Sound and Automated Deductive Verifiers for Advanced Properties

Thibault Dardinier

ETH zürich

Software Bugs

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Heartbleed: Hundreds of thousands of servers at risk from catastrophic bug

Code error means that websites can leak user details including passwords through 'heartbeat' function used to secure connections

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Internet

Sat 11 Dec 2021

The extreme ease the flaw allows an attacker to access a server is what experts say makes it so dangerous. *(Supplied: Accenture)*

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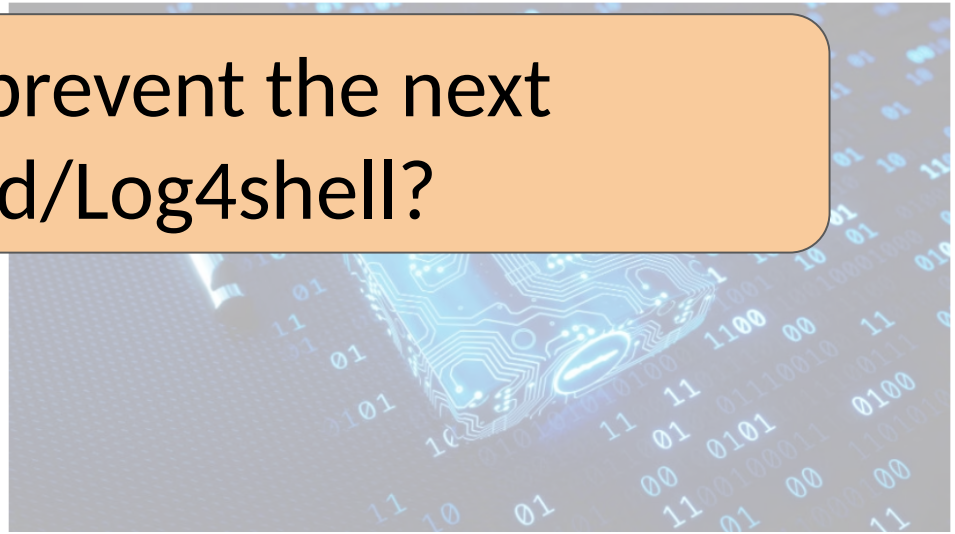


The extreme ease the flaw allows an attacker to access a server is what experts say makes it so dangerous. *(Supplied: Accenture)*

How can we prevent the next Heartbleed/Log4shell?

Preventing the Next Heartbleed/Log4shell

Testing

Preventing the Next Heartbleed/Log4shell

Testing

Fuzzing

Preventing the Next Heartbleed/Log4shell

Testing

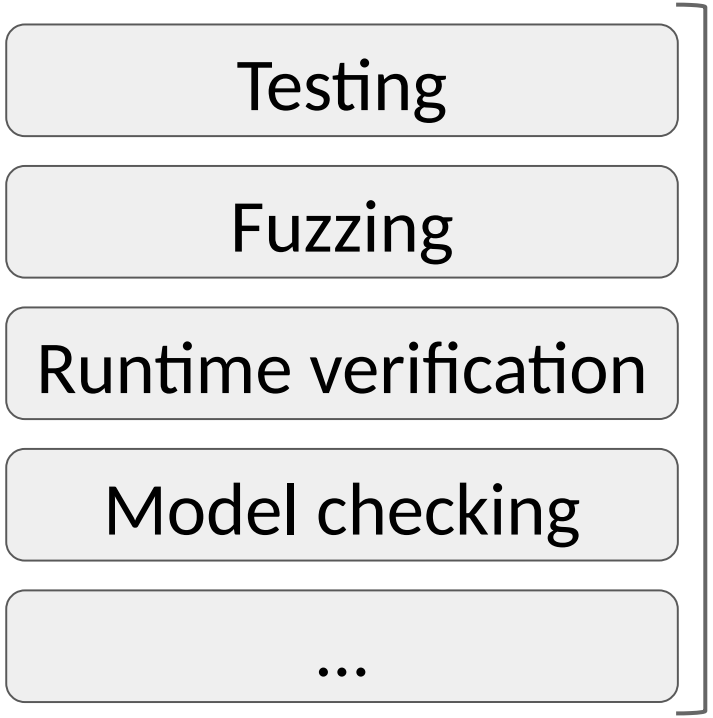
Fuzzing

Runtime verification

Preventing the Next Heartbleed/Log4shell

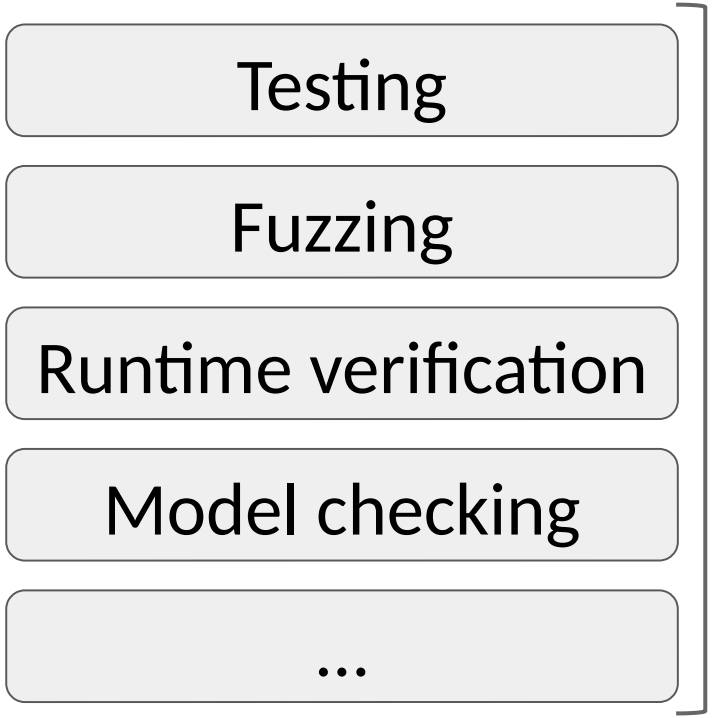
- Testing
- Fuzzing
- Runtime verification
- Model checking

Preventing the Next Heartbleed/Log4shell



can show the **presence** of bugs

Preventing the Next Heartbleed/Log4shell



Might miss bugs and vulnerabilites that attackers can exploit

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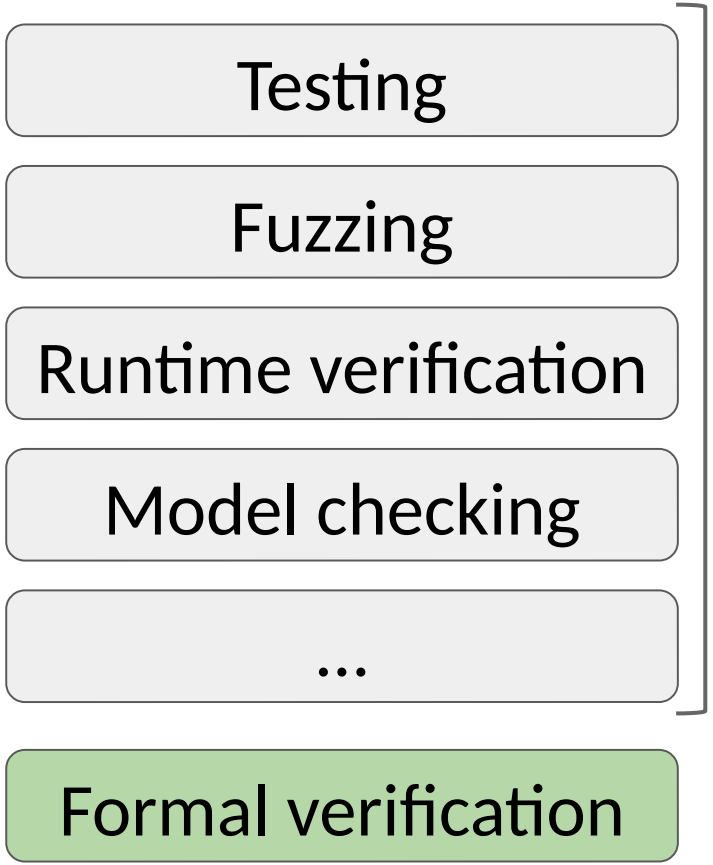

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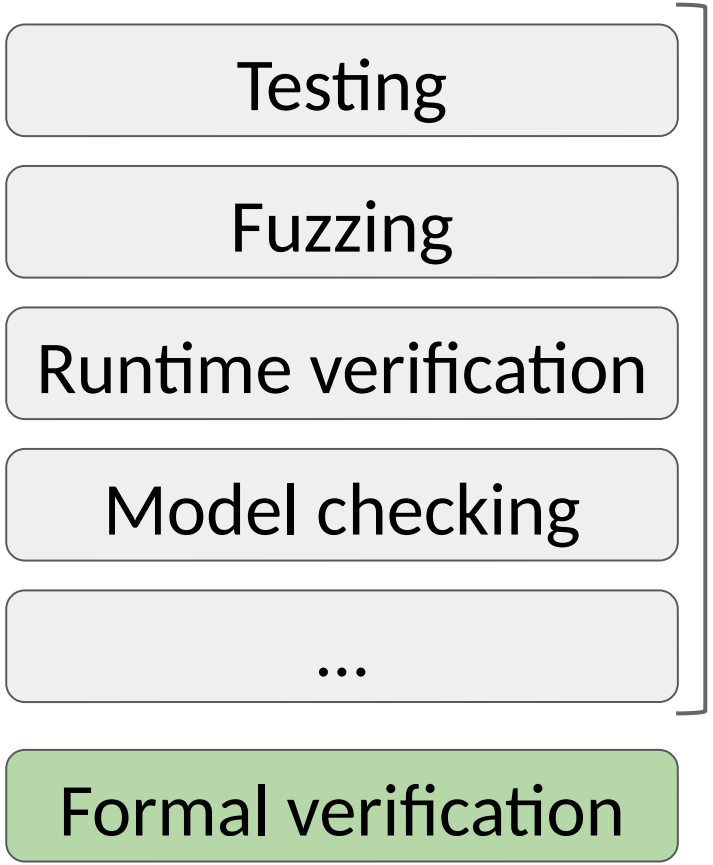


can show the **presence** of bugs

Can formally prove
the absence of classes of attacks

can show the **absence** of bugs

Preventing the Next Heartbleed/Log4shell

Testing

Fuzzing

Runtime verification

Model checking

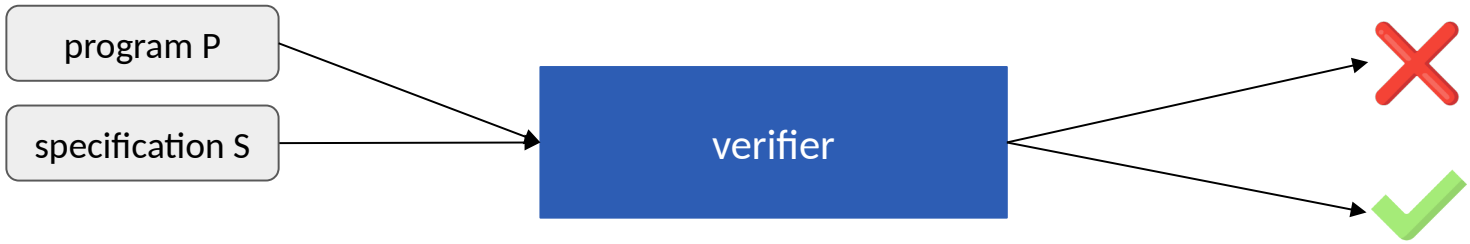
…

can show the **presence** of bugs

Formal verification

can show the **absence** of bugs

Automated Deductive Verifiers



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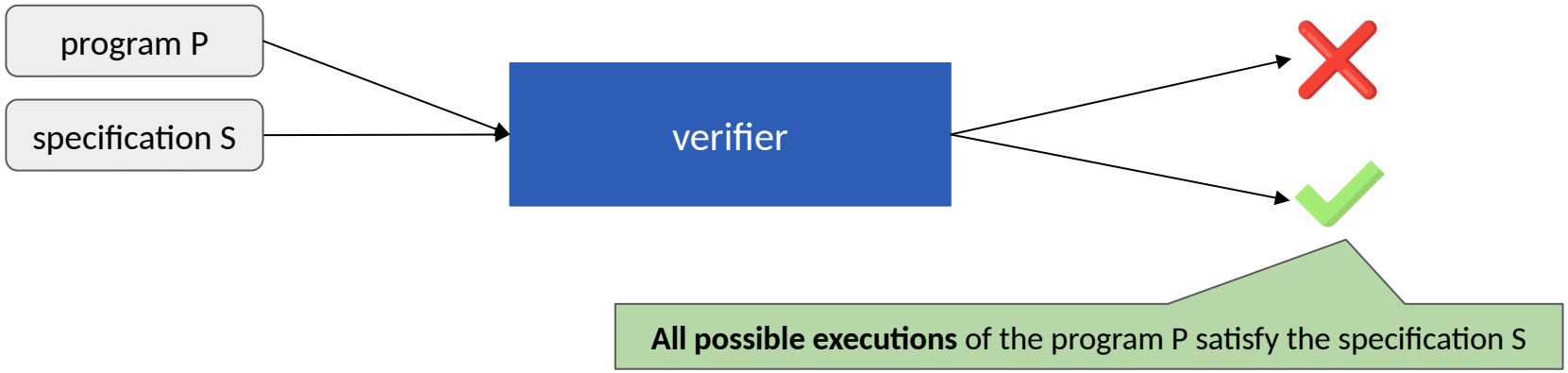

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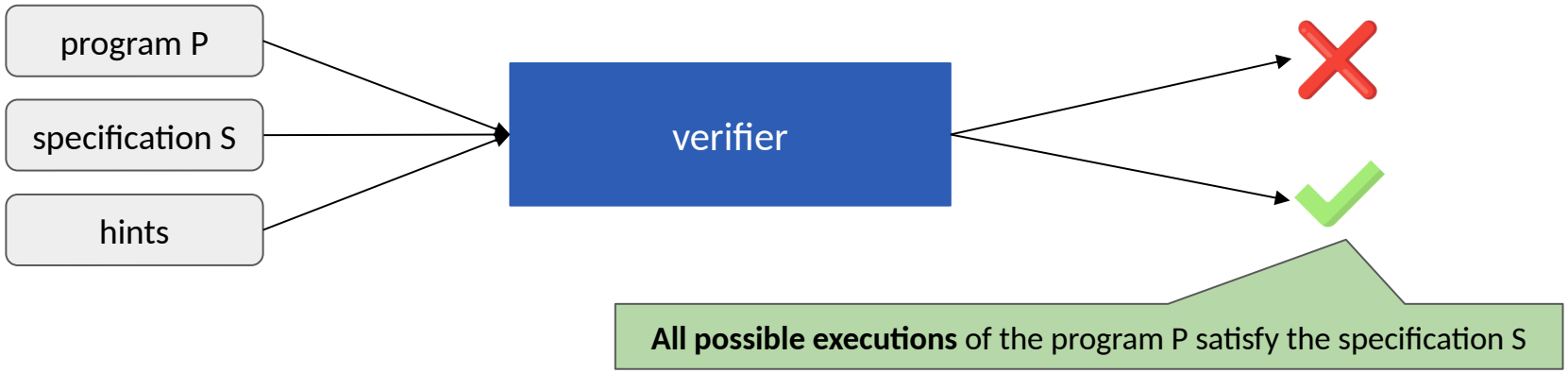

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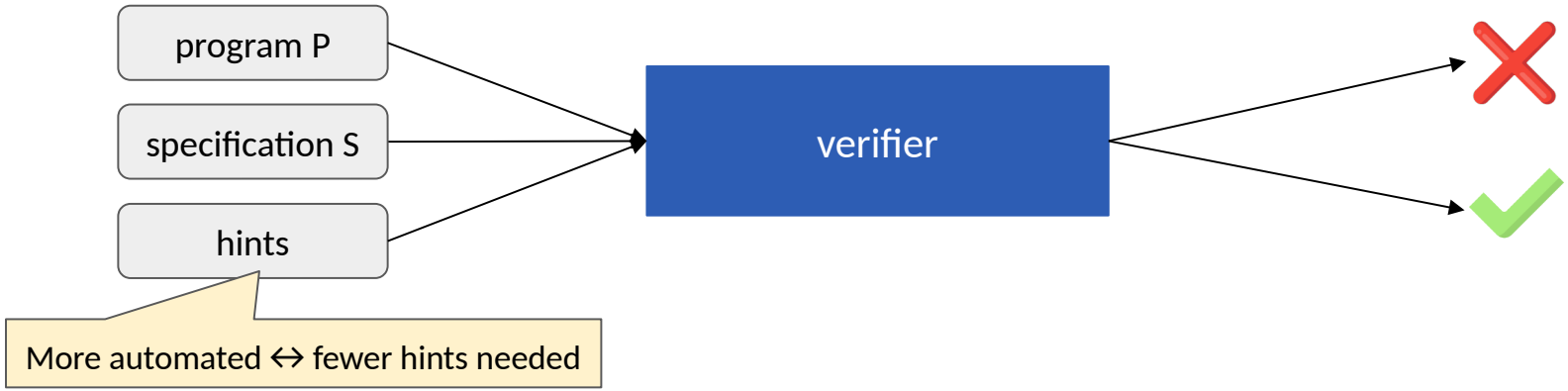

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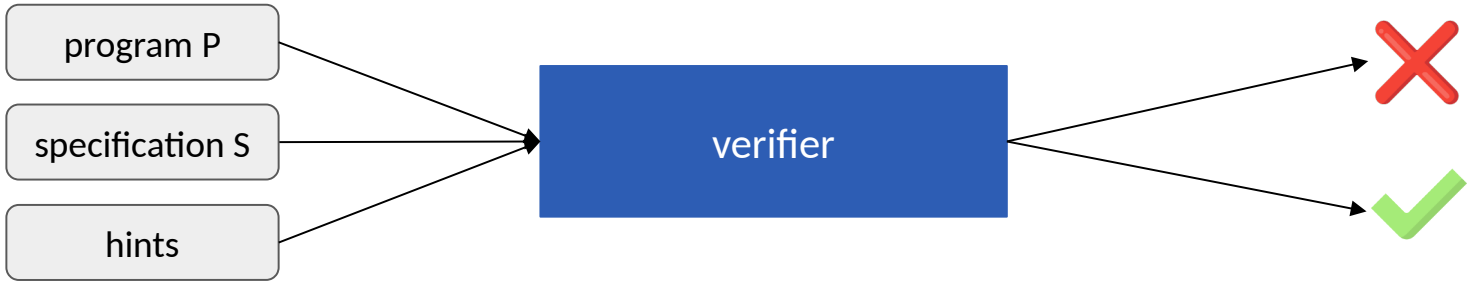
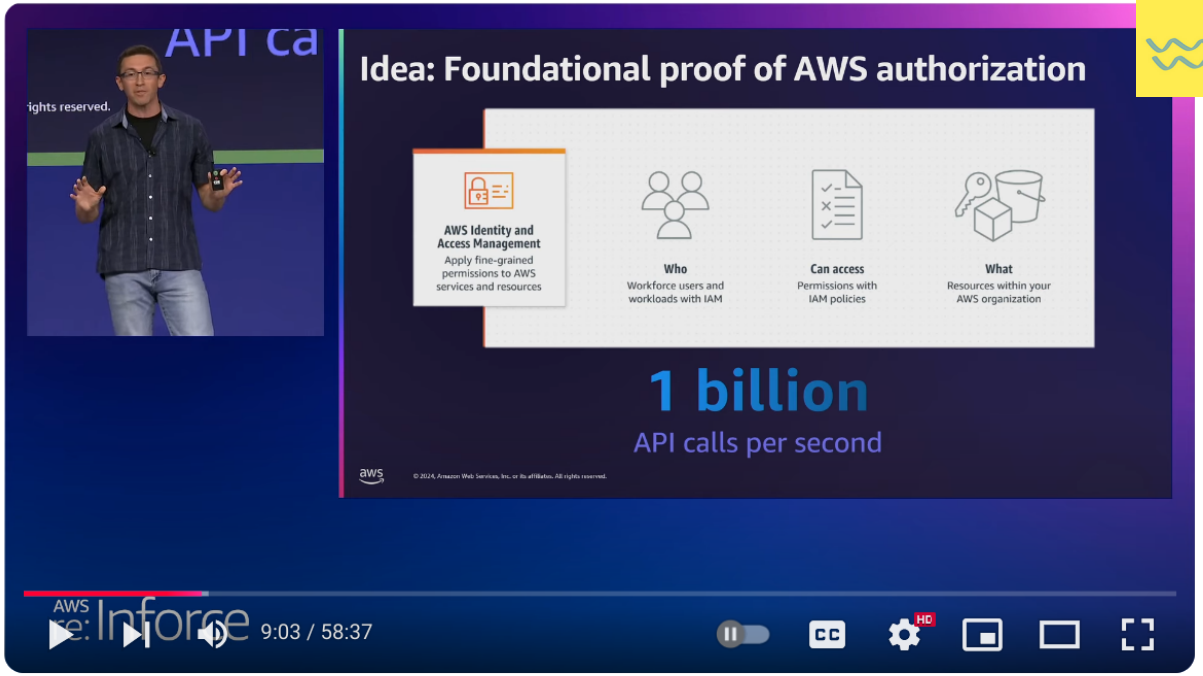


Modern Verifiers are Practical



AWS re:Inforce 2024 - Proving the correctness of AWS authorization (IAM401)

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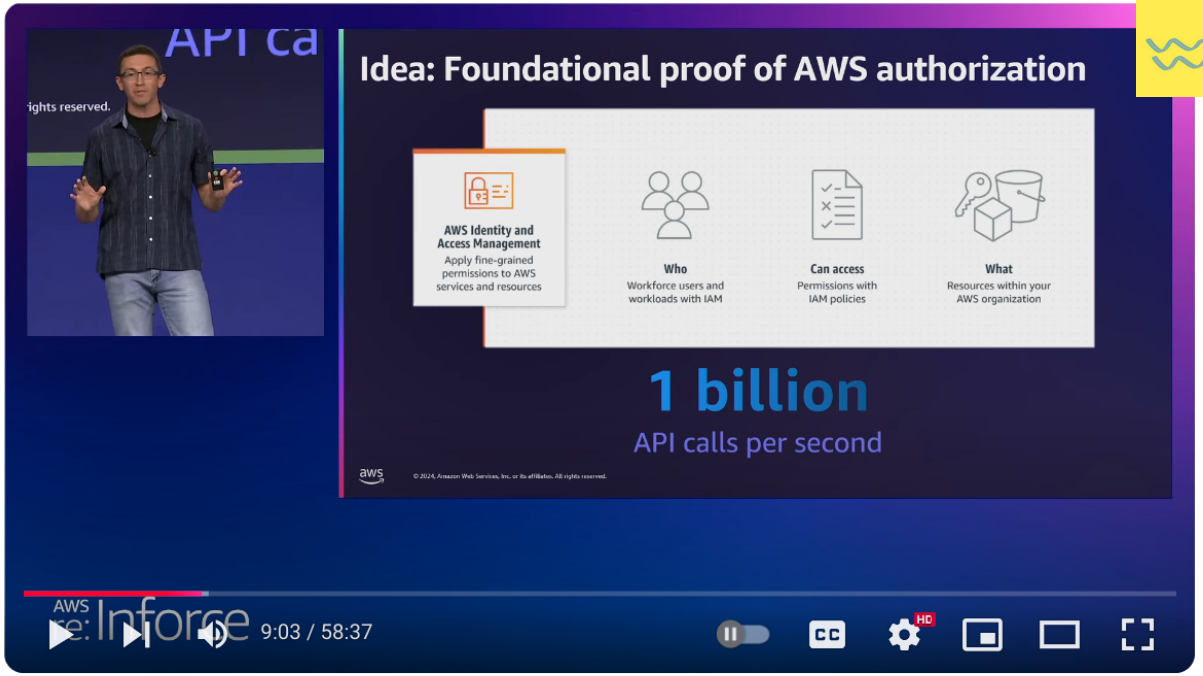

AWS re:Inforce 2024 - Proving the correctness of AWS authorization (IAM401)

