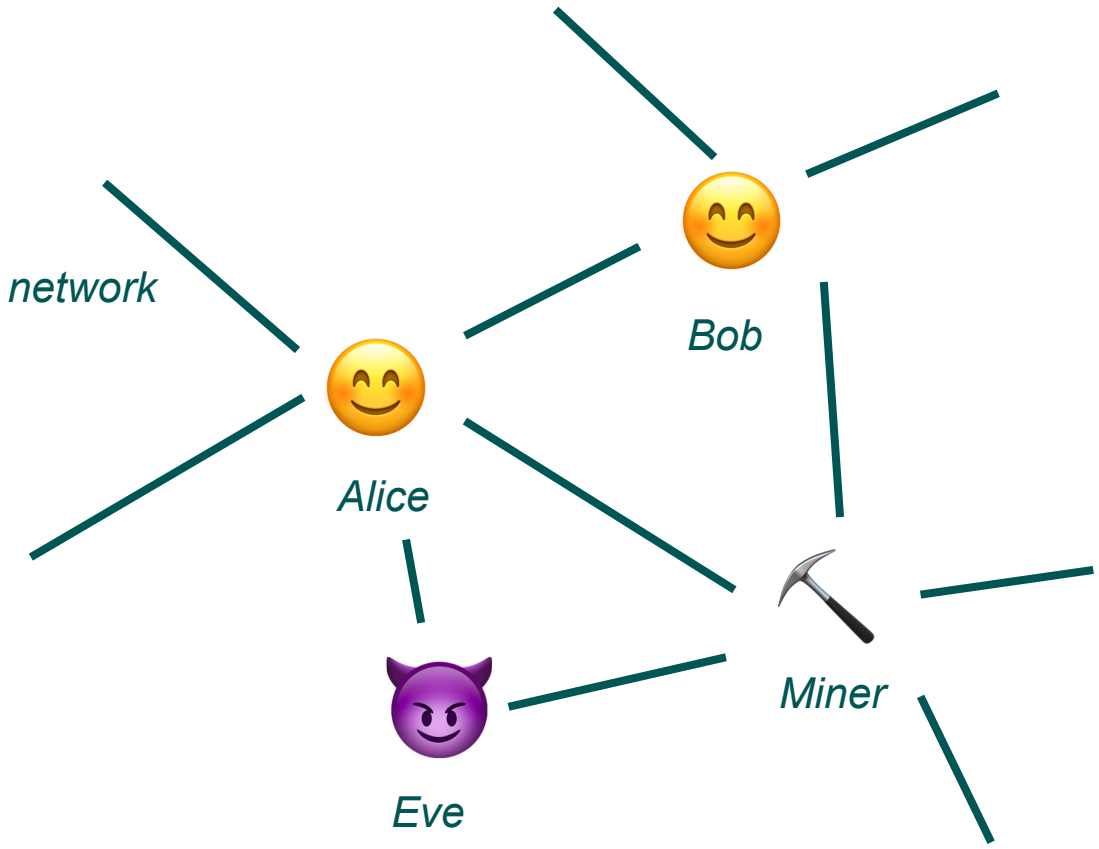

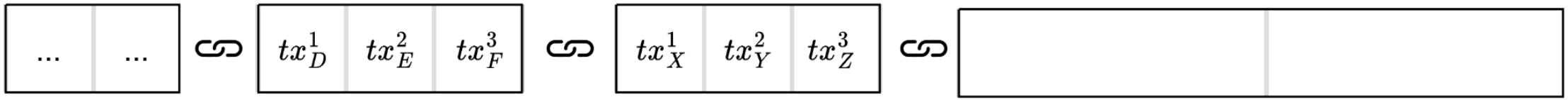

Blockchain

upcoming block

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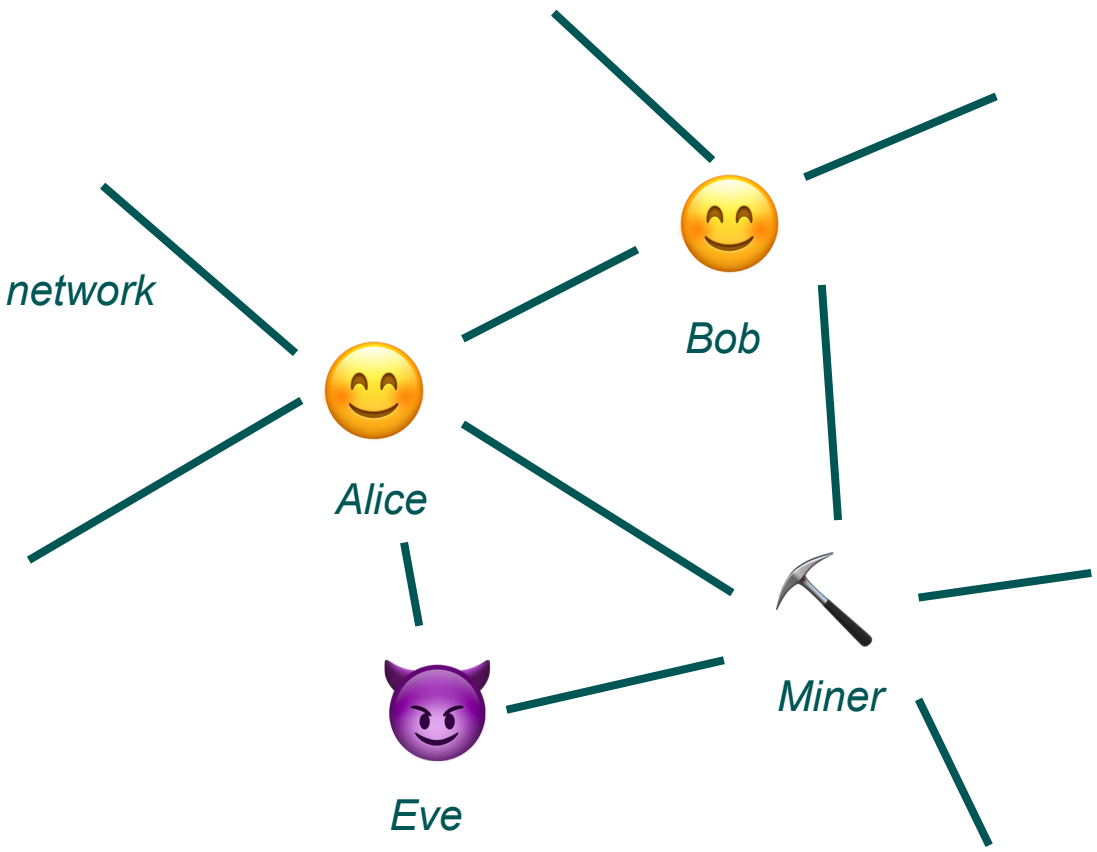
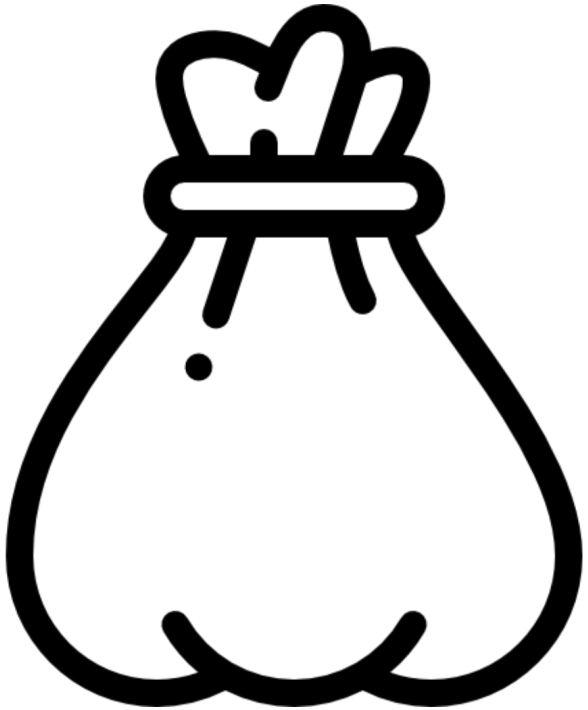
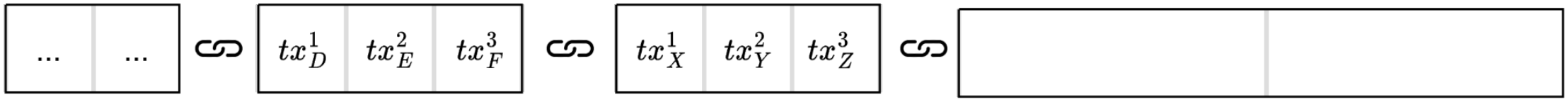




Mempool



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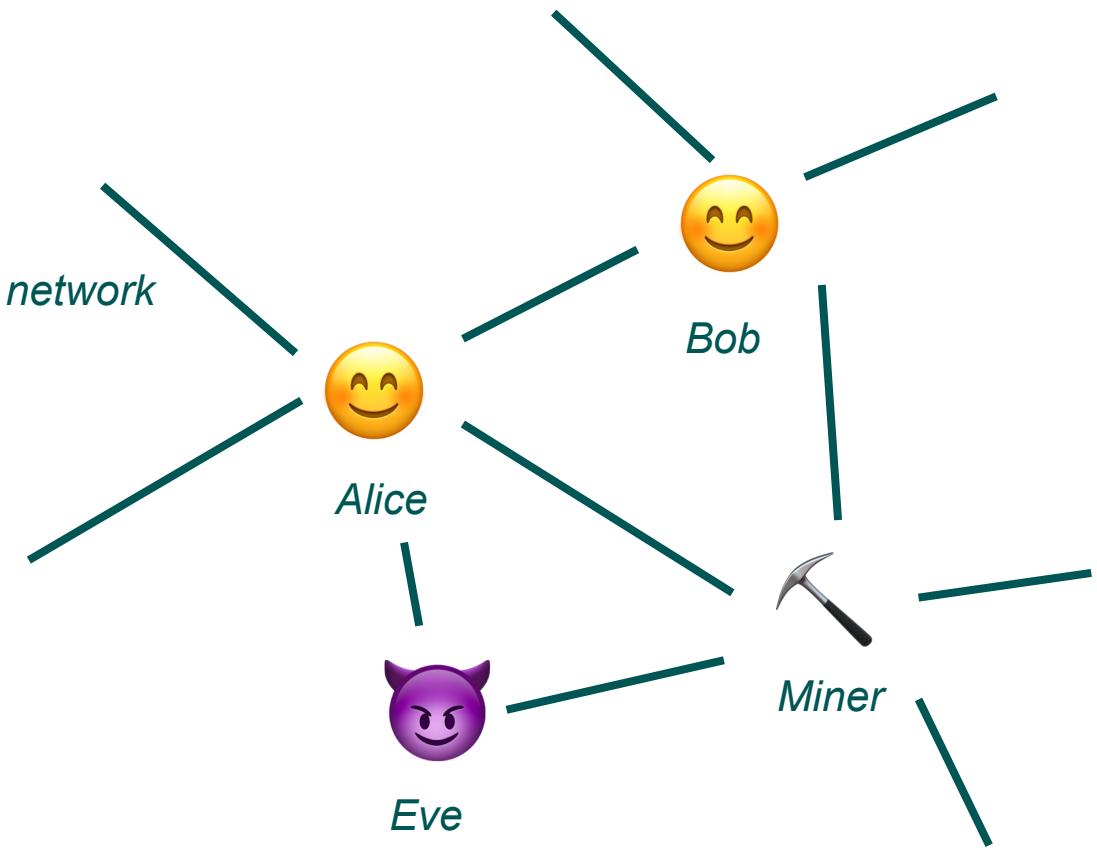

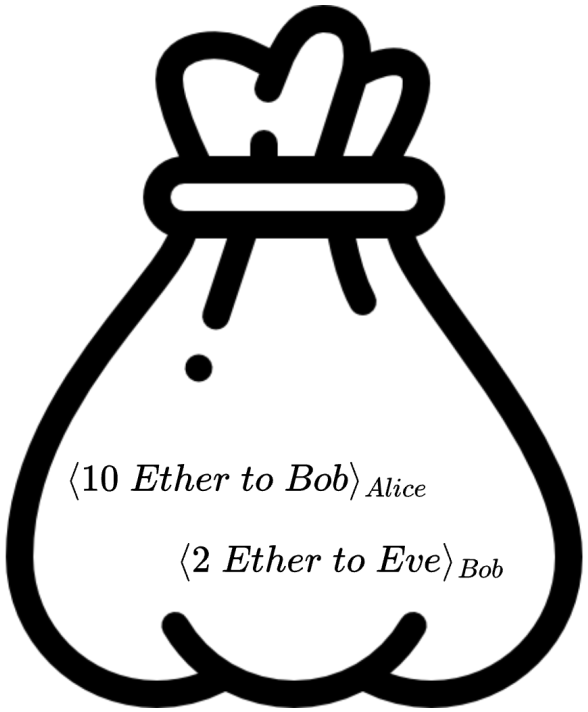

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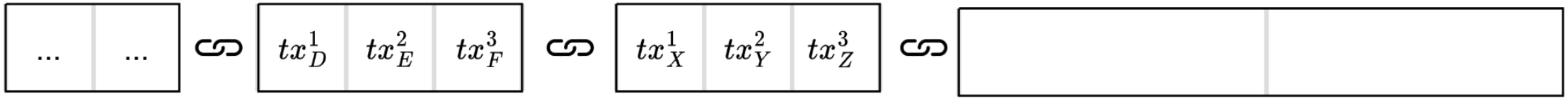

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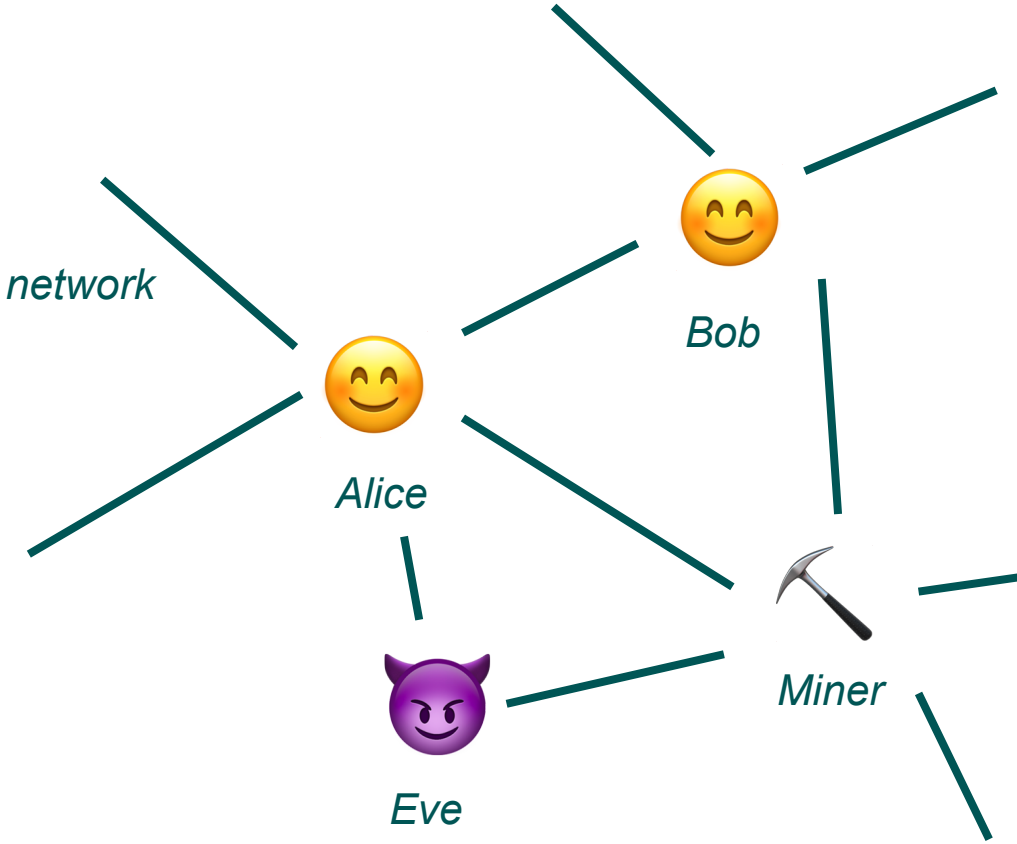

