Interplay of Efficient Model Checking and Secure Processor Design: A Case Study on Secure Speculation

Tingzhen Dong*, Kunpeng Wang*, Yuheng Yang, Yu-Wei Fan,
Qinhan Tan, Thomas Bourgeat, Sharad Malik, Mengjia Yan

This Paper

Formally verify **security** on complex **out-of-order CPUs**

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1. **Decoupling** security and functionality can scale verification
2. New abstraction primitive **HUF**

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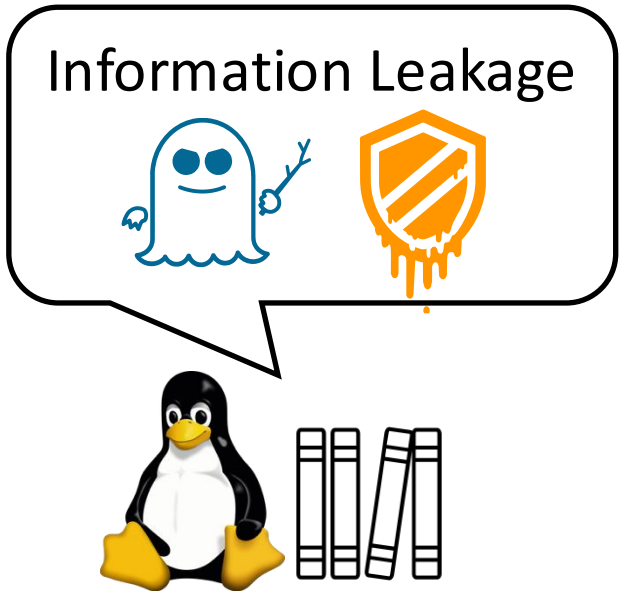
1. **Decoupling** security and functionality can scale verification
2. New abstraction primitive **HUF**

For the first time, we scale **model checking** to verifying secure speculation on **MegaBOOM**

Timing Side-Channel Security



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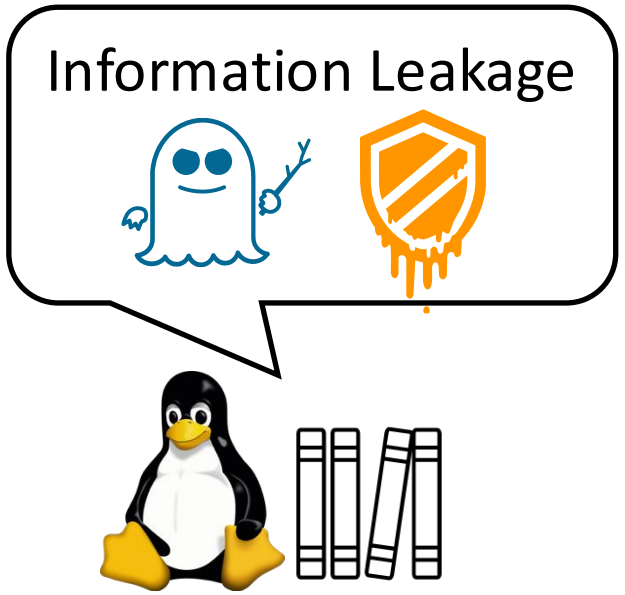

CPU + Spectre Mitigation

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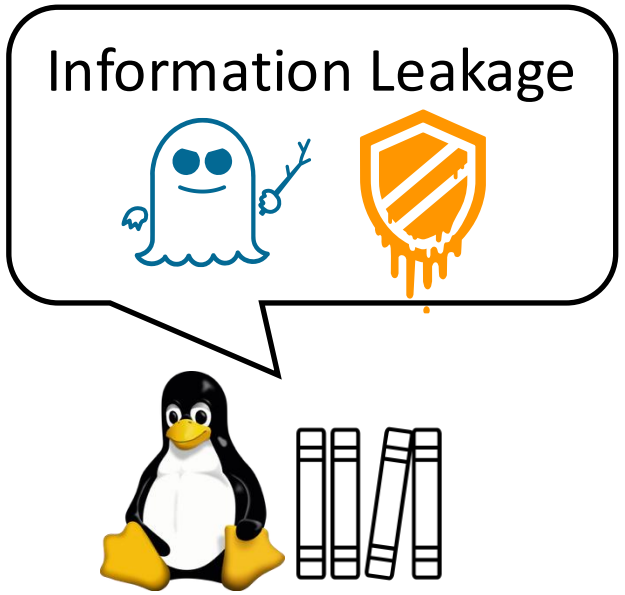

CPU + Spectre Mitigation

Mitigation works properly?
Need **formal verification**
e.g., model checking

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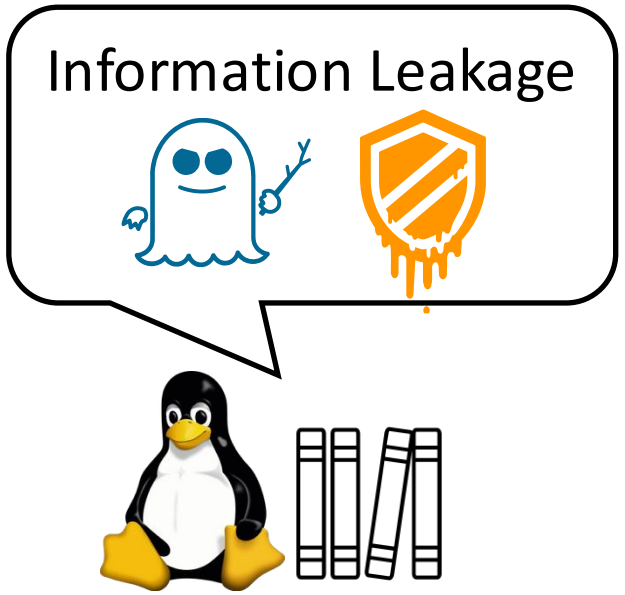

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Security Goal: Ensure no information leakage in CPU using formal verification

Scalability of Model Checker

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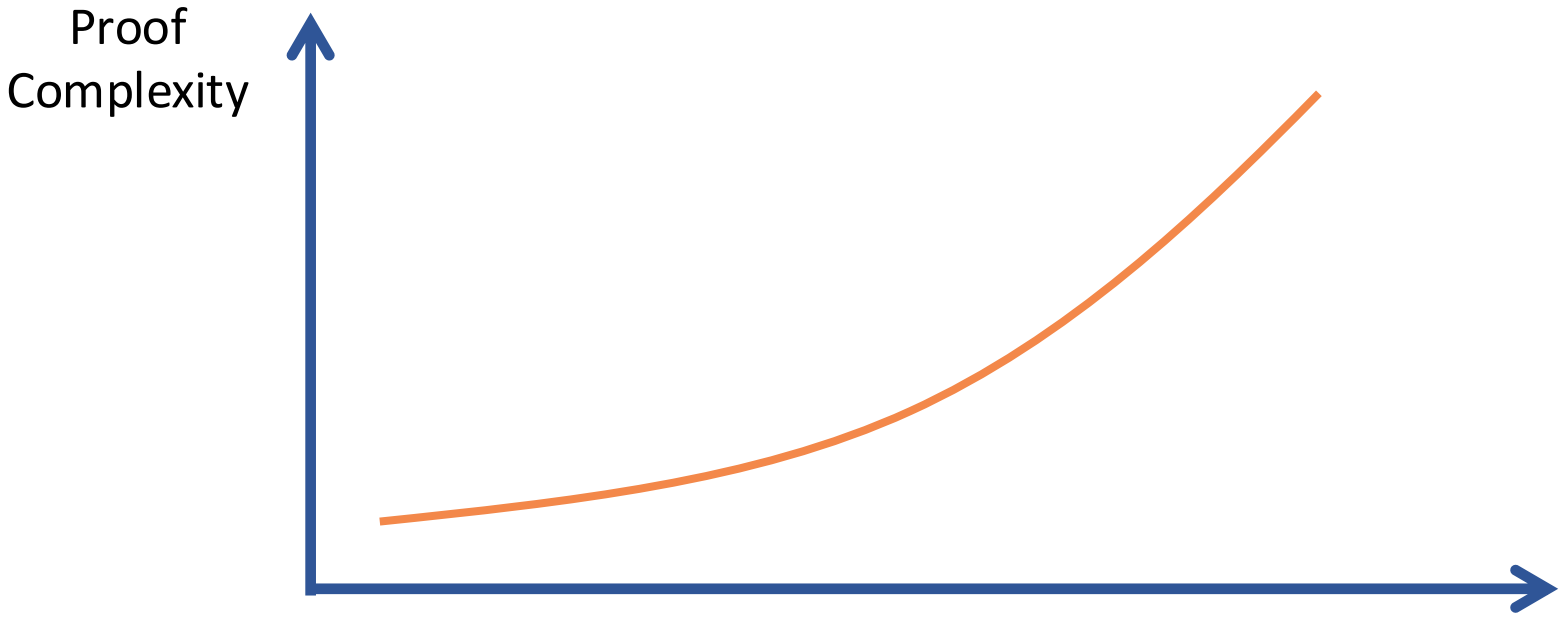

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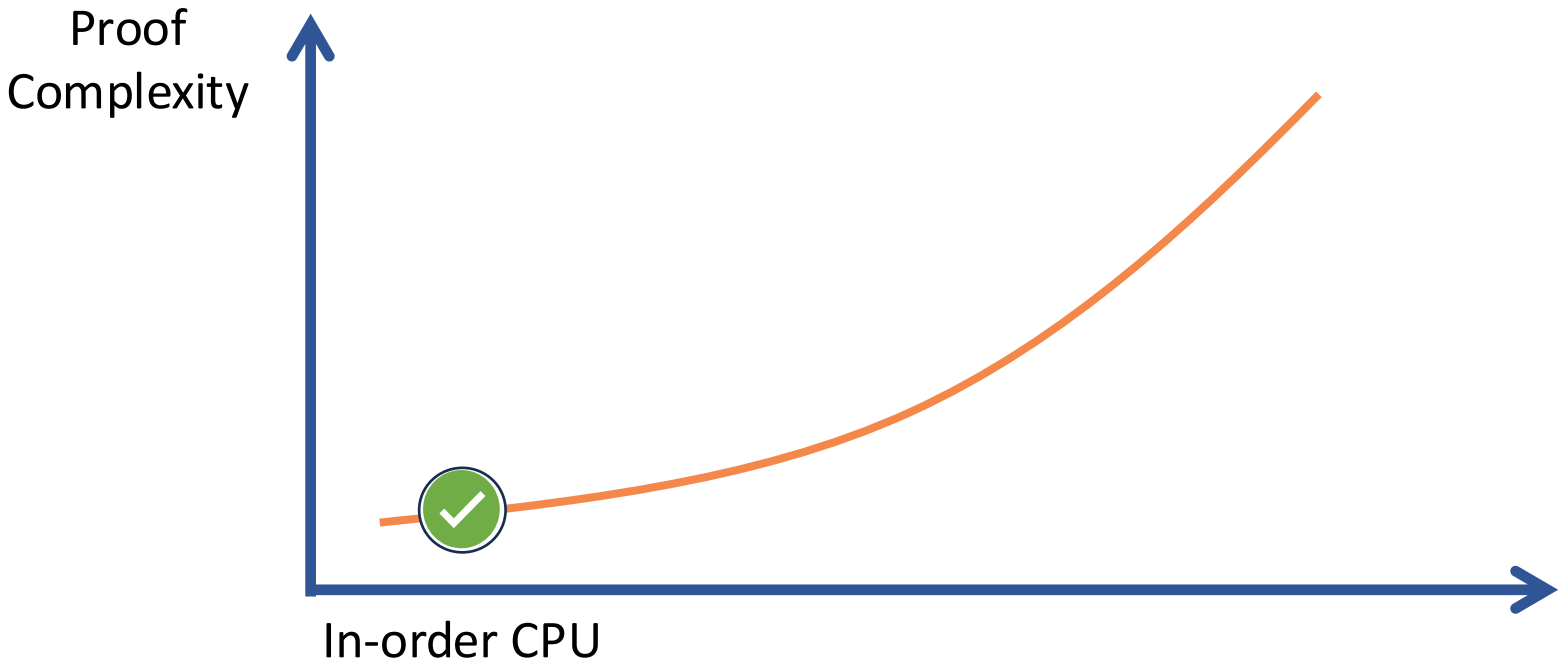

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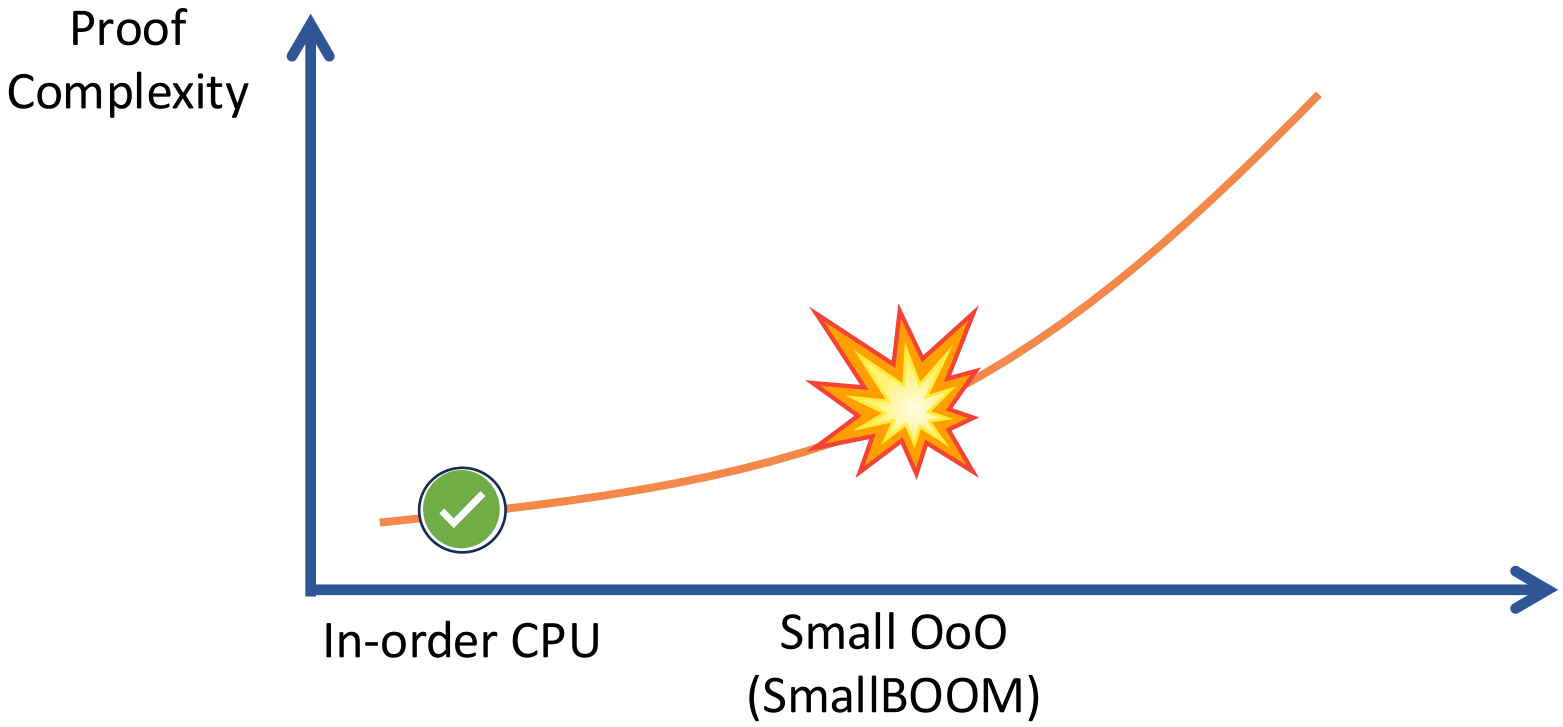