1 billion times/second
3,000 lines of code
3x performance

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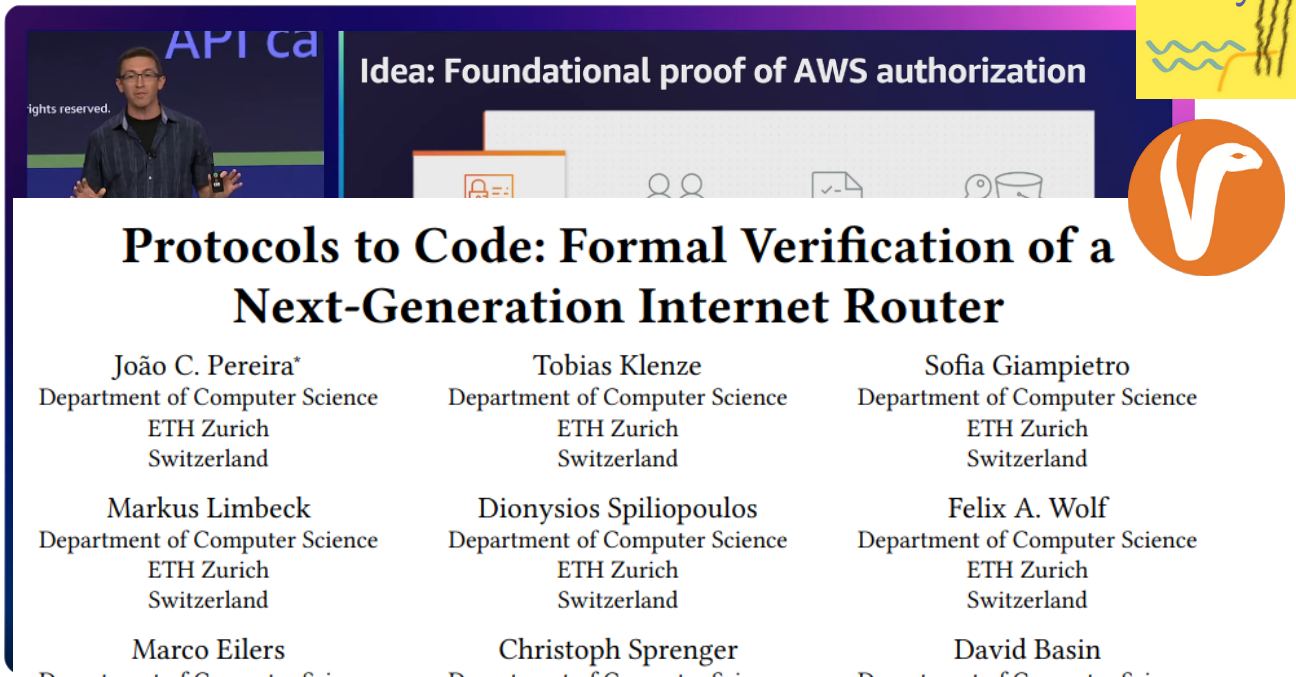

Protocols to Code: Formal Verification of a Next-Generation Internet Router

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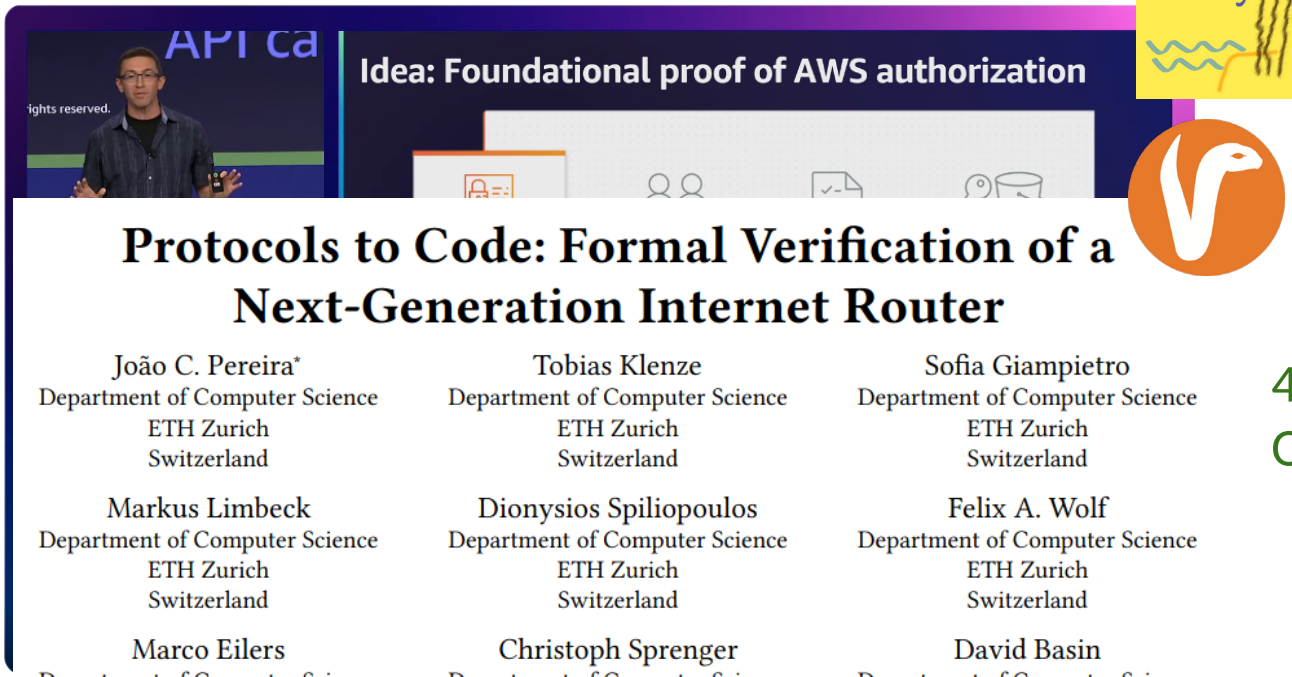

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4,700 lines of Go code
Optimized implementation

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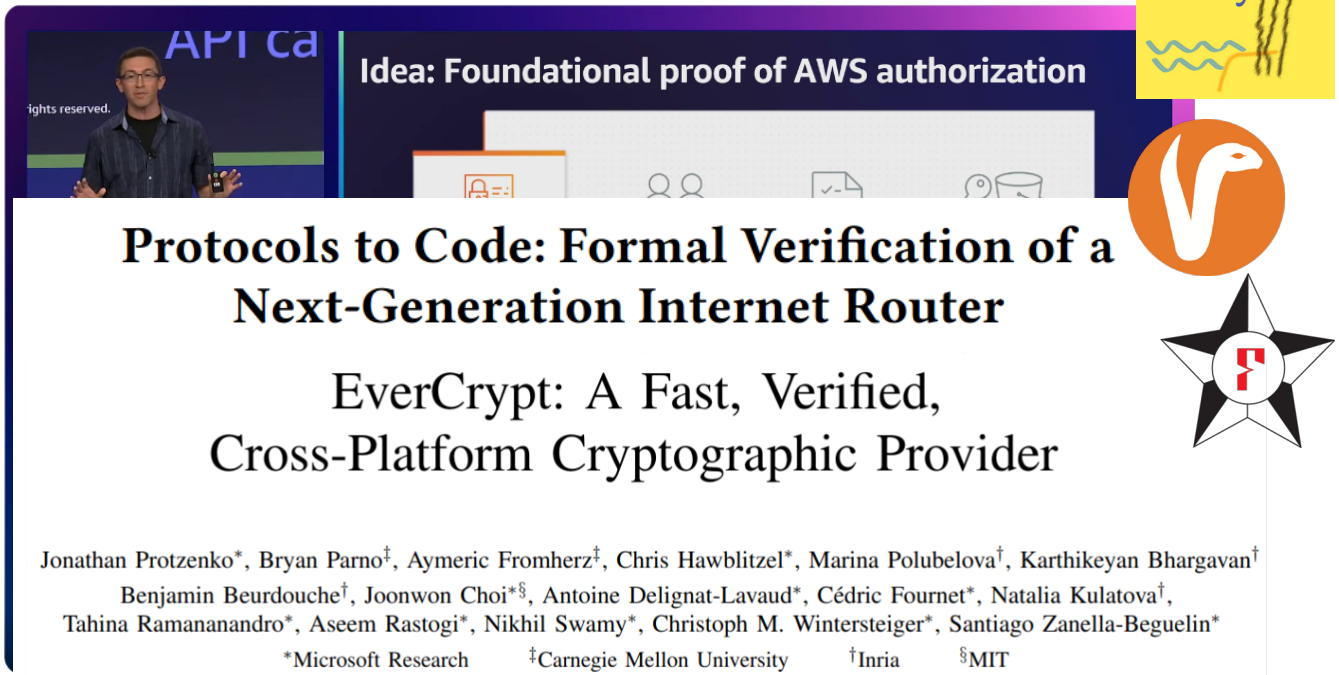

Protocols to Code: Formal Verification of a Next-Generation Internet Router

EverCrypt: A Fast, Verified, Cross-Platform Cryptographic Provider

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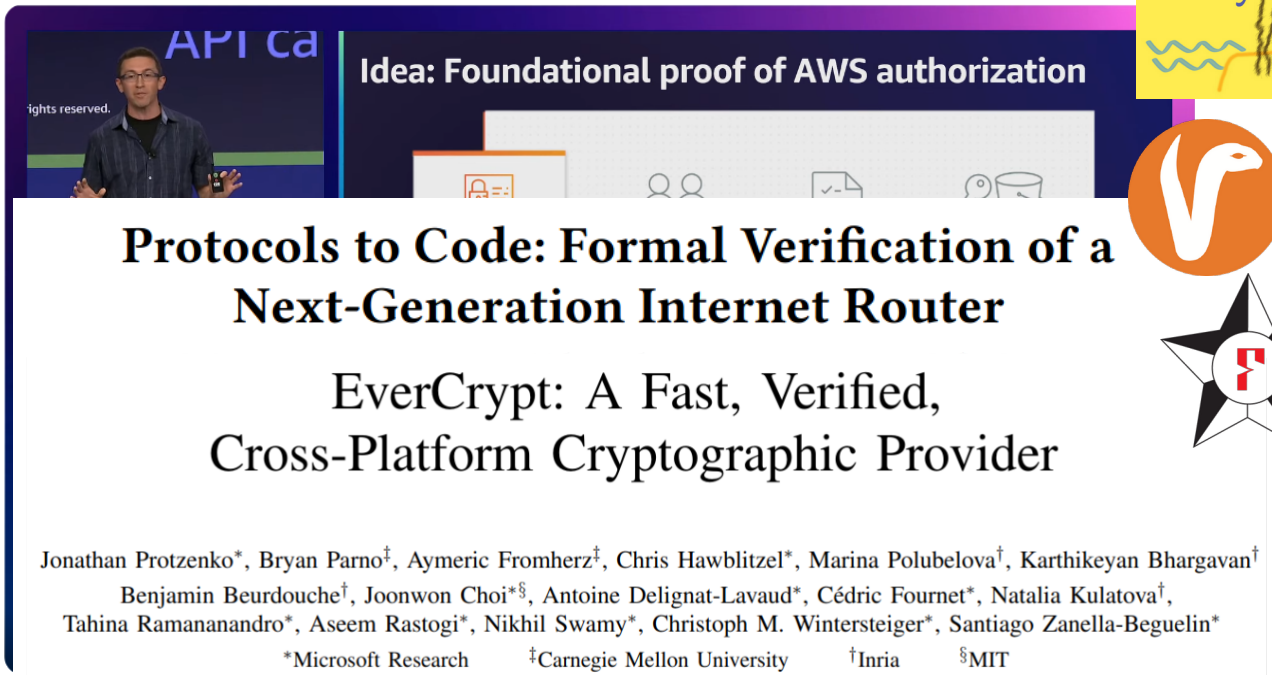

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ETH Zurich Switzerland
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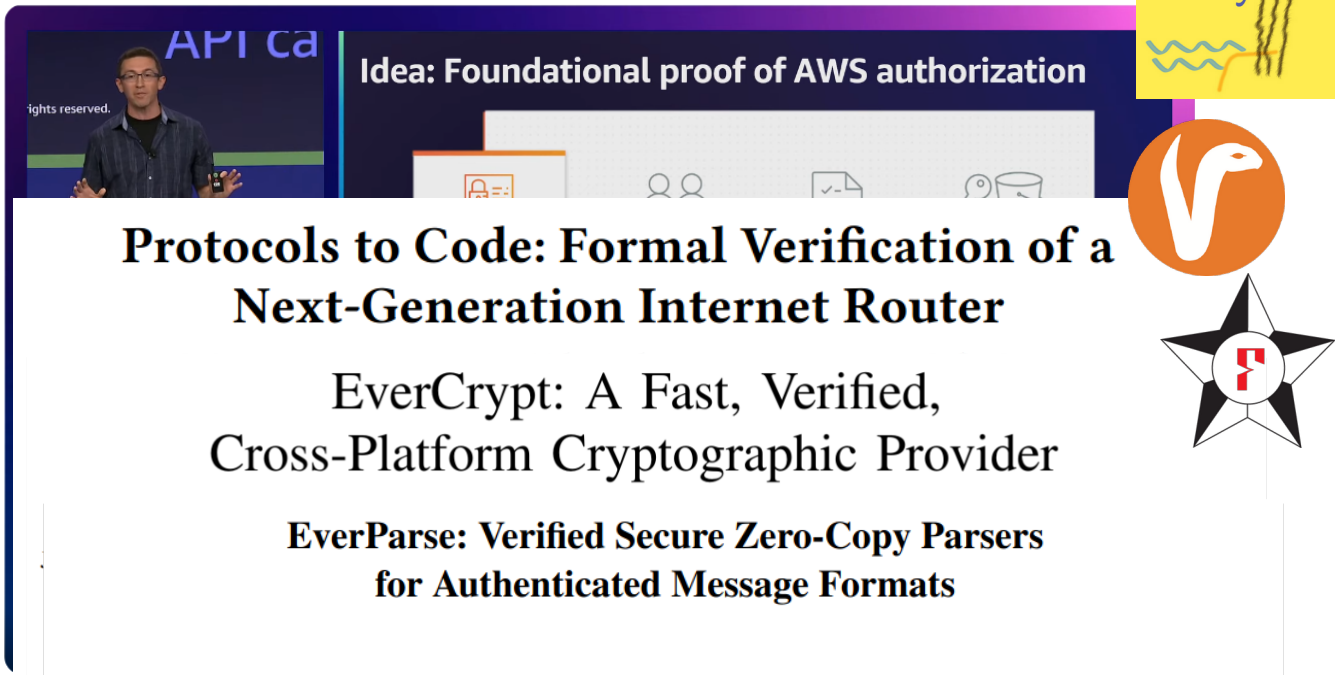
27,000 LoC (C code)
Deployed in

- Firefox
- Linux kernel
- Python (3.12)

Modern Verifiers are Practical



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EverParse: Verified Secure Zero-Copy Parsers for Authenticated Message Formats

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Parses all packets in Azure

Modern Verifiers are Practical

Dafny

Can we use modern automated verifiers to prevent the next Heartbleed/Log4shell?

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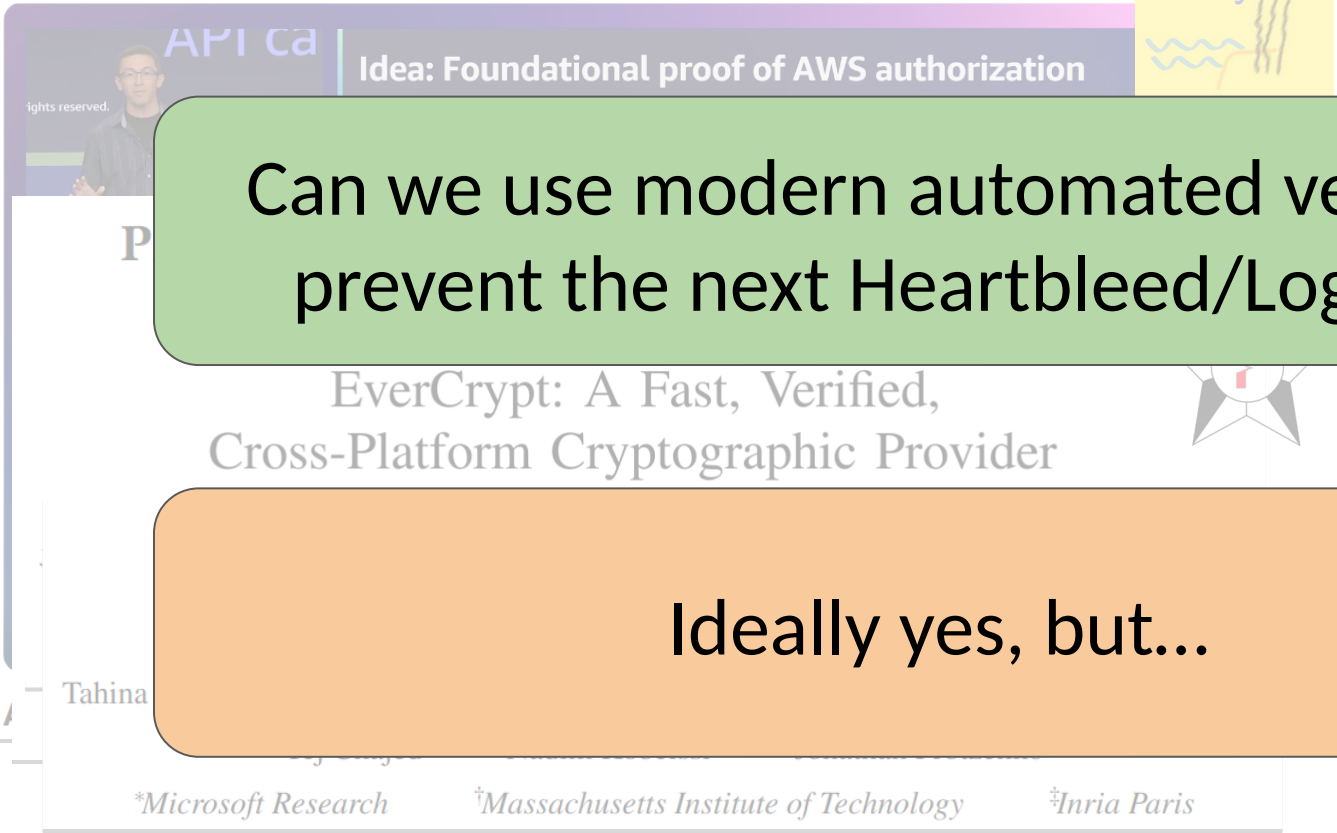
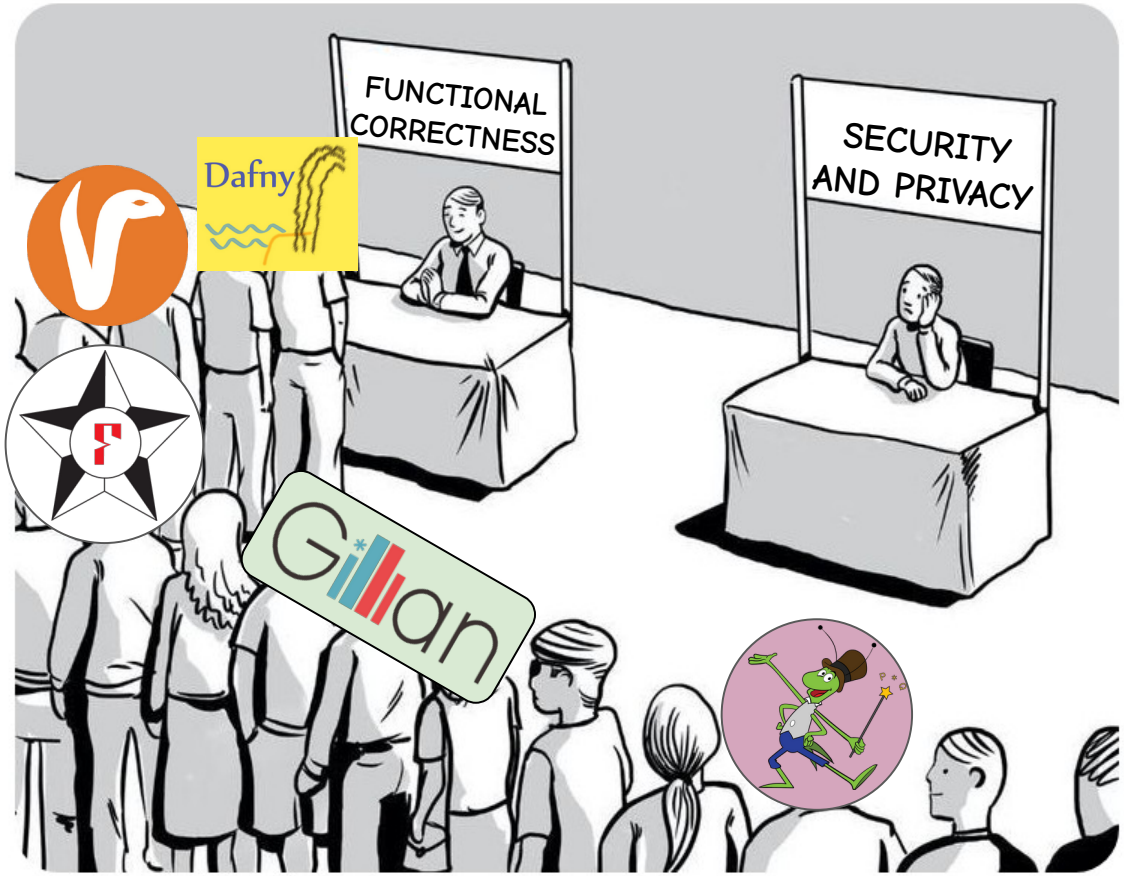


Can we use modern automated verifiers to prevent the next Heartbleed/Log4shell?

Ideally yes, but…

Azure

Problem: Expressiveness



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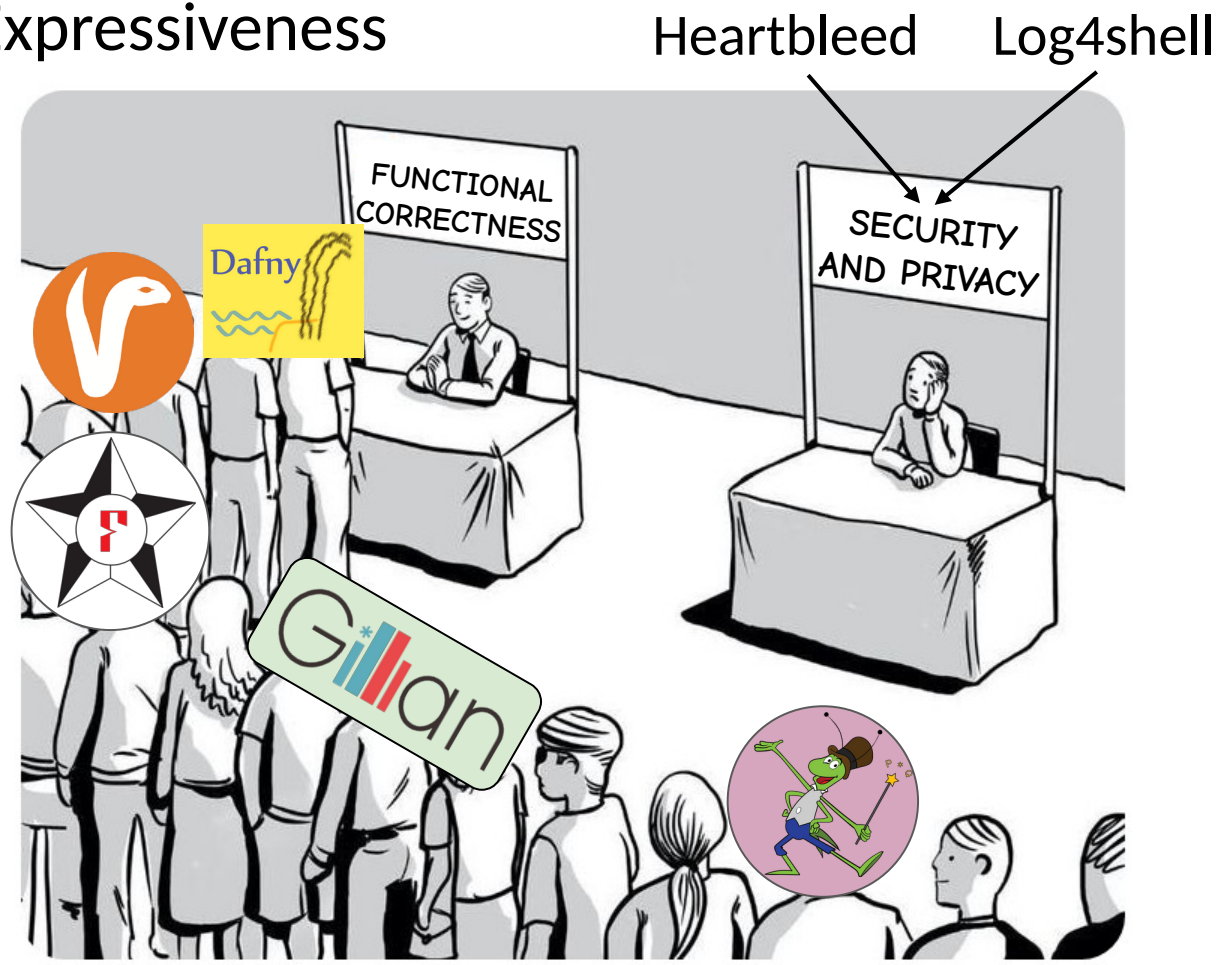
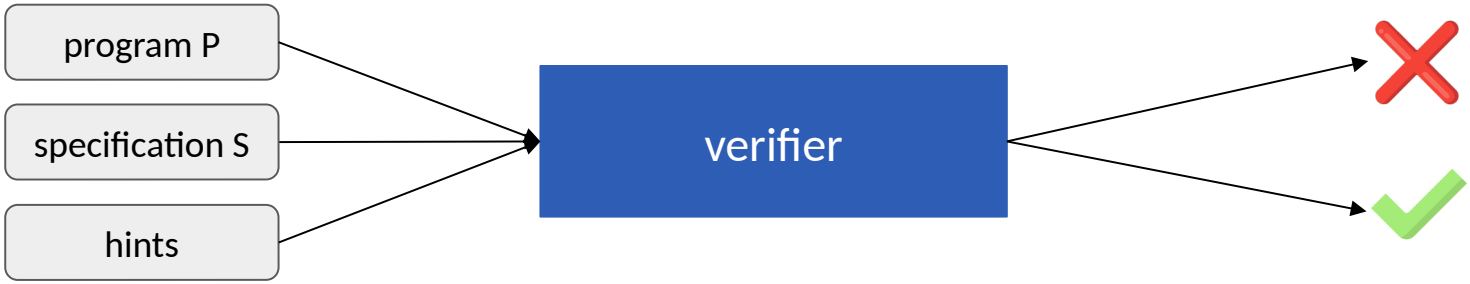