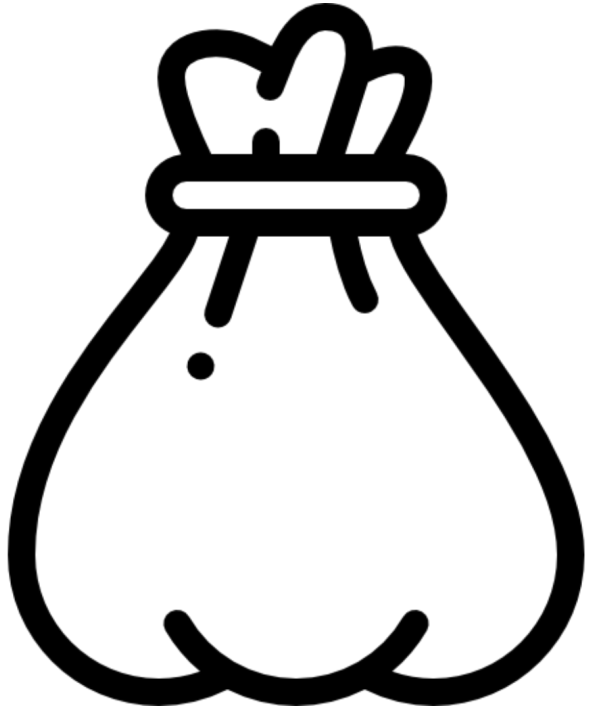

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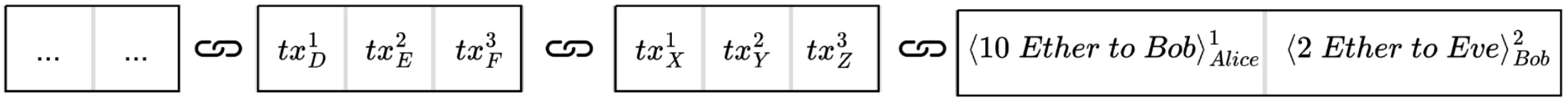
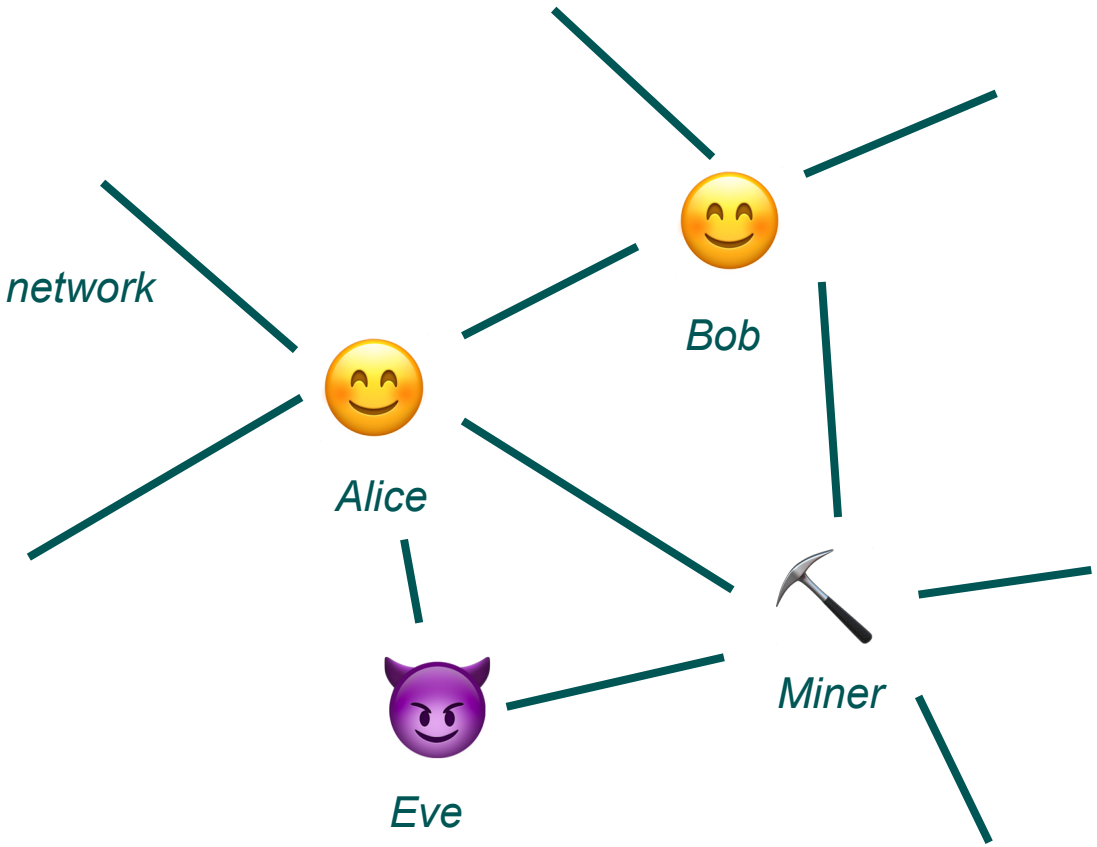
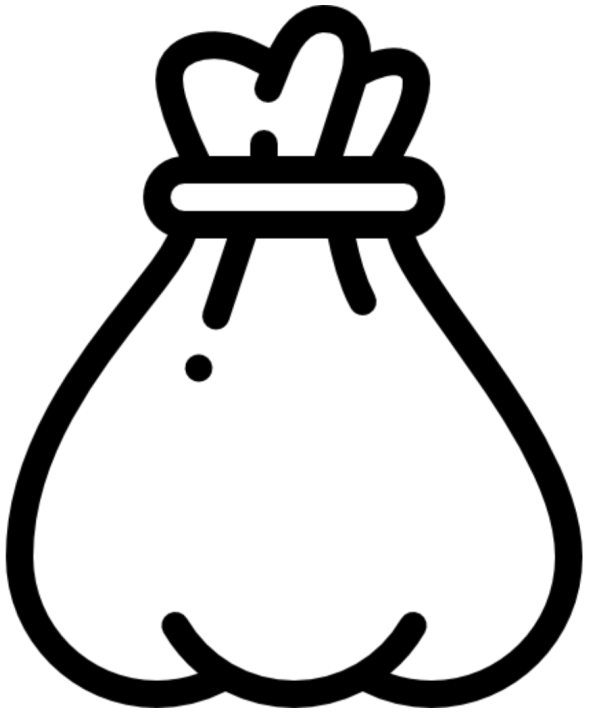


Blockchain

new *block*

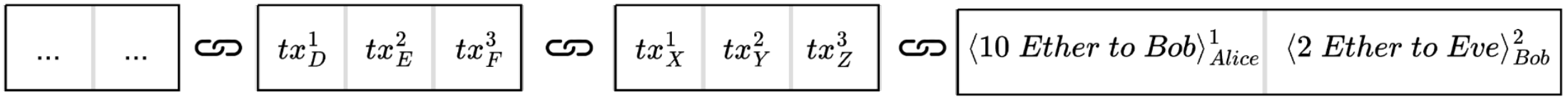
Blockchain 101





Mempool

We focus on **Ethereum** blockchain, which supports **Smart Contracts**.



Blockchain

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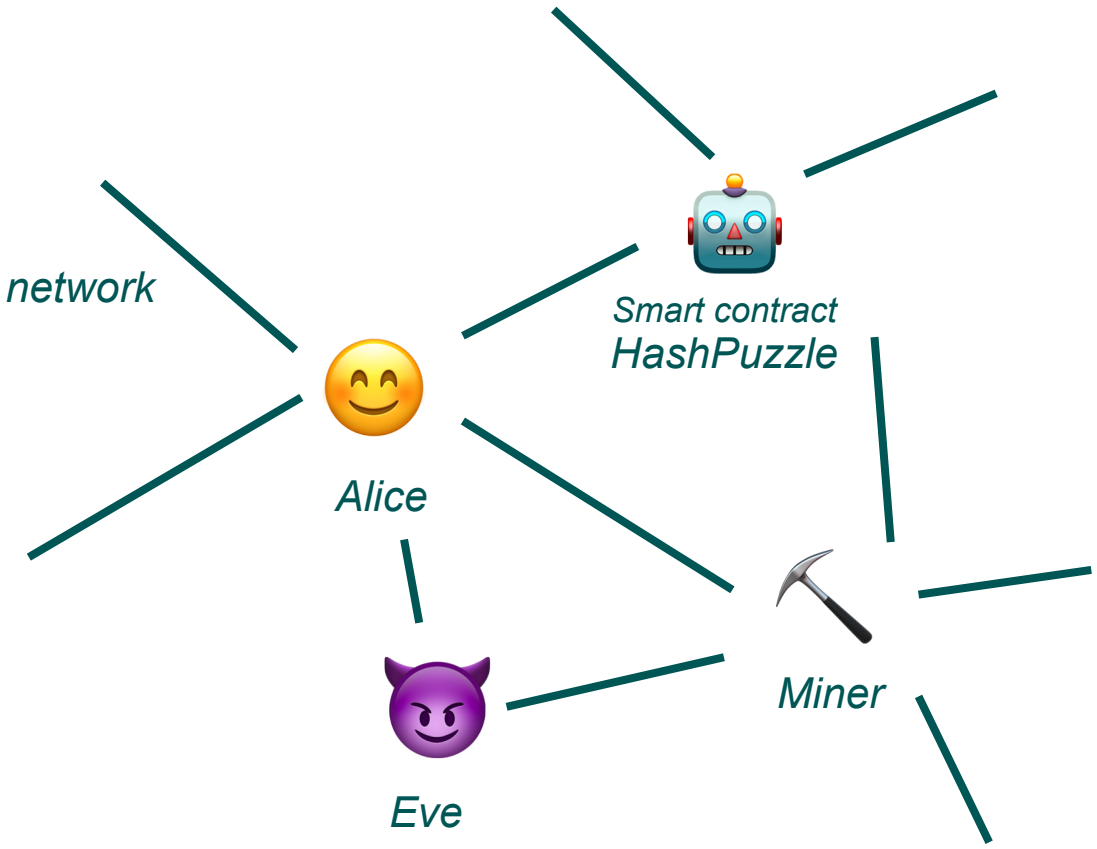
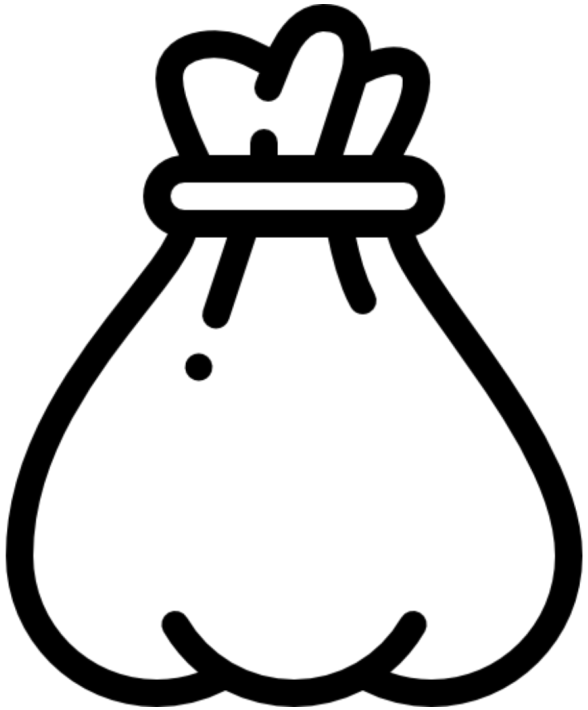
Smart Contracts 101





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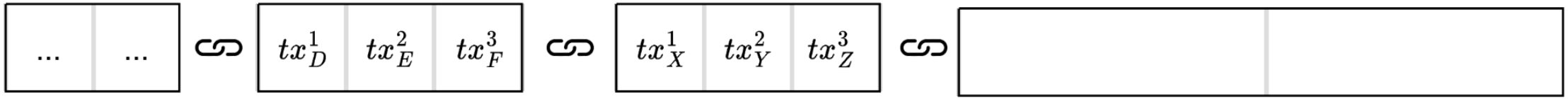

Blockchain

upcoming block

Smart Contracts 101

```
contract HashPuzzle {
    bytes32 public challenge;
    address public winner;
    function solve(bytes32 solution) {
        ...
    }
}
```

Written in Solidity.