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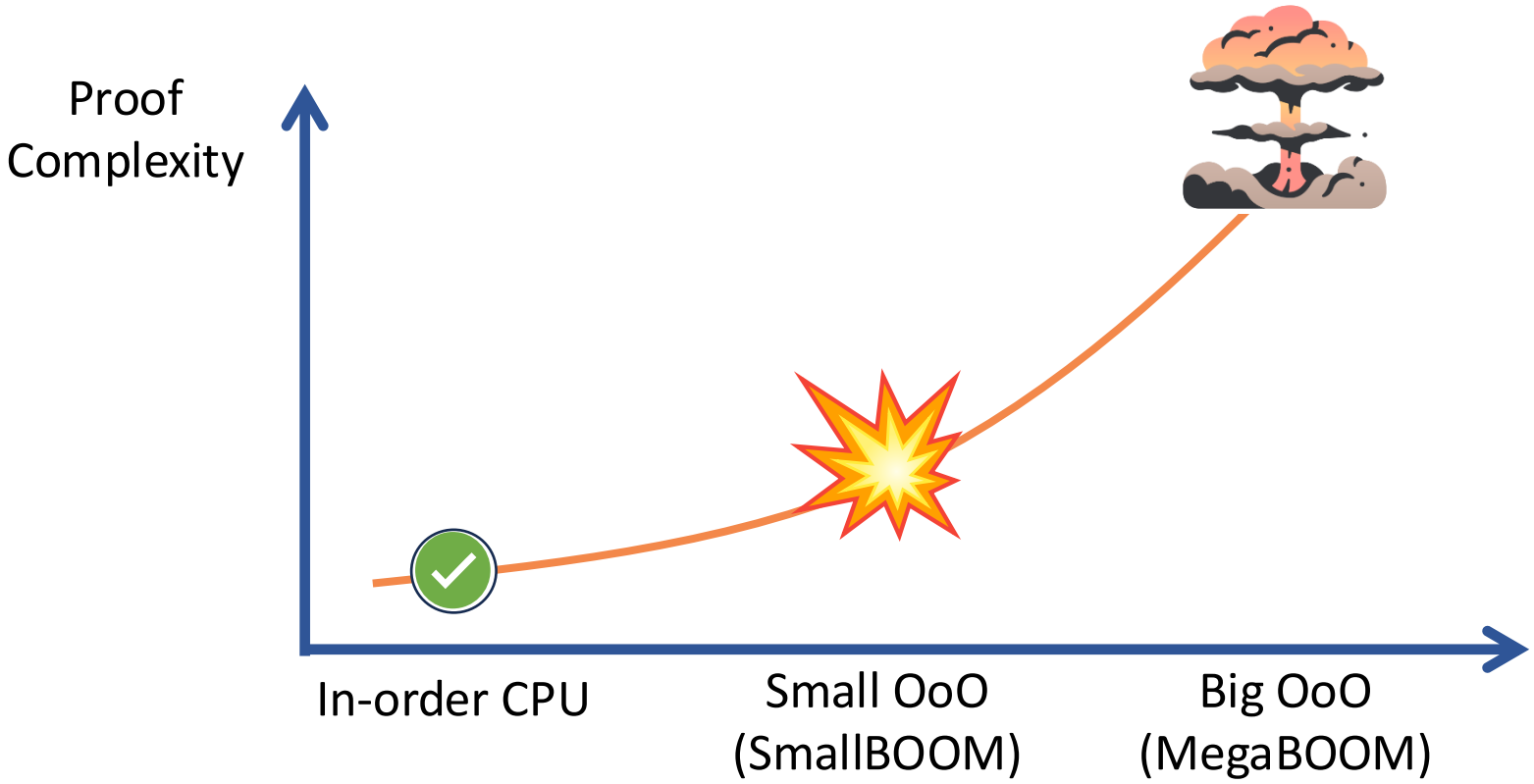

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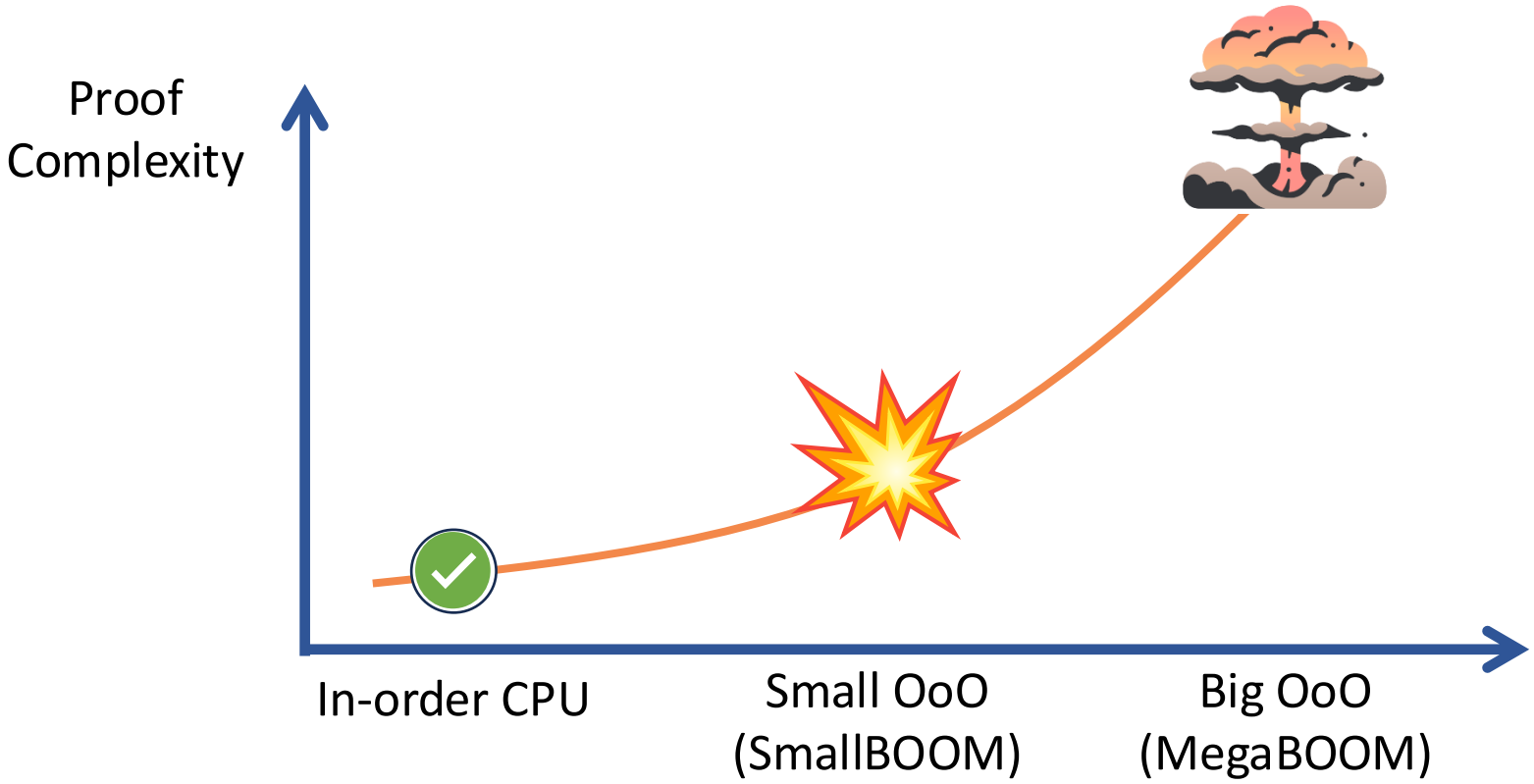

Existing model checkers do not scale to practical designs

Model Checking is a Search Problem

- Search for **invariants**

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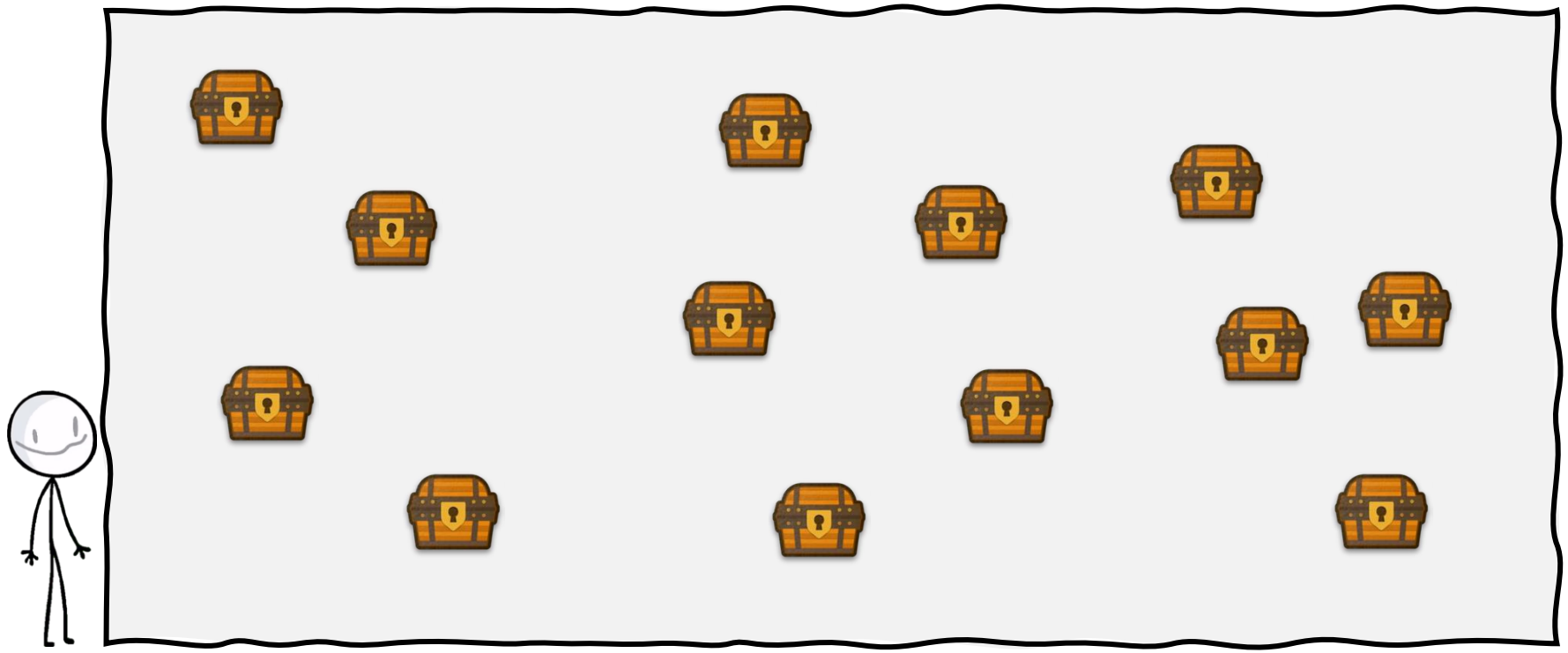

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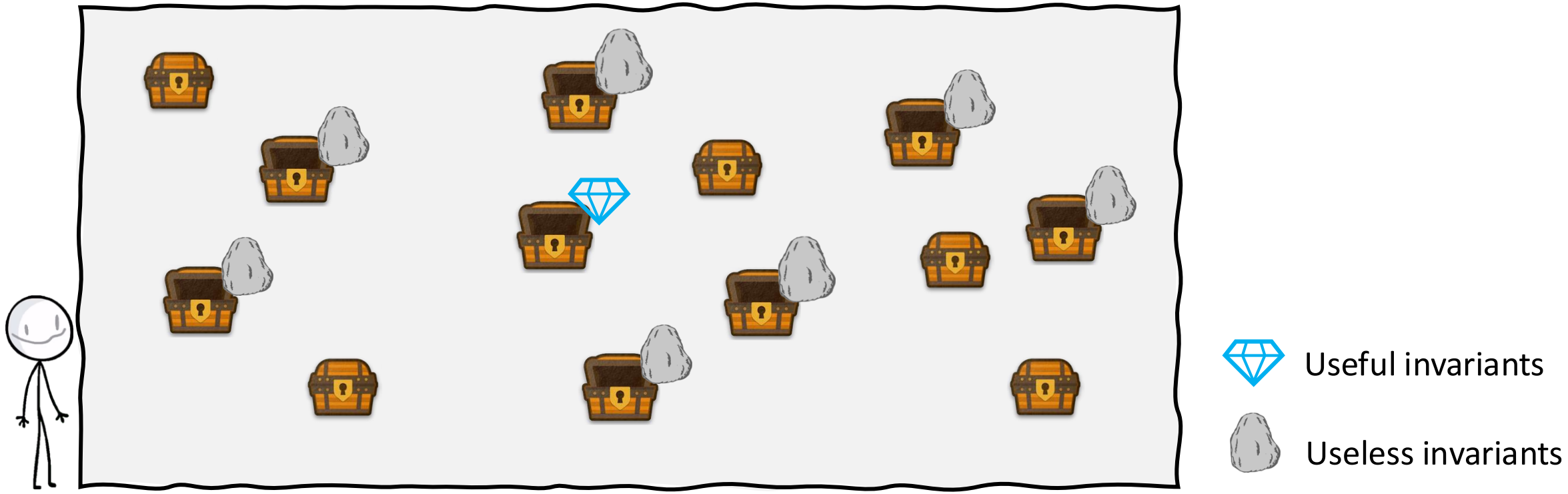