Automated Verifiers



Problem
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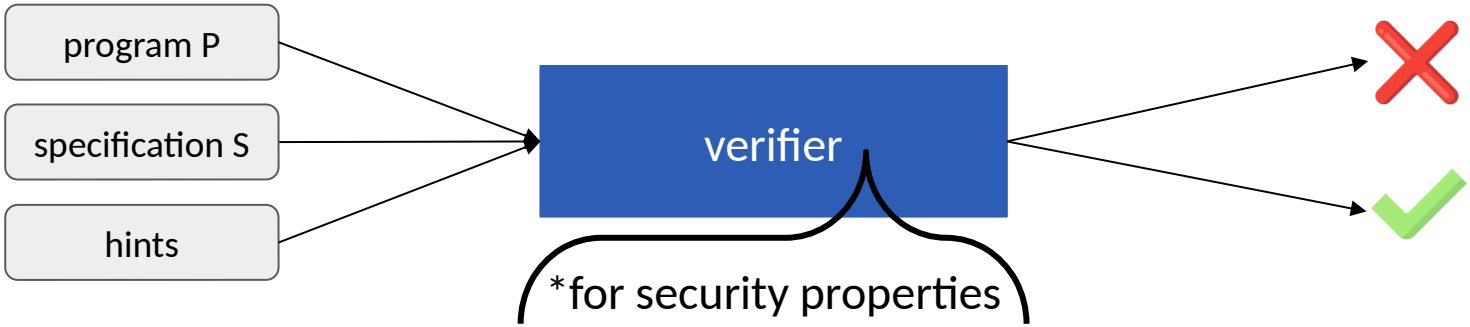

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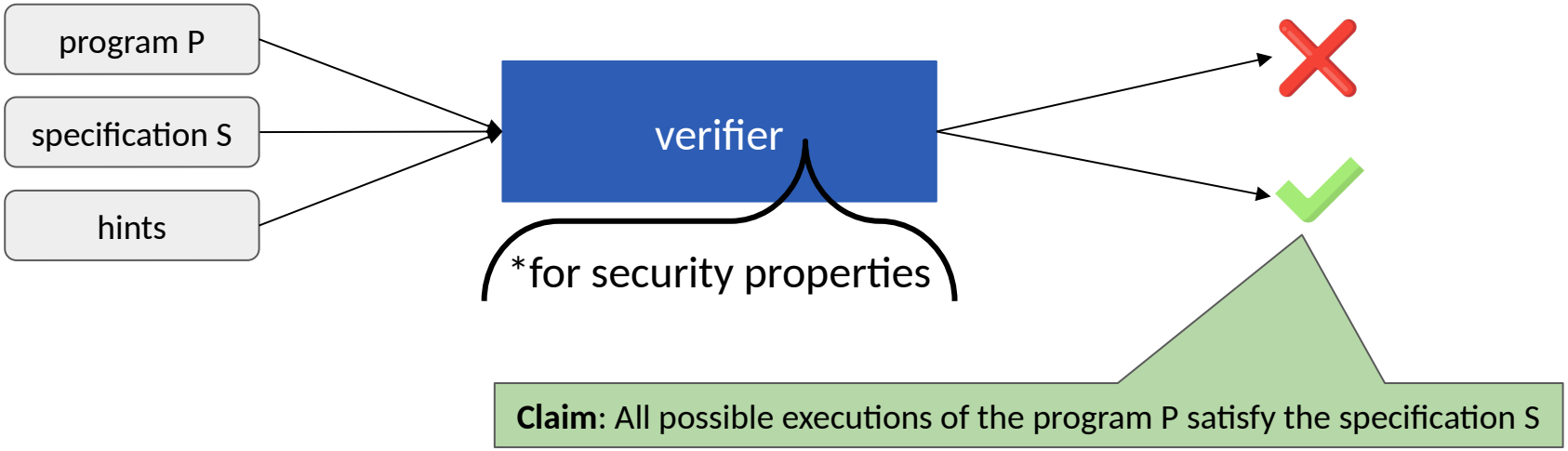

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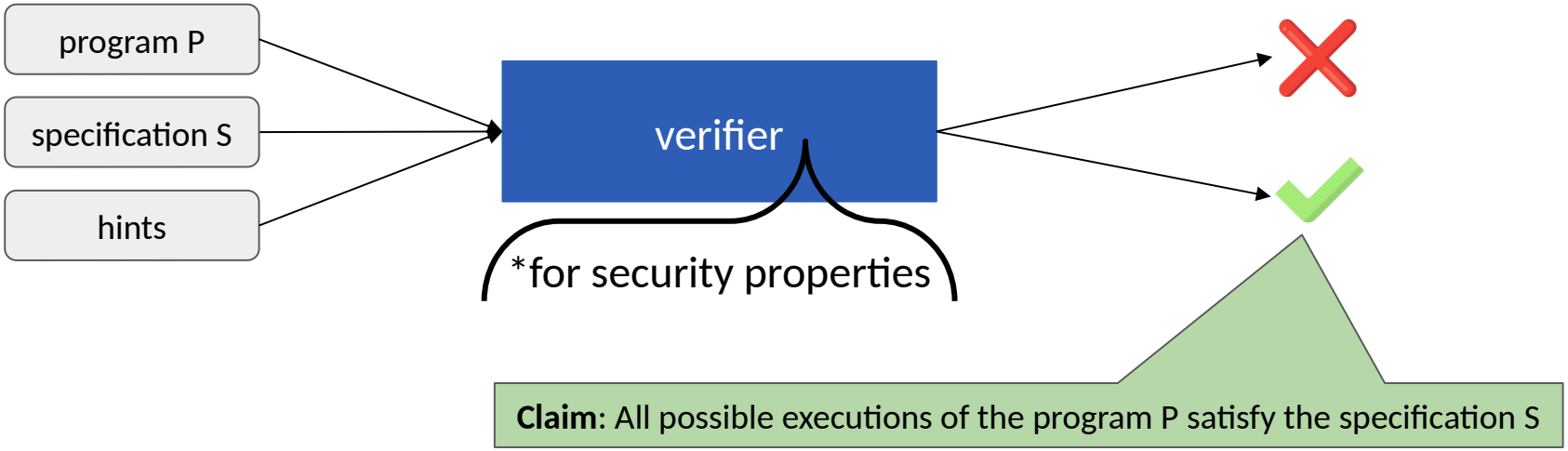
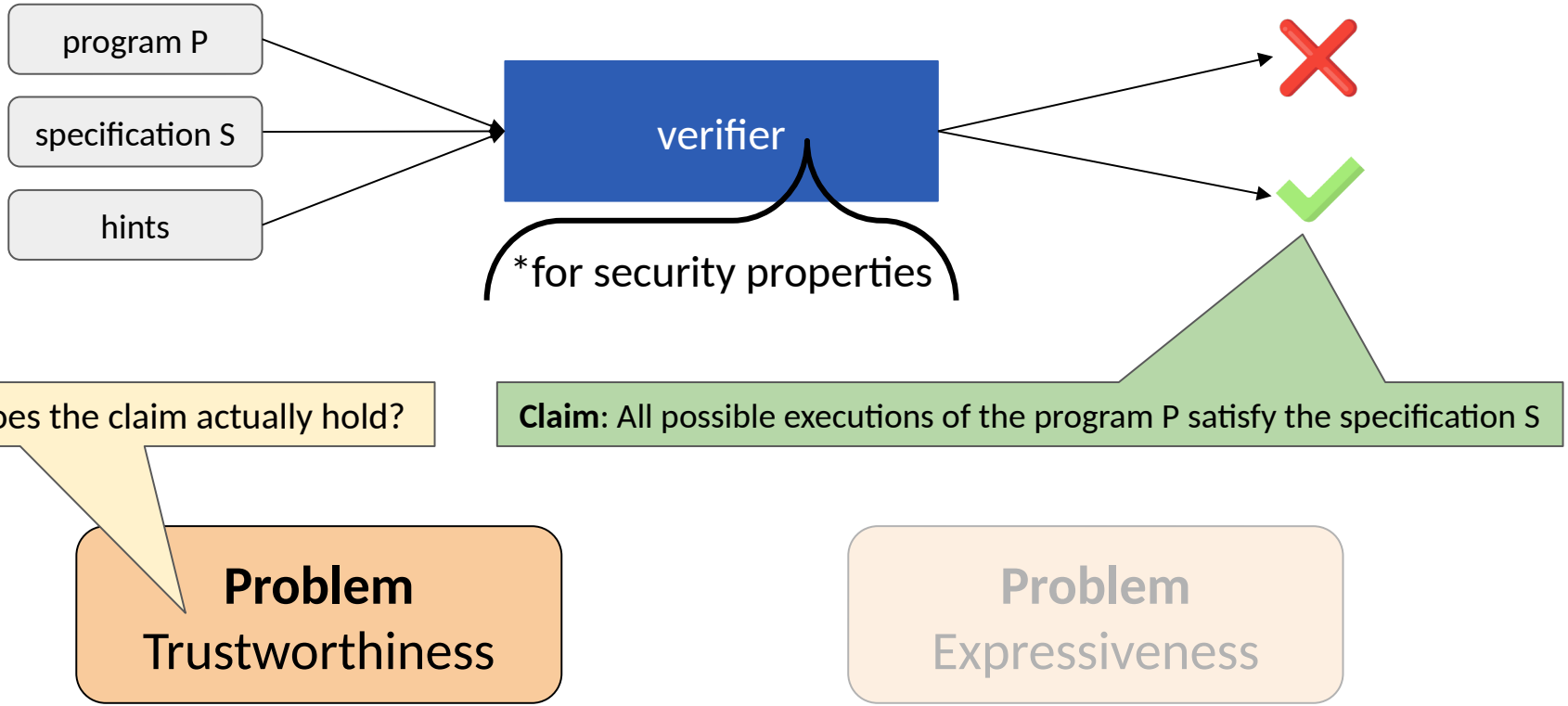


Problem
Trustworthiness

Problem
Expressiveness

Automated Verifiers



Problem: Unsoundnesses Occur Regularly

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RustanLeino opened last week

Dafny version

4.9.1

Code to produce this issue

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method Main() {
  var c: object;
  opaque
    ensures fresh(c)
  {
    c := new object;
  }
  assert false;
}
```

Command to run and resulting output

```
% dafny verify test.dfy

Dafny program verifier finished with 1 verified, 0 errors
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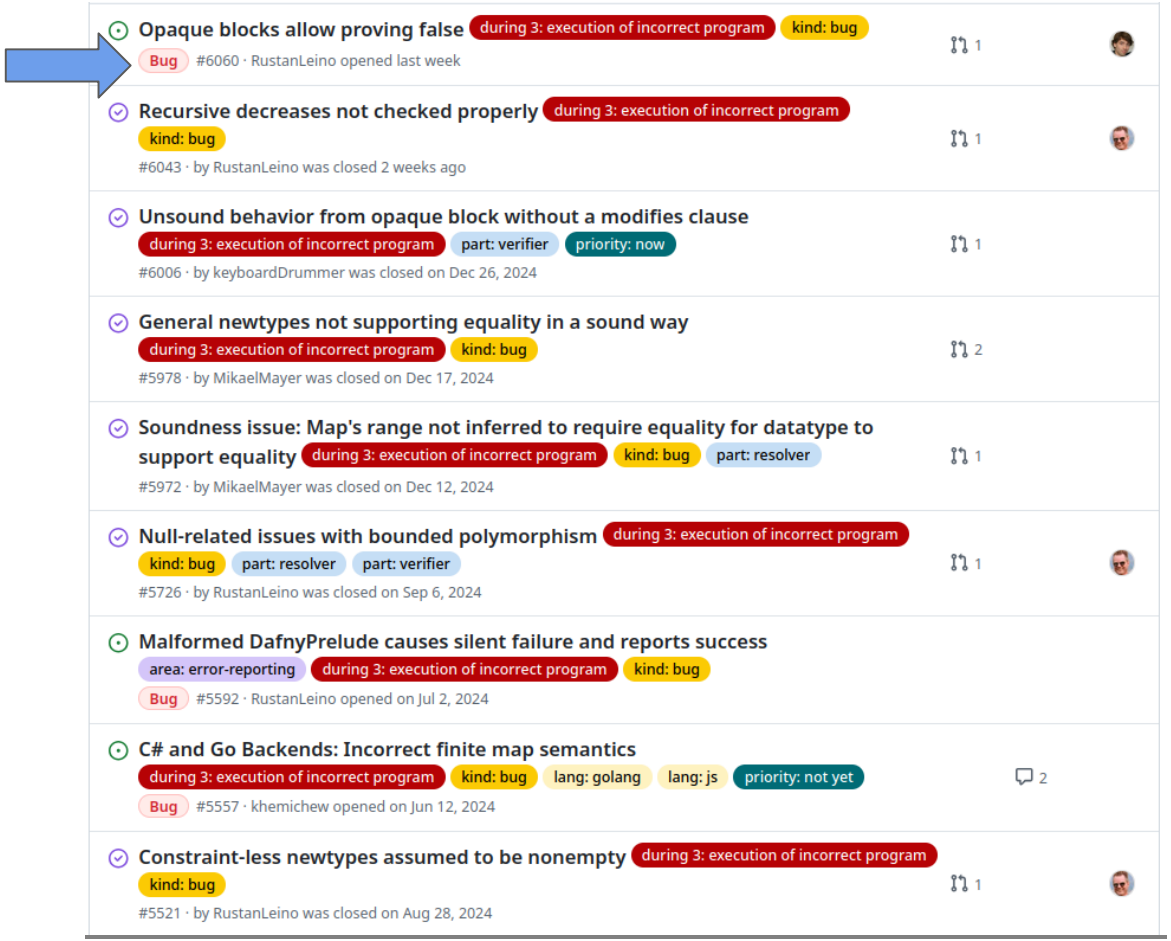

Opaque blocks allow proving false — during 3: execution of incorrect program, kind: bug
Bug #6060 · RustanLeino opened last week — 1

Recursive decreases not checked properly — during 3: execution of incorrect program, kind: bug
#6043 · by RustanLeino was closed 2 weeks ago — 1

Unsound behavior from opaque block without a modifies clause — during 3: execution of incorrect program, part: verifier, priority: now
#6006 · by keyboardDrummer was closed on Dec 26, 2024 — 1

General newtypes not supporting equality in a sound way — during 3: execution of incorrect program, kind: bug
#5978 · by MikaelMayer was closed on Dec 17, 2024 — 2

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#5972 · by MikaelMayer was closed on Dec 12, 2024 — 1

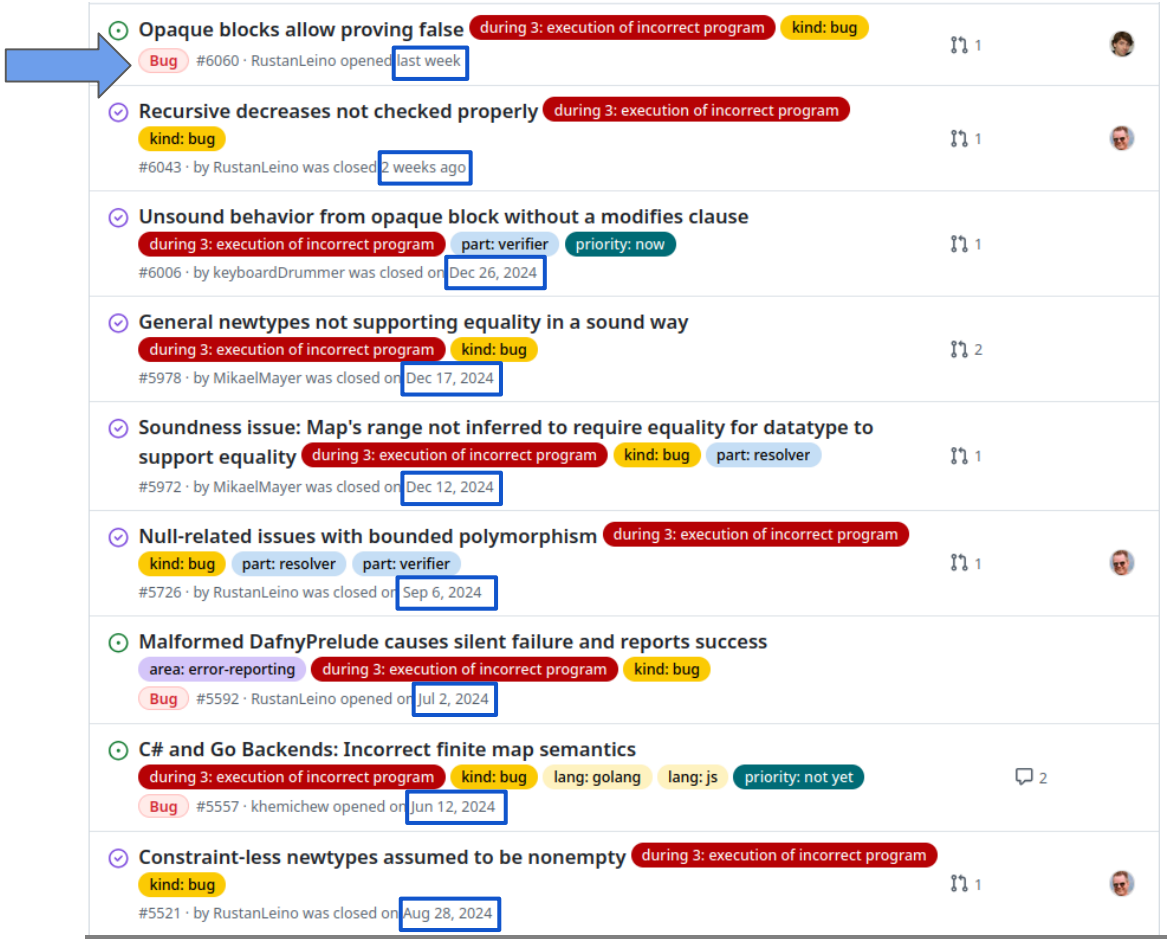
Null-related issues with bounded polymorphism — during 3: execution of incorrect program, kind: bug, part: resolver, part: verifier
#5726 · by RustanLeino was closed on Sep 6, 2024 — 1

Malformed DafnyPrelude causes silent failure and reports success — area: error-reporting, during 3: execution of incorrect program, kind: bug
Bug #5592 · RustanLeino opened on Jul 2, 2024

C# and Go Backends: Incorrect finite map semantics — during 3: execution of incorrect program, kind: bug, lang: golang, lang: js, priority: not yet
Bug #5557 · khemichew opened on Jun 12, 2024 — 2

Constraint-less newtypes assumed to be nonempty — during 3: execution of incorrect program, kind: bug
#5521 · by RustanLeino was closed on Aug 28, 2024 — 1

Problem: Unsoundnesses Occur Regularly



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- **Unsoundness due to bad simplification** `kind/unsoundness`
  #3213 · by mtzguido was closed on Feb 9, 2024
- **Some problems with reflection and simplification of equalities** `component/tactics` `kind/unsoundness`
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- **F* should disallow degenerate effects** `kind/unsoundness`
  #2659 · 857b opened on Jul 25, 2022
- **A soundness issue?** `kind/unsoundness` `priority/high` `status/has-pr`
  #2072 · by wintersteiger was closed on Dec 15, 2020
- **`WellFounded.axiom1` is incompatible with universe-free SMT encoding** `component/smtencoding` `component/universes` `kind/bug` `kind/unsoundness` `priority/high`
  #2069 · by mtzguido was closed on Jan 14, 2021
- **Non-total layered effects reifying as total?** `component/effect-system` `kind/bug` `kind/unsoundness`
  #2055 · by mtzguido was closed on Jun 1, 2020
- **Incorrect handling of machine signed integers** `component/extraction` `component/libraries` `kind/unsoundness` `milestone/everest-v1` `priority/high` `status/has-pr`
  #1803 · by msprotz was closed on Mar 16, 2020

Problem: Unsoundnesses Occur Regularly

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  #2072 · by wintersteiger was closed on Dec 15, 2020
- **`WellFounded.axiom1` is incompatible with universe-free SMT encoding** component/smtencoding component/universes kind/bug kind/unsoundness priority/high
  #2069 · by mtzguido was closed on Jan 14, 2021
- **Non-total layered effects reifying as total?** component/effect-system kind/bug kind/unsoundness
  #2055 · by mtzguido was closed on Jun 1, 2020
- **Incorrect handling of machine signed integers** component/extraction component/libraries kind/unsoundness milestone/everest-v1 priority/high status/has-pr
  #1803 · by msprotz was closed on Mar 16, 2020

- **Unsoundness related to QPs with unsatisfiable conditions** quantified-permissions unsoundness
  #842 · by marcoeilers was closed on May 6, 2024
- **Unsound behavior with QPs without condition** quantified-permissions unsoundness
  #833 · by marcoeilers was closed on May 5, 2024
- **Errors caused by refute statement inside of loop with goto** bug unsoundness
  #773 · by bruggerl was closed on Nov 10, 2023
- **Unsoundness due to loop invariant** bug unsoundness
  #740 · by bruggerl was closed on Aug 14, 2023
- **Exhaling an empty QP allows asserting false** bug critical quantified-permissions unsoundness
  #688 · by vakaras was closed on Mar 13, 2023
- **Unsoundness with quantified permissions** bug duplicate quantified-permissions unsoundness
  #636 · by zgrannan was closed on Sep 2, 2022
- **Silicon verifies example that should fail.** unsoundness
  #630 · by zgrannan was closed on Jul 20, 2022
- **Unsoundness: a heap dependent function is instantiated even when its precondition does not hold** bug functions major unsoundness
  #376 · by viper-admin was closed on Nov 25, 2022
- **Strange behaviour of unconstrained quantified permissions** bug critical quantified-permissions unsoundness
  #342 · by viper-admin was closed on Nov 25, 2022

Problem 1
Trustworthiness

Problem 2
Expressiveness

Problem 1
Trustworthiness

How can we ensure that automated verifiers are **sound**?

Problem 2
Expressiveness

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Trustworthiness

How can we ensure that automated verifiers are **sound**?

Problem 2
Expressiveness

What about **security** properties?

My Research

Build **provably sound** and **automated** deductive verifiers for **advanced properties**.