Smart Contracts 101

```
contract HashPuzzle {
    bytes32 public challenge;
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    function solve(bytes32 solution) {
        require(
                sha256(solution) == challenge);
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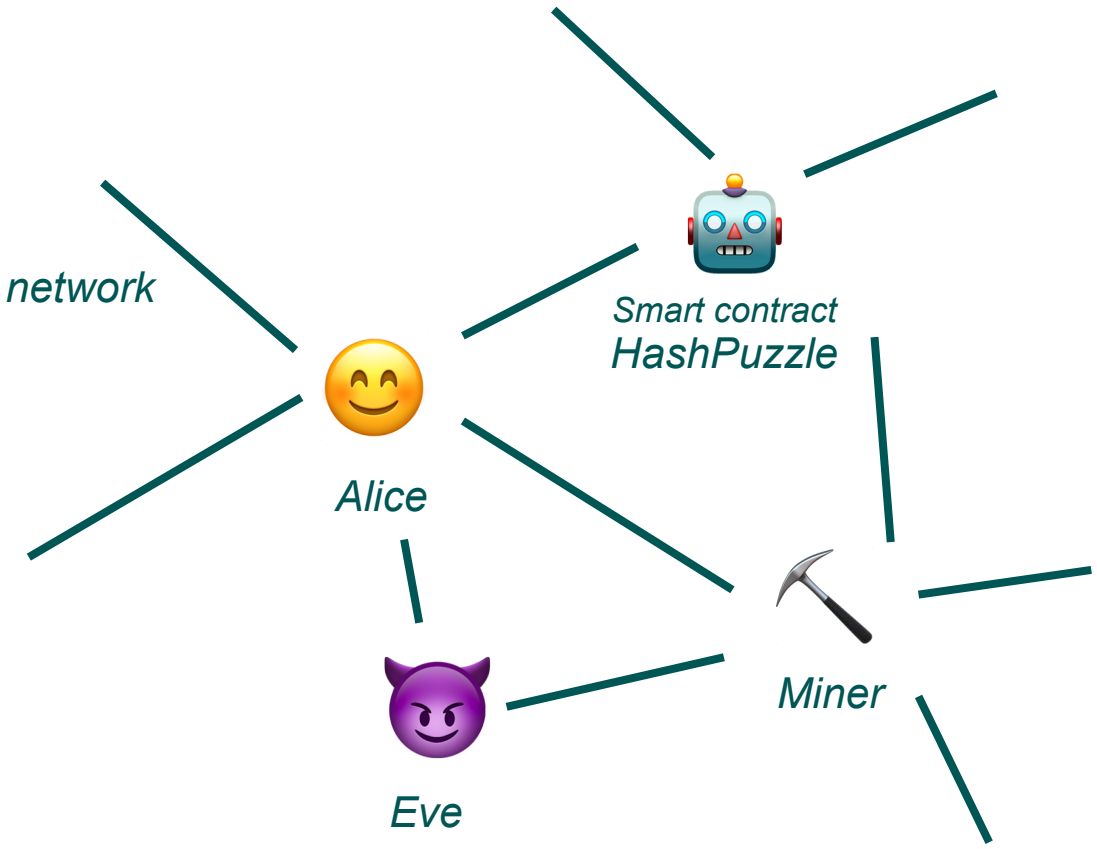
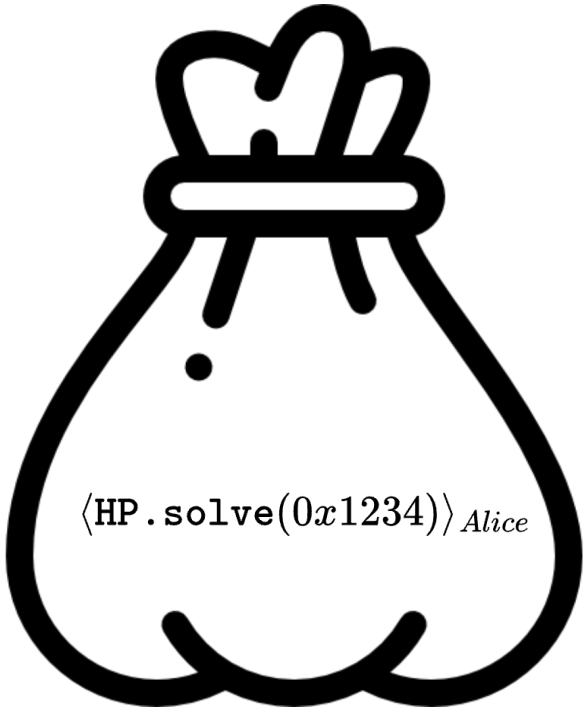
Written in Solidity.

The smart contracts' **state** (state variables, code and balance) is public**.**

Smart Contracts 101





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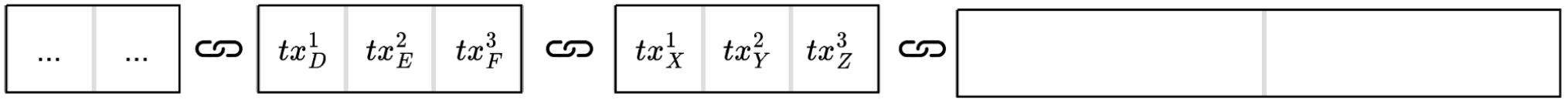
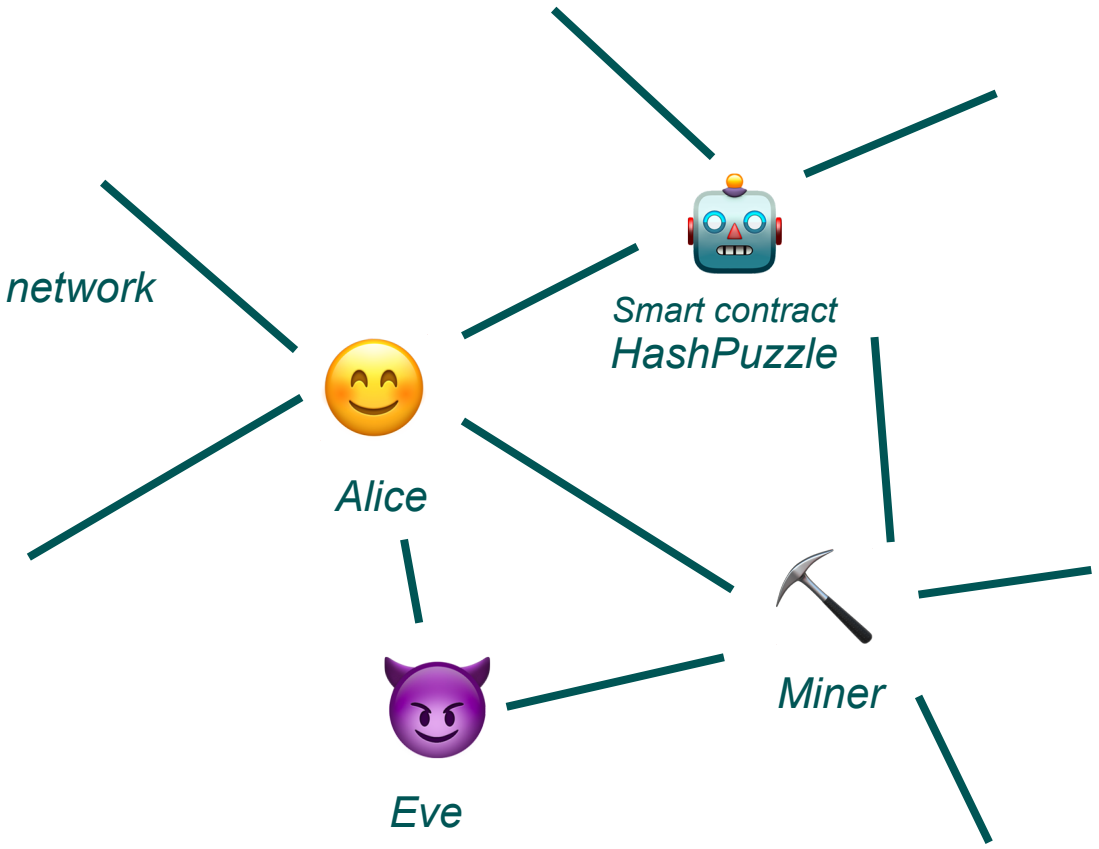
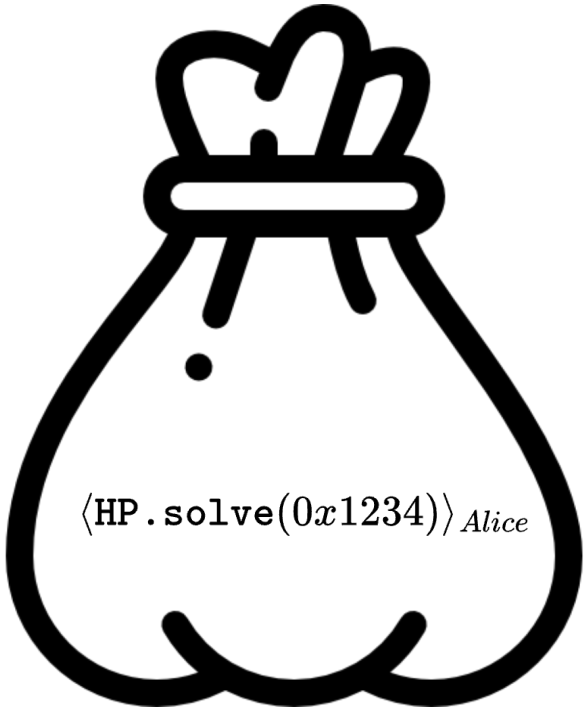


Blockchain

upcoming block

Blockchain as a Transition System





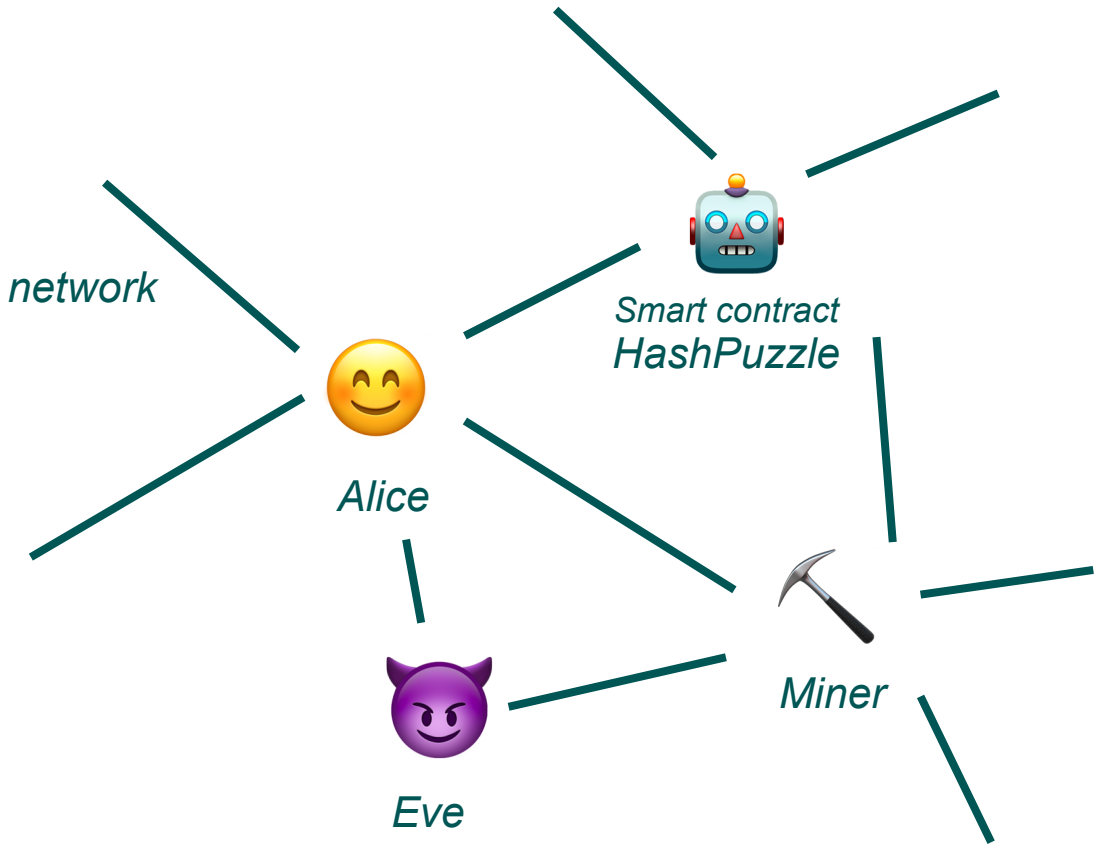
Mempool

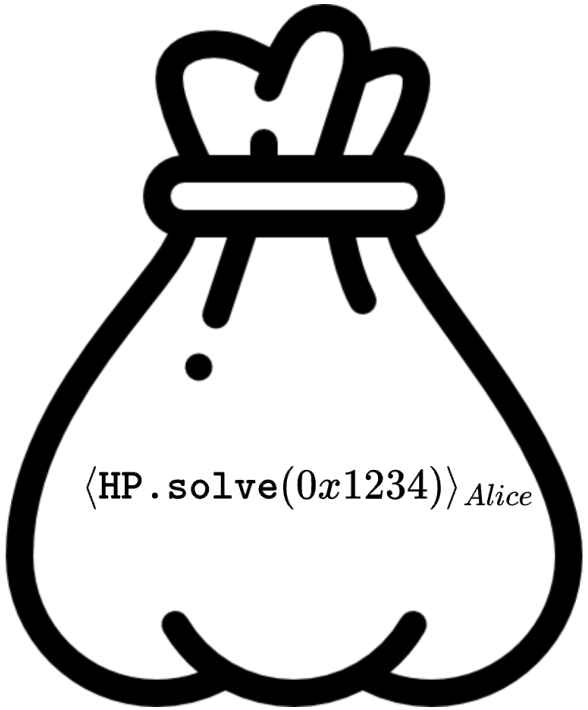
With blockchain semantics $\Gamma \xrightarrow{\langle tx \rangle} \Gamma'$, we reason about blockchain traces:

$$\Gamma_{Init} \xrightarrow{\langle tx_1 \rangle} \Gamma_1 \xrightarrow{\langle tx_2 \rangle} \ldots \xrightarrow{\langle tx_n \rangle} \Gamma_n$$

Motivation

Frontrunning *HashPuzzle*

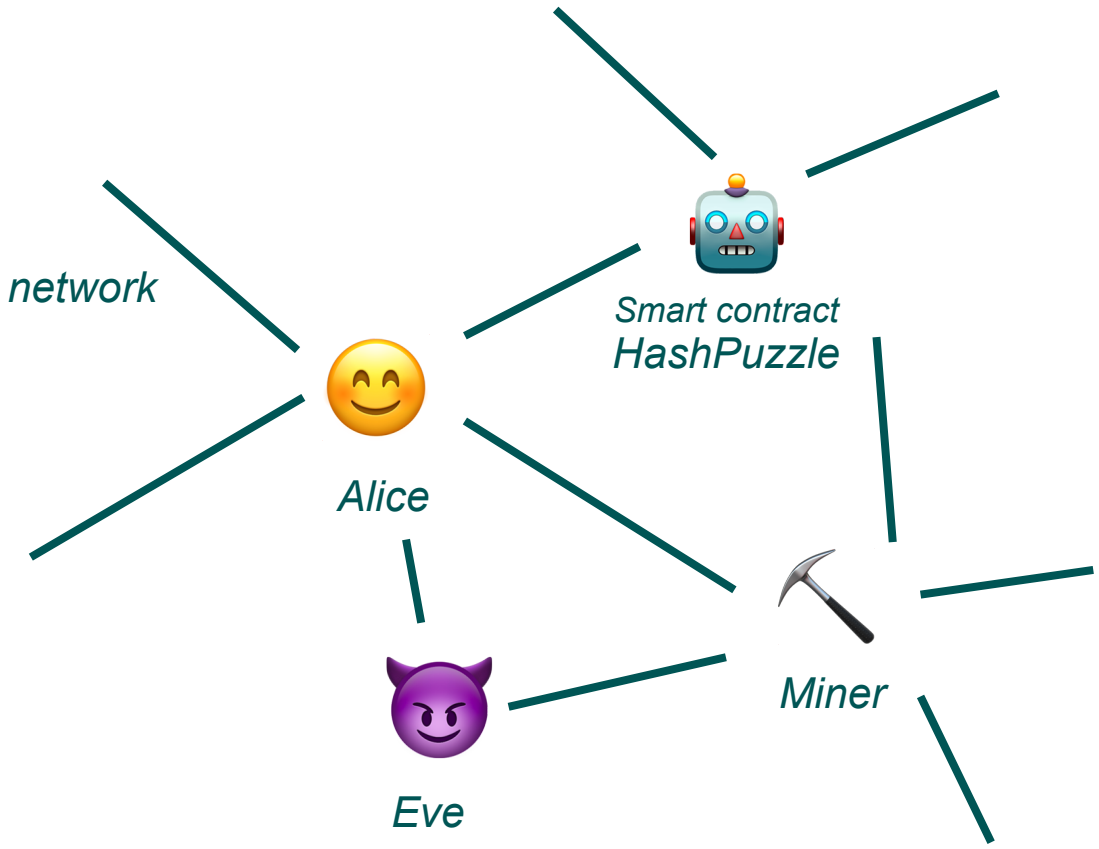


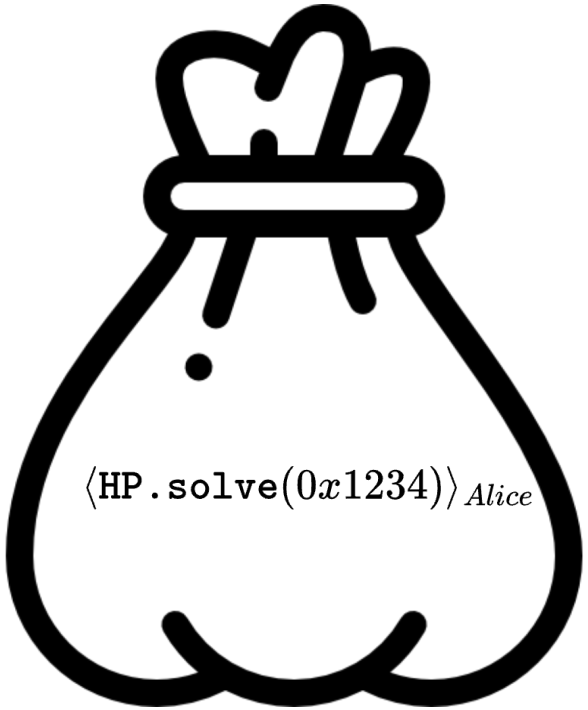


Mempool

Alice thinks, that she *calls* HashPuzzle.

Frontrunning *HashPuzzle*

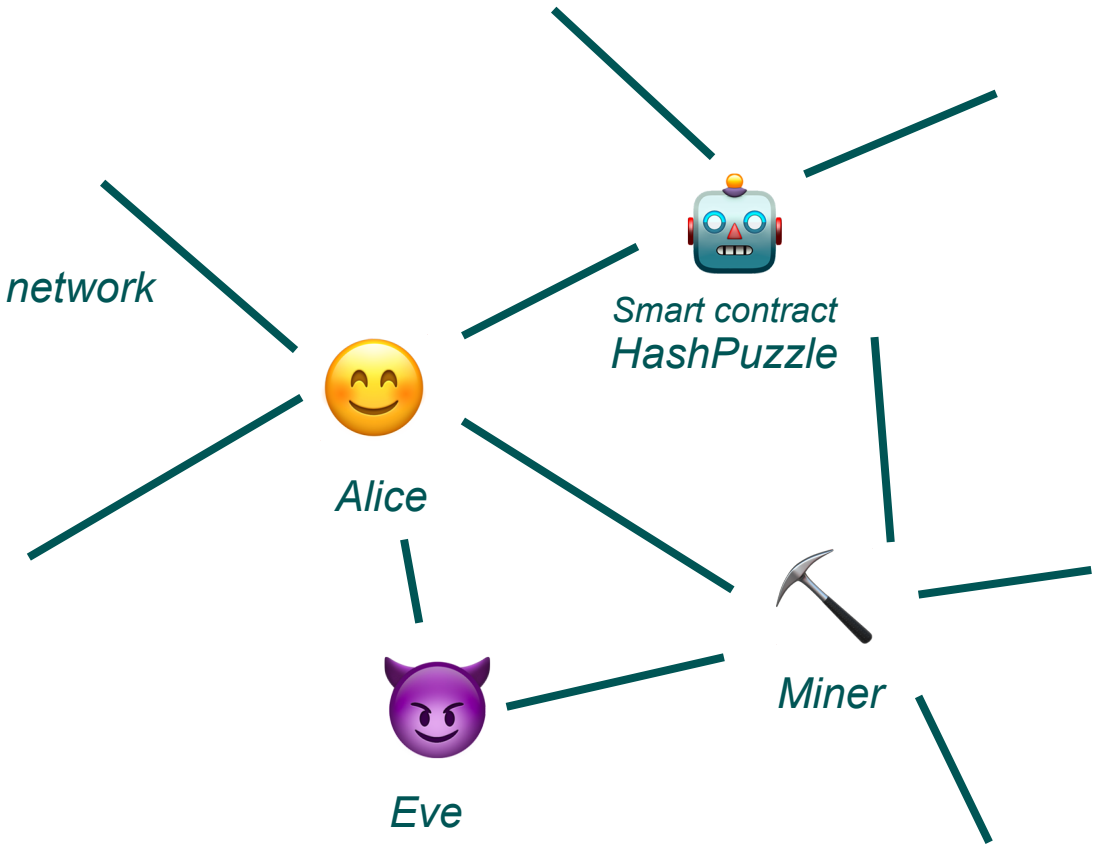


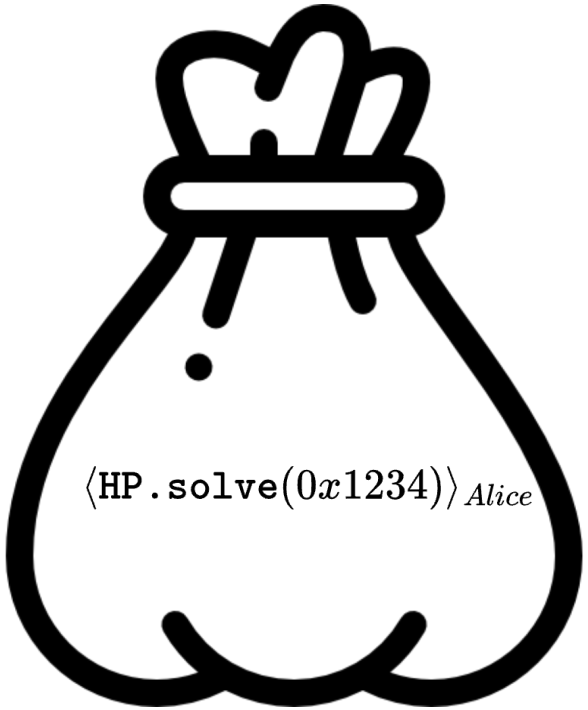


Mempool

Alice thinks, that she *calls* HashPuzzle. But before the block with a transaction is appended, the call has no effect.

Frontrunning *HashPuzzle*

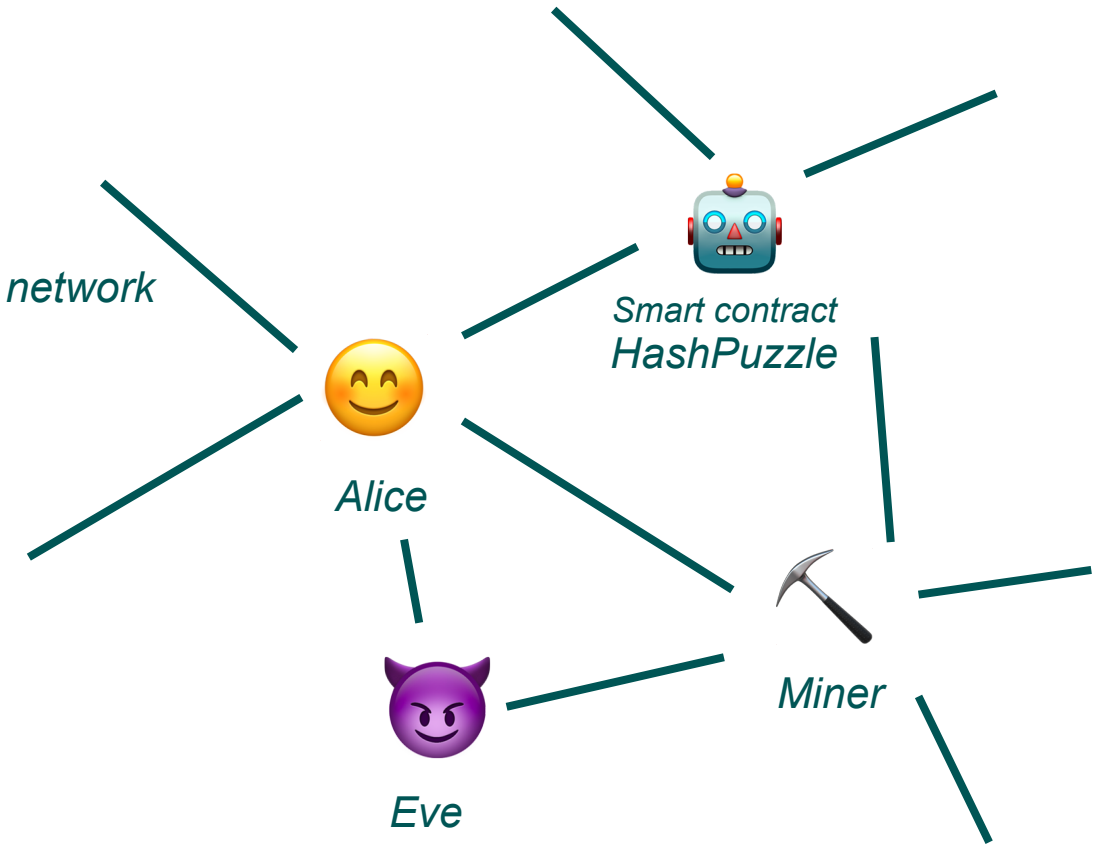


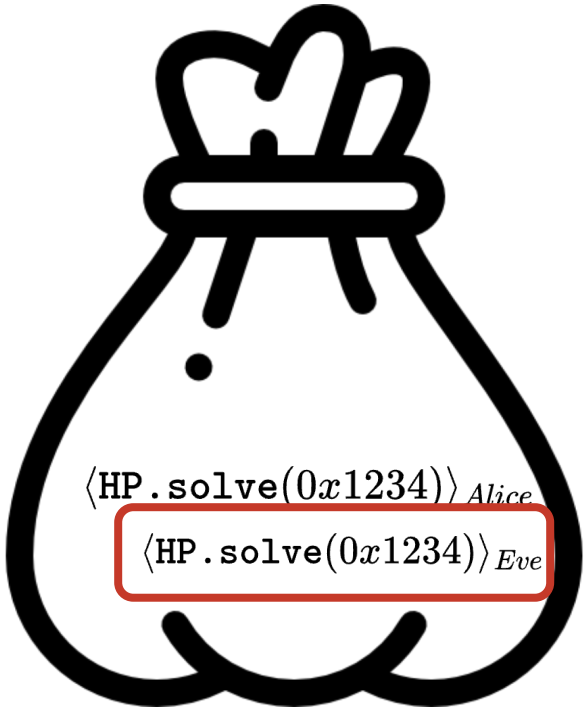


Mempool

Eve sees Alice's transaction **in the mempool** and uses it.

Frontrunning *HashPuzzle*





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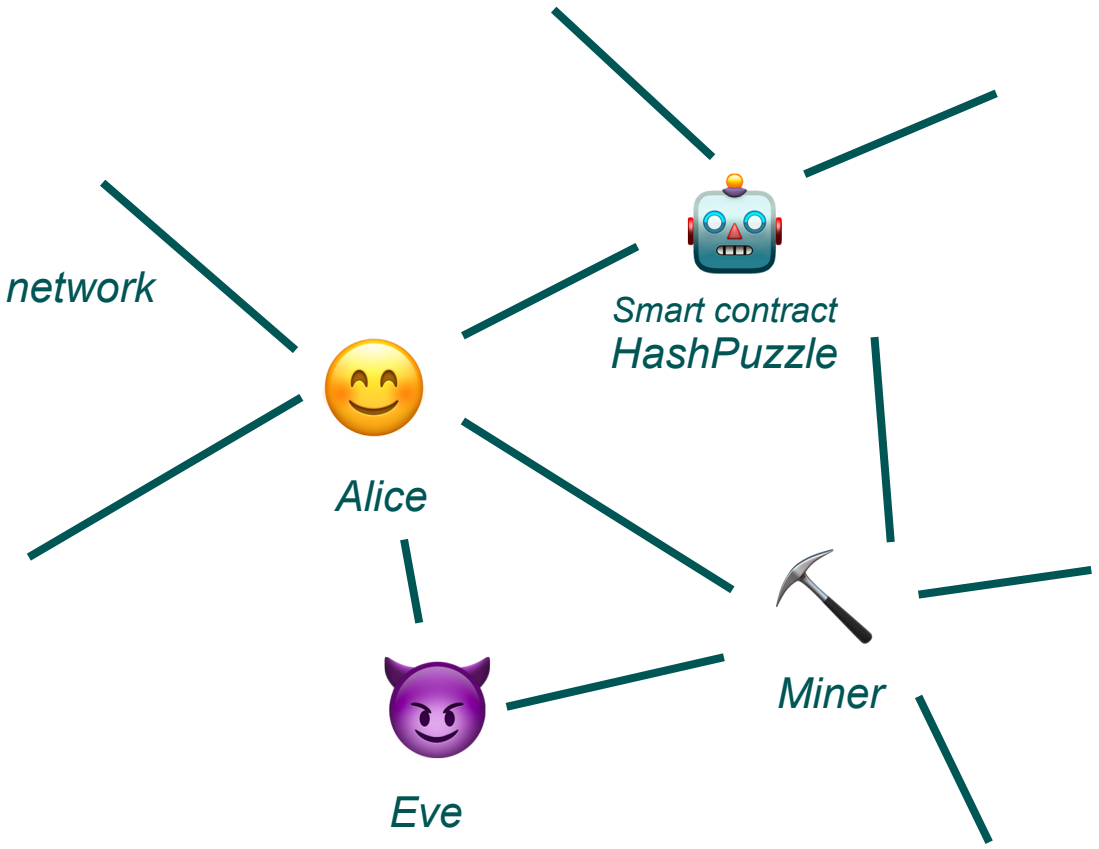
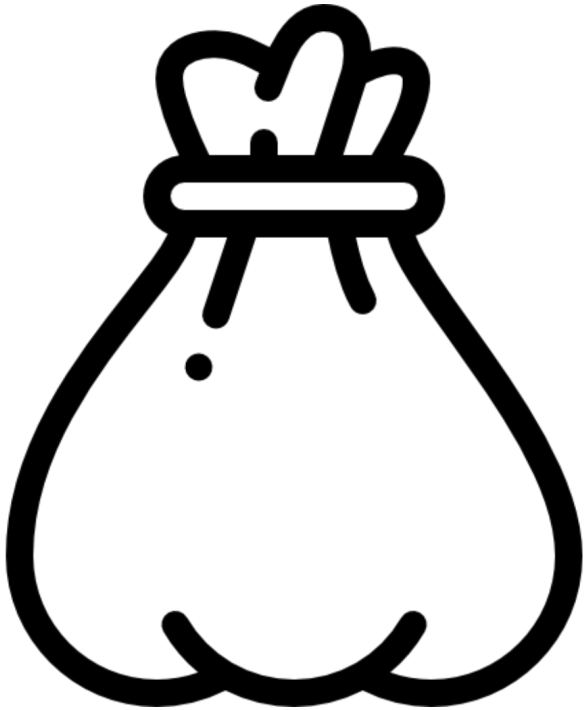
Frontrunning *HashPuzzle*





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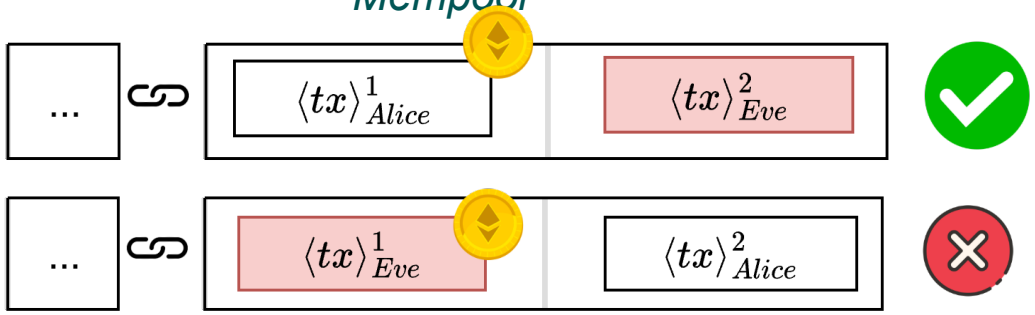

It is now for the miner to decide the order of two transactions:

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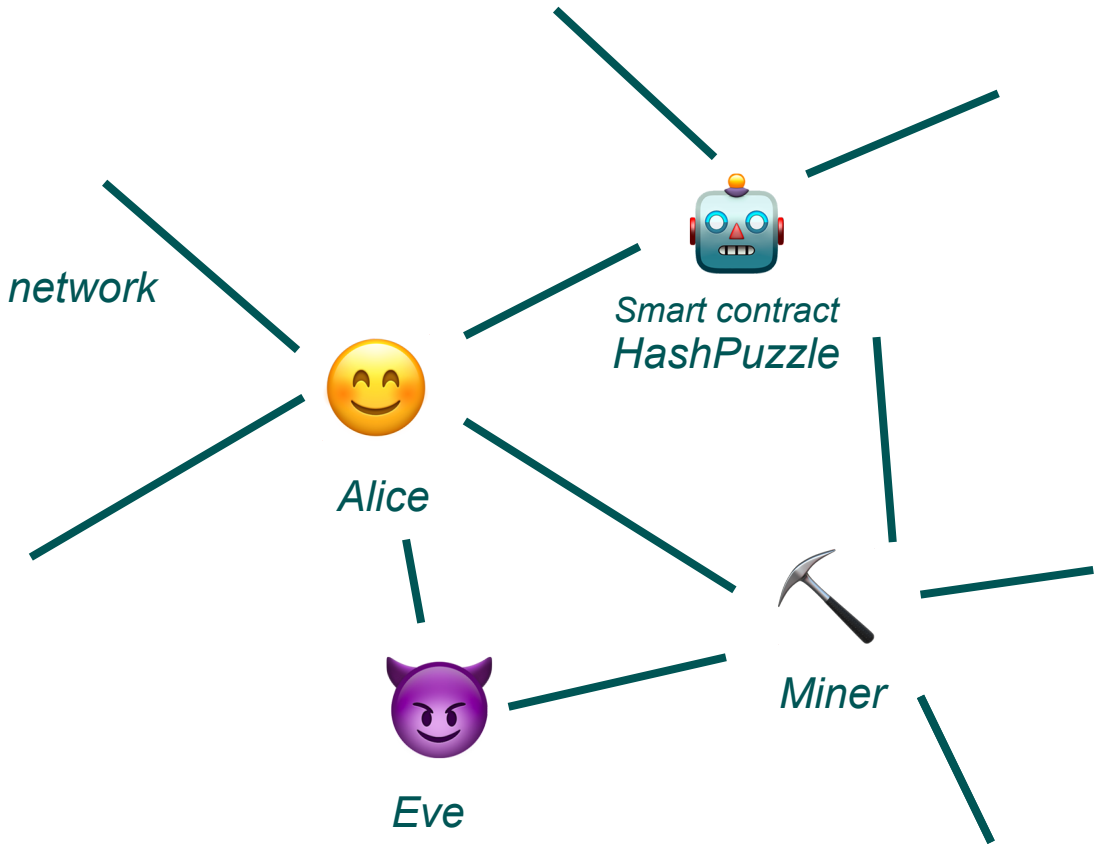

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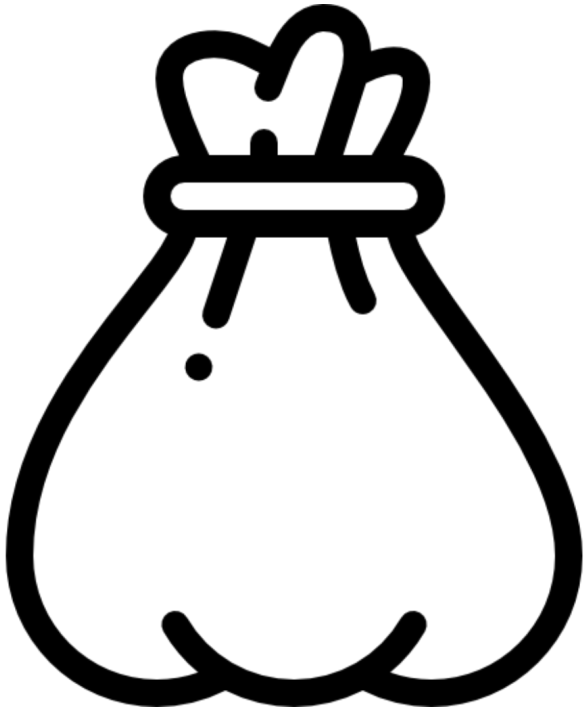

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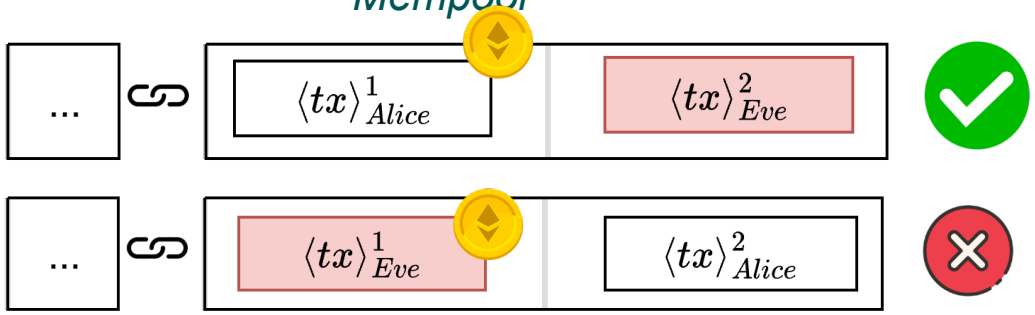

Eve can bribe the miner and ensure they steal the reward! [1]