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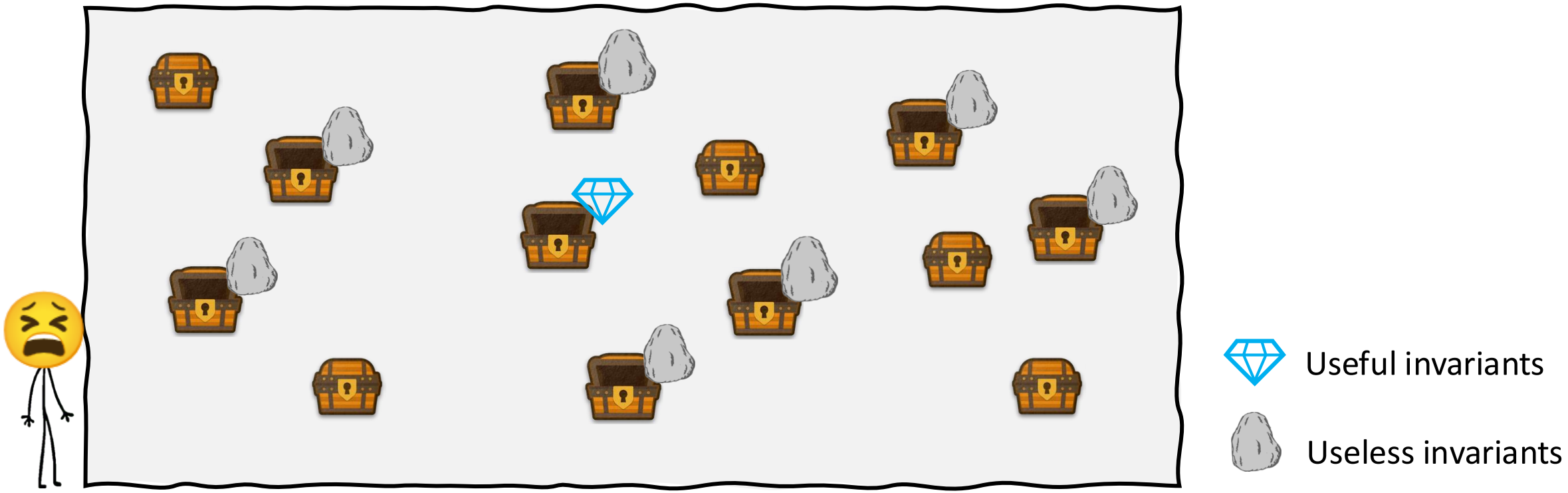

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Bottleneck of Model Checking Security

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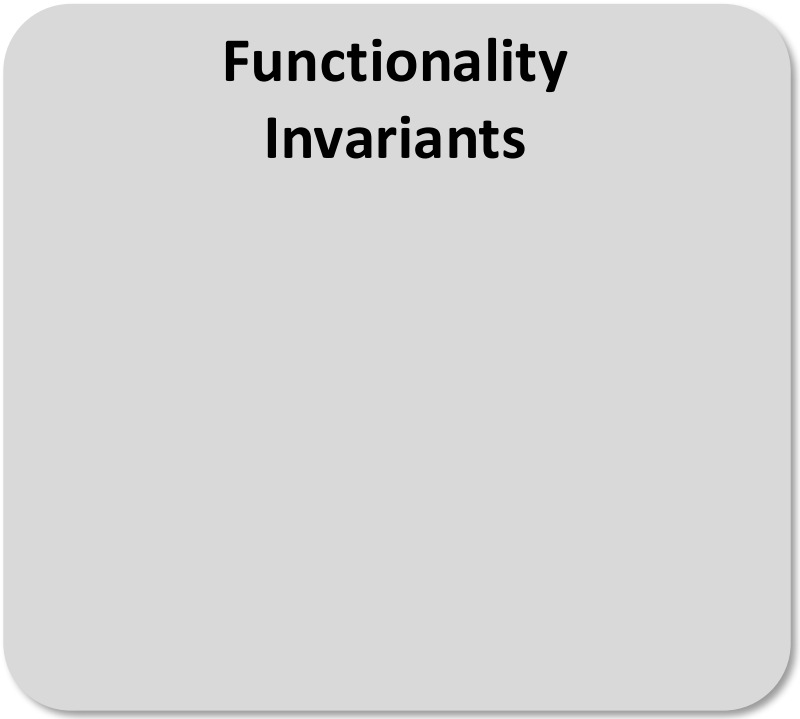

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Inside a timeout model checker: *(running rIC3 on SmallBOOM for 1 hour)*	**>70%**	**<30%**

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Our discovery: Model checking wastes time in **functionality** facts that are **unnecessary** for security

Key Contributions

Our Insight:

Decoupling security and functionality can scale verification

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New abstraction primitive **HUF**

- abstract irrelevant functionality
- preserve necessary information flow

Abstraction Guides Model Checking

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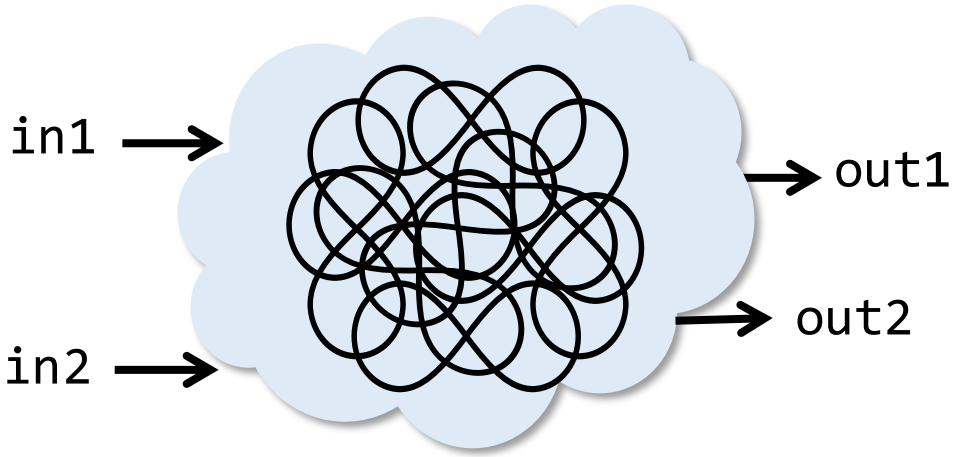
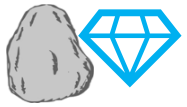
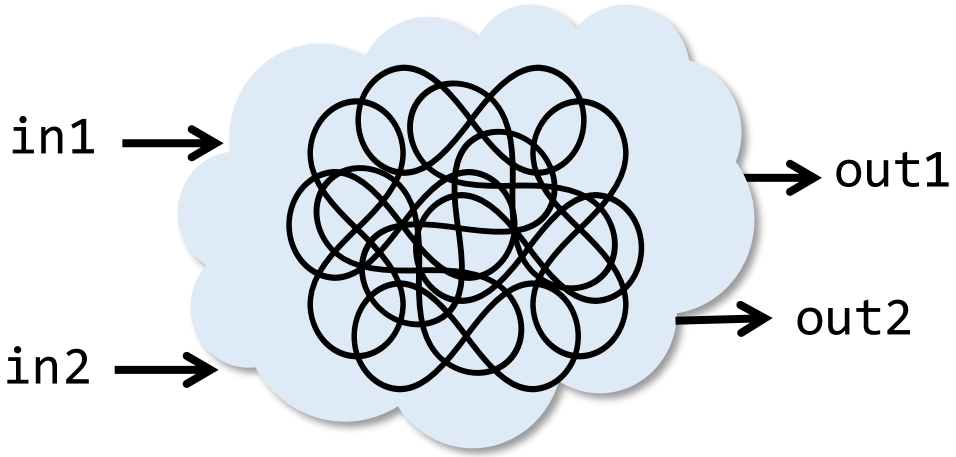
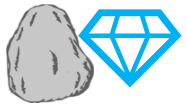


Concrete: complete functionality 

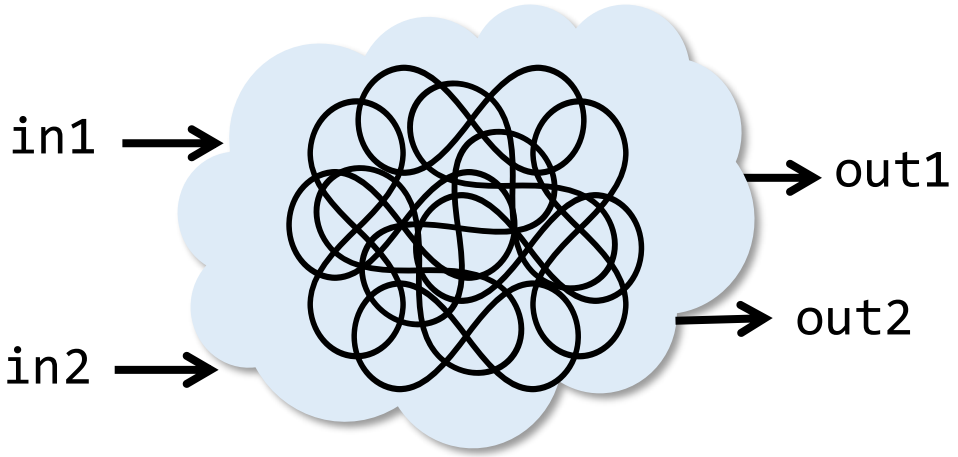
Abstraction Guides Model Checking

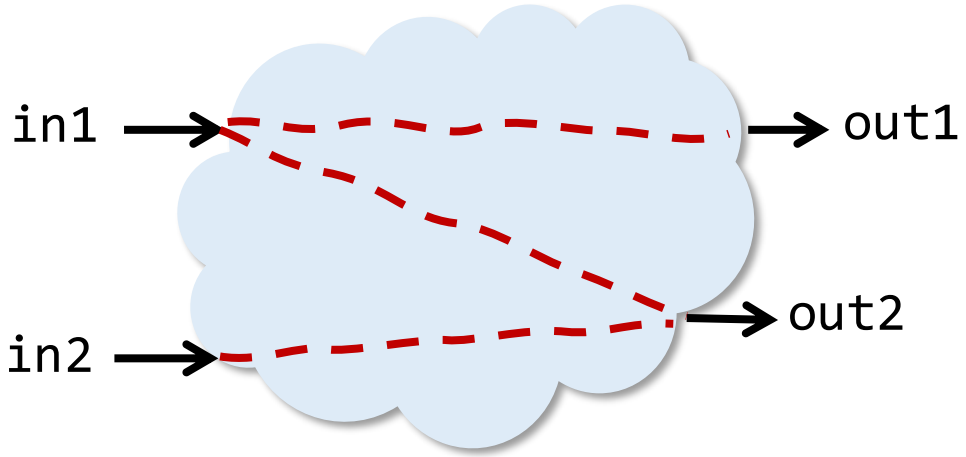


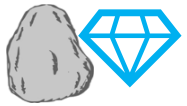
Concrete: complete functionality 

“how inputs influence outputs”

Abstraction Guides Model Checking



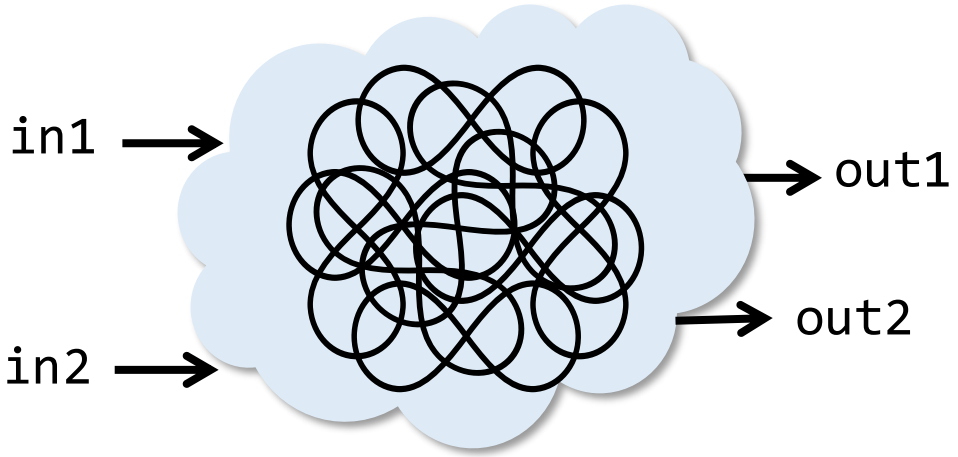


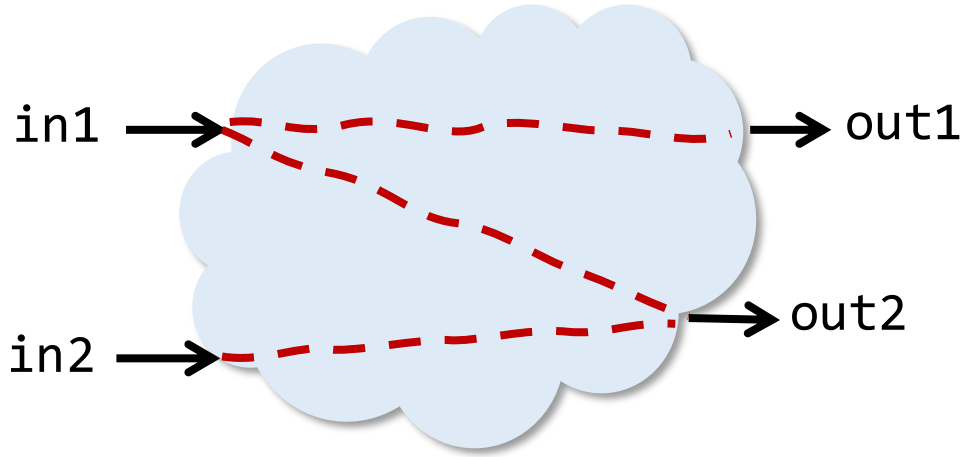
Concrete: complete functionality 

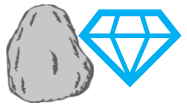
Abstracted: information-flow only 

“how inputs influence outputs”