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Provably sound and automated verifier based on *separation logic*

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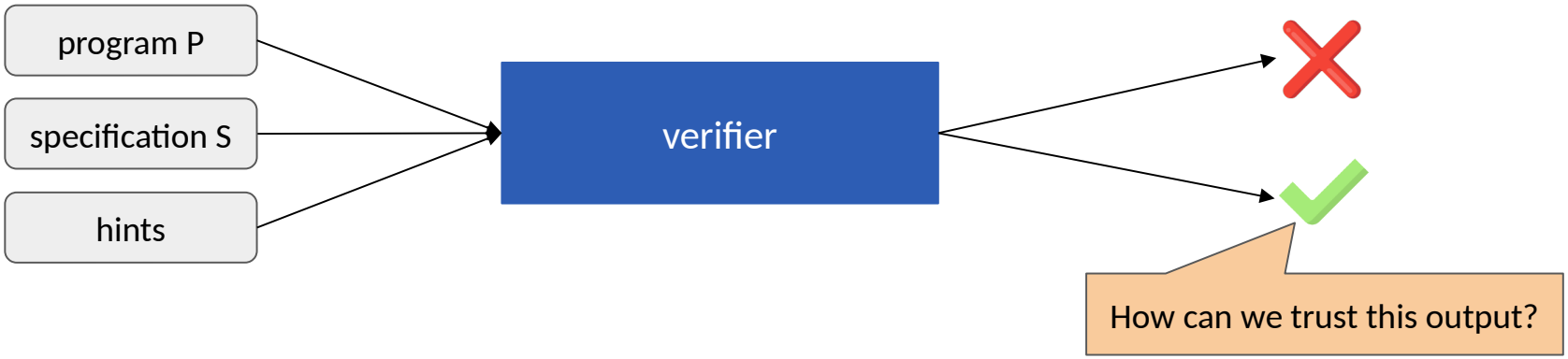
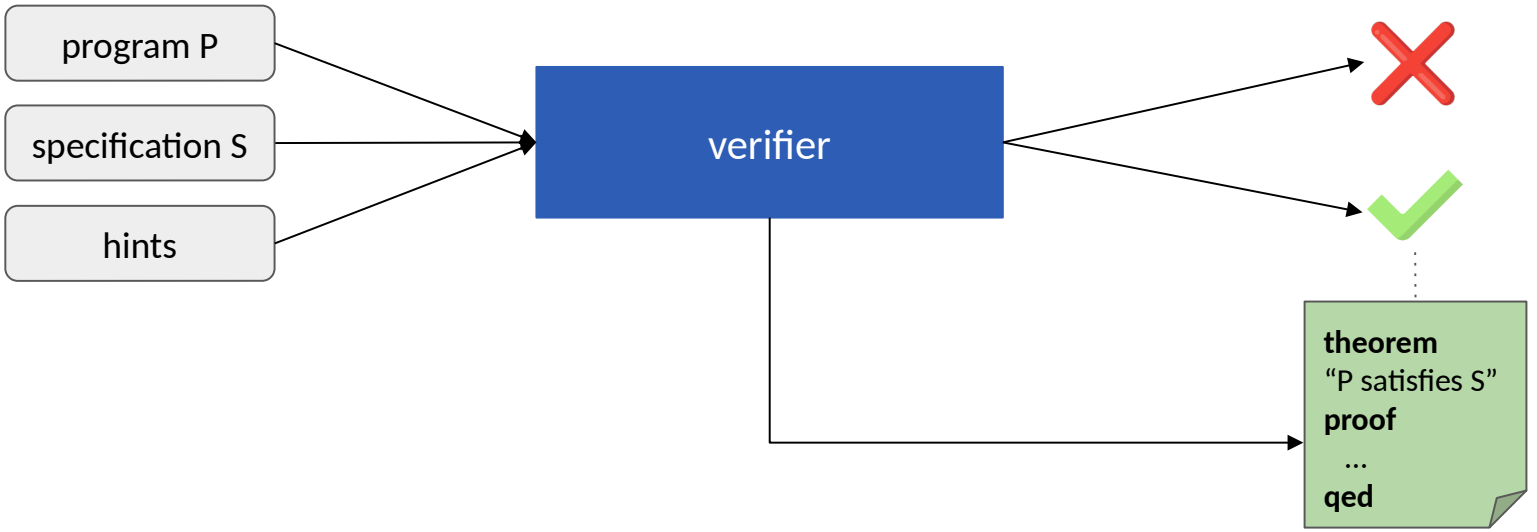
Automated verifier for arbitrary *hyperproperties*

A Trustworthy Automated Verifier

A Trustworthy Automated Verifier



A Trustworthy Automated Verifier



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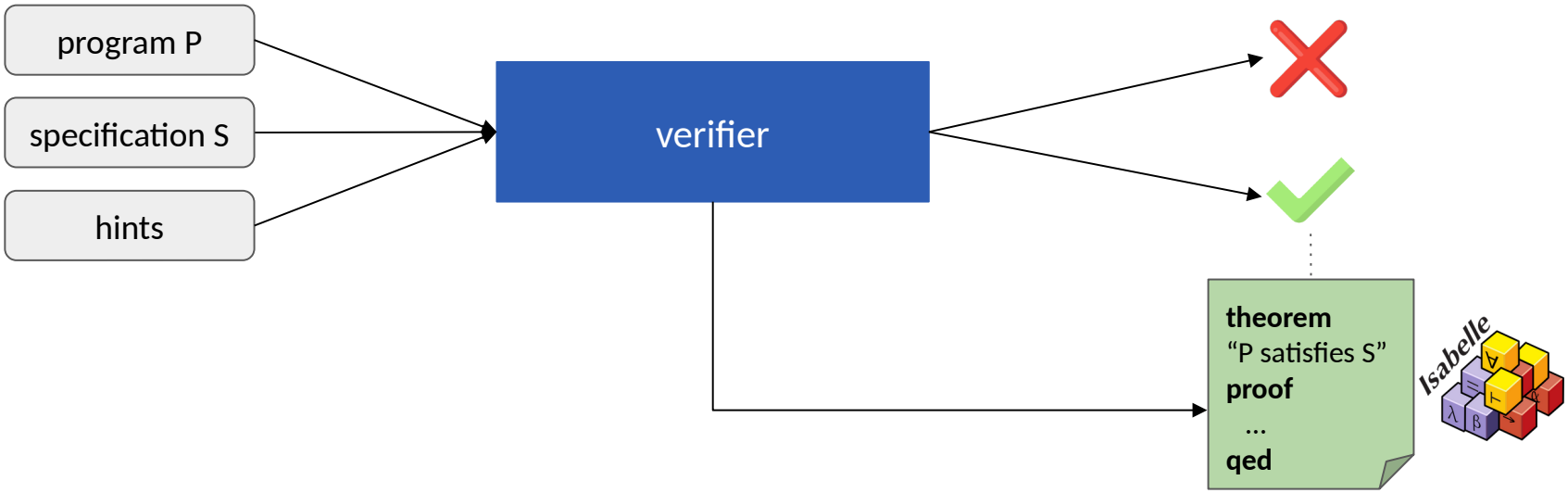

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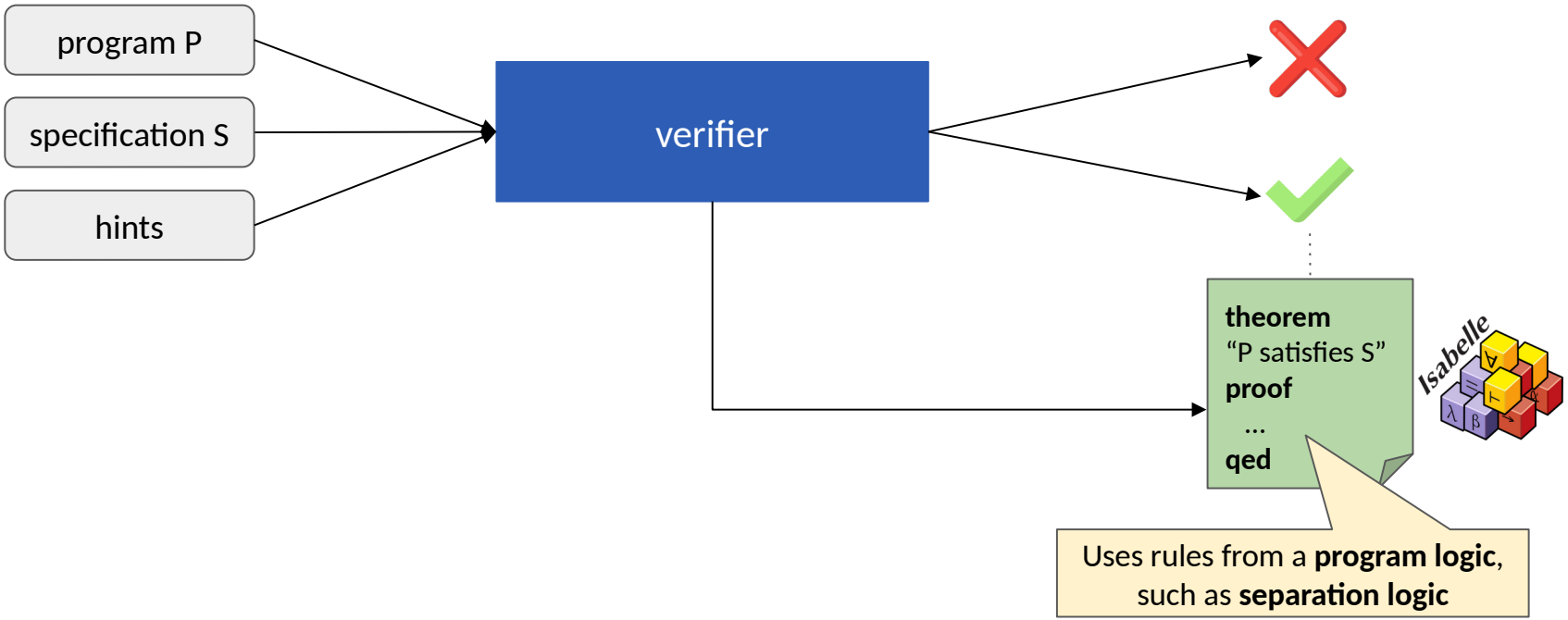

Separation Logic 101

Separation logic: state-of-the-art program logic that enables **modular** reasoning about sequential and concurrent programs that manipulate the heap.

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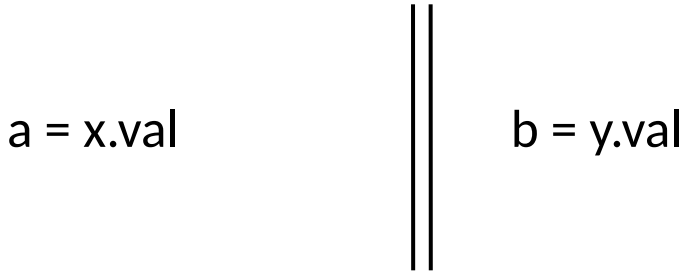

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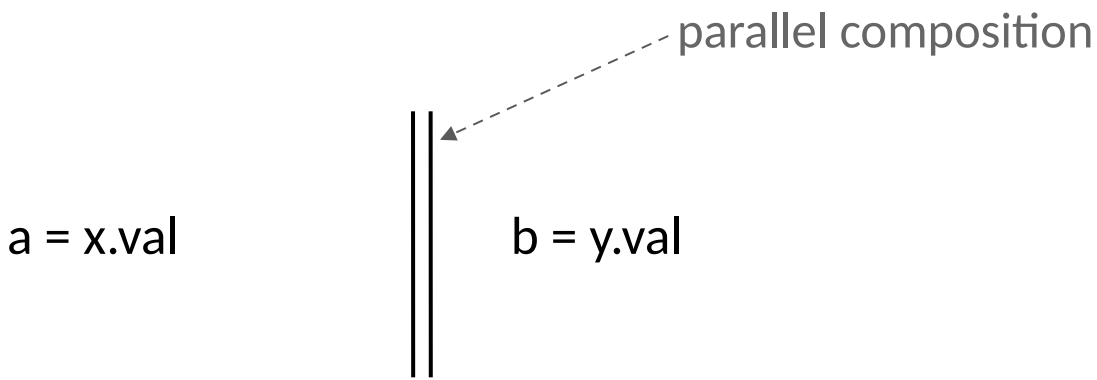

Separation Logic 101

Separation logic: state-of-the-art program logic that enables **modular** reasoning about sequential and concurrent programs that manipulate the heap.

$\{x.val \mapsto 5 * y.val \mapsto 7\}$

a = x.val

b = y.val

$\{x.val \mapsto 5 * a = 5 * y.val \mapsto 7 * b = 7\}$

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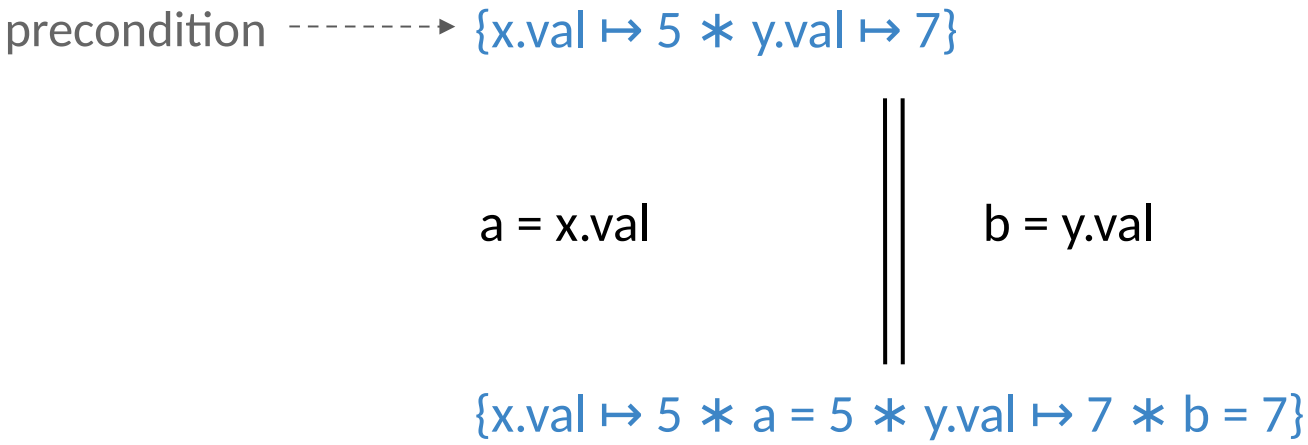

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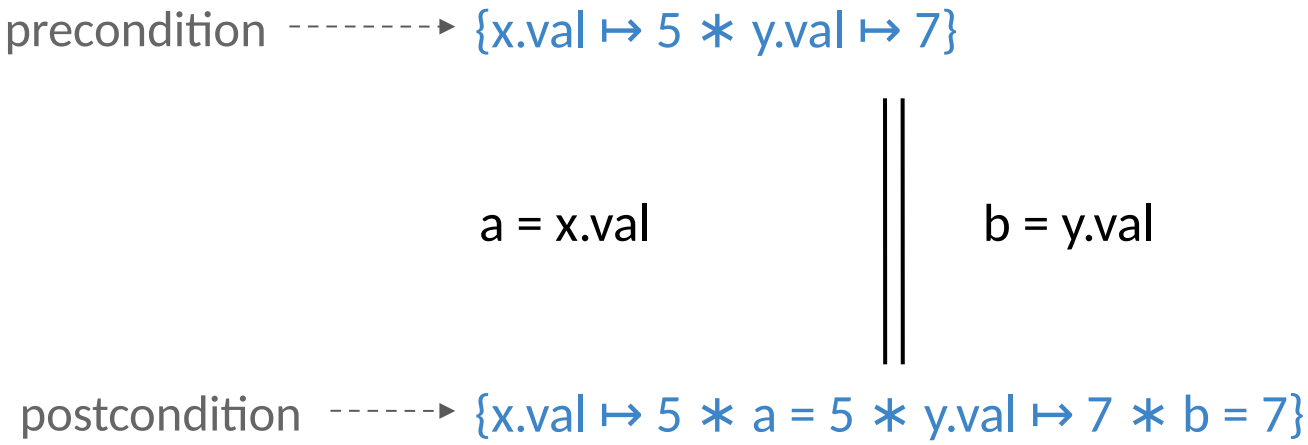

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separating conjunction
conjuncts hold on *disjoint* parts of the heap

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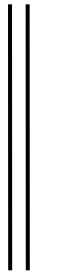
represents **ownership**
required to read and write

separating conjunction
conjuncts hold on *disjoint* parts of the heap

$\{x.val \mapsto 5 * y.val \mapsto 7\}$



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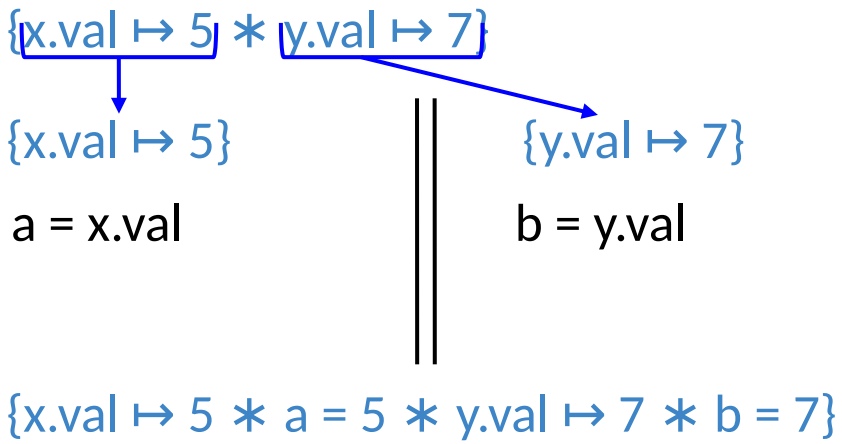

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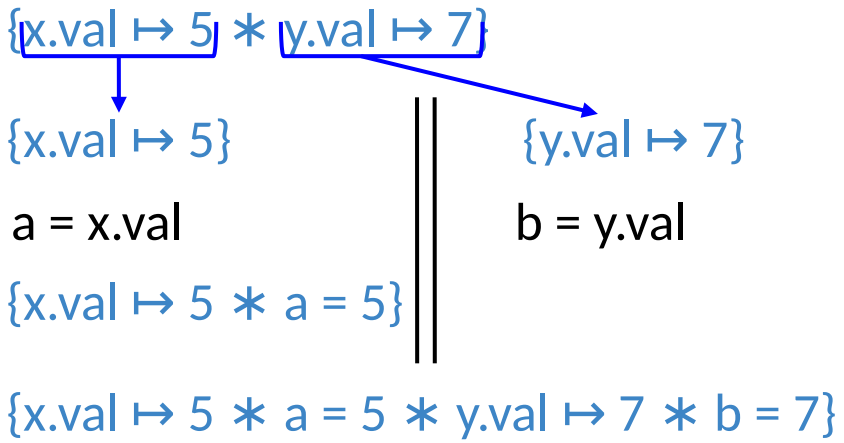

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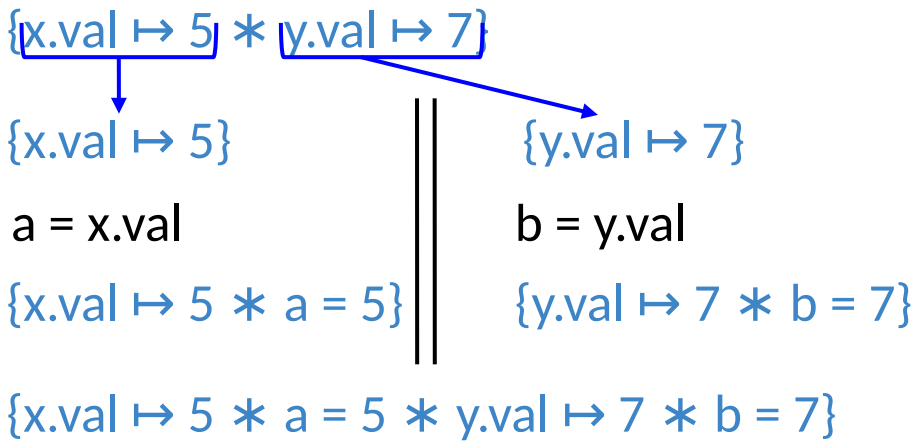

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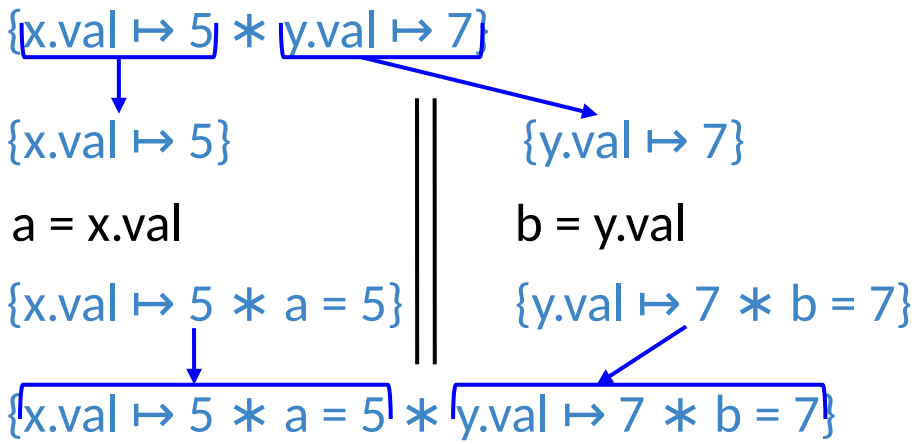

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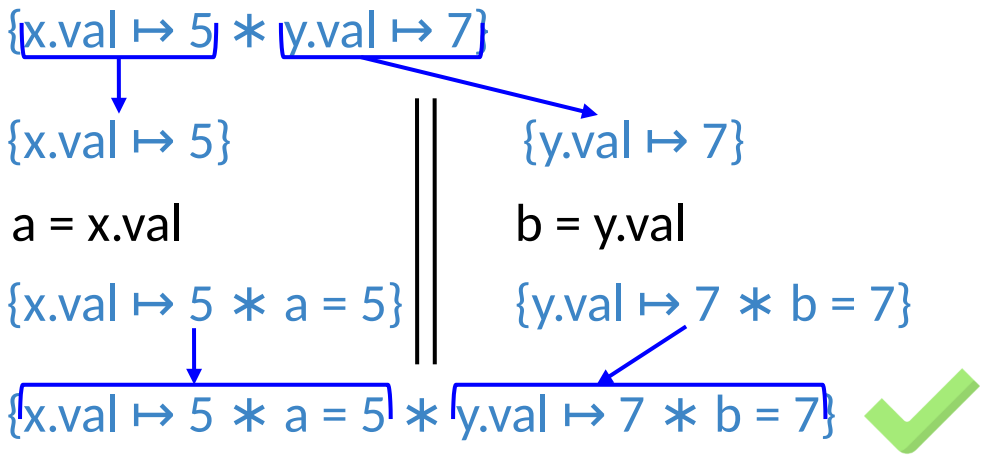
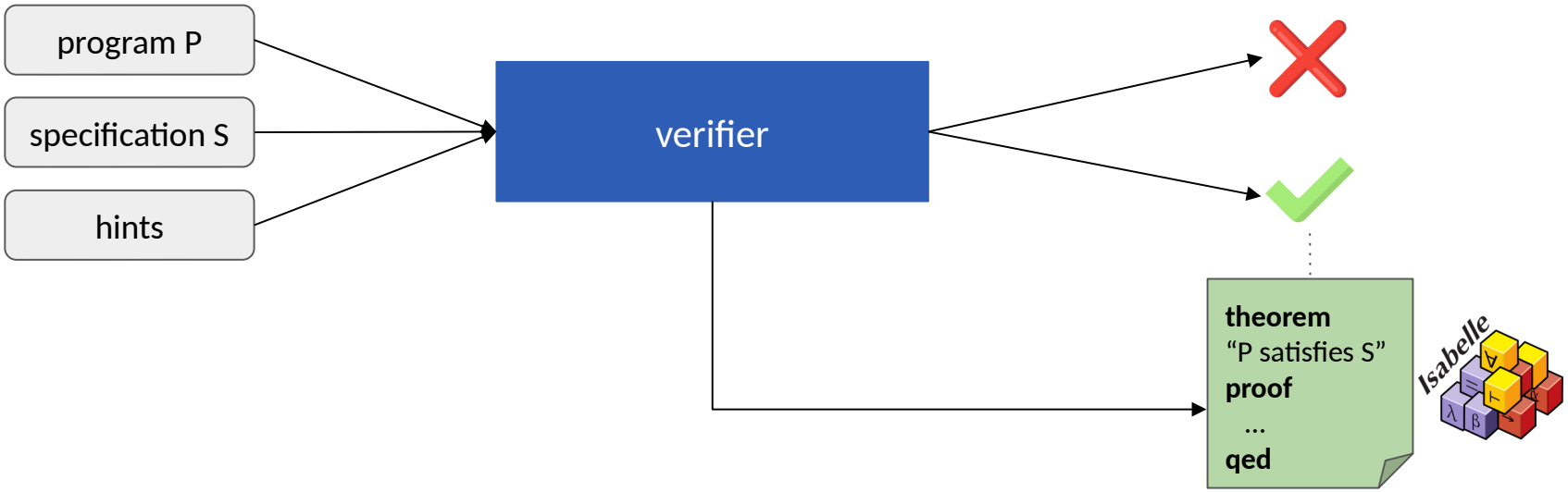


A Trustworthy Automated Verifier



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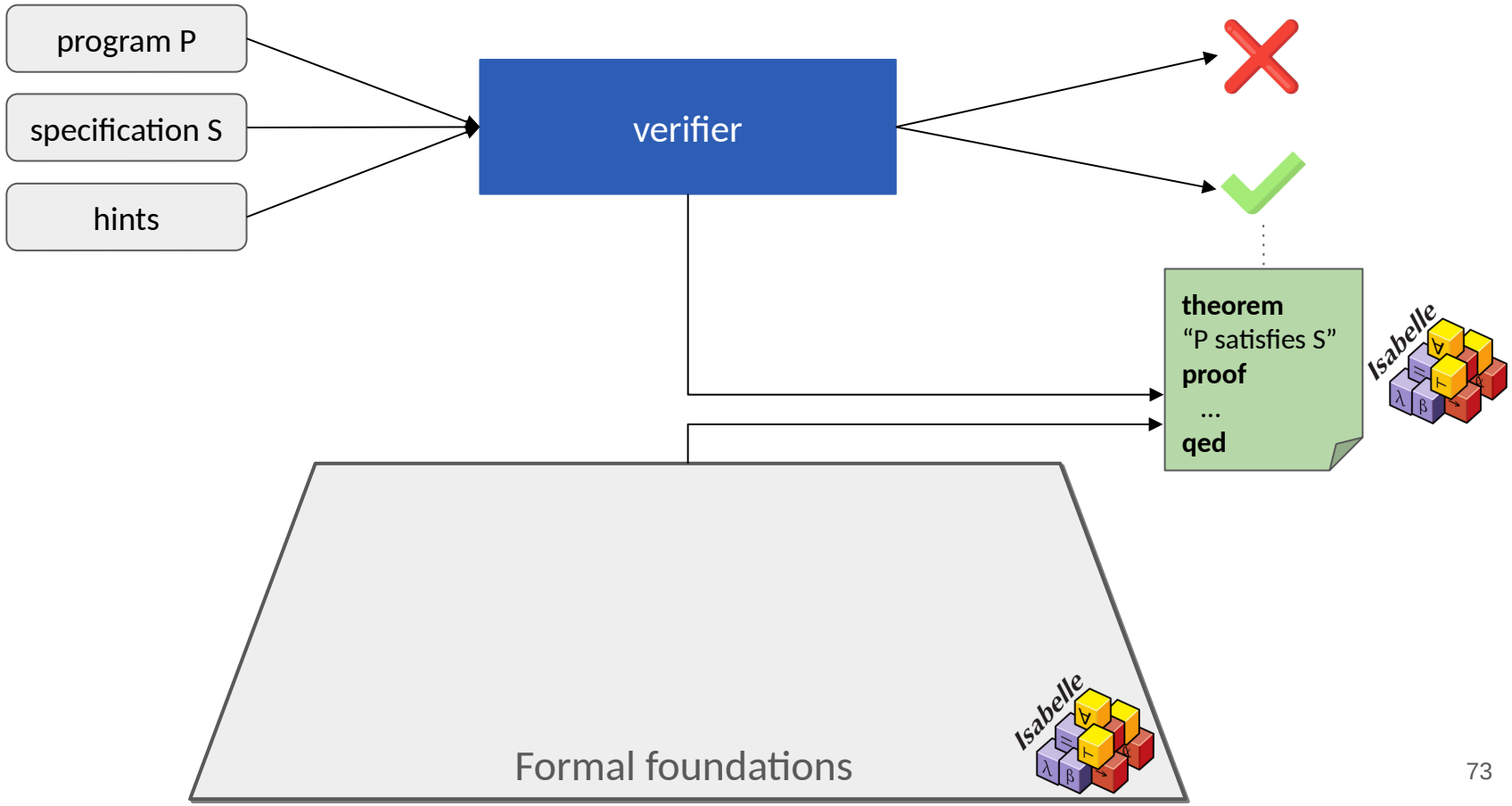