[1] Kaihua Qin, Liyi Zhou, and Arthur Gervais. 2022. Quantifying blockchain extractable value: How dark is the forest?. In 2022 IEEE Symposium on Security and Privacy (SP). IEEE, 198–214.

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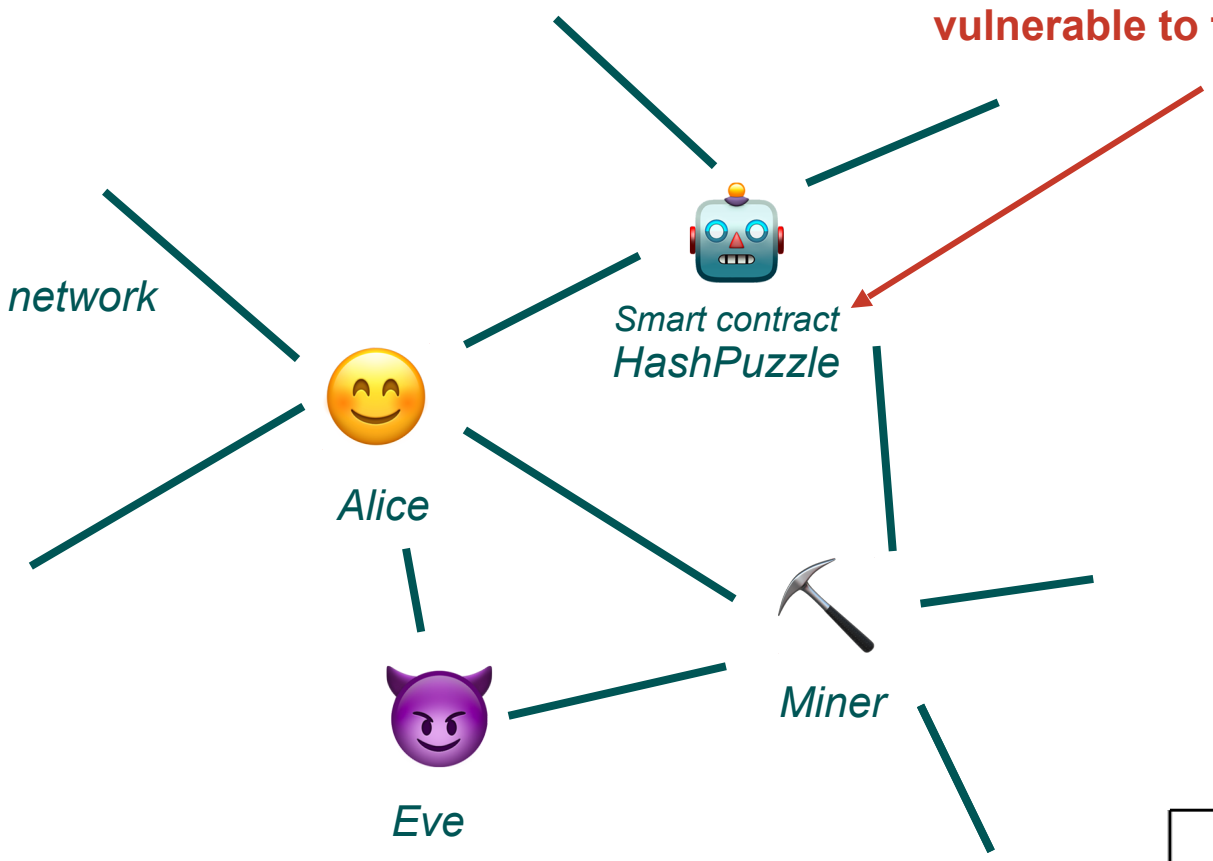

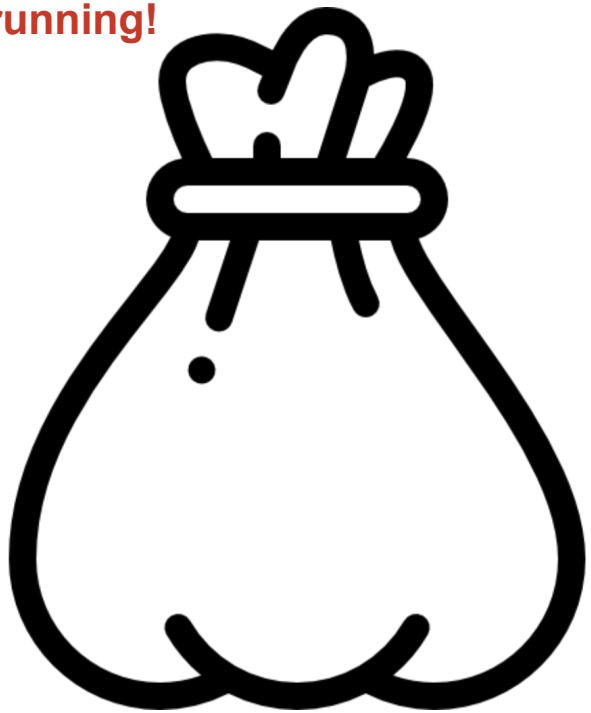

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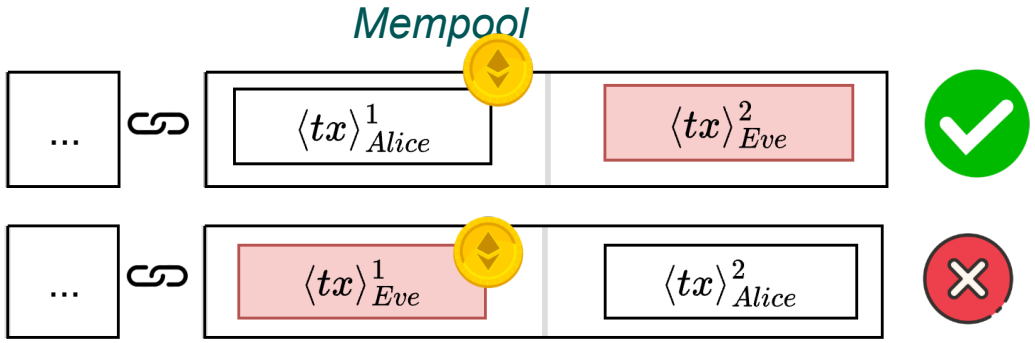

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Frontrunning Attacks [1, 2]

Frontrunning [1, 2] is an attack in which an attacker uses the publicly available information about pending transactions to reorder them profitably, potentially harming users.
Attacker model: strong attacker that observes mempool and can arbitrarily insert and reorder transactions.

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From 2018 to 2021: **540.54M USD** extractable from Ethereum due to frontrunning. **[1]**

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Frontrunning **undermines incentives of rational miners**.

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Transaction Order Dependence (TOD) [3]

If there are two transaction which, after invoking a smart contract, show different effects on blockchain state **depending on the their order**, we say a smart contract is **transaction-order dependent.**

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→ *HashPuzzle is transaction-order dependent, as* tx_{Alice} *and* tx_{Eve} *lead to different blockchain states depending on their order*

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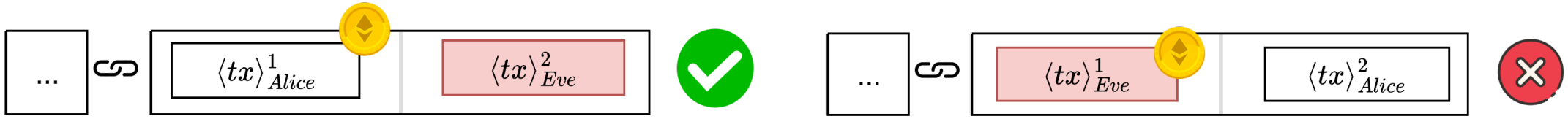

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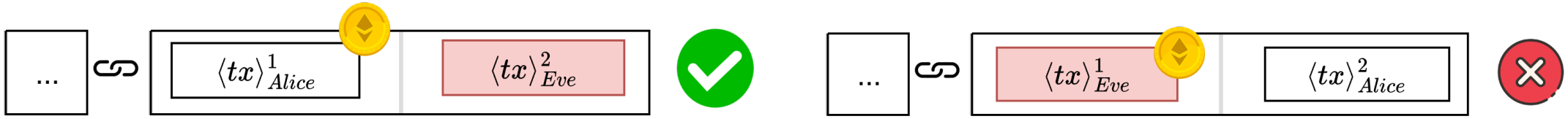

TOD is a **necessary**, but **insufficient** condition for a smart contract to be vulnerable to frontrunning!

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Key idea

Counterexample to TOD being sufficient: Commit-Reveal

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- We can fix *HashPuzzle* by introducing two phases in which it works: **commit** and **reveal**.

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- In the end of the phase, the user's action **is surely executed**.

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- In the end of the phase, the user's action **is surely executed**.