Abstraction Guides Model Checking





Concrete: complete functionality 

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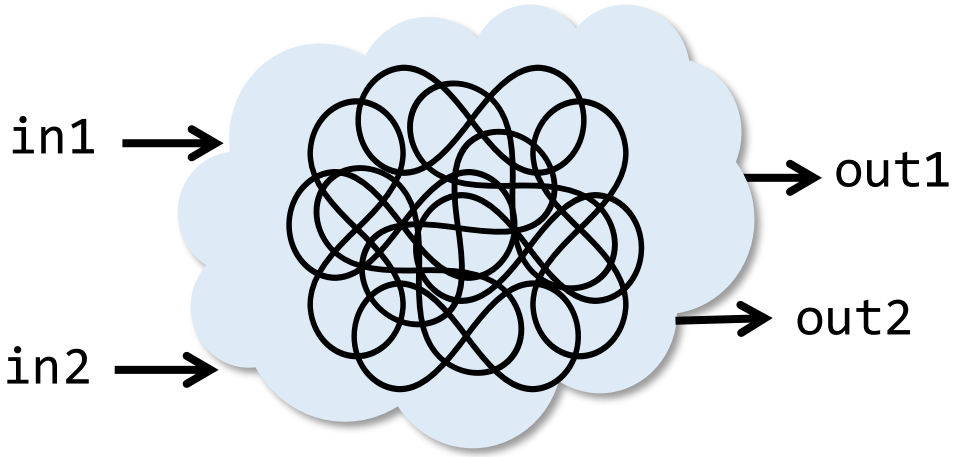
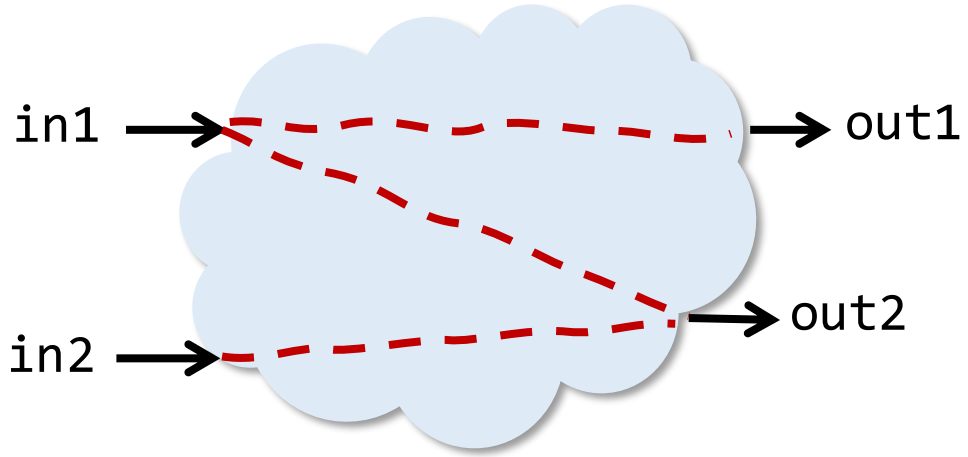
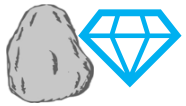
“how inputs influence outputs”

“whether inputs influence outputs”

Abstraction Guides Model Checking





Concrete: complete functionality 

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"how inputs influence outputs"

"whether inputs influence outputs"

Abstraction removes functionality to promote information-flow studying

Proof Construction: Self-Composition

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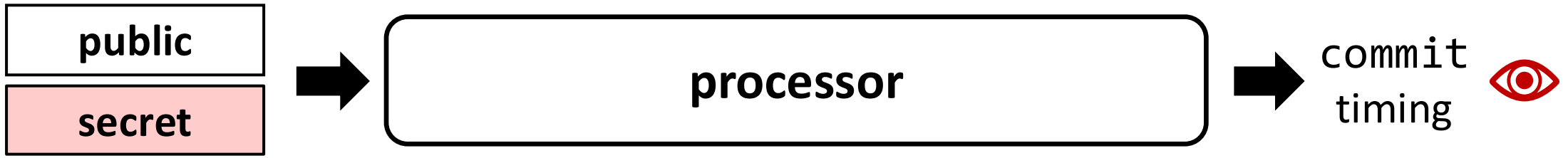

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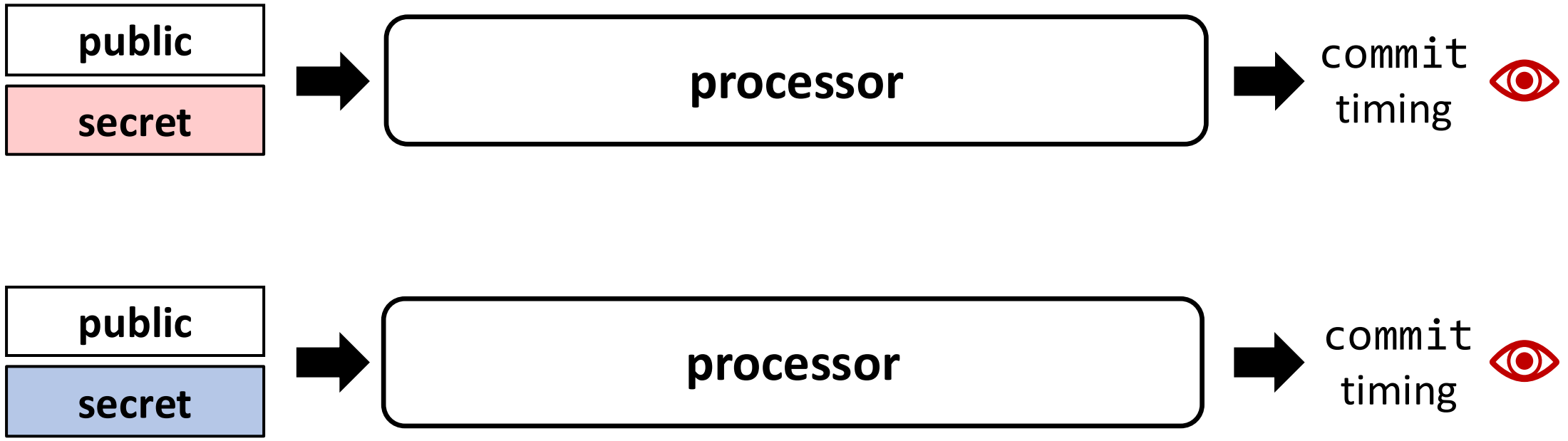

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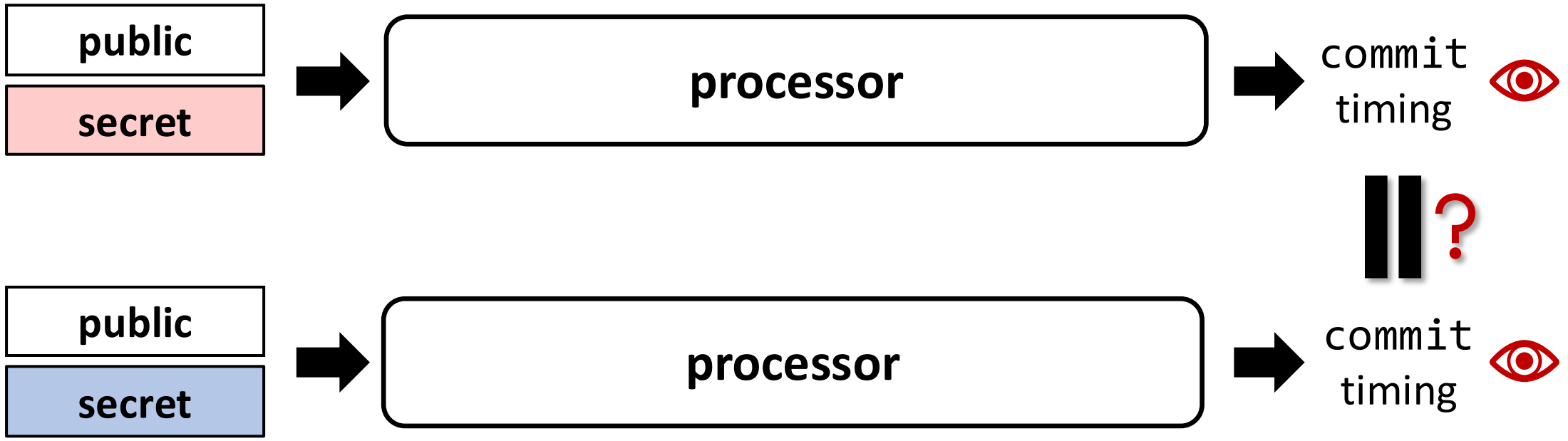

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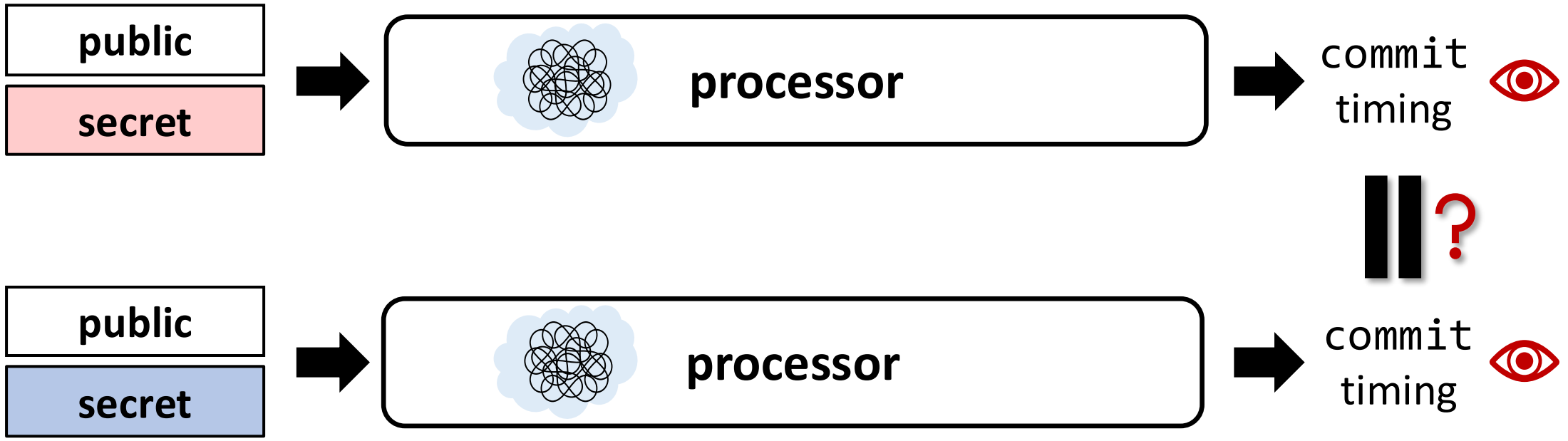
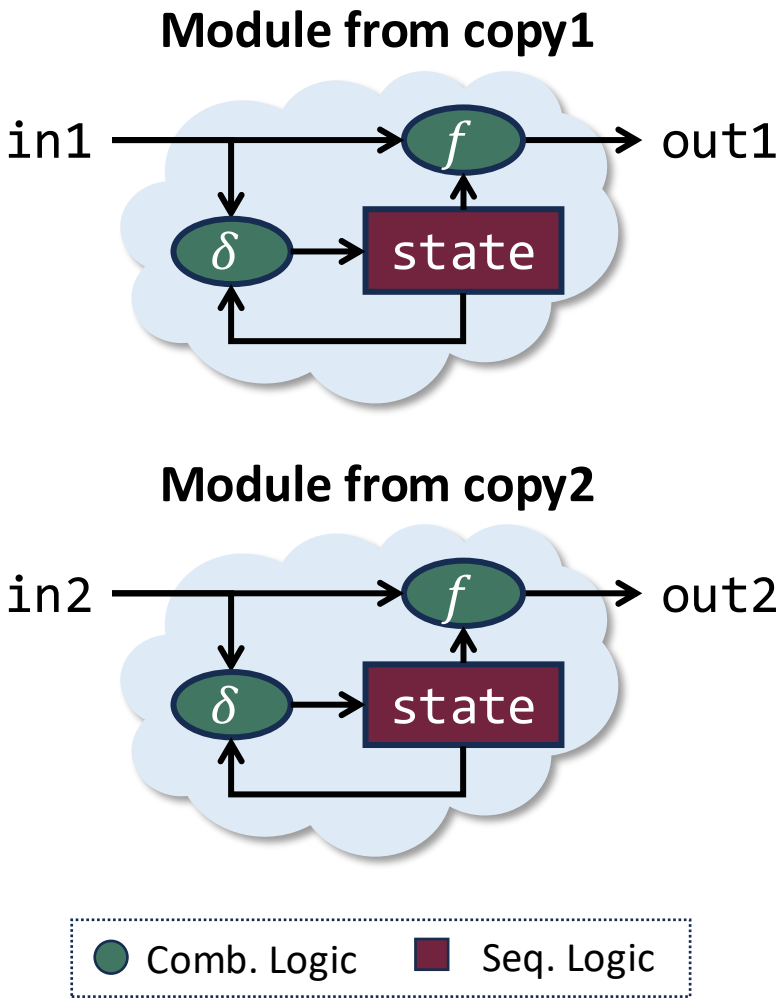