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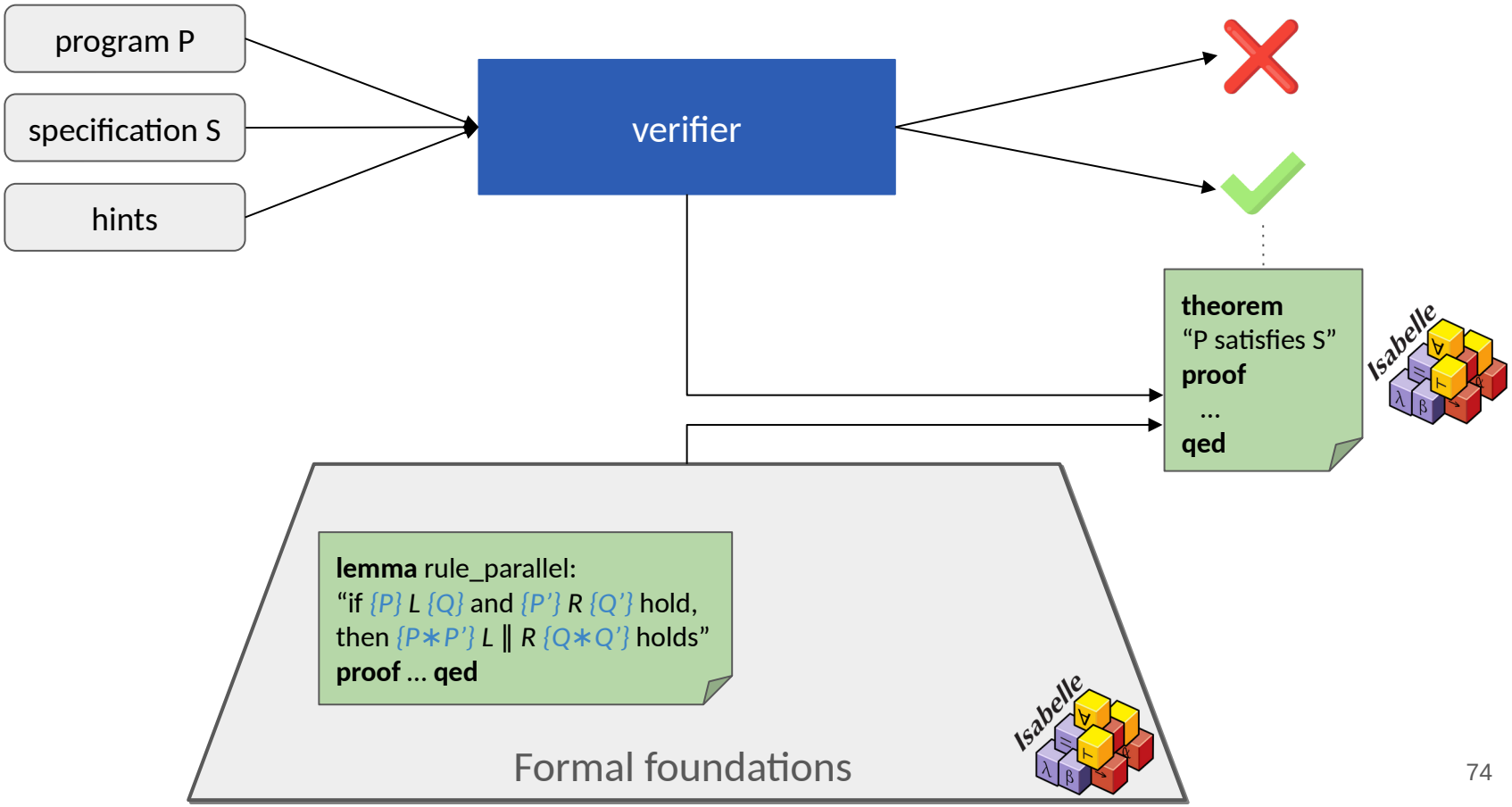

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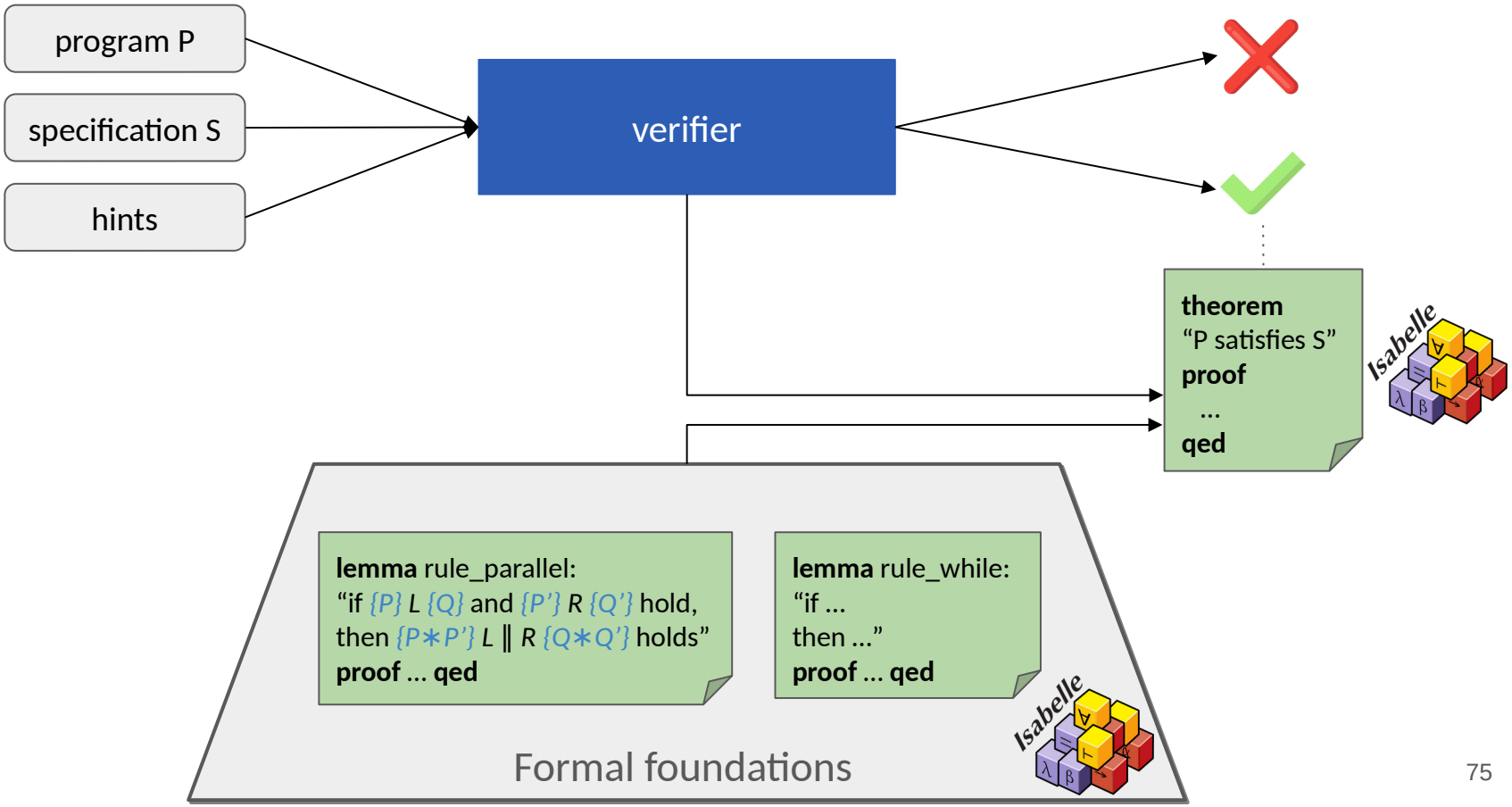

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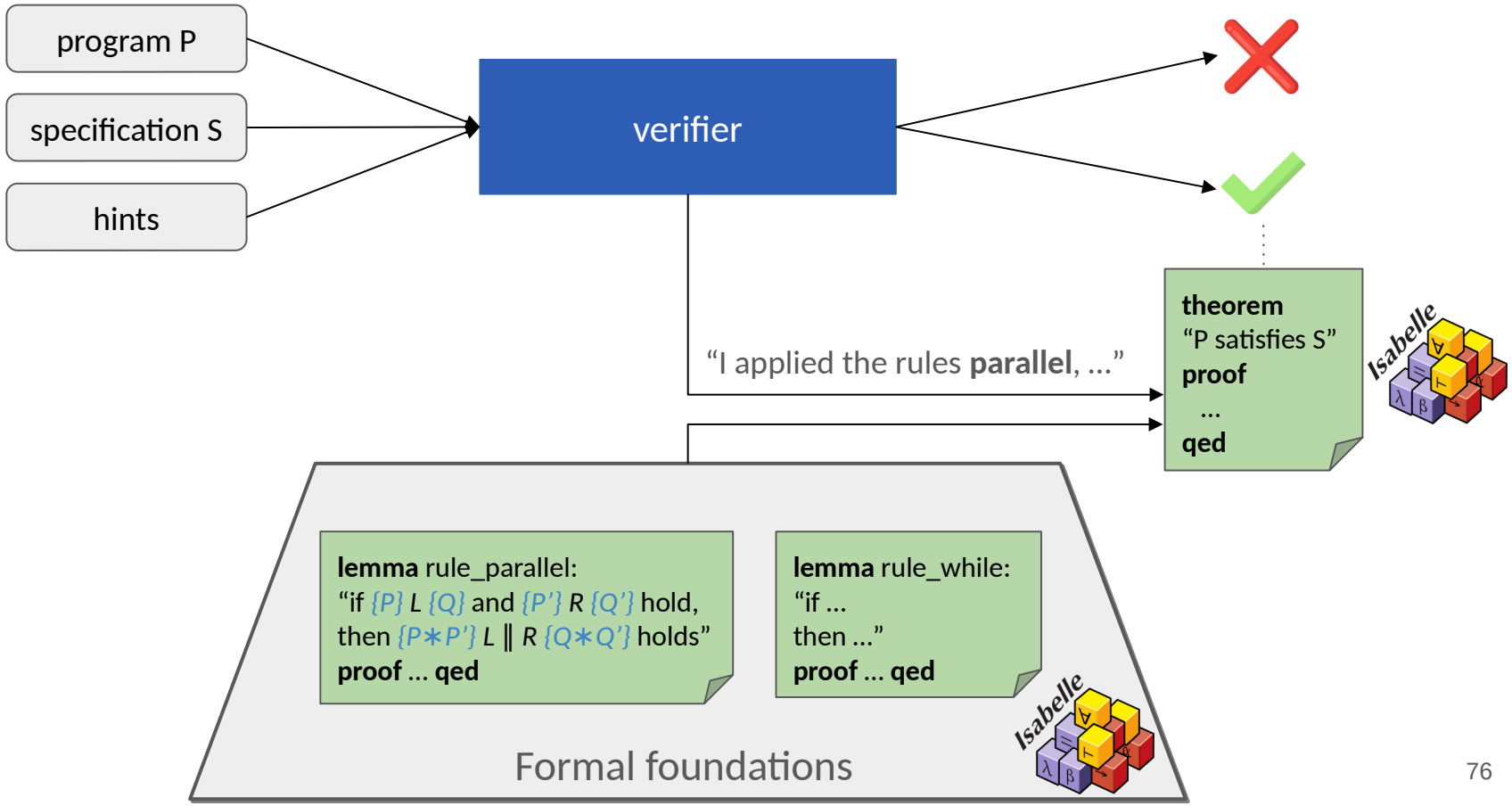

Formal Foundations for Automated Separation Logic Verifiers

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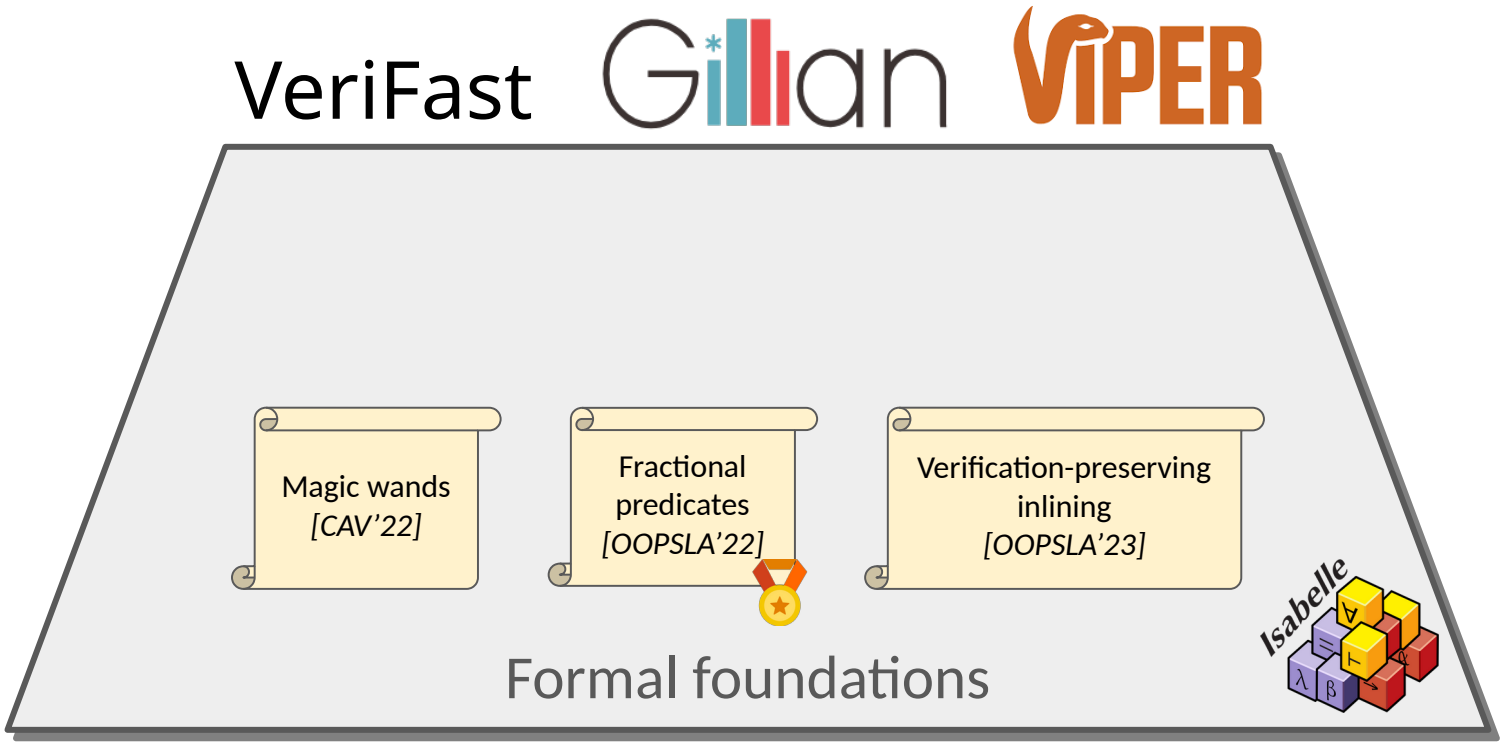

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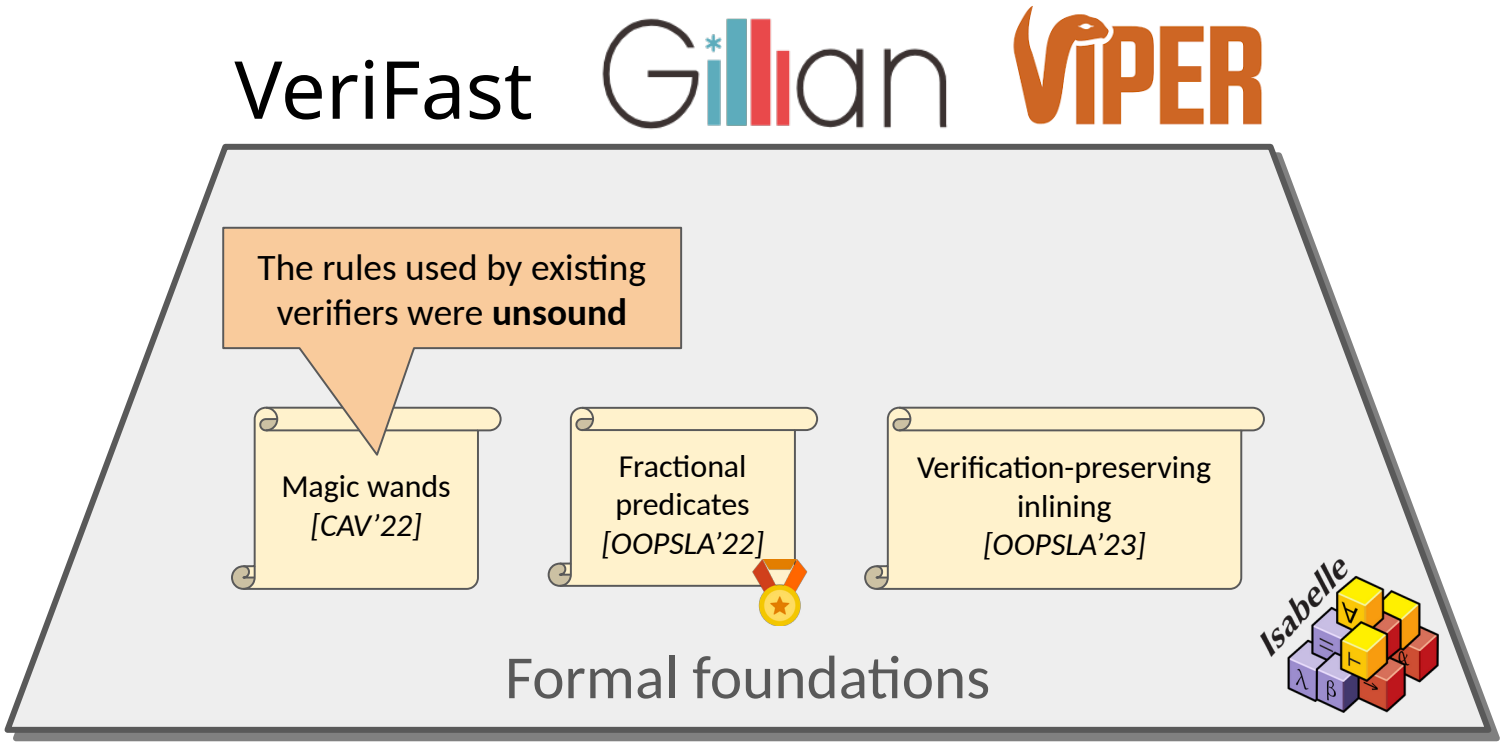

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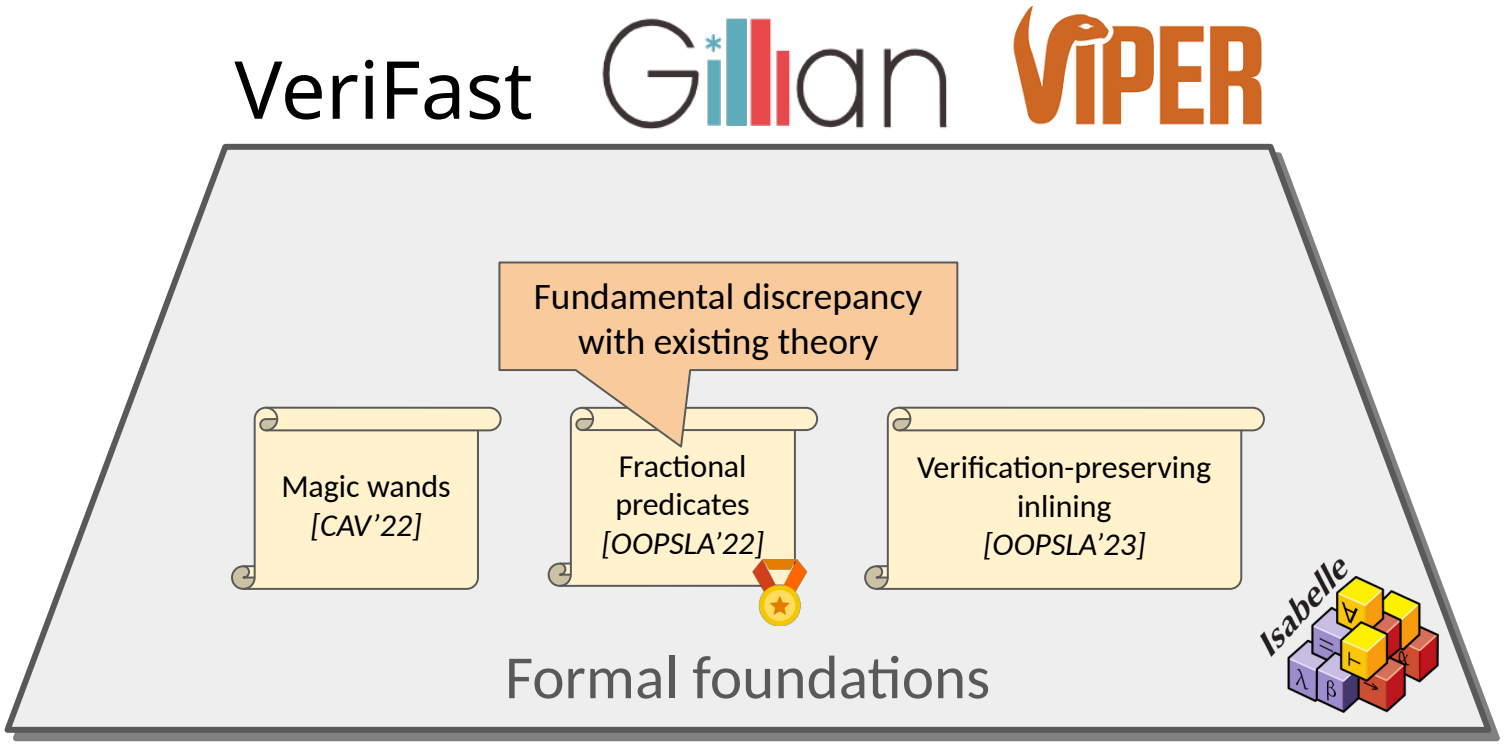

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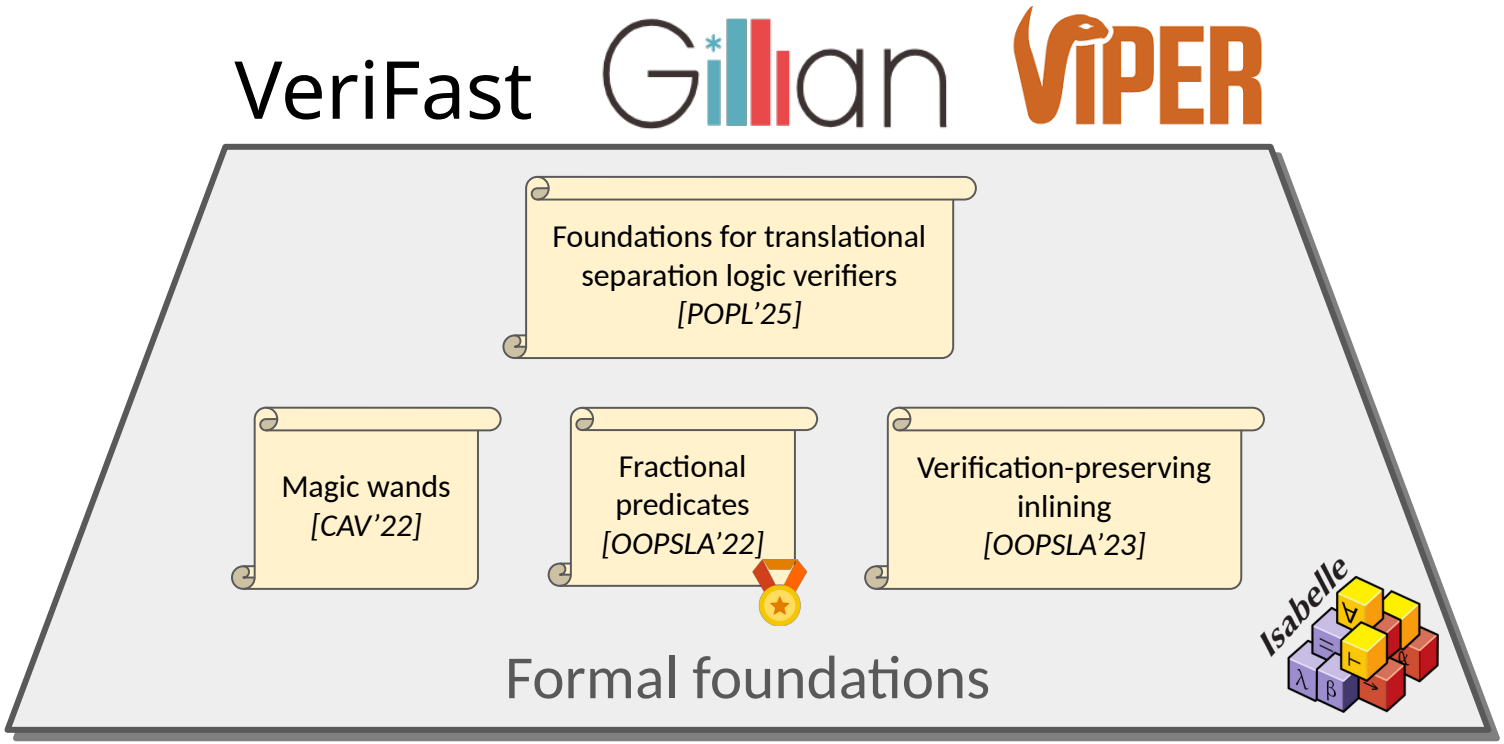