```
contract HashPuzzleFix {
        …
    function commit(bytes32 commitment) {
            require(phase == Commit);
        …
    }
    function reveal(bytes32 solution) {
            require(phase == Reveal);
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```

Counterexample to TOD being sufficient: Commit-Reveal

```
contract HashPuzzleFix {
        …
    mapping(address => bytes32) public commitments;
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}
```

Counterexample to TOD being sufficient: Commit-Reveal

- The fix is to get hashed solutions as commitments.

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```

Counterexample to TOD being sufficient: Commit-Reveal

- The fix is to get hashed solutions as commitments.
- This is secure, as after **commit** phase no new solution can be proposed.

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contract HashPuzzleFix {
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Counterexample to TOD being sufficient: Commit-Reveal

- However, an **irrational** honest user may leak their solution!
- TOD **checks all smart contracts states**, so it renders this fix vulnerable.

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Key idea

The **honest user behavior** is the missing piece for the precise analysis, as it defines which **states of the smart contracts** are **reachable** when interacting with users.

Property

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We check if in all blockchain executions R that conform to the honest user protocol and honest user transactions yielded by the protocol,
an attacker cannot extract value (due to commutativity of attacker/honest user transactions).

Caveat

Property

$$\forall R.\ \text{😇}\vdash R \wedge \text{😇}(R) = \langle \text{😇} \rangle \wedge R_n = \Gamma \Longrightarrow$$
$$\forall \langle \text{😈} \rangle.\ \forall \Gamma', \Gamma''.\ \Gamma \overset{\text{😈}}{\rightarrow}\overset{\text{😇}}{\rightarrow} \Gamma' \wedge \Gamma \overset{\text{😇}}{\rightarrow}\overset{\text{😈}}{\rightarrow} \Gamma'' \Longrightarrow \Gamma' \approx \Gamma''$$

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Problem: Verification of hyperproperty is computationally complex.

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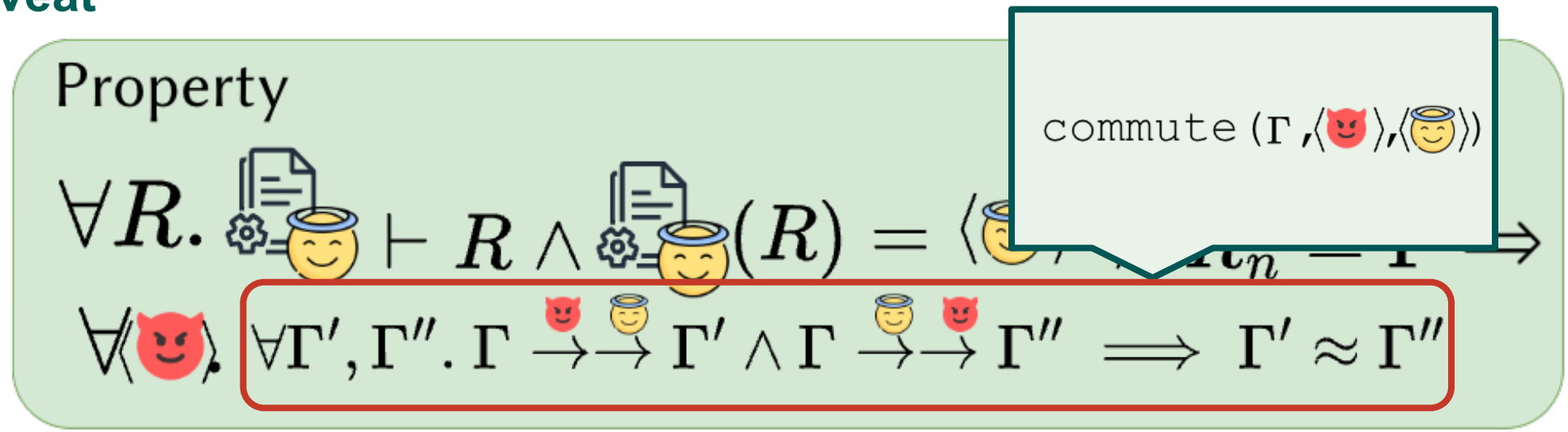
Solution: reduce the verification to **reachability analysis** by precomputing **commutating states.**

Caveat



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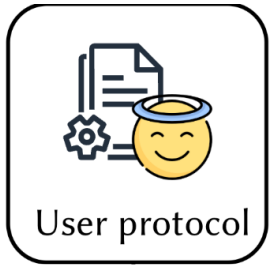