HUF Abstracts Sequential Modules



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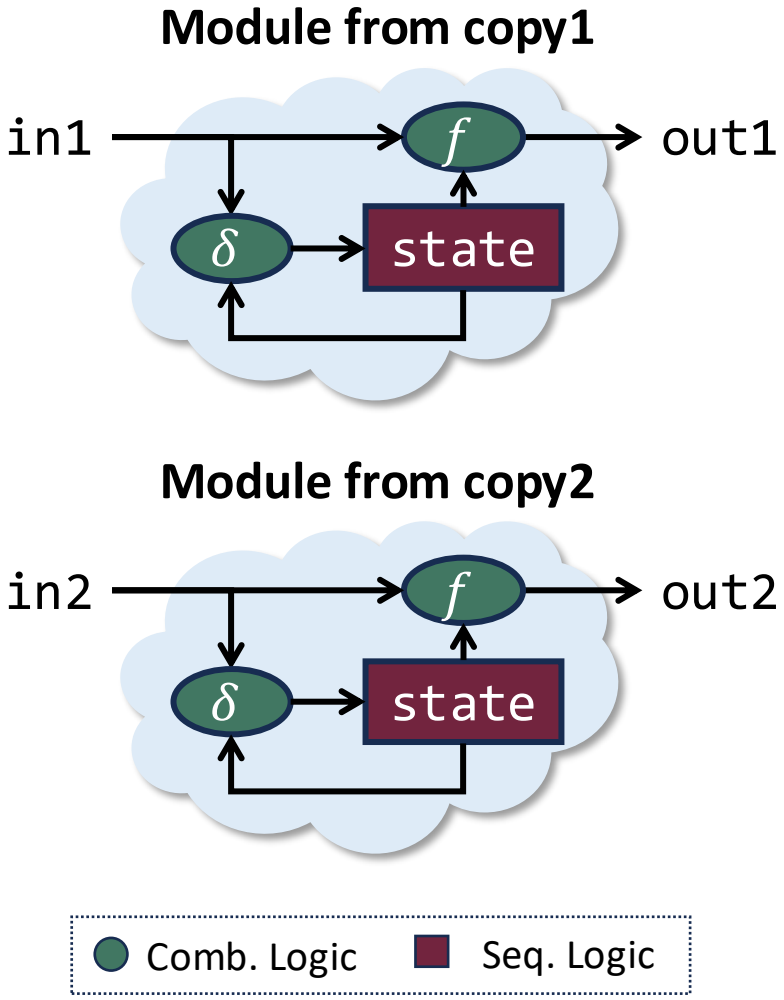

Goal of HUF

1. model **whether** `in` influences `out`
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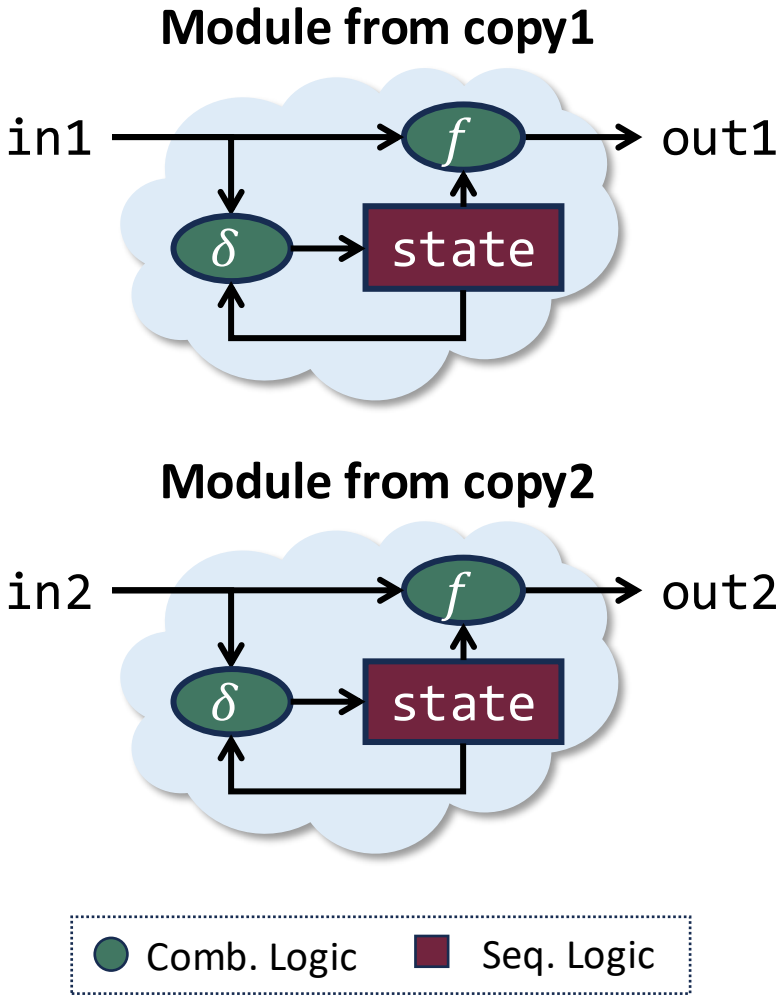

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Outputs must be equal,
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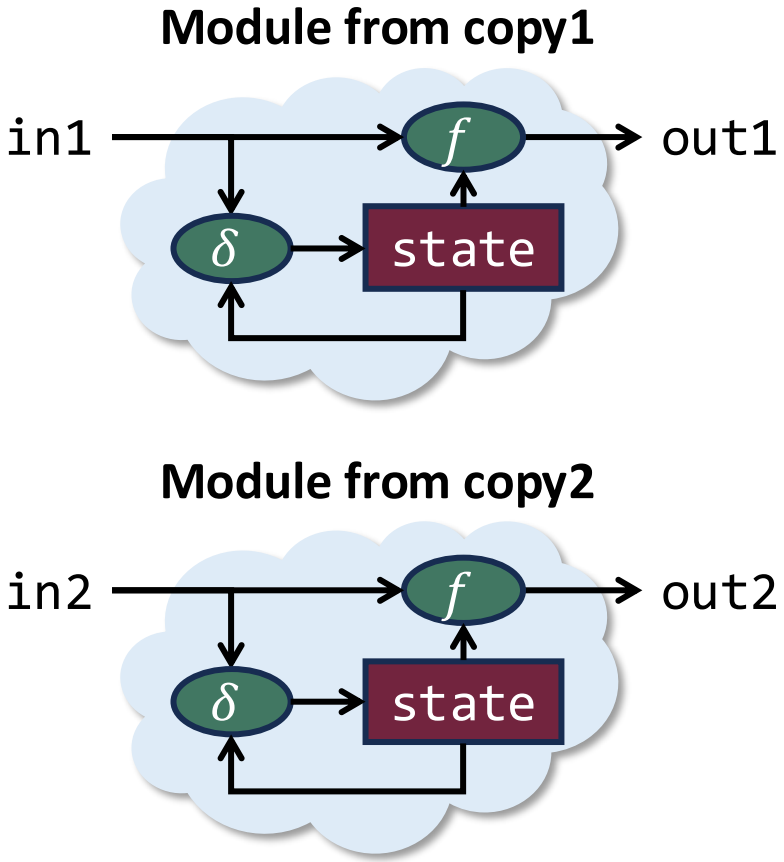

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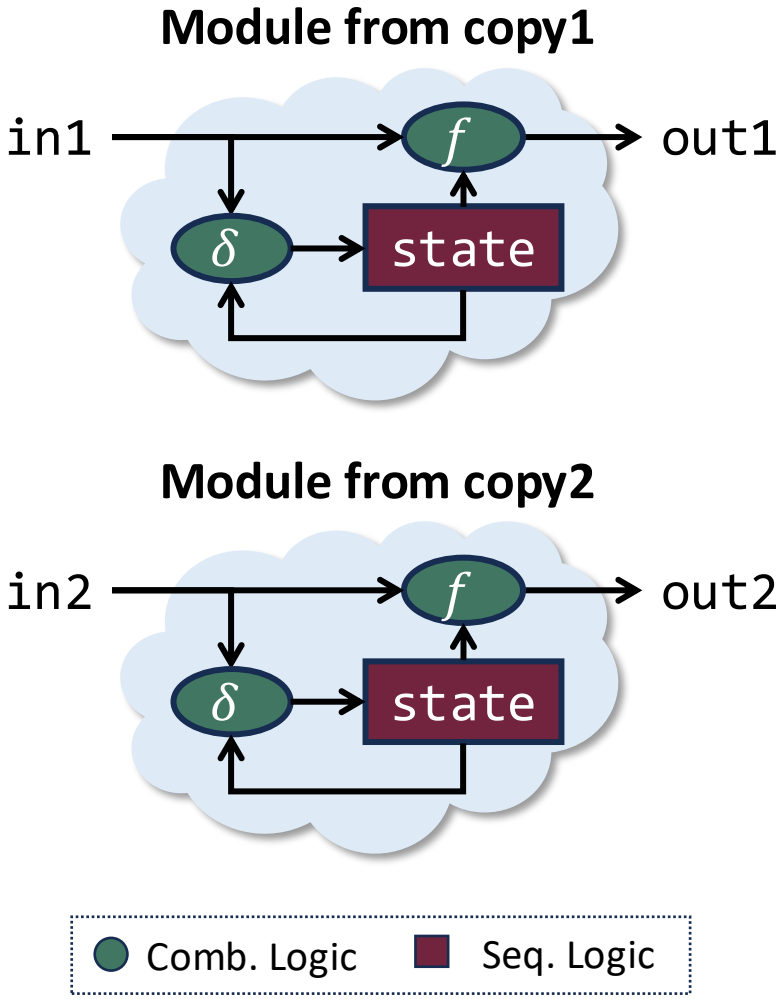

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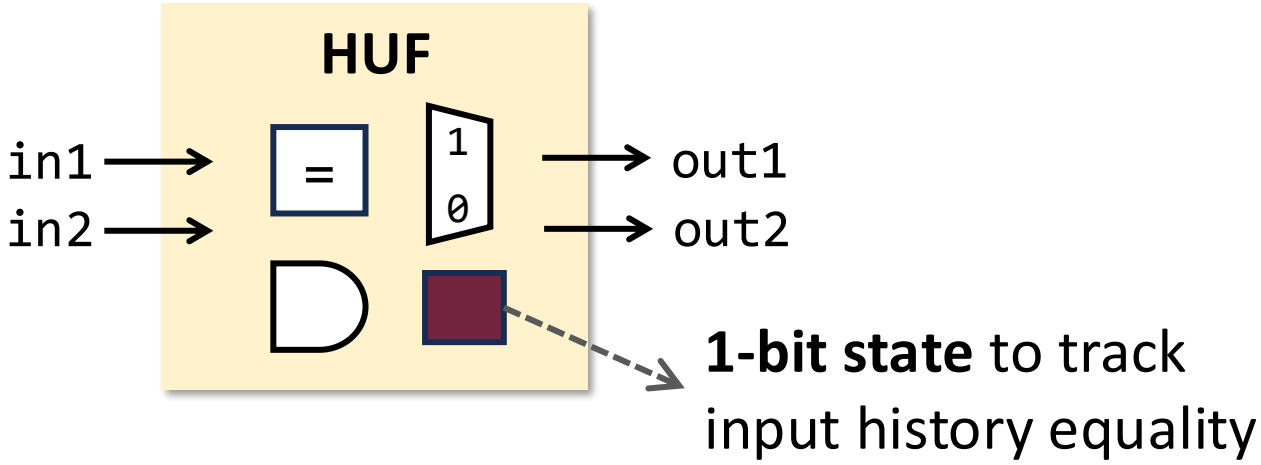

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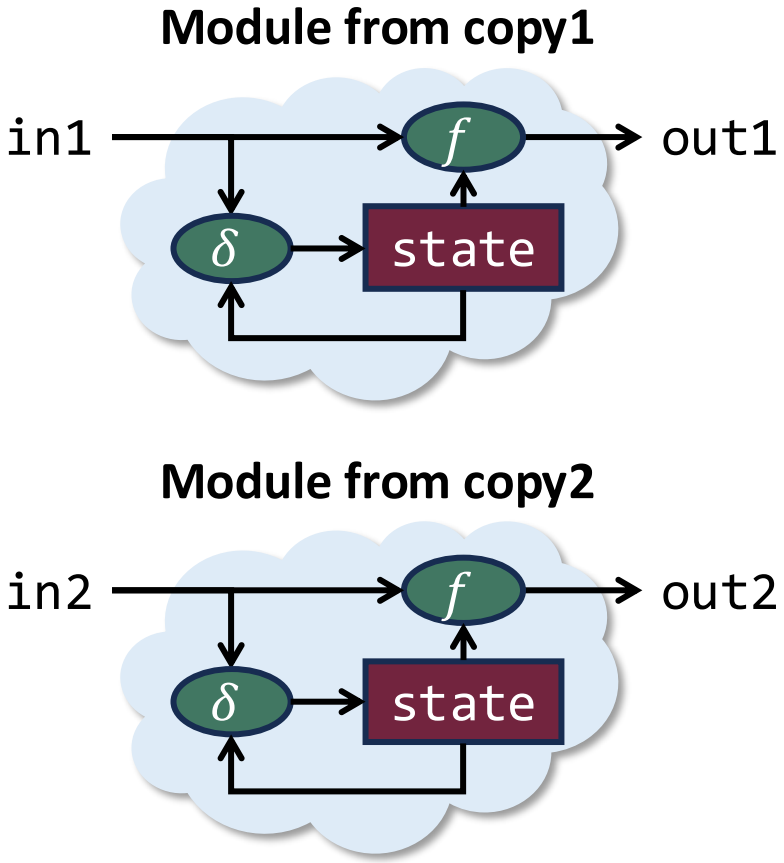