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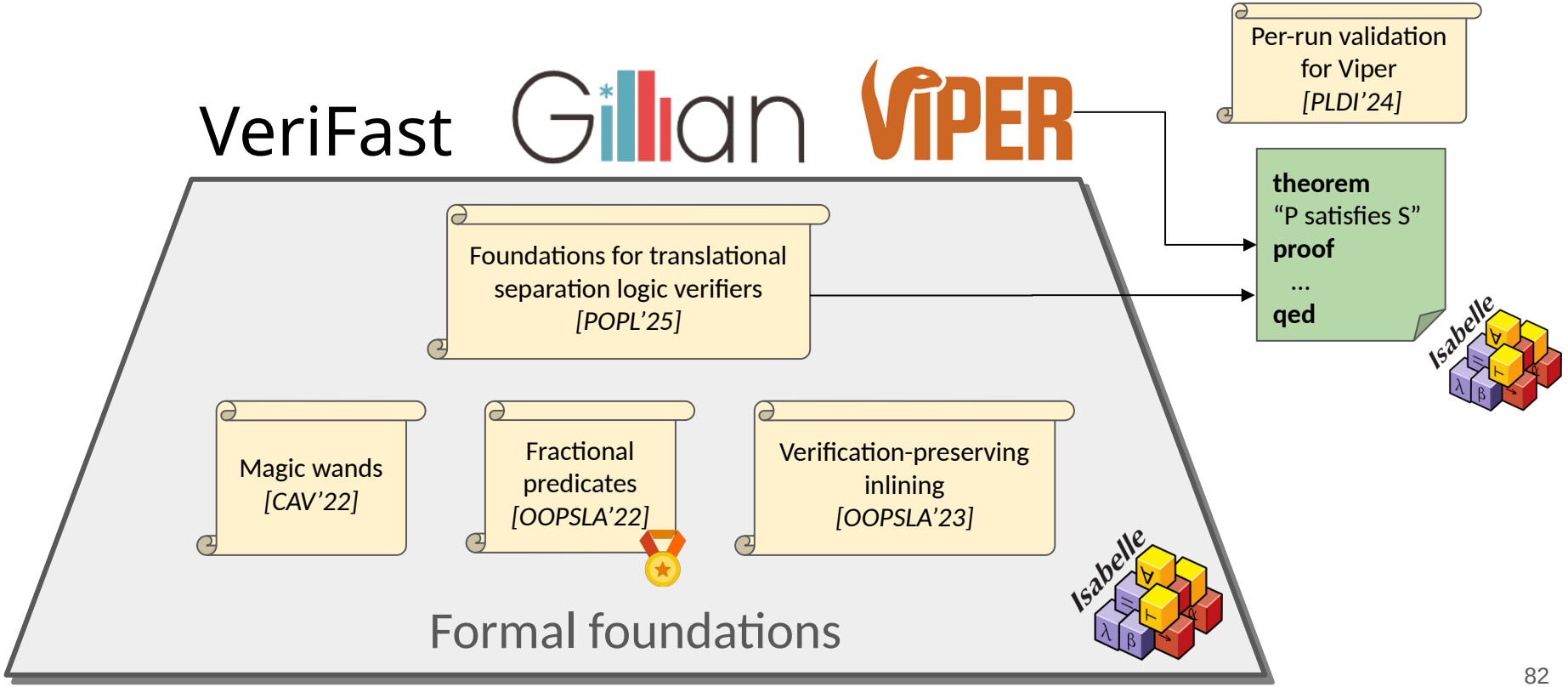

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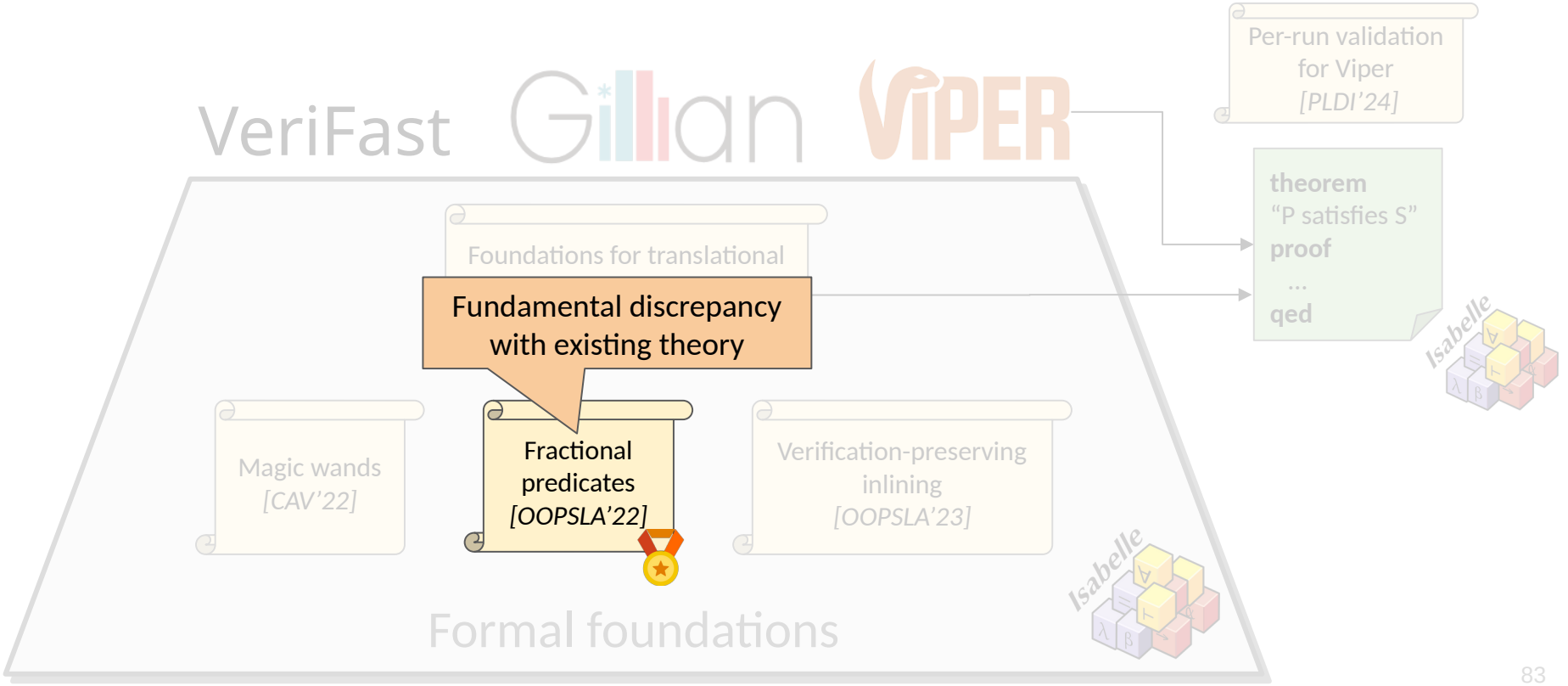
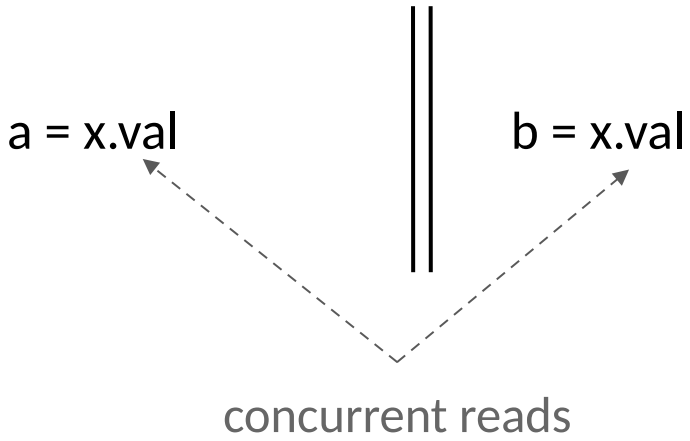


Fractional Permissions



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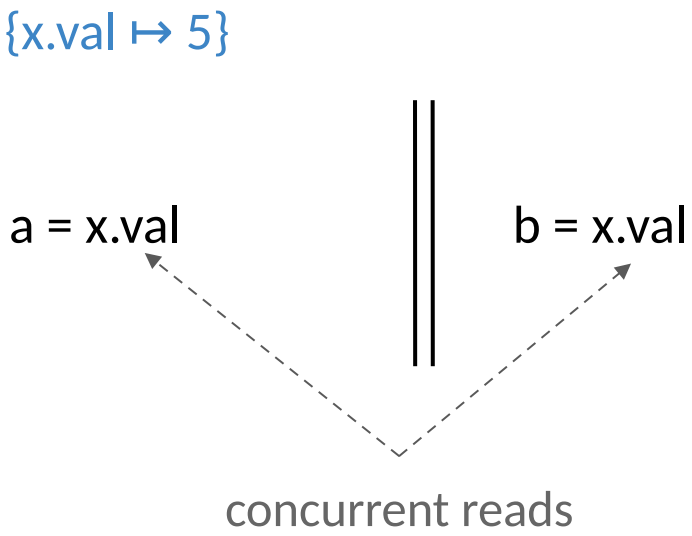

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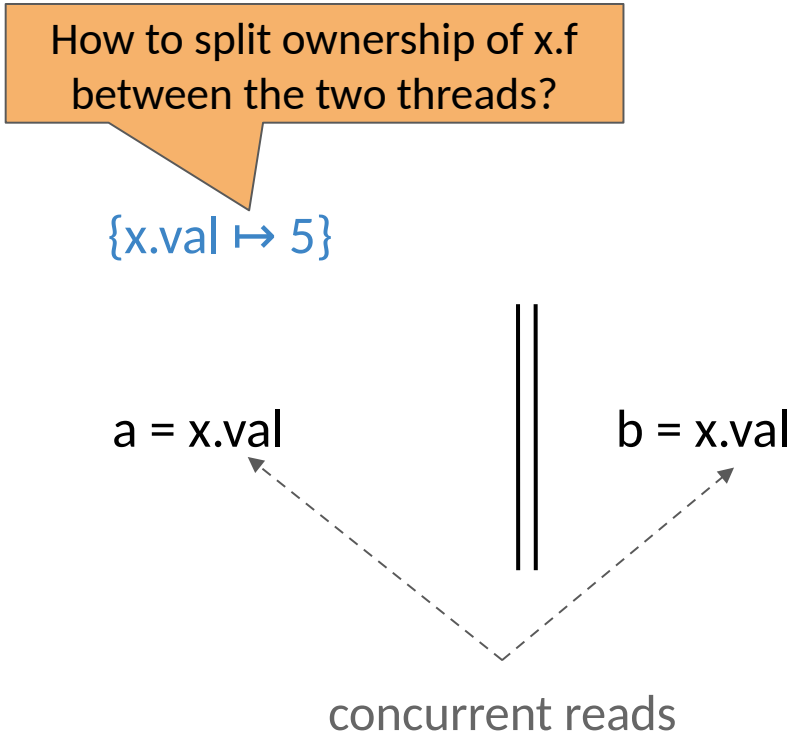

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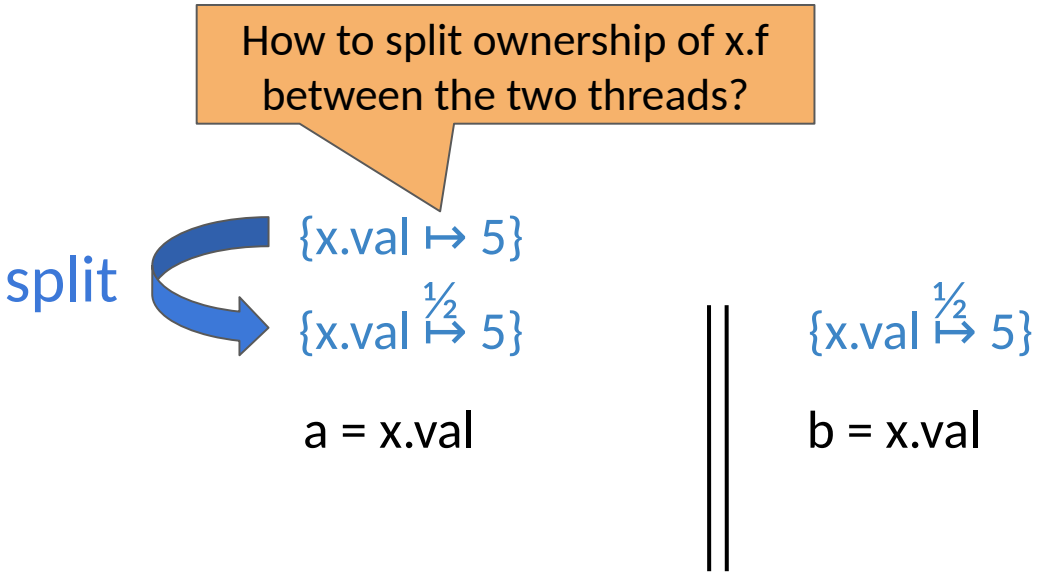

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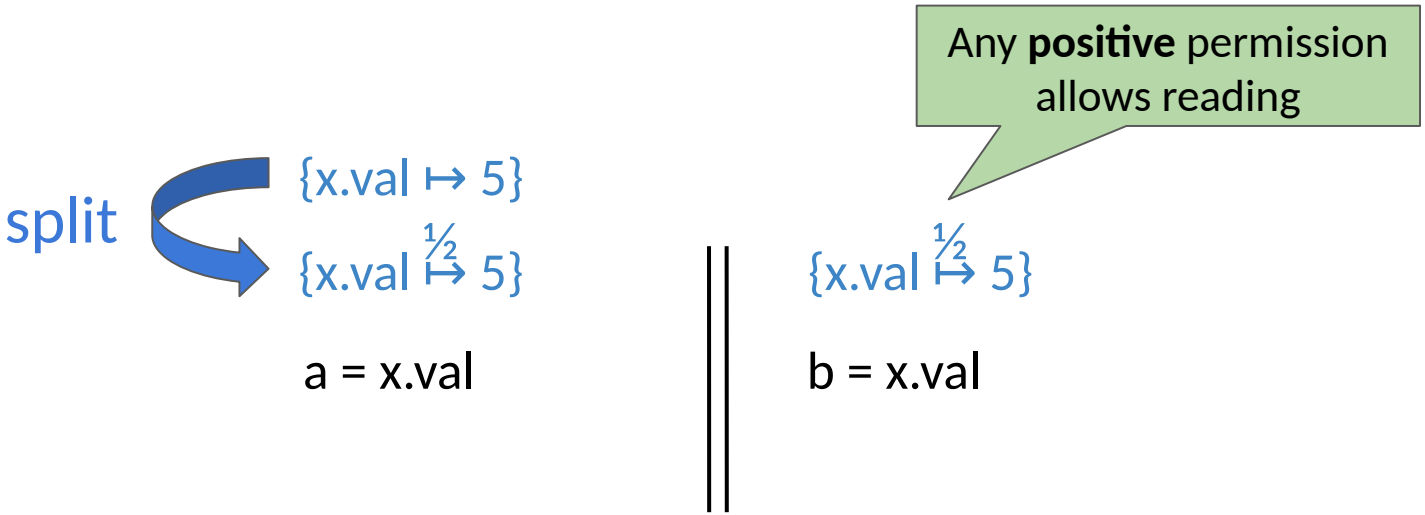

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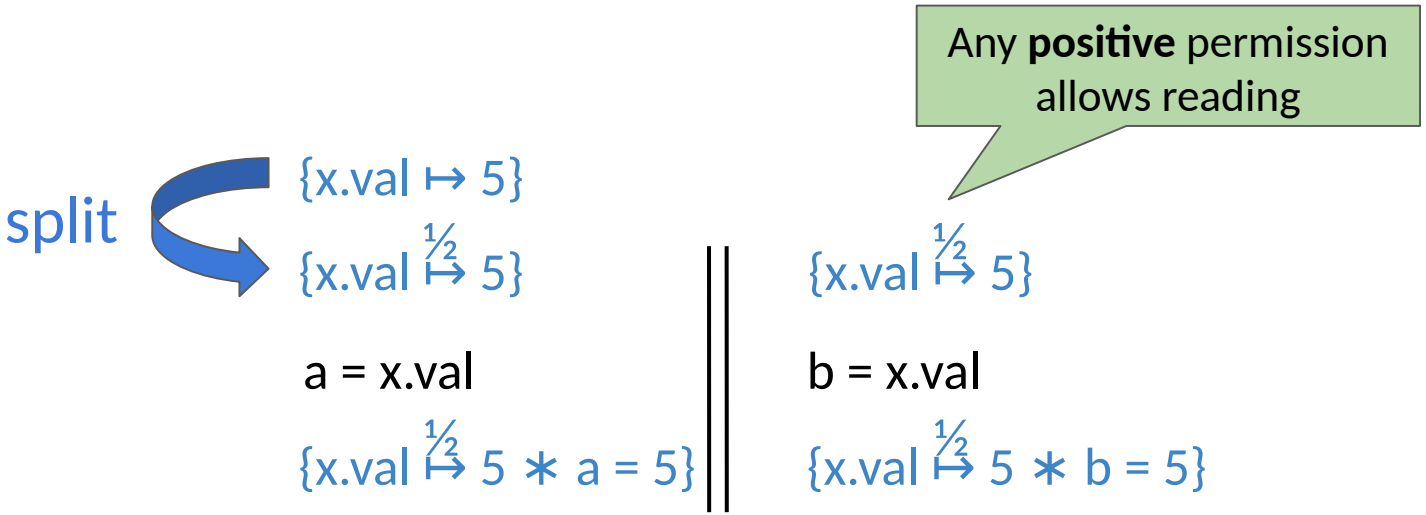

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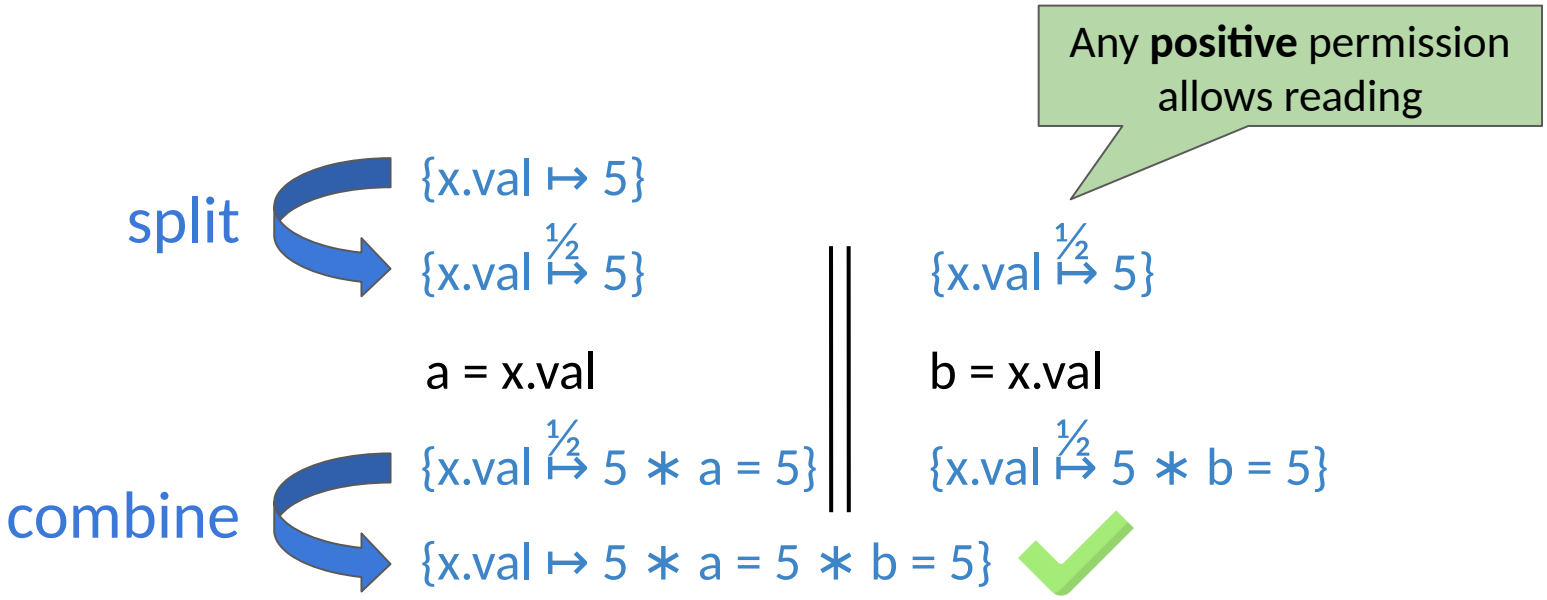
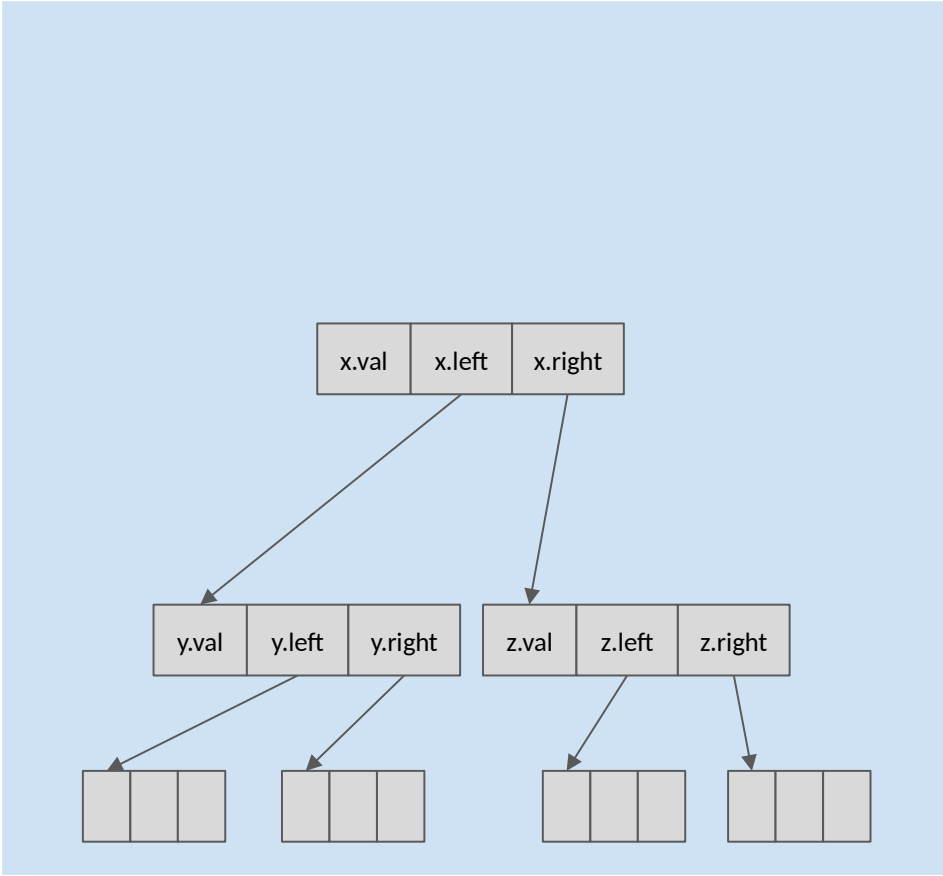