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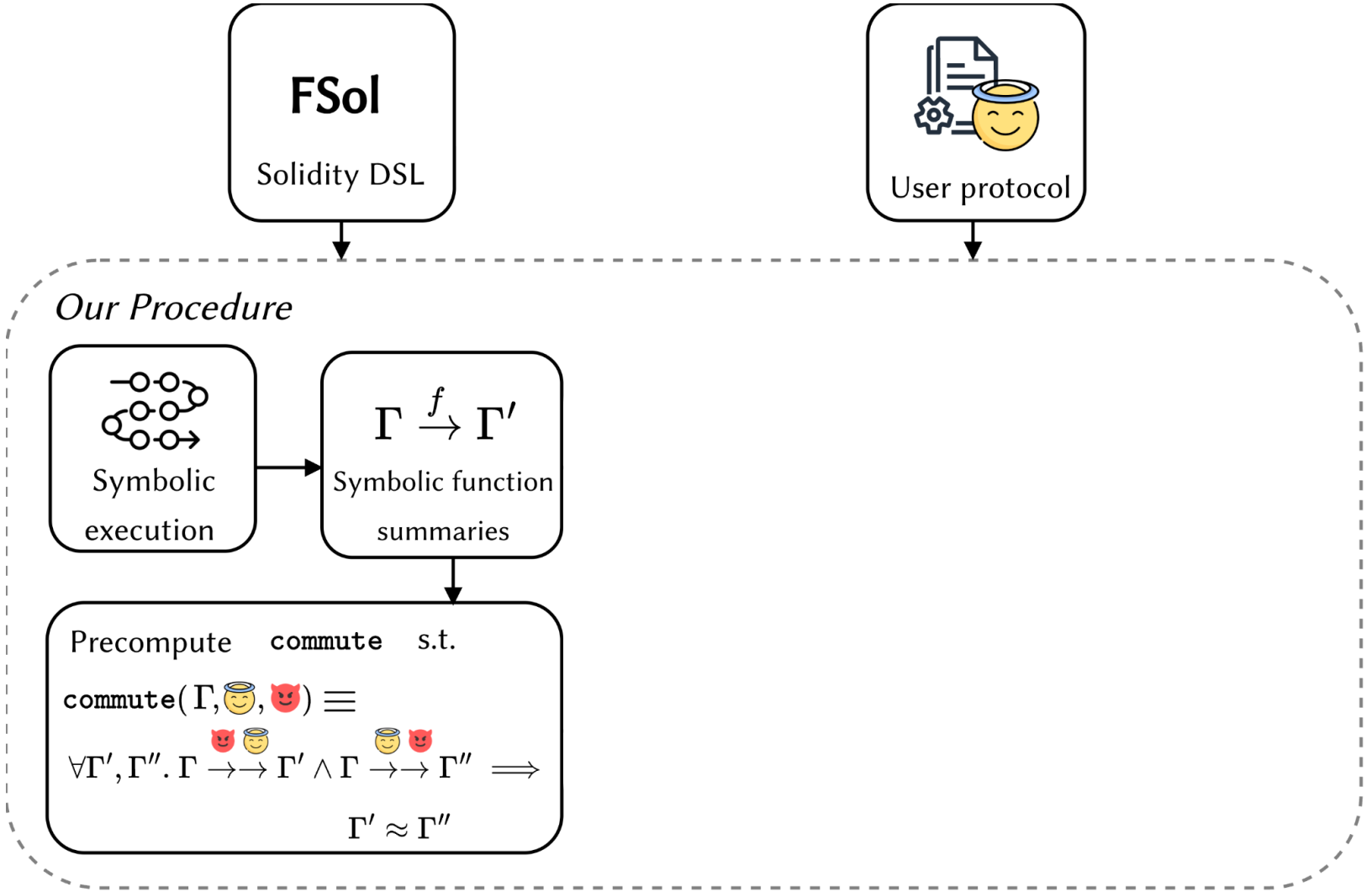
FSol
Solidity DSL
User protocol
Our Procedure
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$\Gamma \xrightarrow{f} \Gamma'$
Symbolic function summaries
Precompute commute s.t.
commute(Γ, 😇, 😈) ≡
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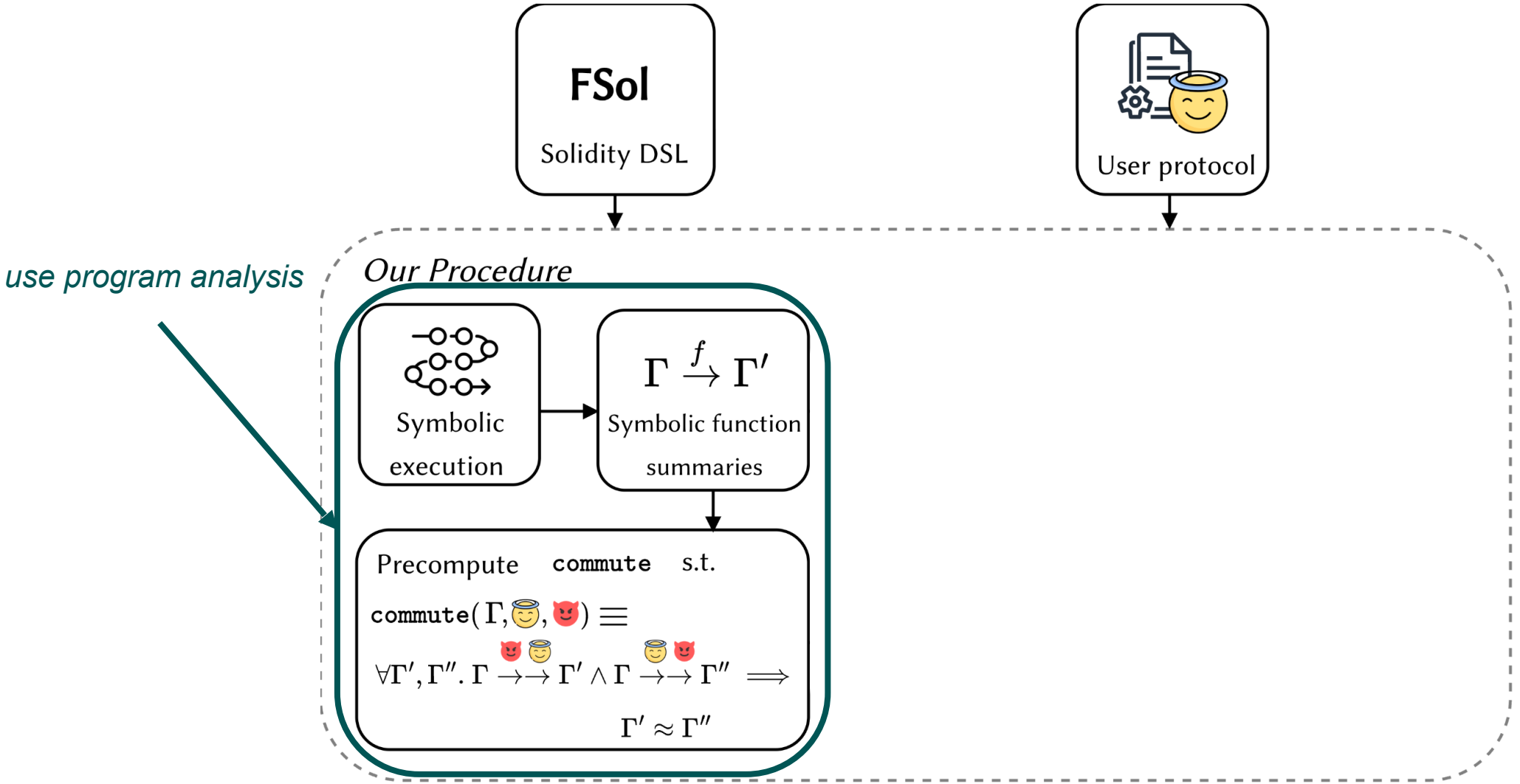
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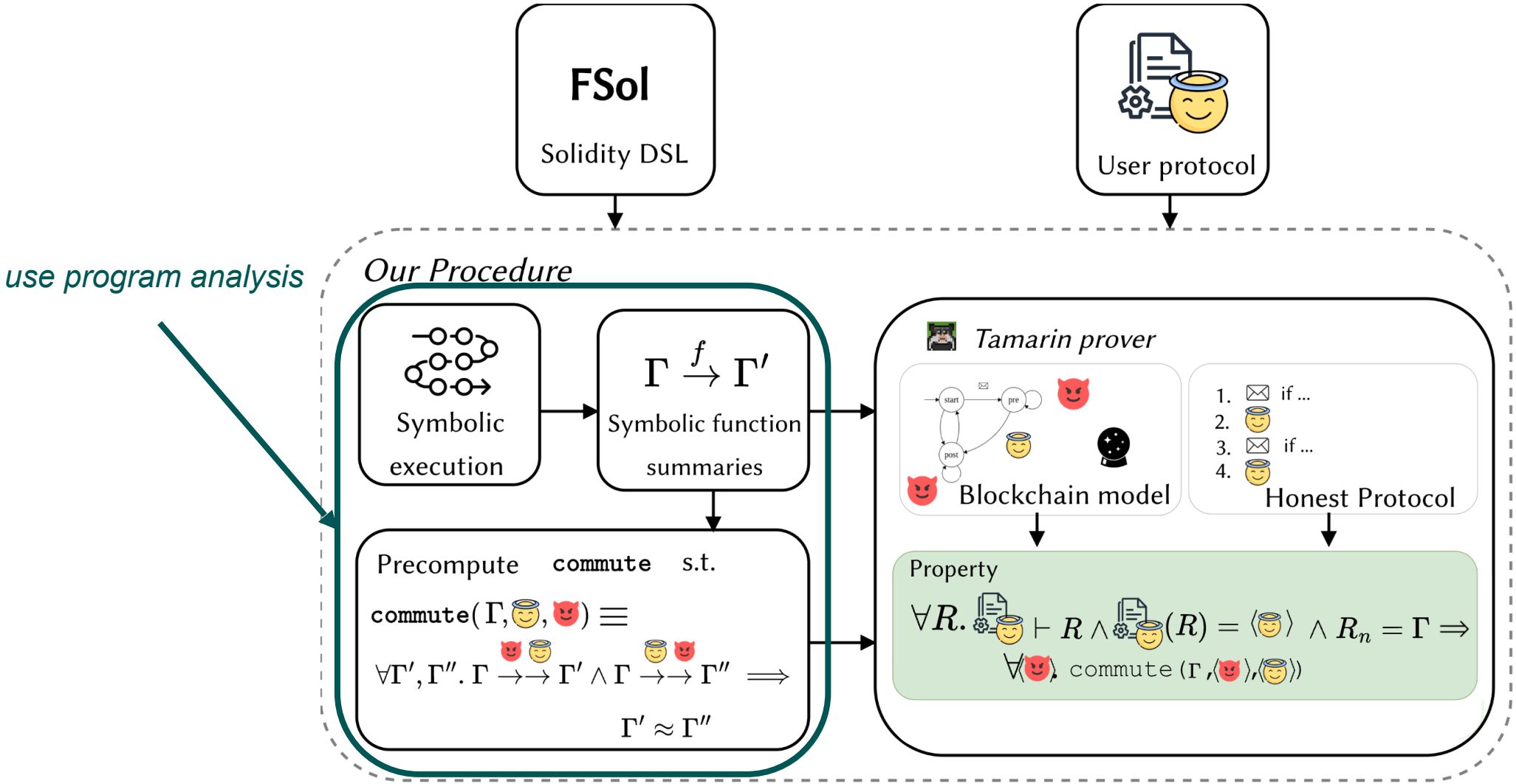
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pre
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Blockchain model
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3. if ...
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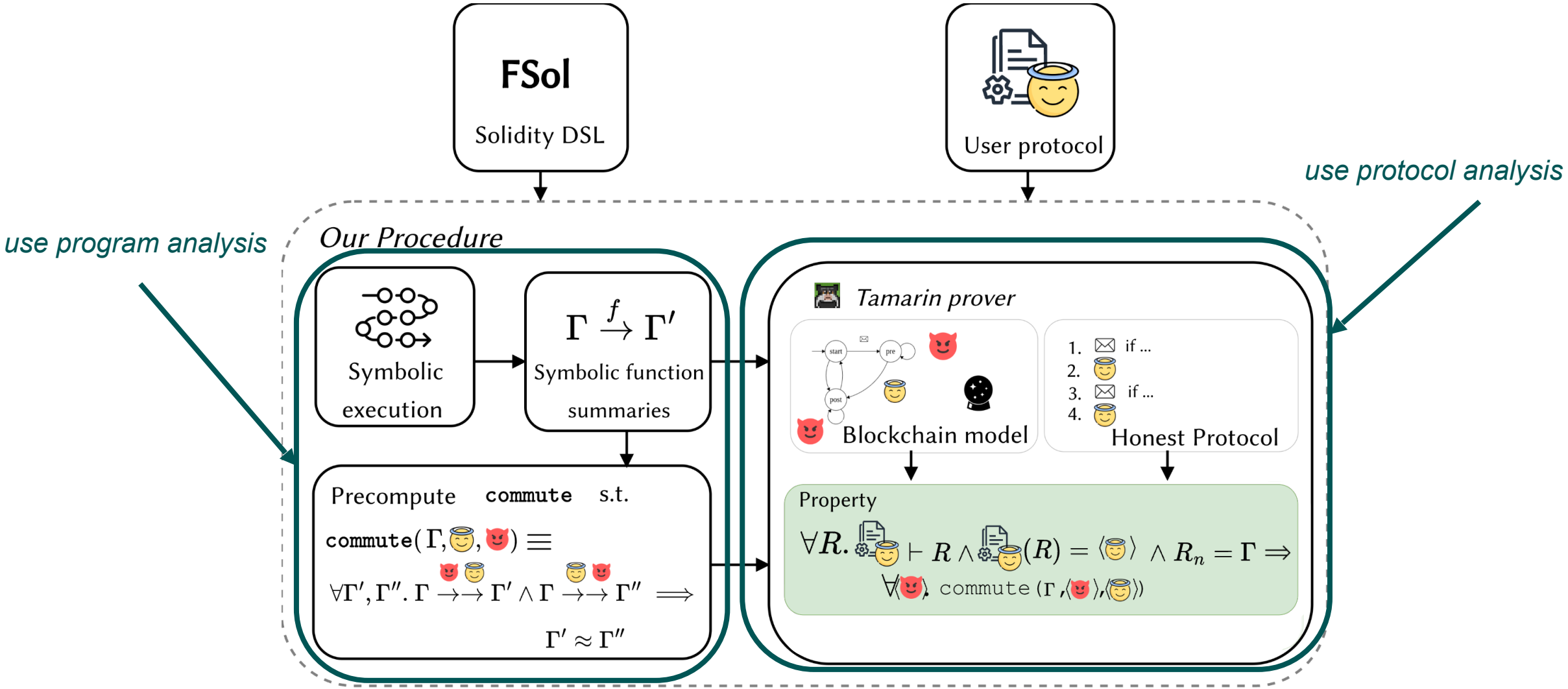
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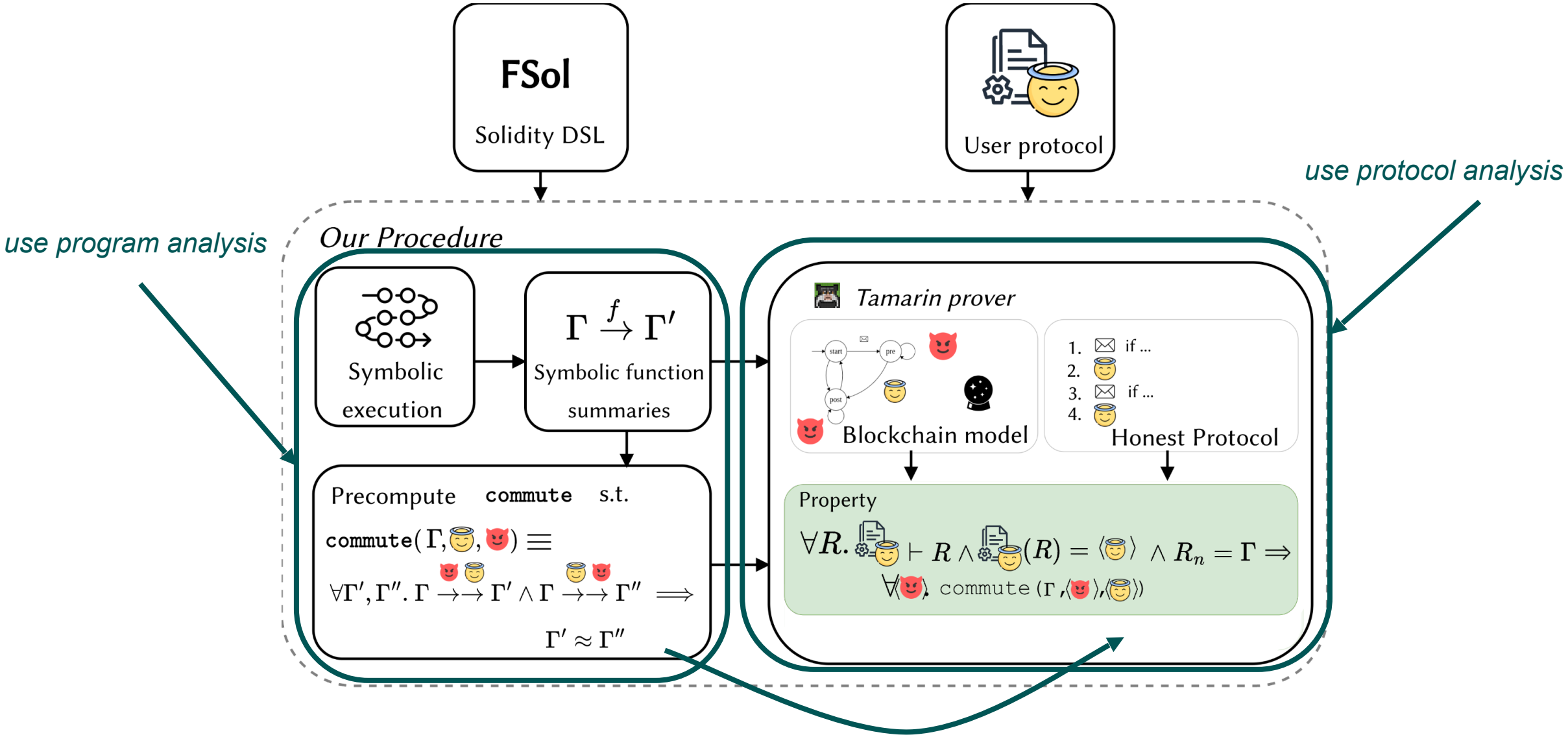
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FSol: DSL for frontrunning resistance

FSol by example

```
contract HashPuzzleFix {
    phases [] [Commit, Reveal];
    state address winner = None;
    state mapping(address => bytes32) commitments;
    state bytes32 solution;

                …
}
```

FSol by example

```
contract HashPuzzleFix {
    phases [] [Commit, Reveal];
    state address winner = None;
    state mapping(address => bytes32) commitments;
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            function commit(bytes32 commitment) [Commit] {
            commitments[msg.sender] = commitment;
        }
            …
}
```

FSol by example

```
contract HashPuzzleFix {
    phases [] [Commit, Reveal];
    state address winner;
    state mapping(address => bytes32) commitments;
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        function commit(bytes32 commitment) [Commit] {
                commitments[msg.sender] = commitment;
        }

                function reveal(bytes32 res) [Reveal] {
                require(winner == None);
                require(hash(res) == sol);

                …
        }
}
```

Compiling FSol to Solidity

```
function reveal(bytes32 res) [Reveal] {
    require(winner == None);
    require(hash(res) == sol);

    winner = msg.sender;
    payable(msg.sender)
            .transfer(this.balance);
}
```

Function in FSol

Annotation-based translation

```
/// @custom:symex public-function
/// @custom:symex phase-indicator Reveal
/// @custom:symex safe-input-args 1
/// @custom:symex mapping none
function reveal(bytes32 res) public {
        /// injected function
    require(phase == Reveal);

    require(winner == address(0));
    require(hash(res) == sol);

    winner = msg.sender;

        payable(msg.sender)
                .transfer(this.balance);
}
```

Translated function in Solidity

Program analysis:

computing commutativity conditions

Goal: precompute commuting states

Step 1: symbolically execute each function to encode **state updates**

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function reveal(bytes32 res) [Reveal] {
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}
```

Function in FSol


```
winner ↦
        If(And(
                hash(res) == solution,
                winner == None,
                phase == Reveal),
           sender,
           winner)
```

*Symbolic summary for **reveal***

Goal: precompute commuting states

Step 2: symbolically execute each pair of smart contract's functions to encode **sequential state updates**.

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Similar to step 1 by reusing computed function summaries.

Goal: precompute commuting states

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- Have: state updates of **f; g** for all functions **f, g** of a smart contract.

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$$\forall \psi \in CC_{\alpha,\beta}.\ \forall \Gamma.\ \psi(\Gamma) \implies \mathbf{Comm}(\Gamma, \alpha, \beta)$$

Goal: precompute commuting states

- Current approach: use **counterexample-guided abstraction refinement [4].**
- Refine the conditions for commutativity.
- The **Servois2 [5]** tool implements it, with heuristic for smaller conditions.

[4] Clarke, E., Grumberg, O., Jha, S., Lu, Y., Veith, H. (2000). Counterexample-Guided Abstraction Refinement . In: Emerson, E.A., Sistla, A.P. (eds) Computer Aided Verification. CAV 2000. Lecture Notes in Computer Science, vol 1855. Springer, Berlin, Heidelberg
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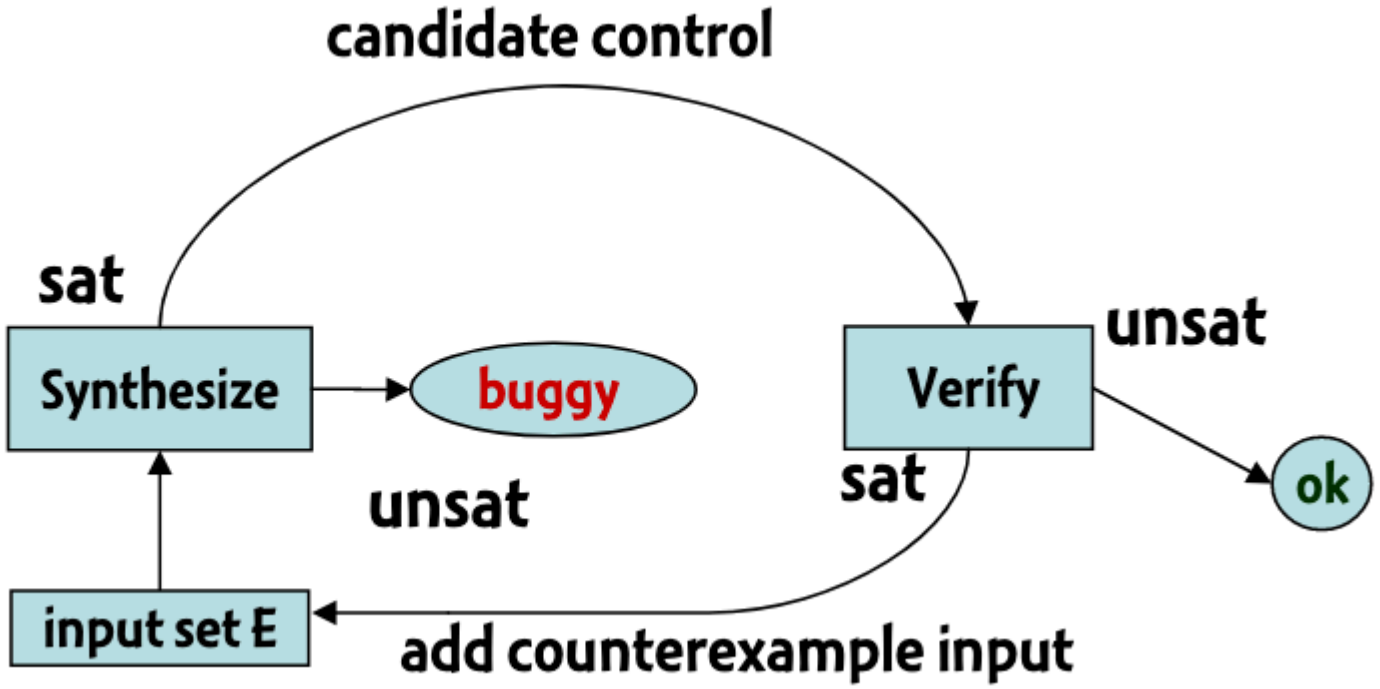

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Commutativity conditions generation

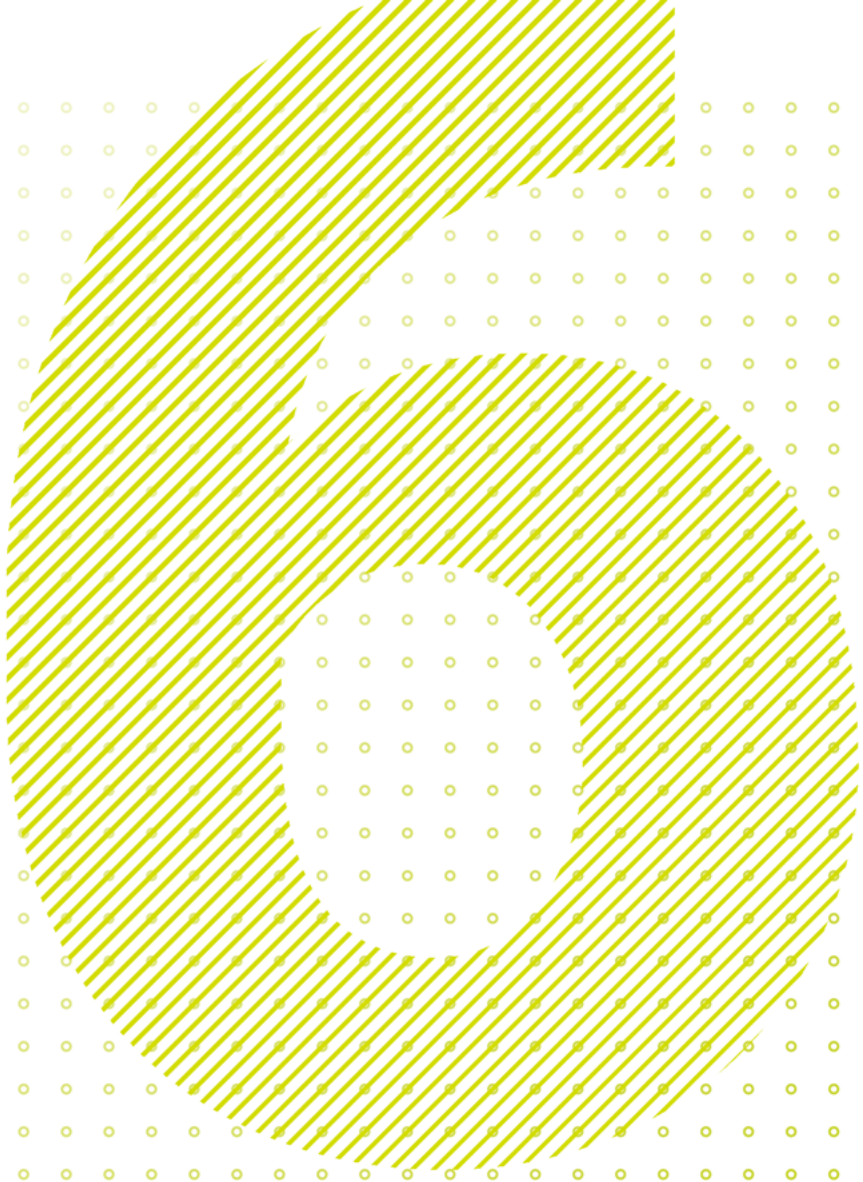
- *HashPuzzle* commutativity conditions for **(solve, solve)** pair are:

```
contract HashPuzzle {
    bytes32 public challenge;
    address public winner;
    function solve(bytes32 solution) {
        require(
                        sha256(solution) == challenge);
                payable(msg.sender)
                        .transfer(this.balance);
        this.winner = msg.sender;
    }
}
```

*Vulnerable **HashPuzzle** smart contract.*

```
(or (= attackerAddress honestAddress)
    (not (= winner None))
    (= attackerAddress None)
    (= honestAddress None)
    (not (= challenge
            (sha256 solution_honest))))
    (not (= challenge
            (sha256 solution_attacker)))))
```

*Conditions on initial state, under which function pair **solve, solve** commutes.*



Protocol analysis using Tamarin

Goal: construct conforming traces

Property

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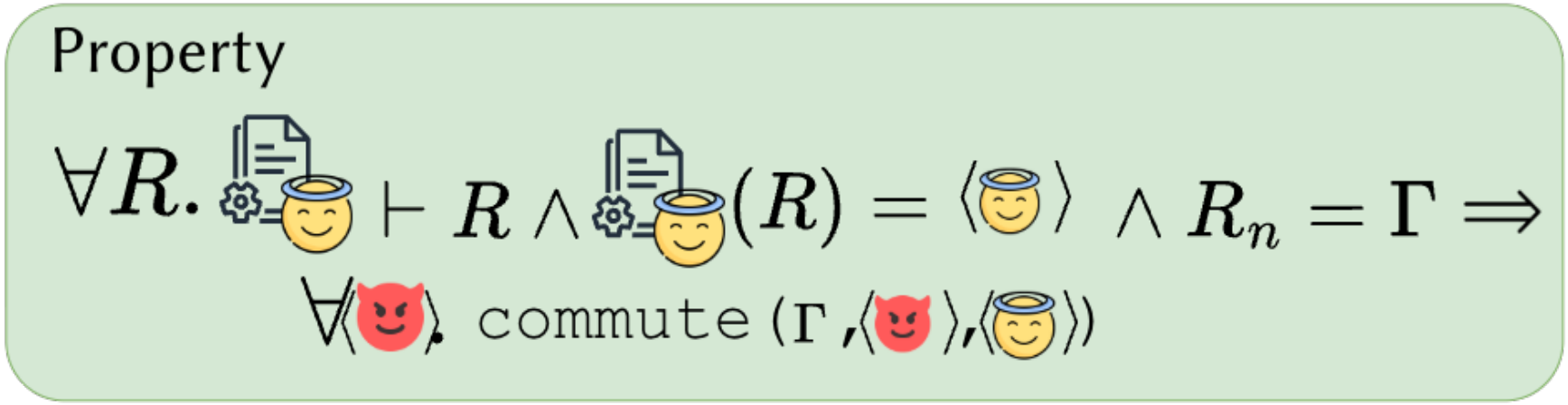
- So far: we have sound approximation of commuting states.



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- Now: use protocol analysis tools to construct traces that *conform to honest user protocol.*

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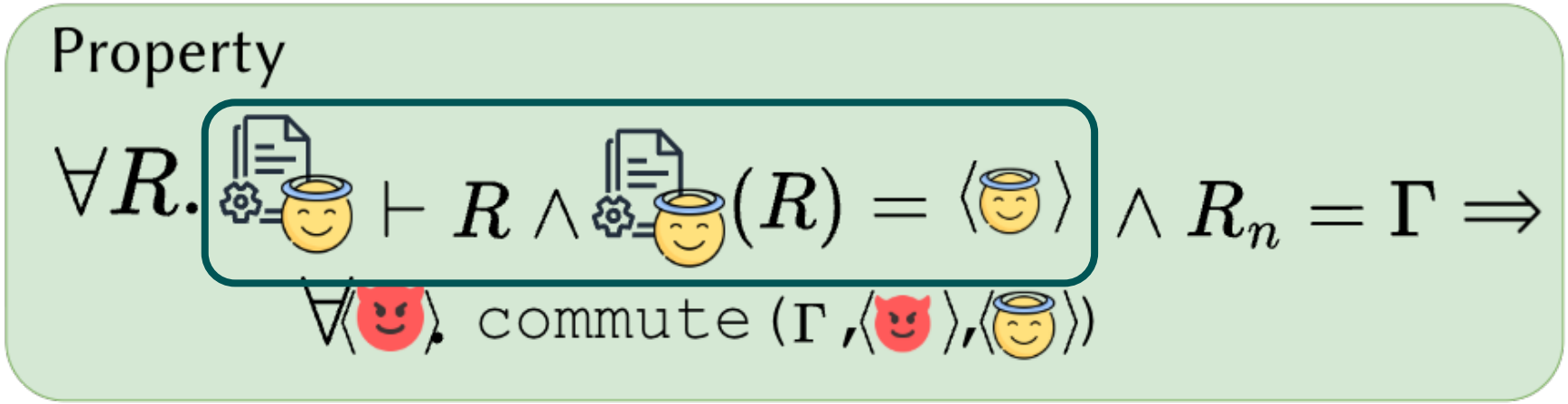
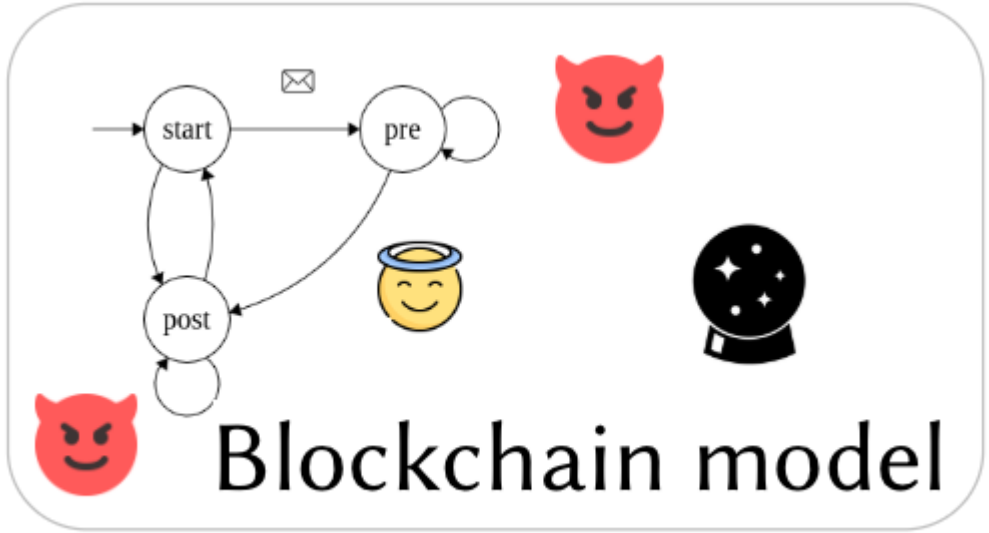
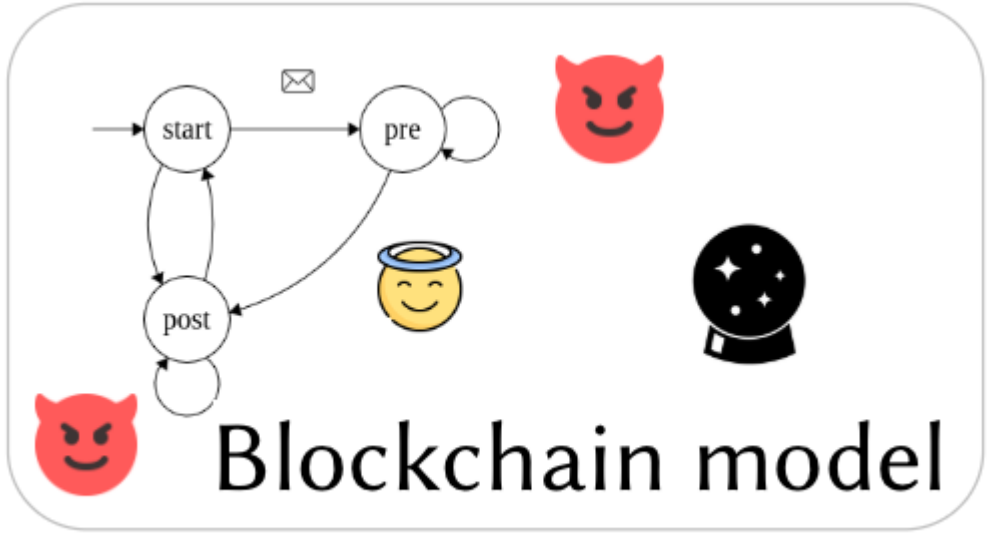


Blockchain model



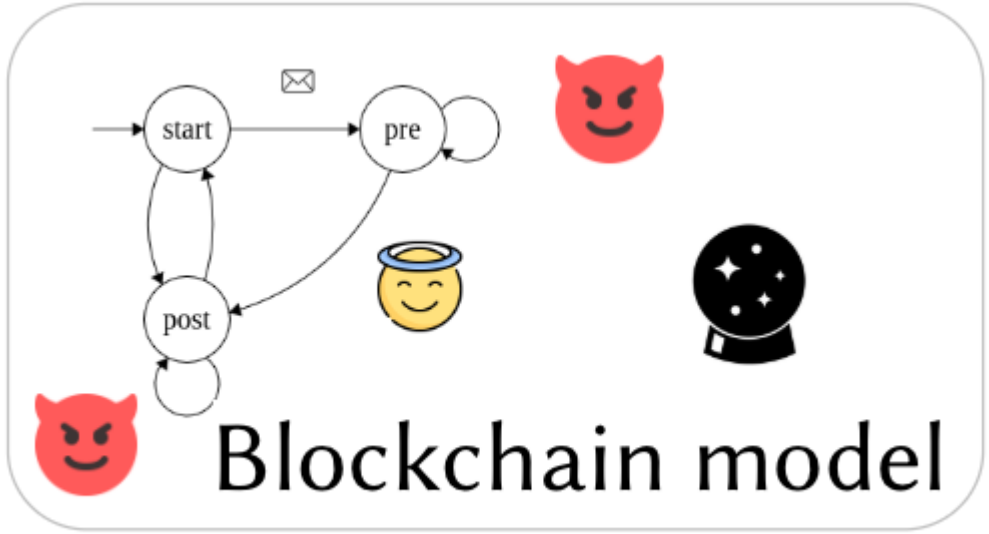
Blockchain model

- We provide a model of blockchain in Tamarin. We assume a **phase-based execution** in it.



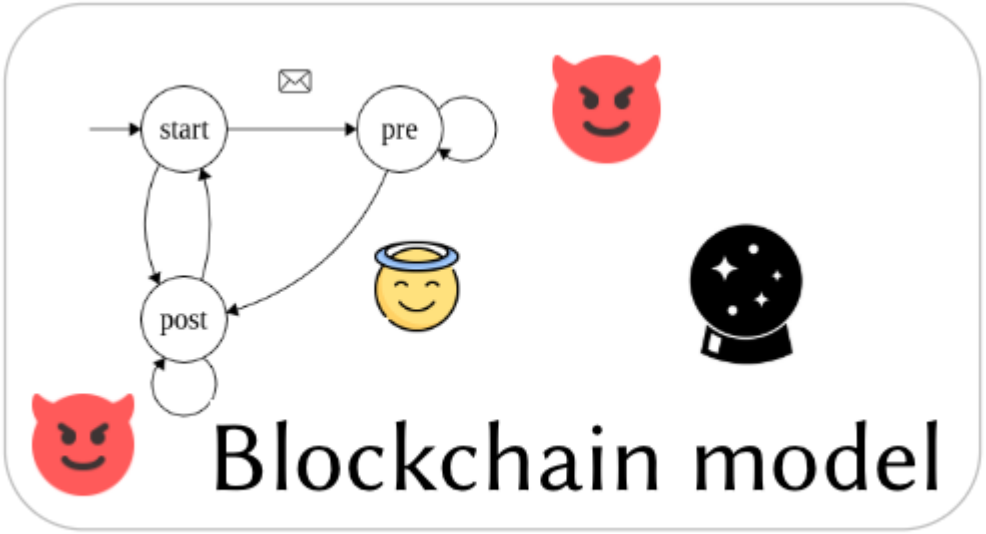
Blockchain model

- We provide a model of blockchain in Tamarin. We assume a **phase-based execution** in it.