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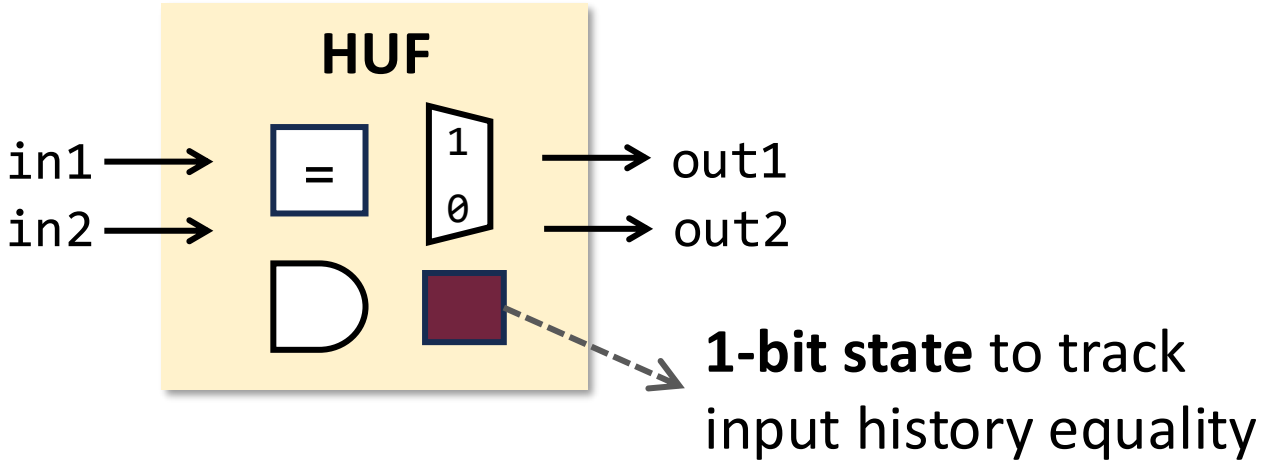
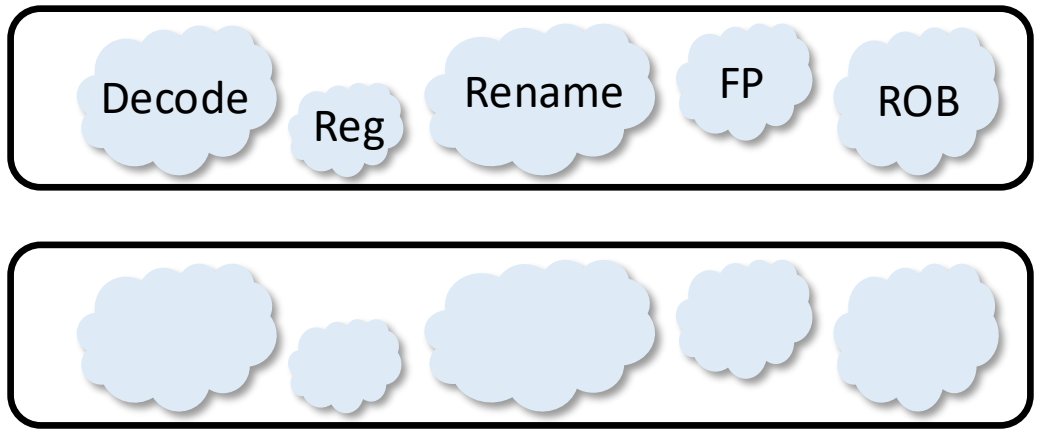


HUF reduces a sequential module to 1-bit state of history + simple gates, enabling efficient invariant searching

HUF Verification Flow

Verification target:
Self-composed processor pair



HUF Verification Flow

Select modules

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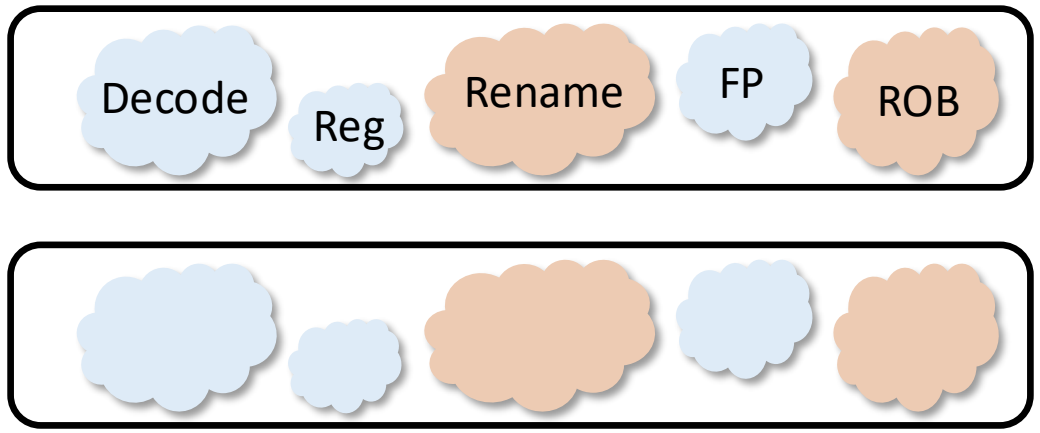

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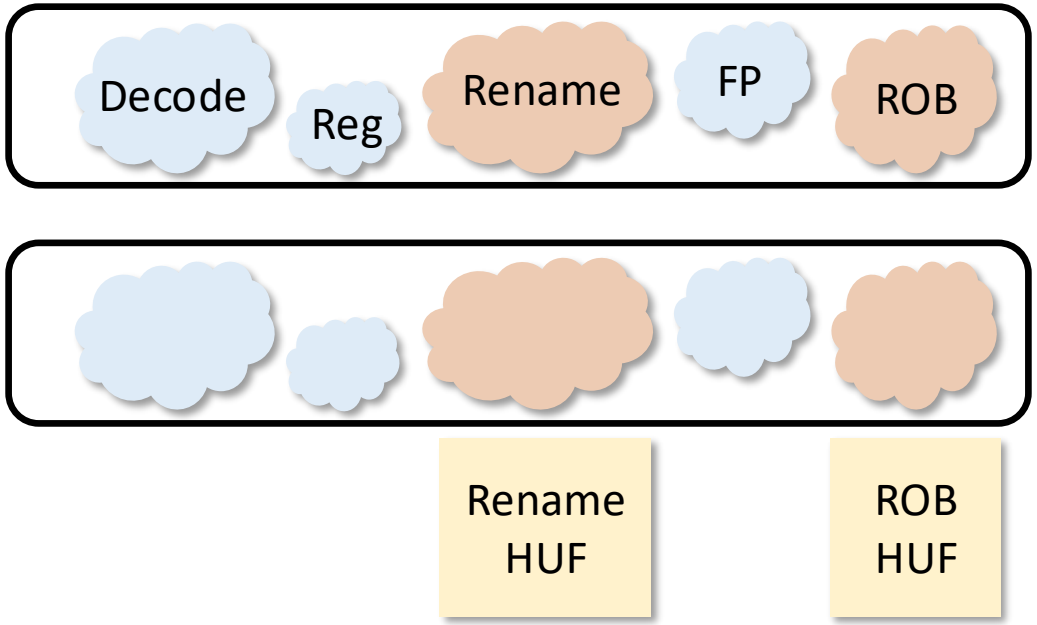

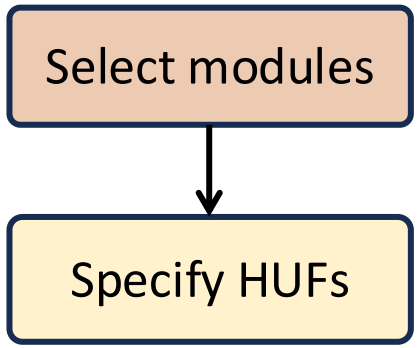

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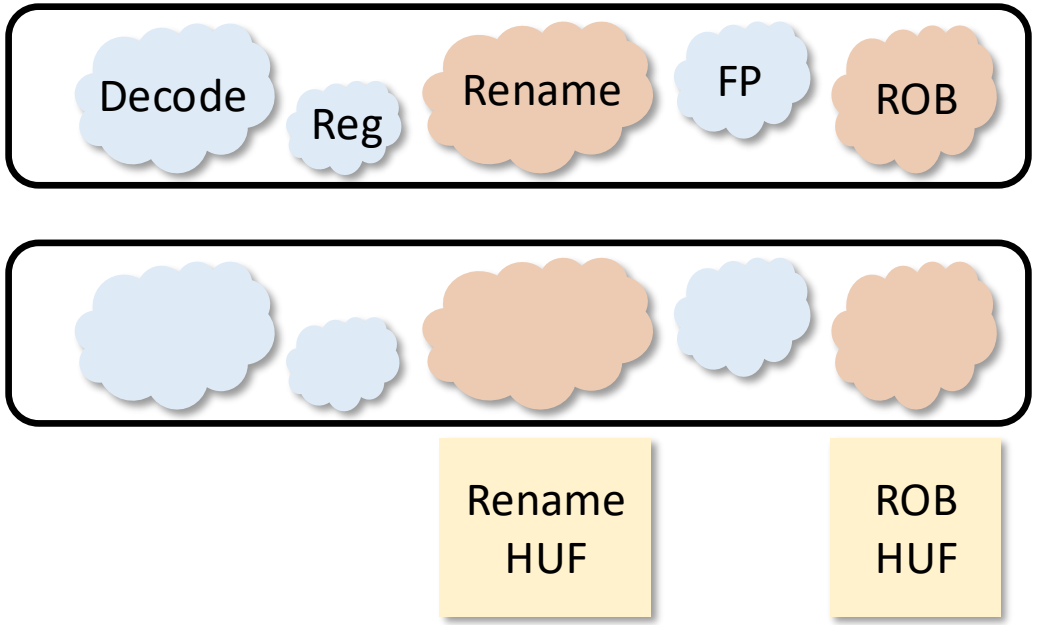

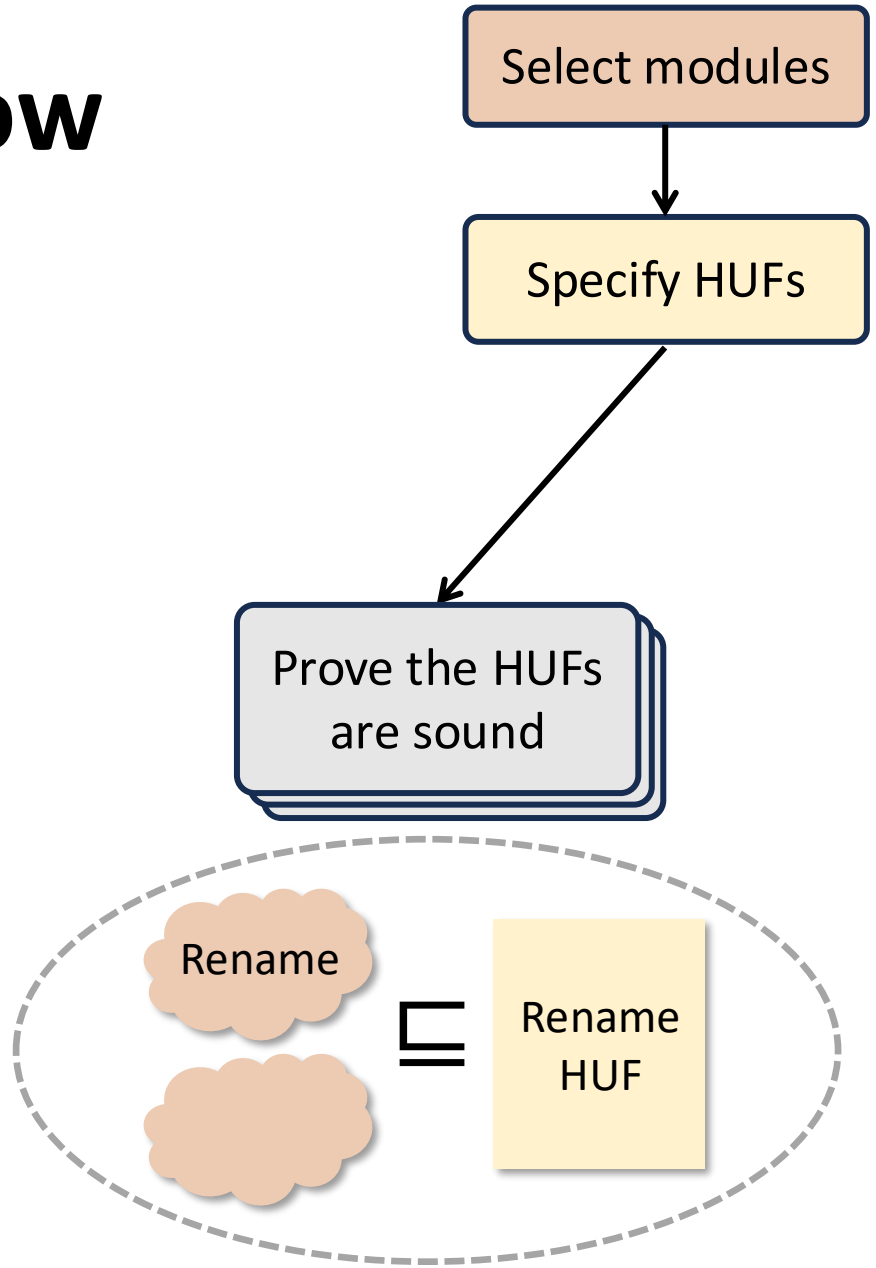

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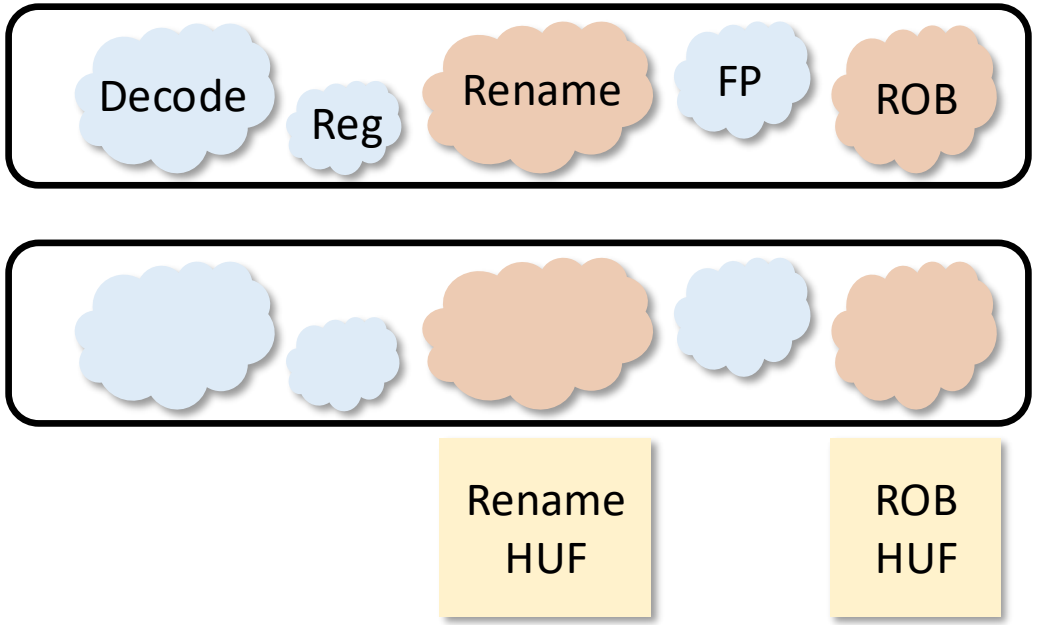