Fractional Predicates



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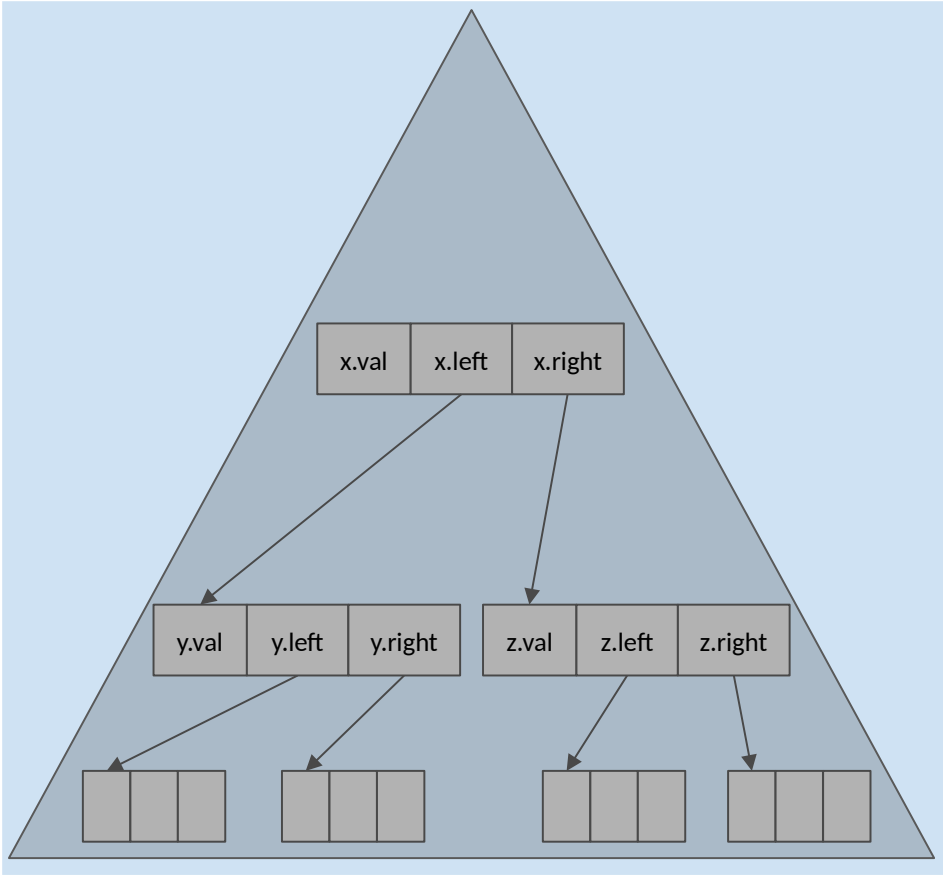
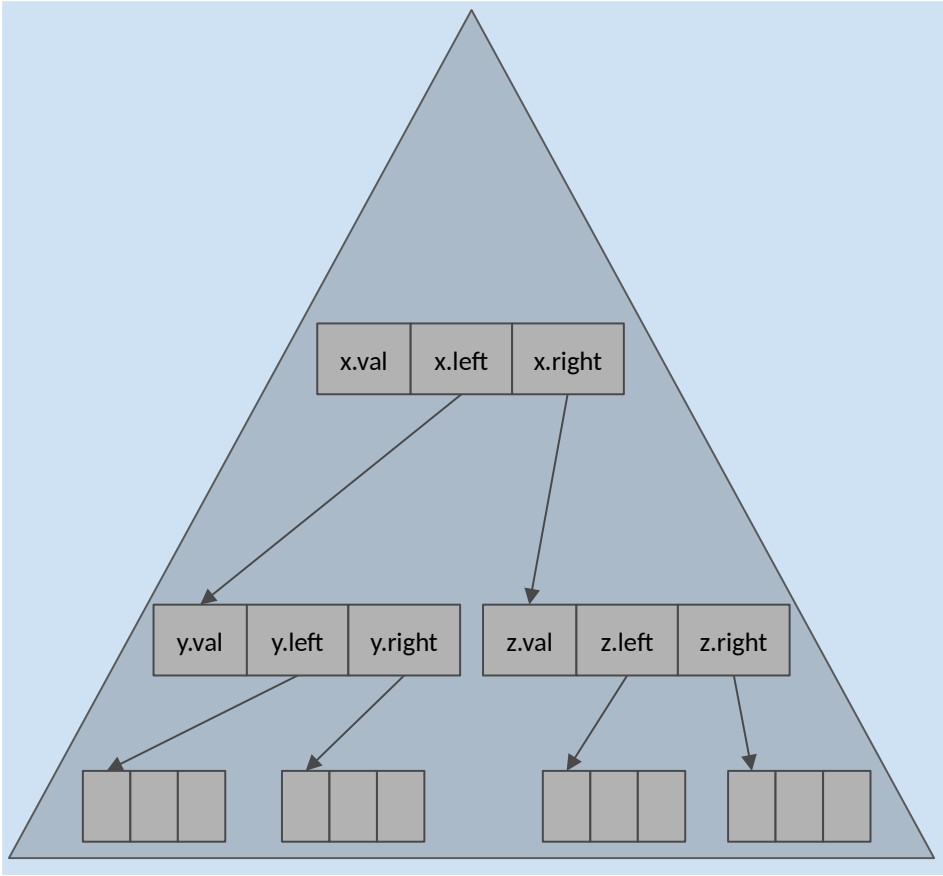


$$\text{tree}(x) \triangleq (x = \textbf{null} \vee (x.\text{val} \mapsto \_ * (\exists l, r.\ x.\text{left} \mapsto l * x.\text{right} \mapsto r * \text{tree}(l) * \text{tree}(r))))$$

Fractional Predicates

Permits to **read** and **write** nodes

tree(x)



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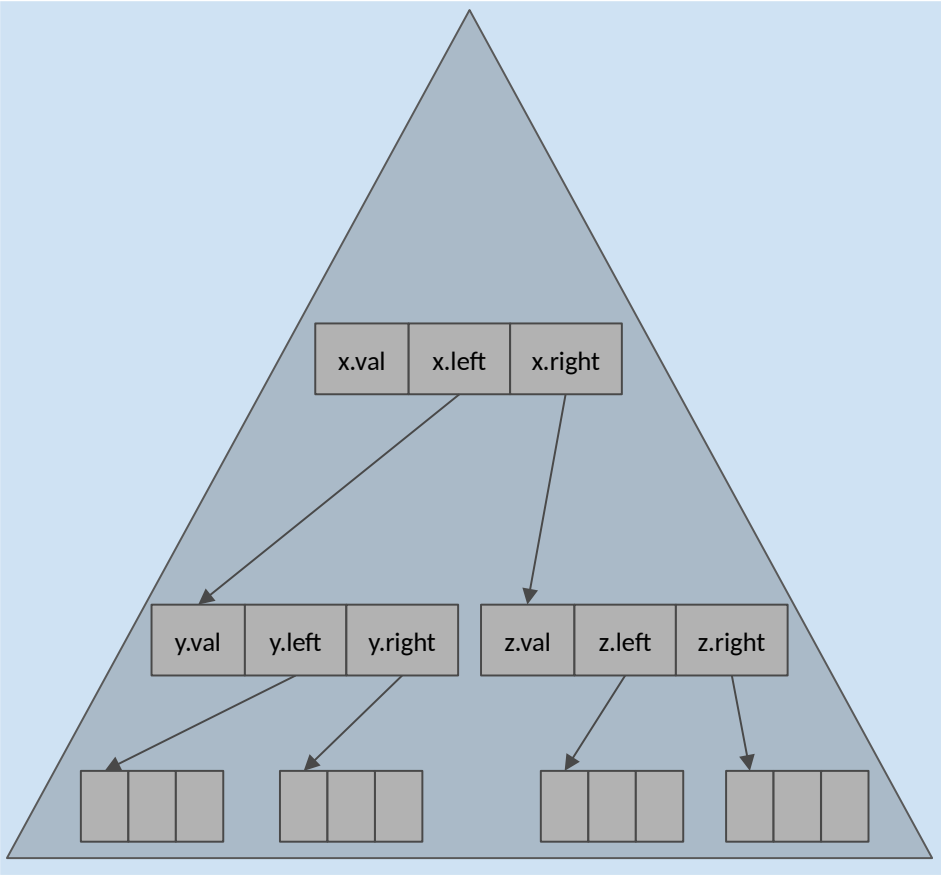
α ⊙ tree(x)



tree(x) ≜ (x = **null** ∨ (x.val ↦ _ ∗ (∃l, r. x.left ↦ l ∗ x.right ↦ r ∗ tree(l) ∗ tree(r))))

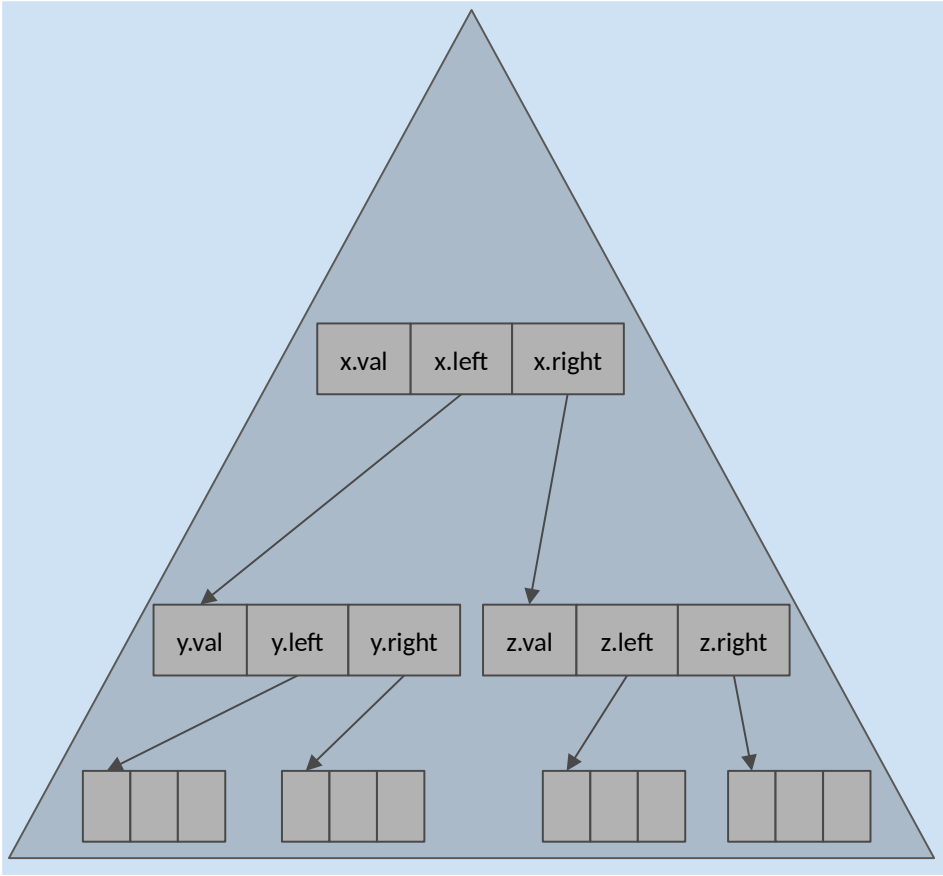
Fractional Predicates

Permits to **read** and **write** nodes

tree(x)

α ⊙ tree(x)

Permits only to **read** nodes



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Fractional Predicates – Key Rules

$$\text{tree}(x) \triangleq (x = \textbf{null} \lor (x.\text{val} \mapsto \_ * (\exists l.\ \exists r.\ x.\text{left} \mapsto l * x.\text{right} \mapsto r * \text{tree}(l) * \text{tree}(r))))$$

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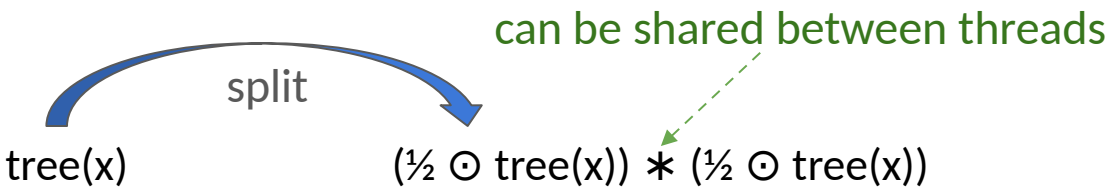
$\text{tree}(x) \triangleq (x = \textbf{null} \vee (x.\text{val} \mapsto \_ * (\exists l.\ \exists r.\ x.\text{left} \mapsto l * x.\text{right} \mapsto r * \text{tree}(l) * \text{tree}(r))))$

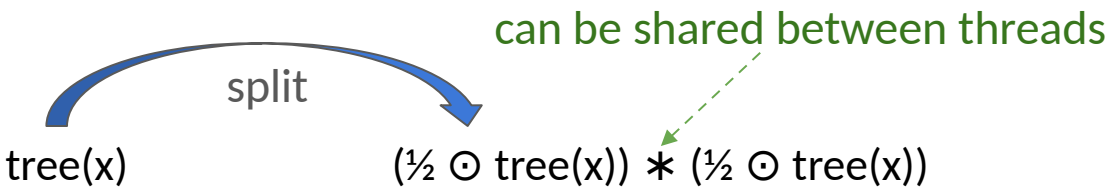
Fractional Predicates – Key Rules

$$\text{tree}(x) \triangleq (x = \textbf{null} \lor (x.\text{val} \mapsto \_ * (\exists l.\ \exists r.\ x.\text{left} \mapsto l * x.\text{right} \mapsto r * \text{tree}(l) * \text{tree}(r))))$$



Fractional Predicates – Key Rules

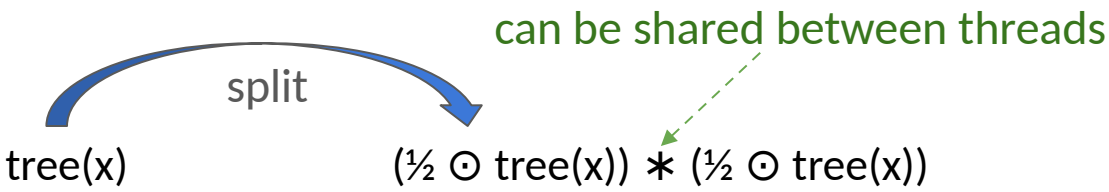
$\text{tree}(x) \triangleq (x = \textbf{null} \lor (x.\text{val} \mapsto \_ * (\exists l.\ \exists r.\ x.\text{left} \mapsto l * x.\text{right} \mapsto r * \text{tree}(l) * \text{tree}(r))))$

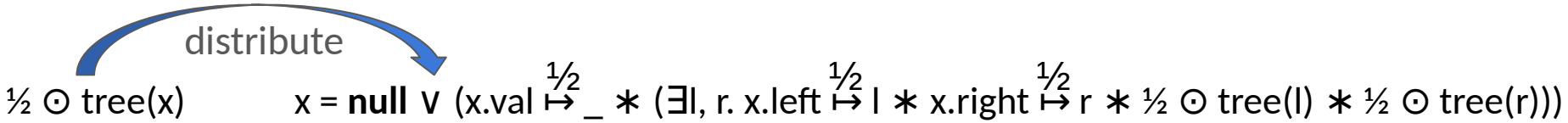


½ ⊙ tree(x)

Fractional Predicates – Key Rules

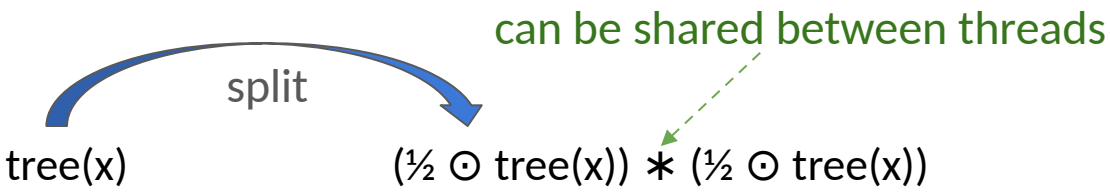
$\text{tree}(x) \triangleq (x = \textbf{null} \lor (x.\text{val} \mapsto \_ * (\exists l.\ \exists r.\ x.\text{left} \mapsto l * x.\text{right} \mapsto r * \text{tree}(l) * \text{tree}(r))))$

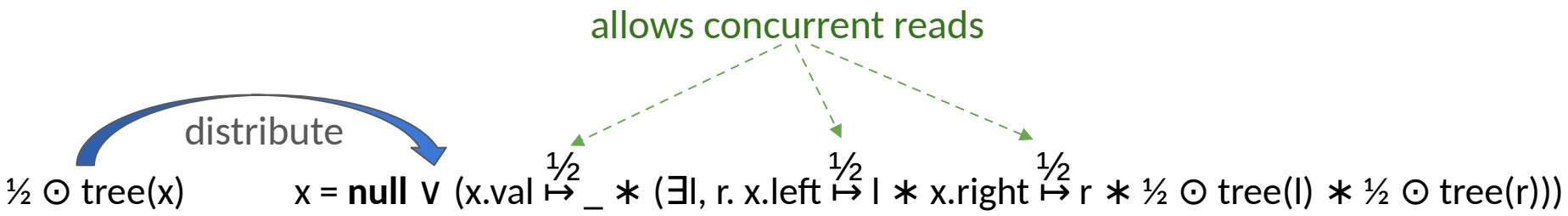




Fractional Predicates – Key Rules

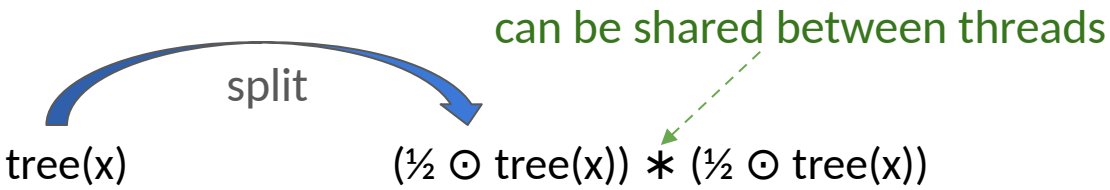
$\text{tree}(x) \triangleq (x = \textbf{null} \lor (x.\text{val} \mapsto \_ * (\exists l.\ \exists r.\ x.\text{left} \mapsto l * x.\text{right} \mapsto r * \text{tree}(l) * \text{tree}(r))))$

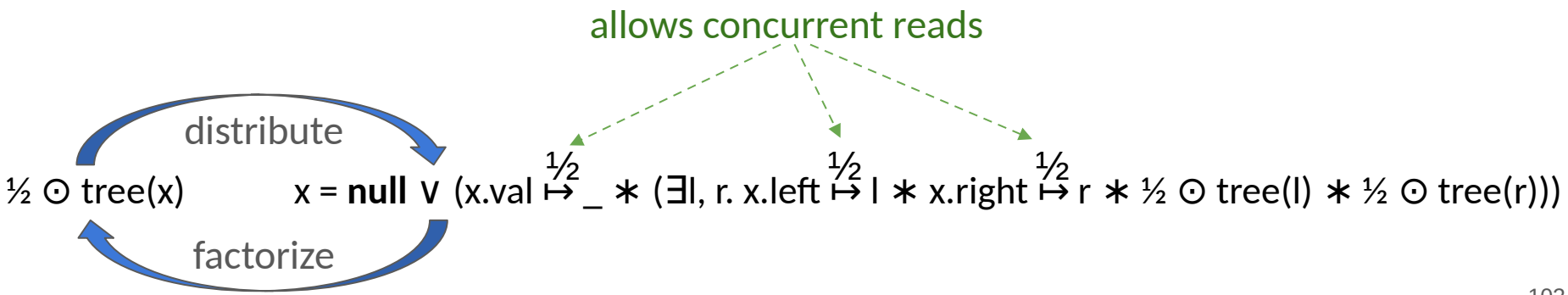




Fractional Predicates – Key Rules

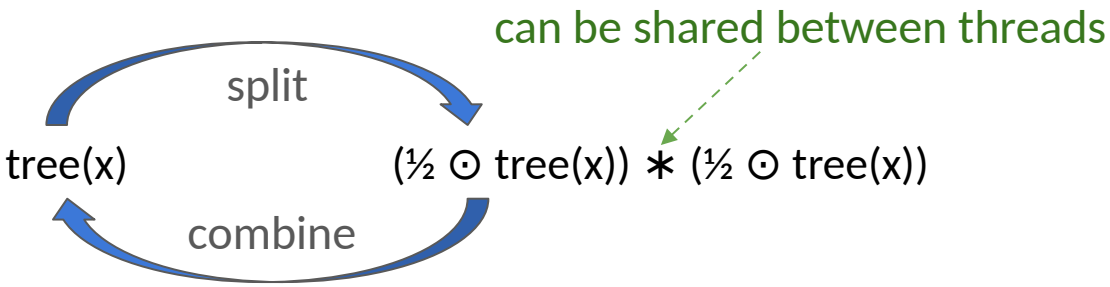
$\text{tree}(x) \triangleq (x = \textbf{null} \lor (x.\text{val} \mapsto \_ * (\exists l.\ \exists r.\ x.\text{left} \mapsto l * x.\text{right} \mapsto r * \text{tree}(l) * \text{tree}(r))))$

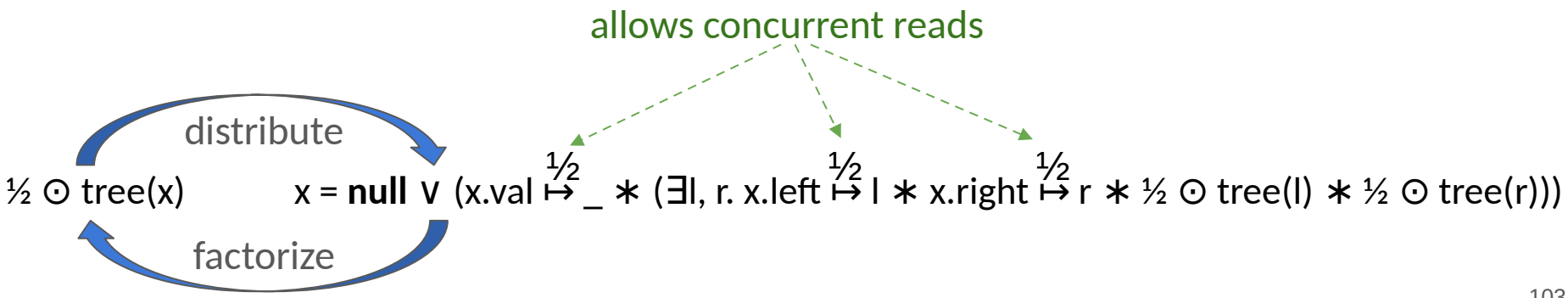




Fractional Predicates – Key Rules

$\text{tree}(x) \triangleq (x = \textbf{null} \lor (x.\text{val} \mapsto \_ * (\exists l.\ \exists r.\ x.\text{left} \mapsto l * x.\text{right} \mapsto r * \text{tree}(l) * \text{tree}(r))))$

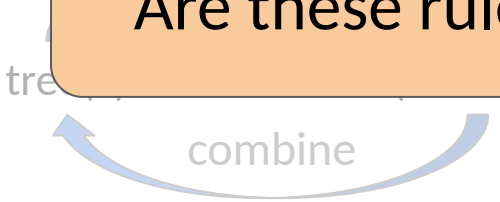




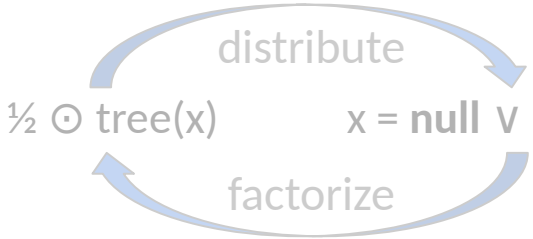
Fractional Predicates – Key Rules

tree(x) ≜ (x = **null** ∨ (x.val ↦ _ ∗ (∃l. ∃r. x.left ↦ l ∗ x.right ↦ r ∗ tree(l) ∗ tree(r))))

Are these rules (used in existing verifiers) **sound**?



allows concurrent reads



Fractional Predicates – Key Rules

tree(x) ≜ (x = **null** ∨ (x.val ↦ _ ∗ (∃l. ∃r. x.left ↦ l ∗ x.right ↦ r ∗ tree(l) ∗ tree(r))))

Are these rules (used in existing verifiers) **sound**?

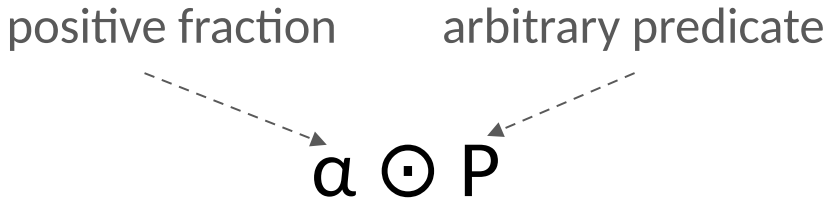
combine

What is the formal meaning of **α ⊙ P**?