- With phases, honest users only do one action per phase, and then wait until this action is executed on blockchain.

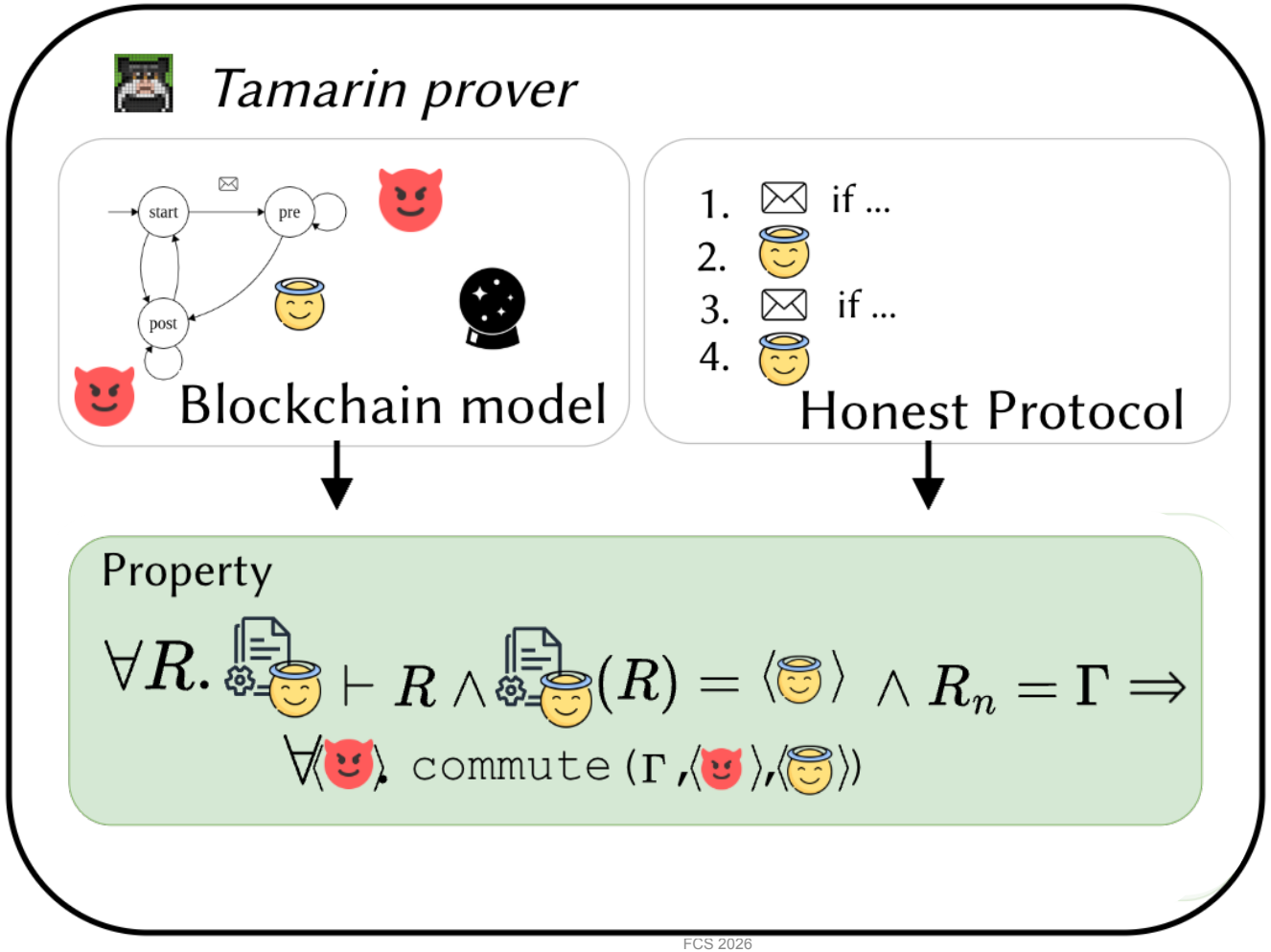


Honest user protocol

- We embed the provided honest user protocol to the blockchain model.
- The honest user protocol defines when the trace conforms to the trace.

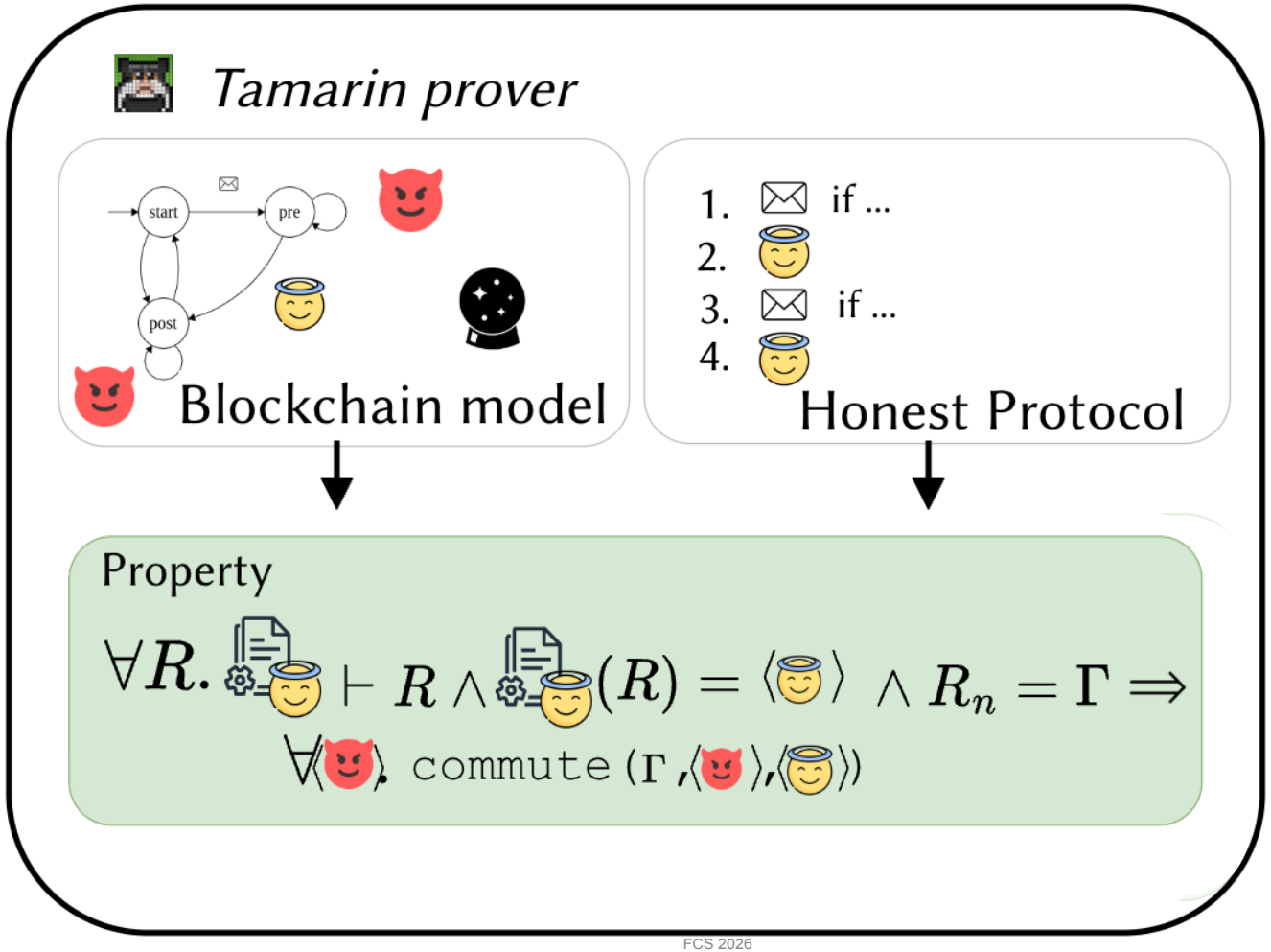


Query verification

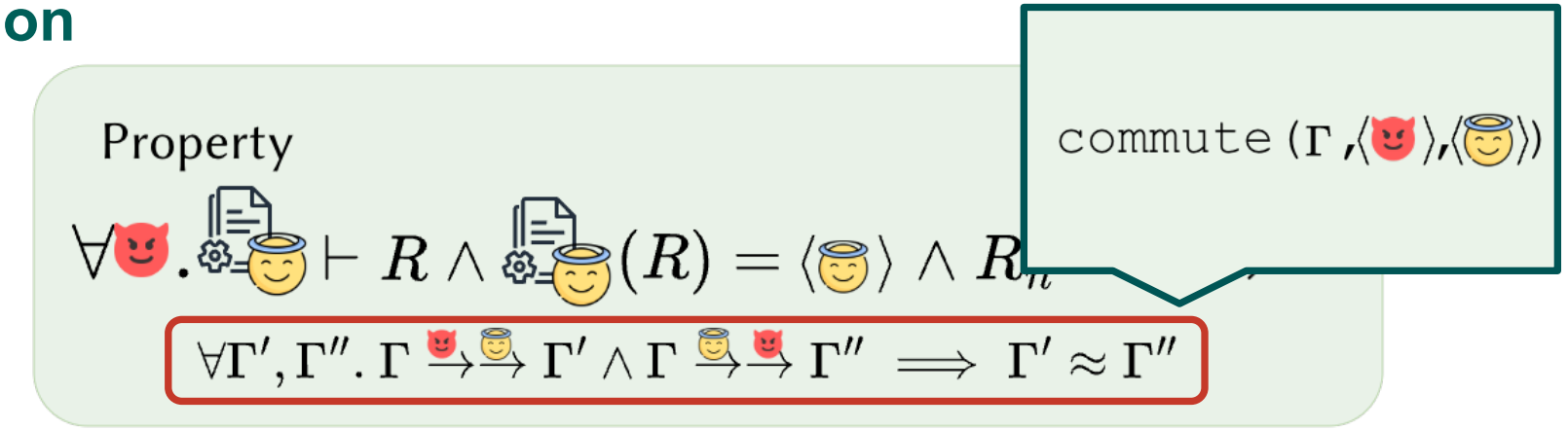


Query verification

- Lastly, we use the pre-computed commutativity conditions to check frontrunning resistance.



Conclusion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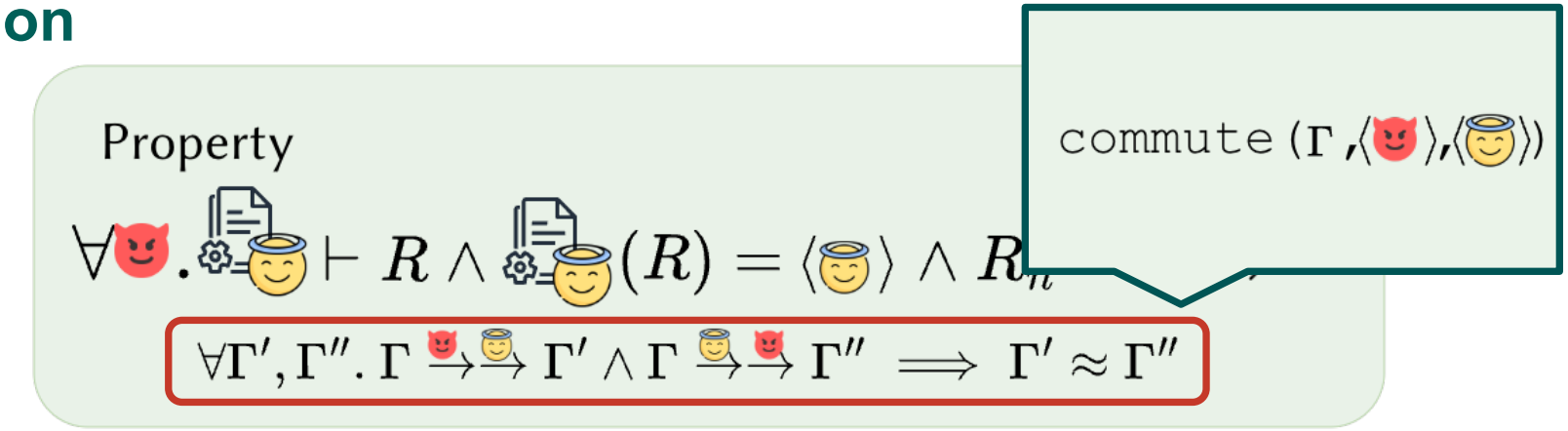
$\forall \Gamma', \Gamma''. \Gamma \overset{😈}{\rightarrow}\overset{😇}{\rightarrow} \Gamma' \wedge \Gamma \overset{😇}{\rightarrow}\overset{😈}{\rightarrow} \Gamma'' \implies \Gamma' \approx \Gamma''$

Conclusion



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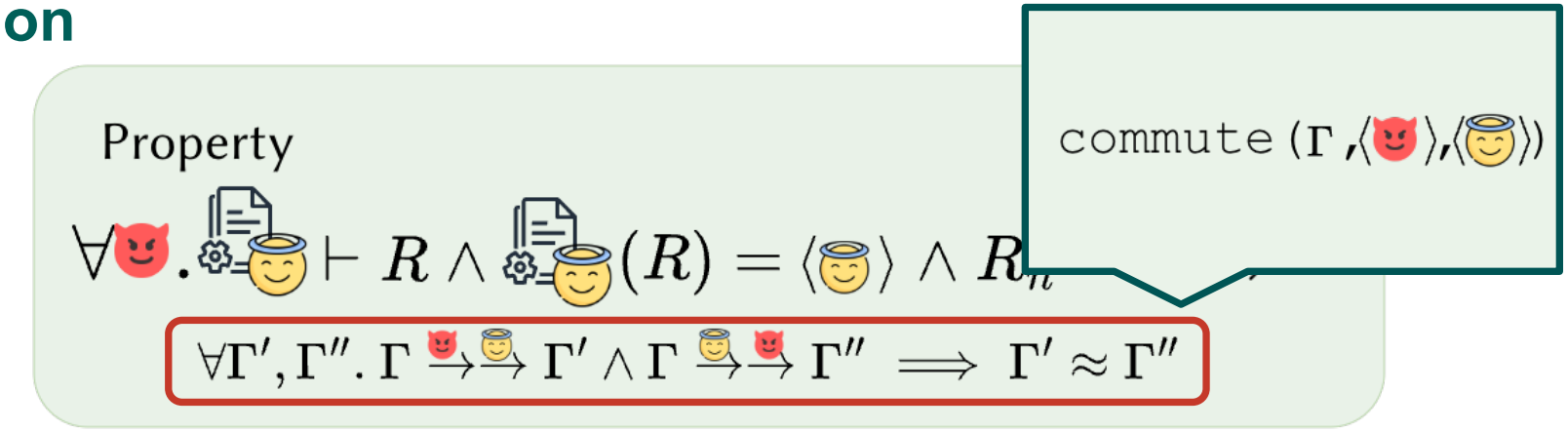
Conclusion



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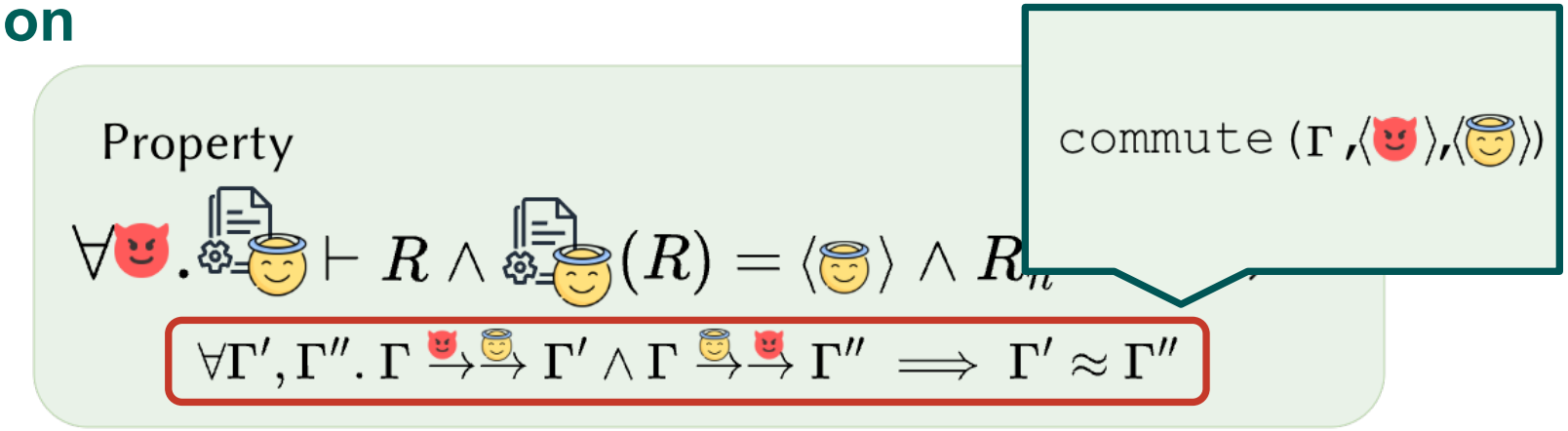
Conclusion



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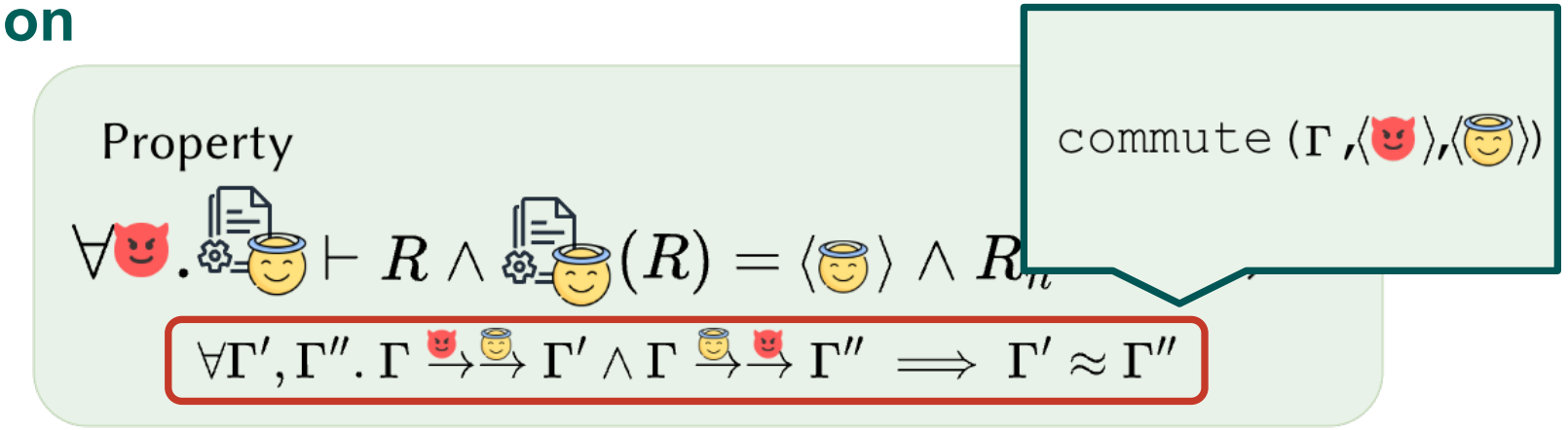

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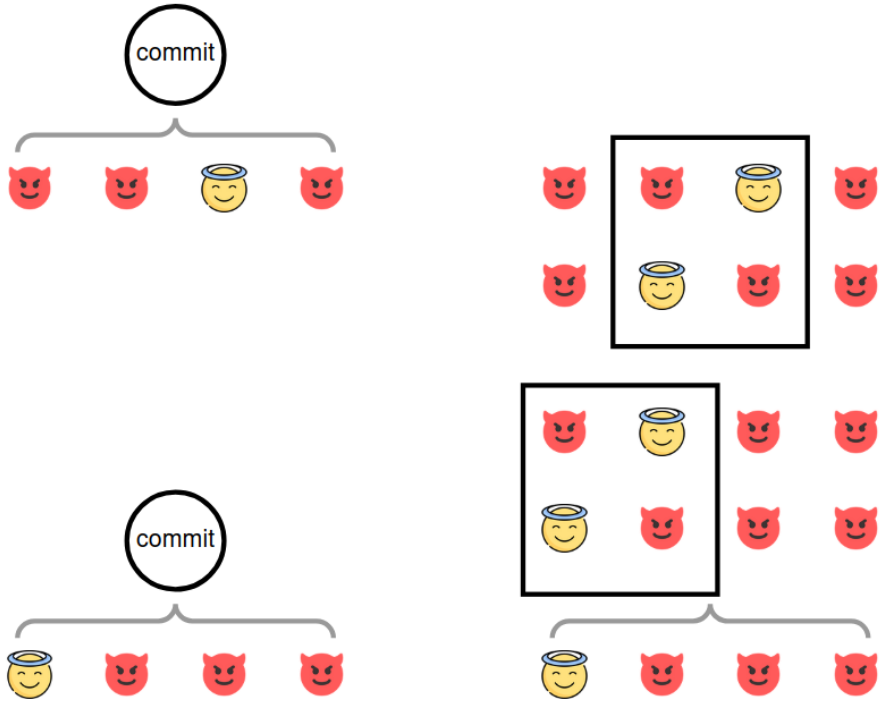
Thank you!

If you have further questions or want to collaborate, contact:

Email: sebastian.holler@mpi-sp.org, yan.farba@mpi-sp.org

I'm happy to connect on LinkedIn!

Backup slide: Soundness of protocol analysis



- Idea: We symbolically execute the user strategy S for every possible attacker and check that honest user transaction commutes