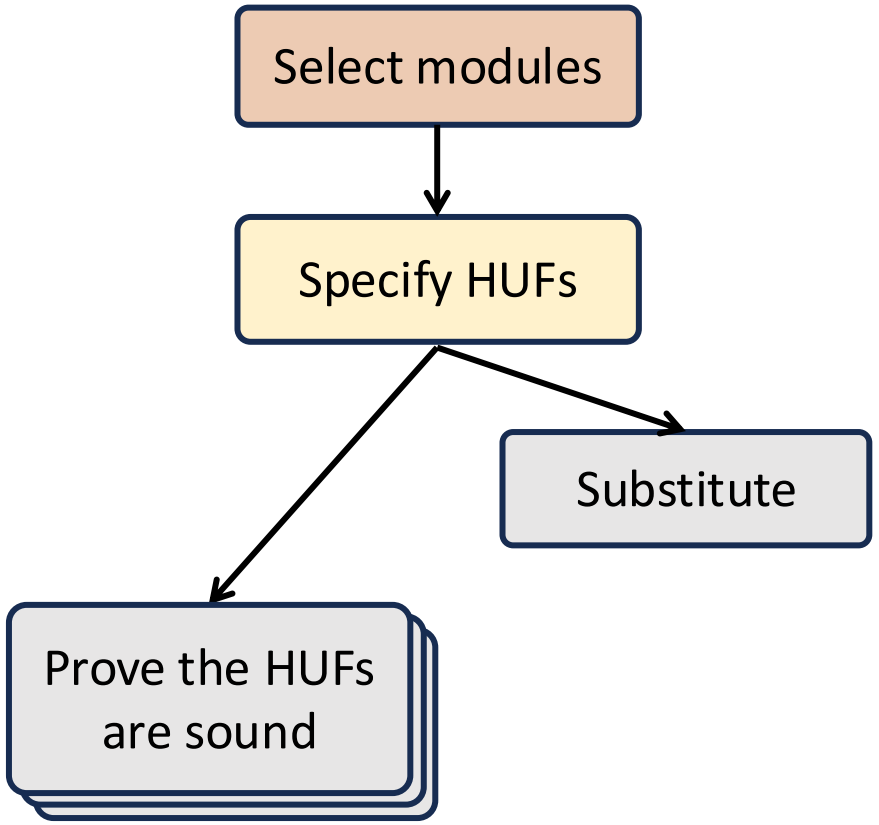

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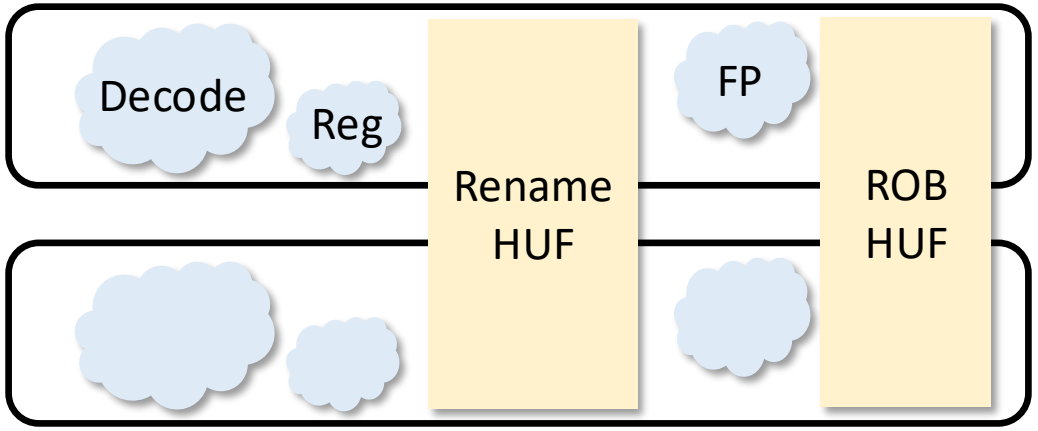
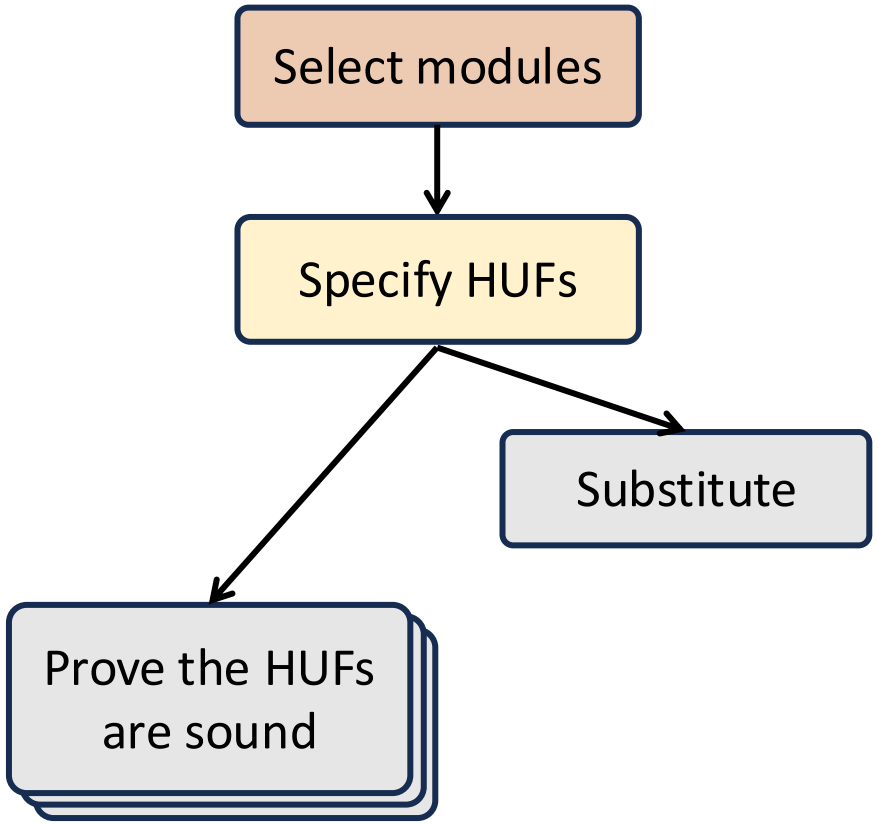
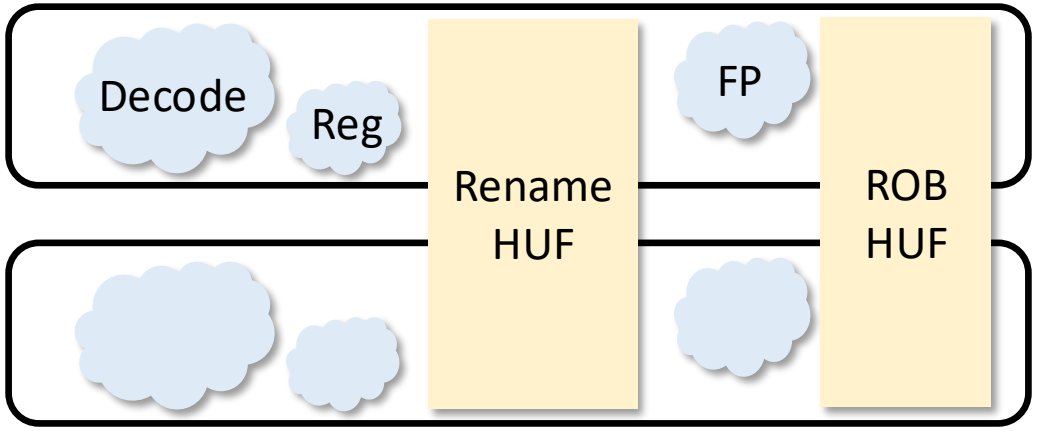
Verification target:
Self-composed processor pair

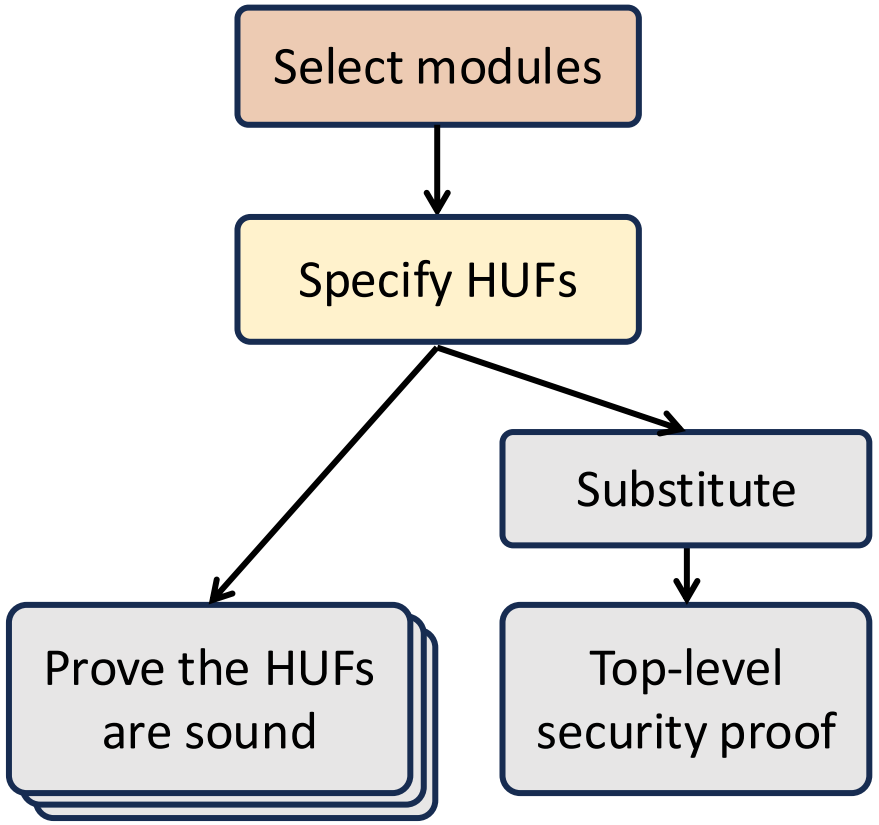




HUF Verification Flow

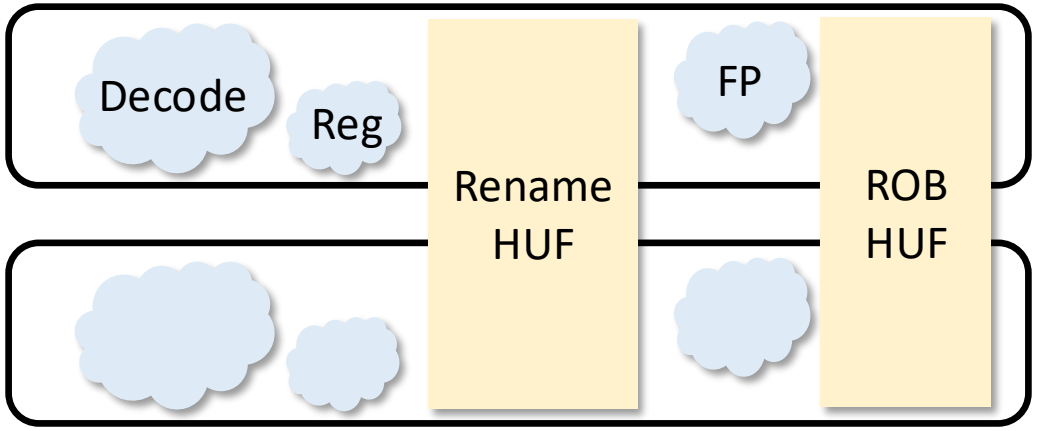
Verification target:
Self-composed processor pair

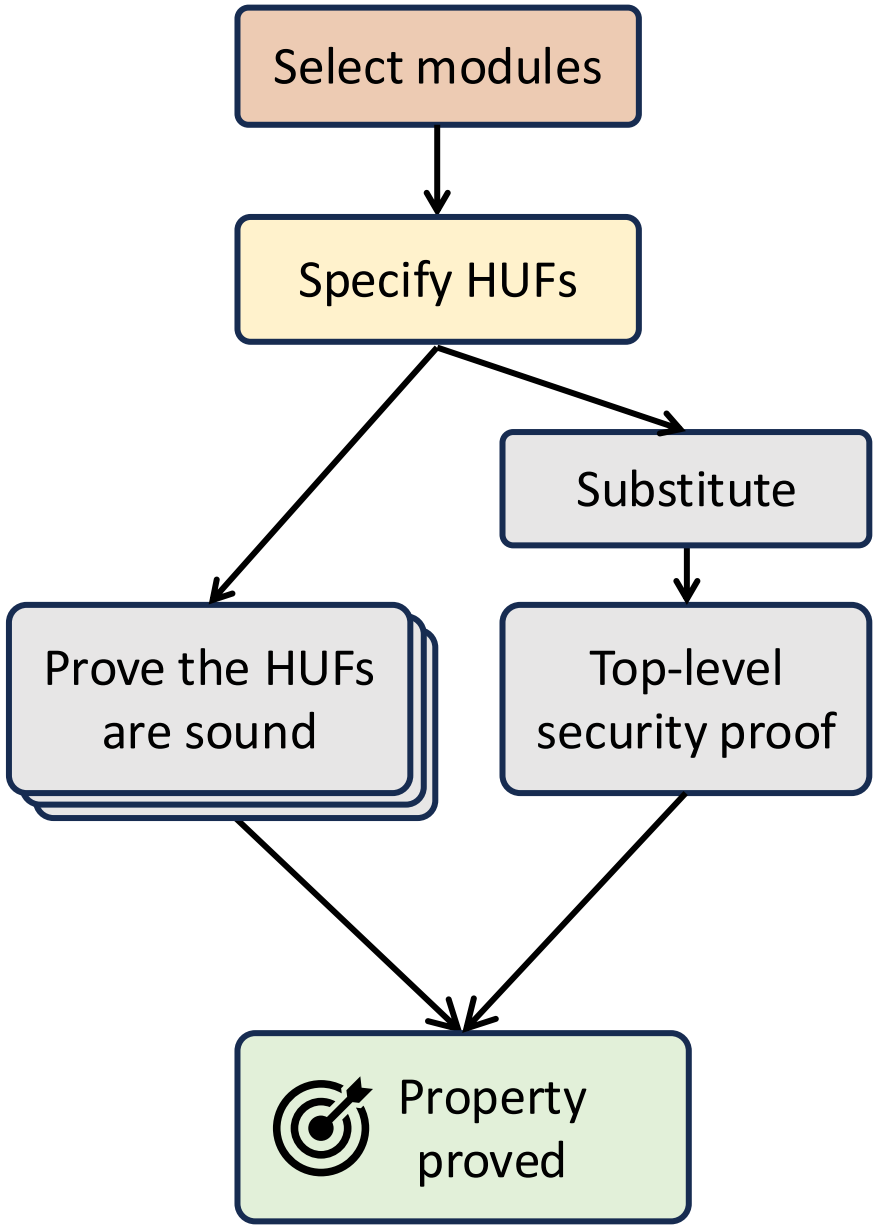




HUF Verification Flow

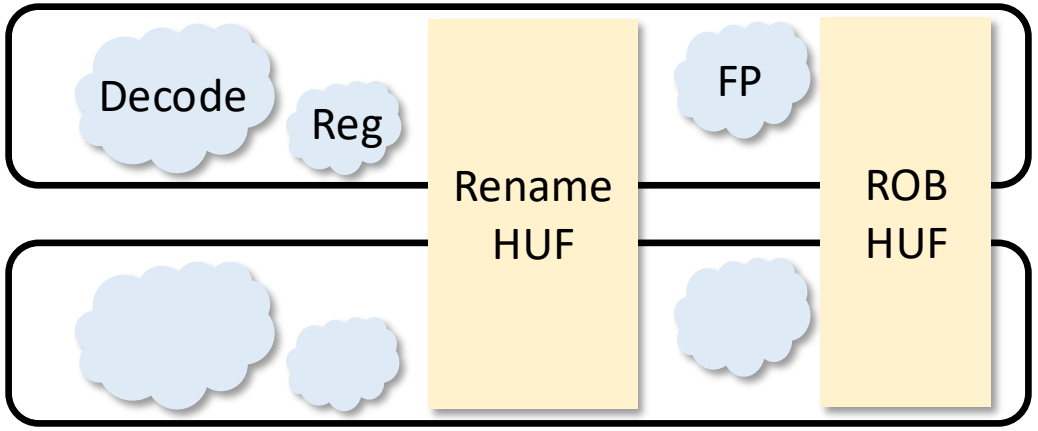
Verification target:
Self-composed processor pair

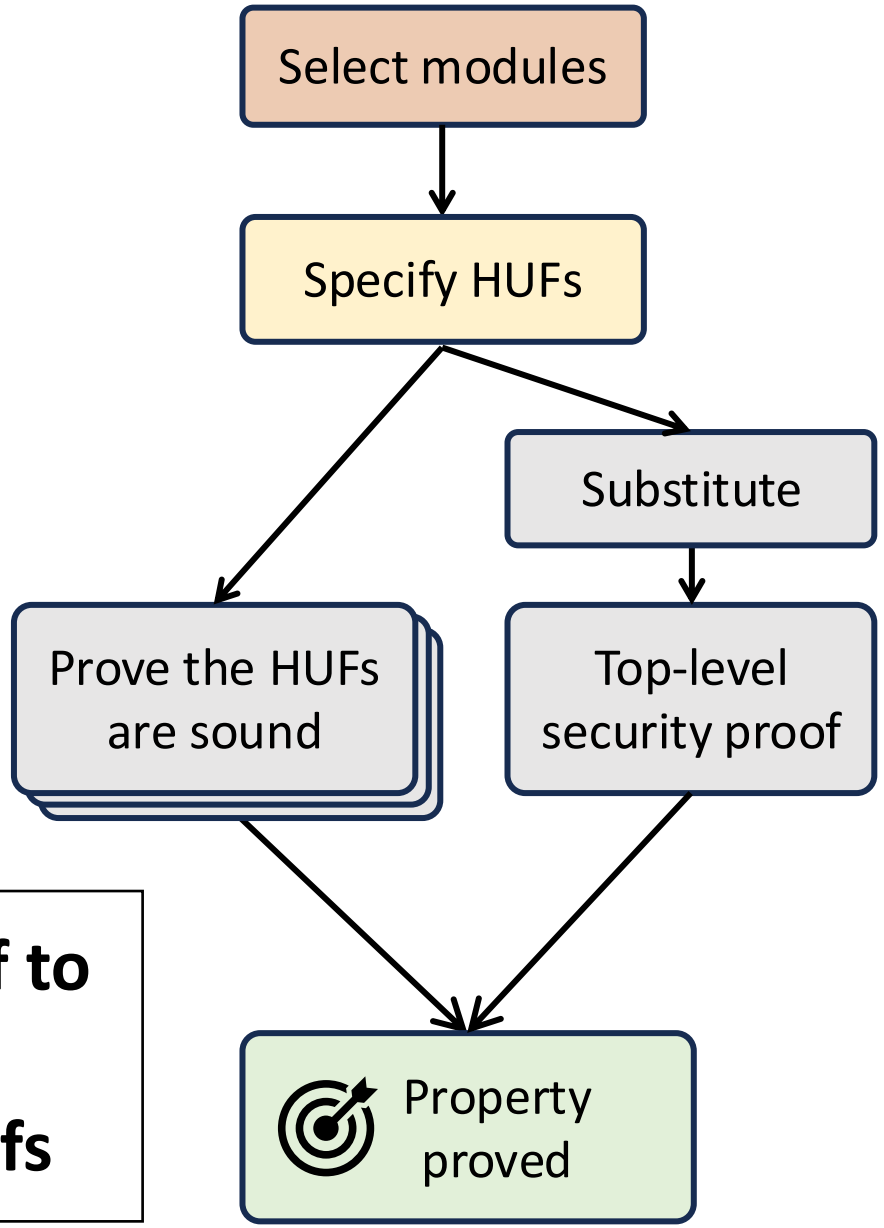




HUF Verification Flow

Verification target:
Self-composed processor pair





HUF decomposes a large monolithic proof to

- **one smaller top-level property proof**
- **multiple module-level soundness proofs**

Verification time is obtained using the open-source model checker rIC3

Evaluation Results

Verification time is obtained using the open-source model checker rIC3

Evaluation Results

Property 1: Constant-Time Instruction Set

Verification time is obtained using the open-source model checker rIC3

Evaluation Results

Property 1: Constant-Time Instruction Set

H-Houdini (160 cores)	**7 mins**	**3 hours**

Verification time is obtained using the open-source model checker rIC3

Evaluation Results

Property 1: Constant-Time Instruction Set

		
H-Houdini (160 cores)	**7 mins**	**3 hours**
HUF **(11 cores)**	**30 s** **(14x faster)**	**15 mins** **(12x faster)**

Verification time is obtained using the open-source model checker rIC3

Evaluation Results

Property 1: Constant-Time Instruction Set

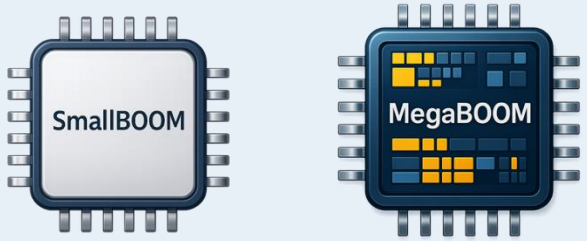
H-Houdini (160 cores)	**7 mins**	**3 hours**
HUF **(11 cores)**	**30 s** **(14x faster)**	**15 mins** **(12x faster)**

Property 2: Secure Speculation

Verification time is obtained using the open-source model checker rIC3

Evaluation Results

Property 1: Constant-Time Instruction Set



H-Houdini (160 cores)	**7 mins**	**3 hours**
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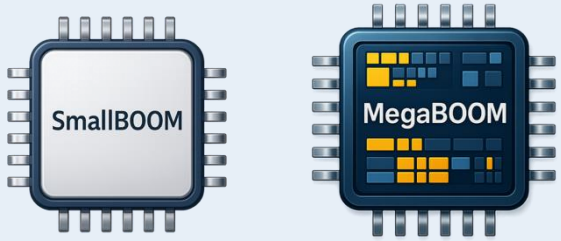
Property 2: Secure Speculation

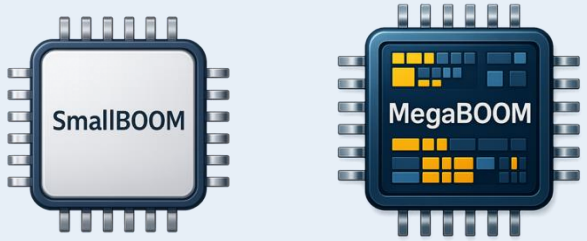


Contract Shadow Logic	✗ **Cannot verify**	✗

Verification time is obtained using the open-source model checker rIC3

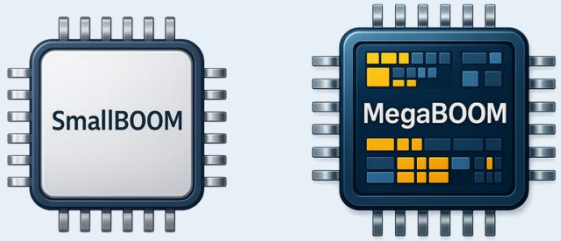
Evaluation Results

Property 1: Constant-Time Instruction Set



	SmallBOOM	MegaBOOM
H-Houdini (160 cores)	**7 mins**	**3 hours**
HUF **(11 cores)**	**30 s** **(14x faster)**	**15 mins** **(12x faster)**

Property 2: Secure Speculation

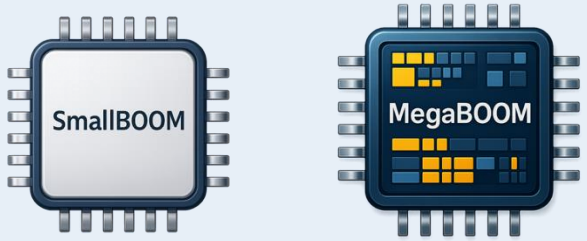


	SmallBOOM	MegaBOOM
Contract Shadow Logic	✗ **Cannot verify**	✗
HUF	✓ **3 mins**	✓ **3 hours**

Verification time is obtained using the open-source model checker rIC3

Evaluation Results

Property 1: Constant-Time Instruction Set



	SmallBOOM	MegaBOOM
H-Houdini (160 cores)	**7 mins**	**3 hours**
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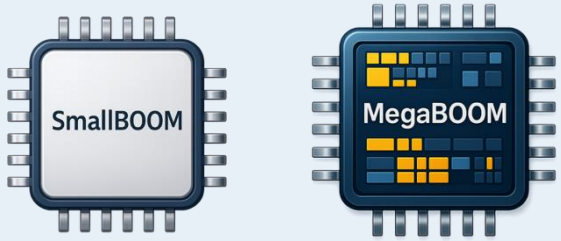
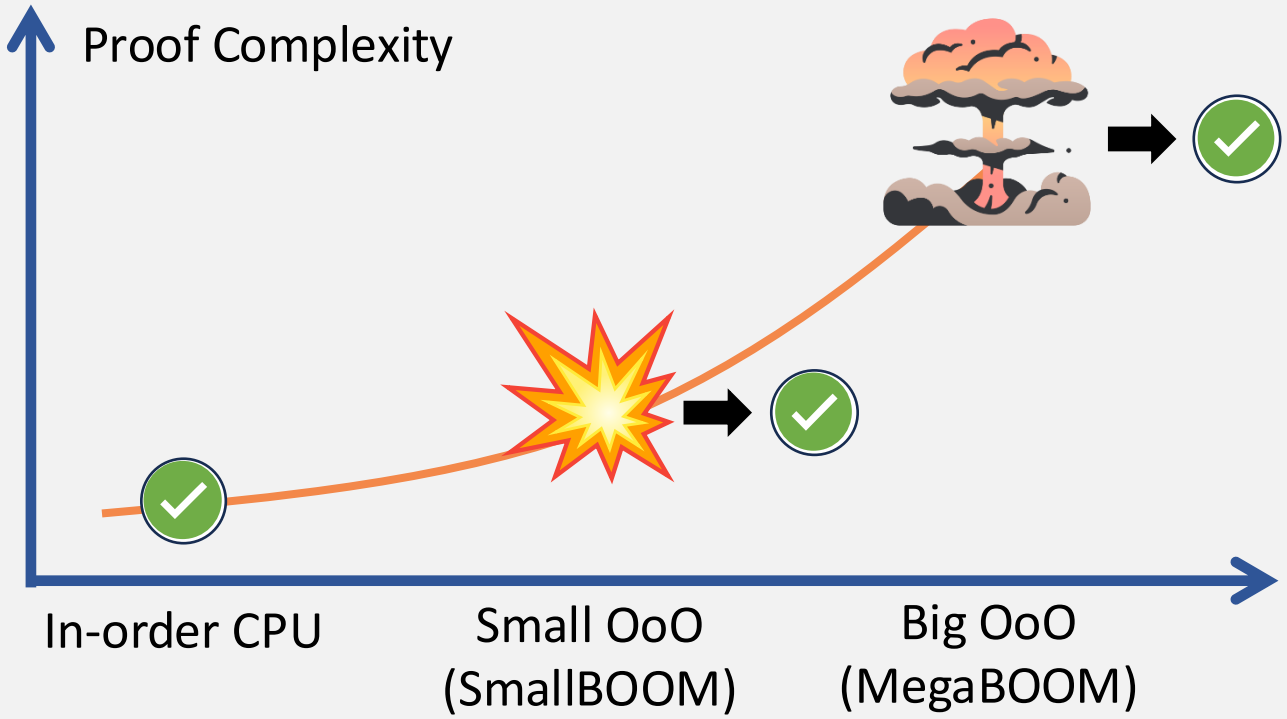
Property 2: Secure Speculation



	SmallBOOM	MegaBOOM
Contract Shadow Logic	✗ **Cannot verify**	✗
HUF	✓ **3 mins**	✓ **3 hours**

HUF scales verification to previously out-of-reach complex OoO CPU

HUF: Uninterpreted Function with History



Thank you!

rogerdtz@mit.edu

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