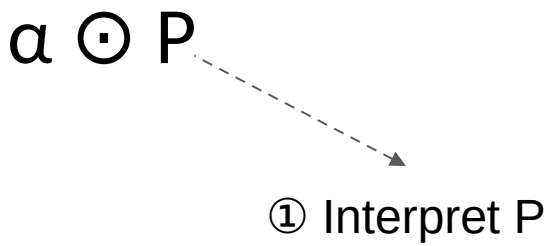
½ ⊙ tree(x) x = **null** ∨ (x.val $\overset{½}{\mapsto}$ _ ∗ (∃l, r. x.left $\overset{½}{\mapsto}$ l ∗ x.right $\overset{½}{\mapsto}$ r ∗ ½ ⊙ tree(l) ∗ ½ ⊙ tree(r)))

factorize

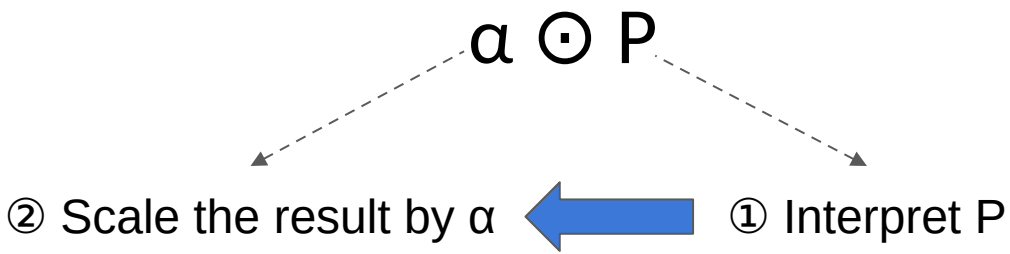
Fractional Predicates – Existing Theory [ESOP'18, CAV'20]



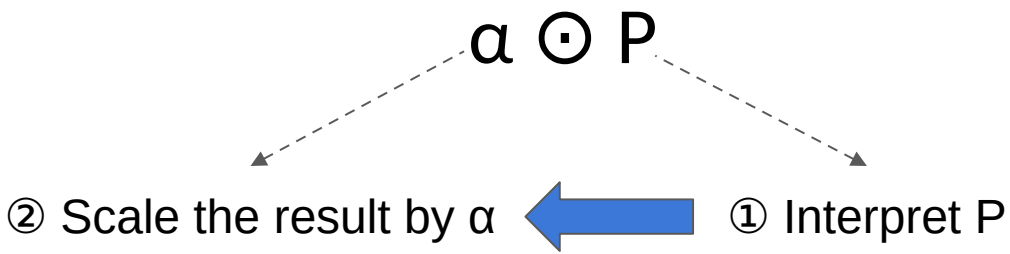
Fractional Predicates – Existing Theory [ESOP'18, CAV'20]



Fractional Predicates – Existing Theory [ESOP'18, CAV'20]

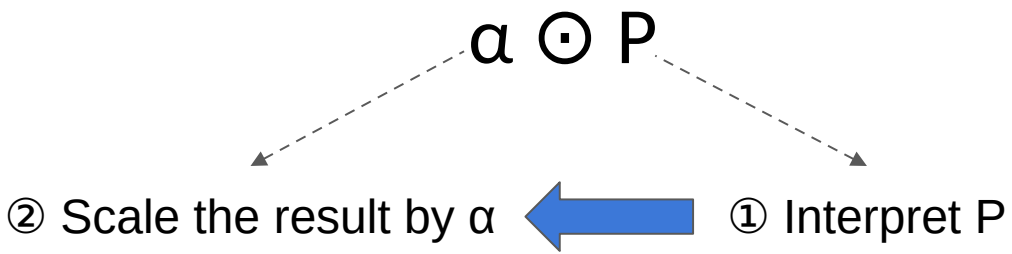


Fractional Predicates – Existing Theory [ESOP'18, CAV'20]



	Split	Combine	Distribute	Factorize
Existing theory	✓	~	✓	✗

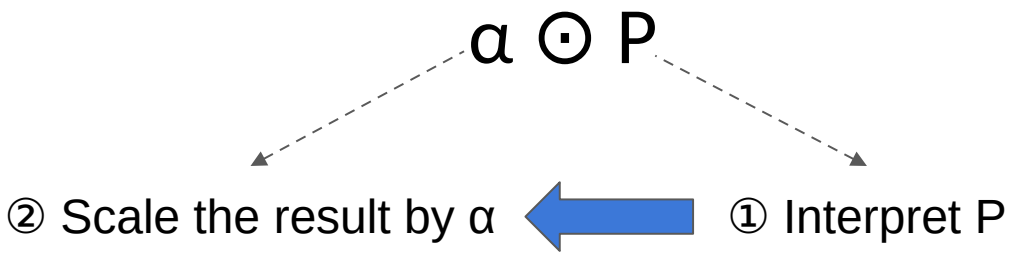
Fractional Predicates – Existing Theory [ESOP'18, CAV'20]



Is this rule fundamentally unsound?

	Split	Combine	Distribute	Factorize
Existing theory	✓	~	✓	✗

Fractional Predicates – Existing Theory [ESOP'18, CAV'20]



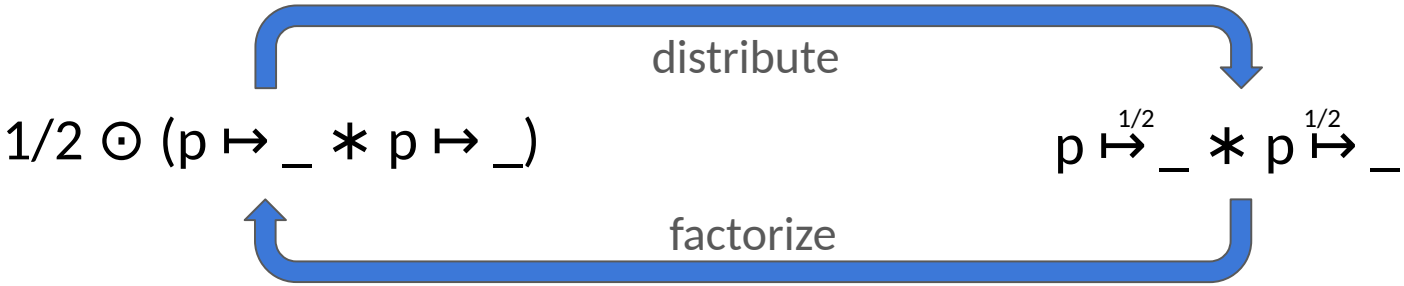
	Split	Combine	Distribute	Factorize
Existing theory	✓	~	✓	✗
Our novel model	✓	✓	✓	✓

Fractional Predicates – Distribute and Factorize

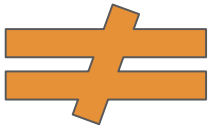
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

$p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

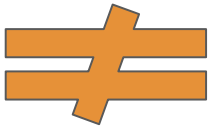
Fractional Predicates – Distribute and Factorize



Fractional Predicates – Distribute and Factorize

$1/2 \odot (p \mapsto \_ * p \mapsto \_)$  $p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

Fractional Predicates – Distribute and Factorize

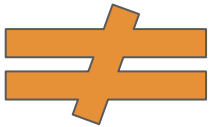
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$  $p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

satisfiable

Fractional Predicates – Distribute and Factorize

$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

unsatisfiable



$p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

satisfiable

Fractional Predicates – Distribute and Factorize

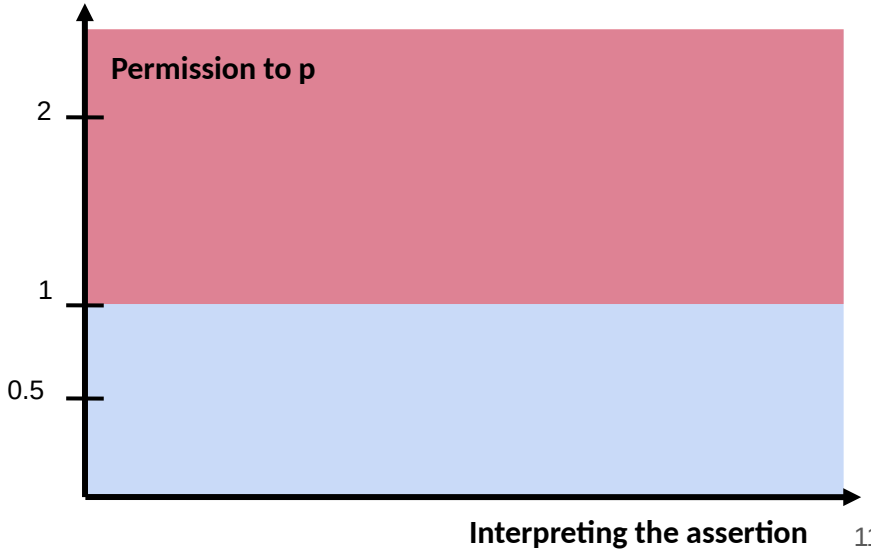
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

unsatisfiable

$\neq$

$p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

satisfiable



Fractional Predicates – Distribute and Factorize

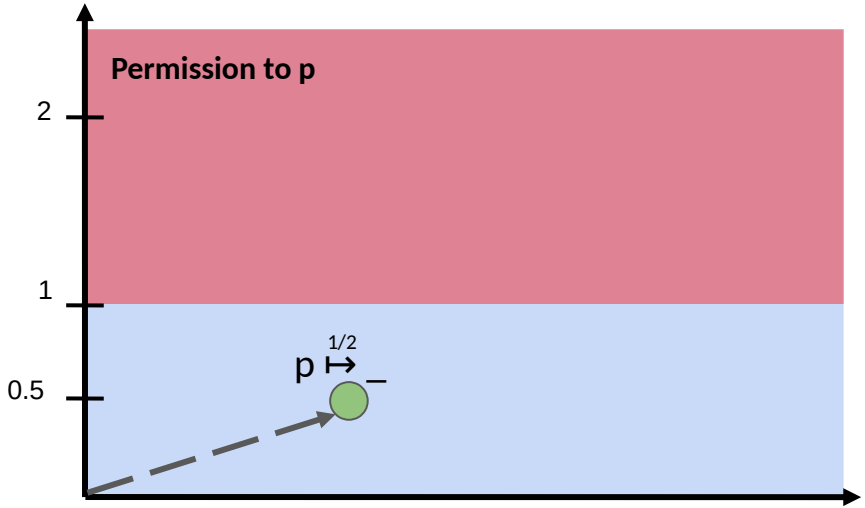
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

unsatisfiable

$\neq$

$p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

satisfiable



Fractional Predicates – Distribute and Factorize

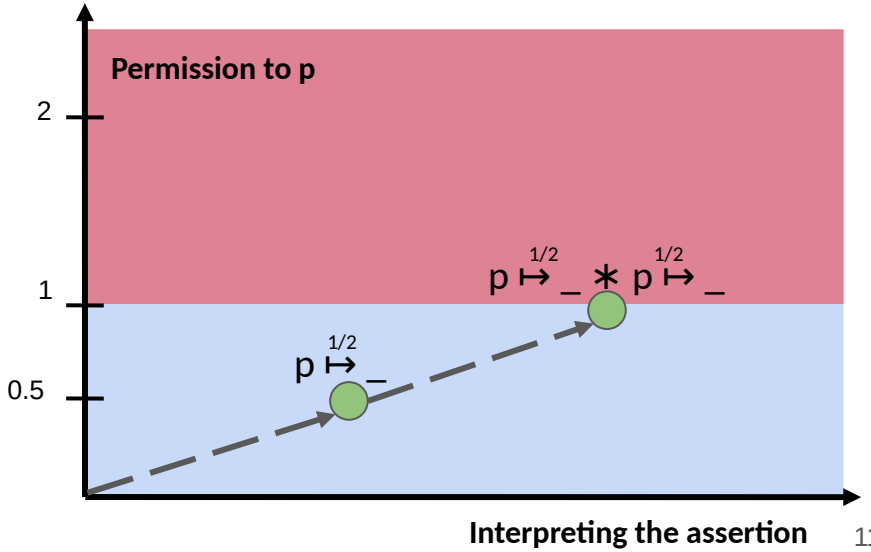
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

unsatisfiable

$\neq$

$p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

satisfiable



Fractional Predicates – Distribute and Factorize

$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

unsatisfiable

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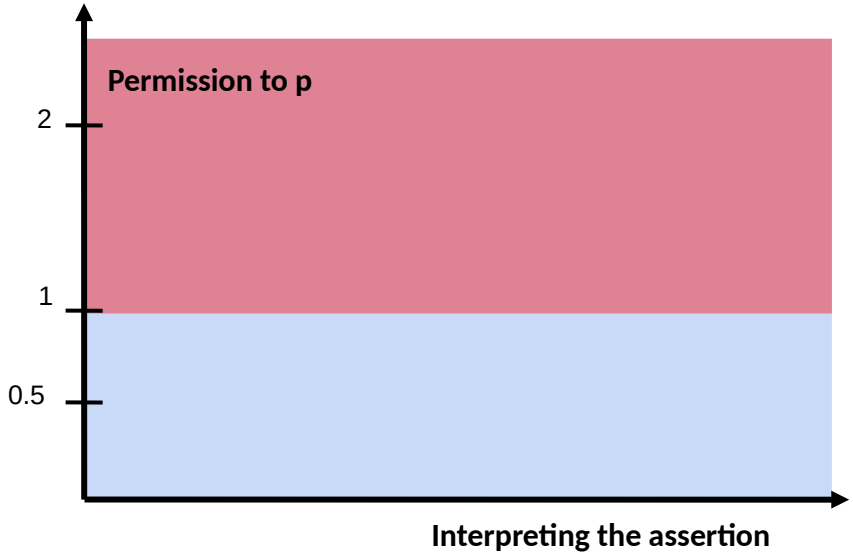
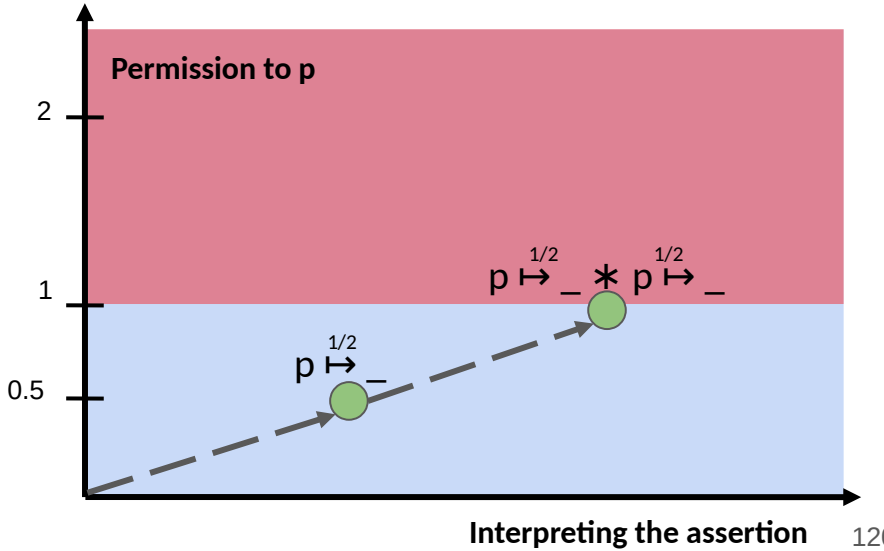




Fractional Predicates – Distribute and Factorize

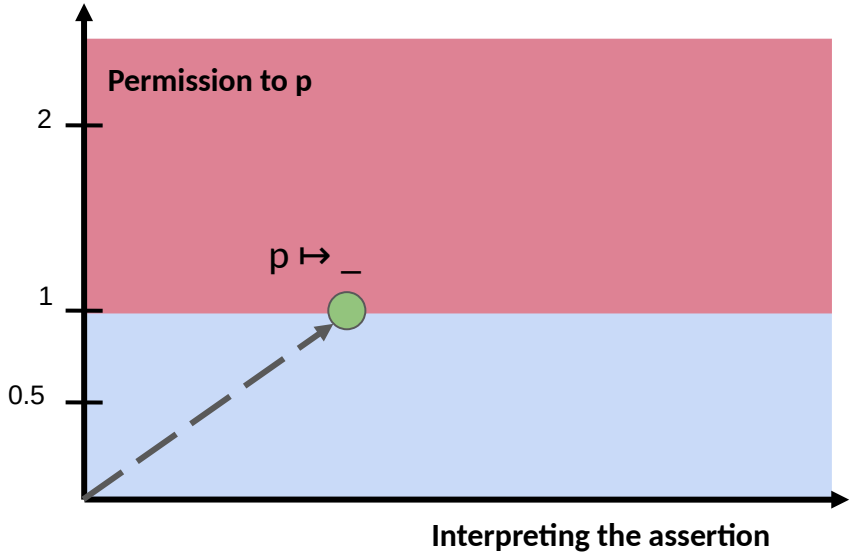
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

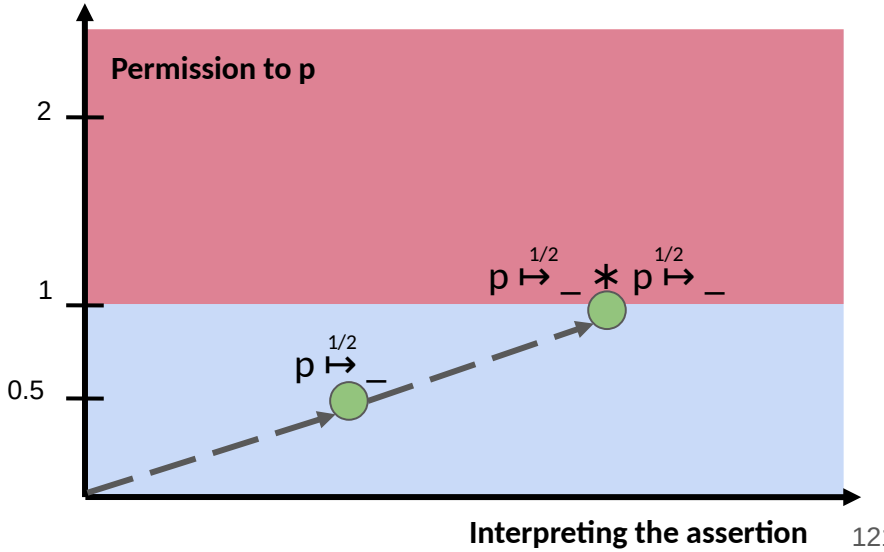
unsatisfiable

$\neq$

$p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

satisfiable





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unsatisfiable

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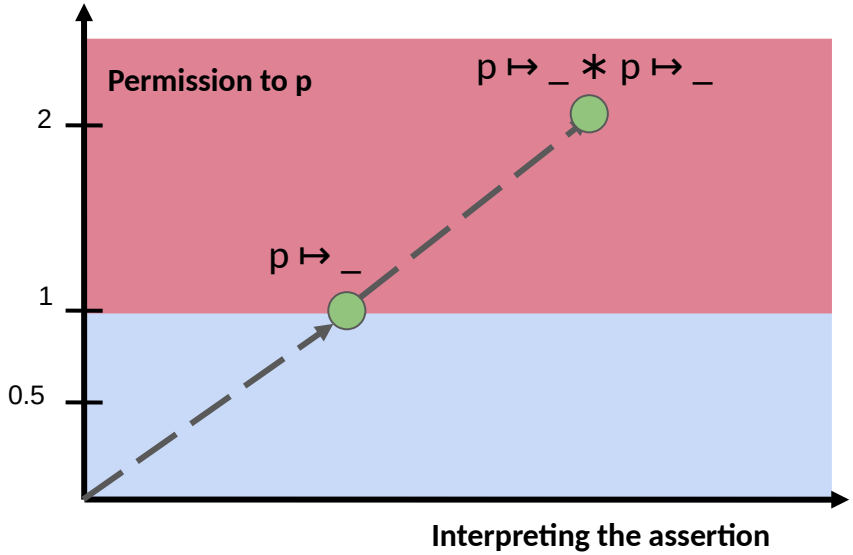
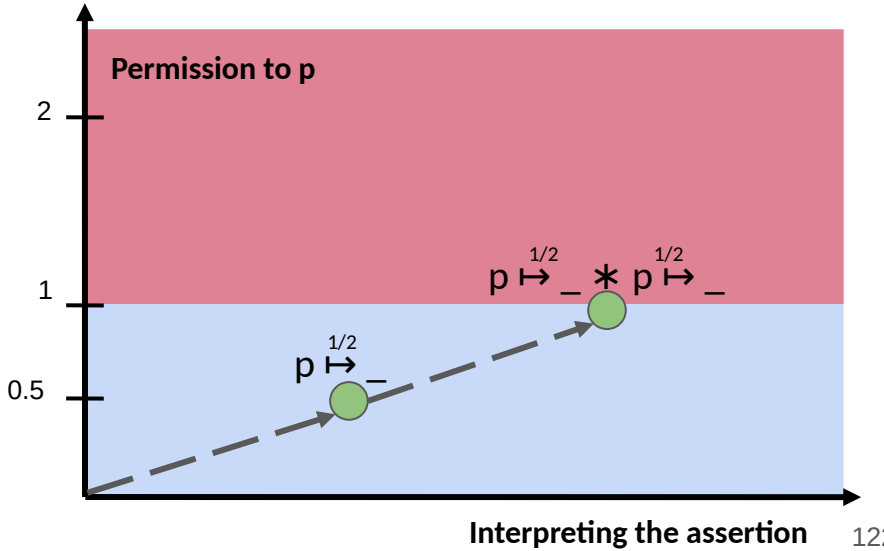
satisfiable





Fractional Predicates – Distribute and Factorize

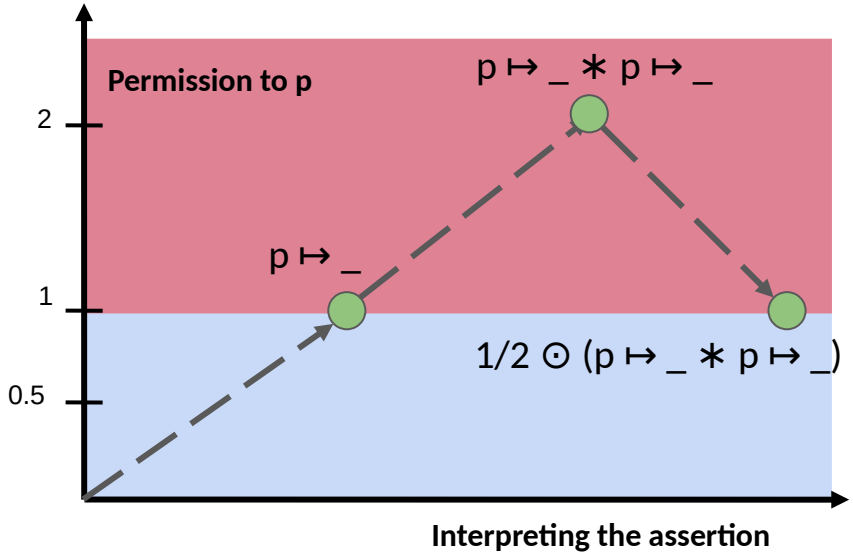
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

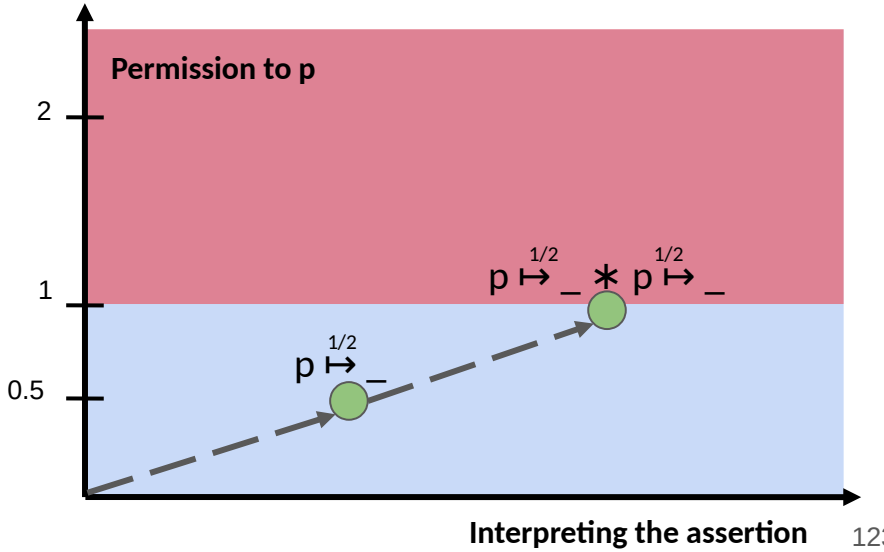
unsatisfiable

$\neq$

$p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

satisfiable





Fractional Predicates – Distribute and Factorize

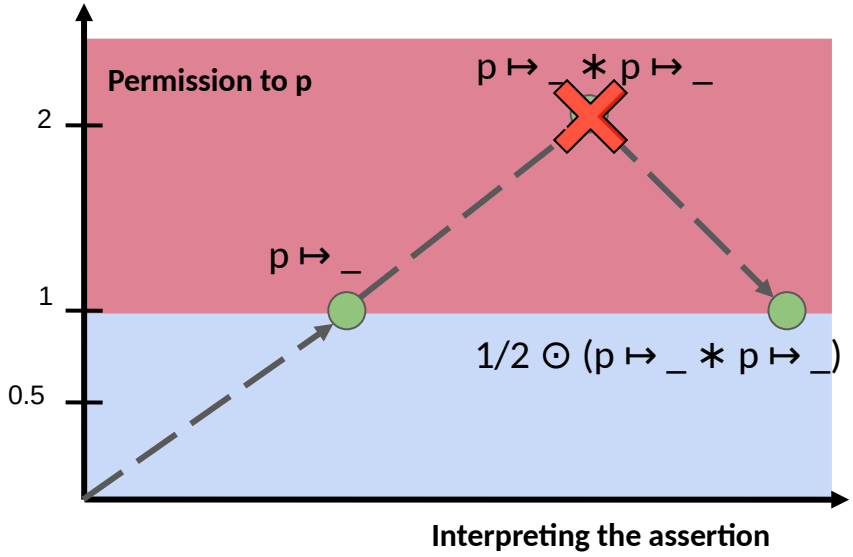
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

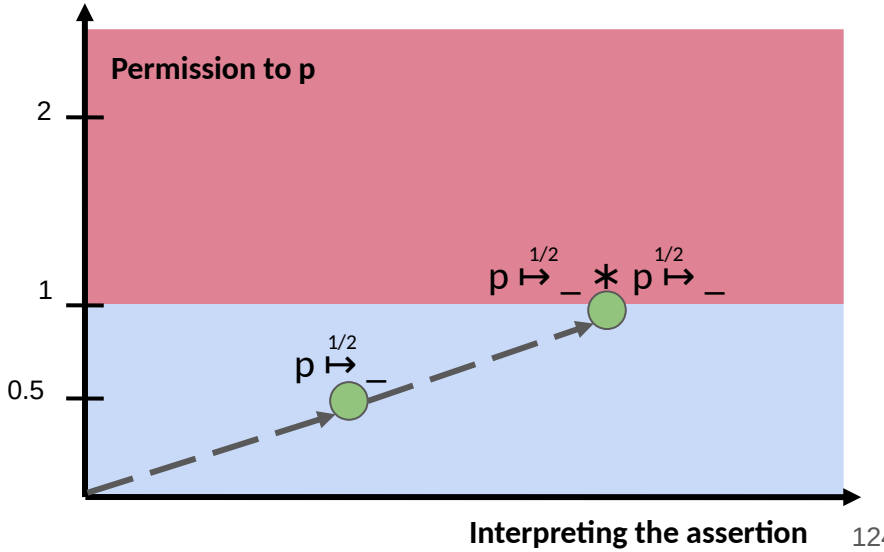
unsatisfiable

$\neq$

$p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

satisfiable





Fractional Predicates – Distribute and Factorize

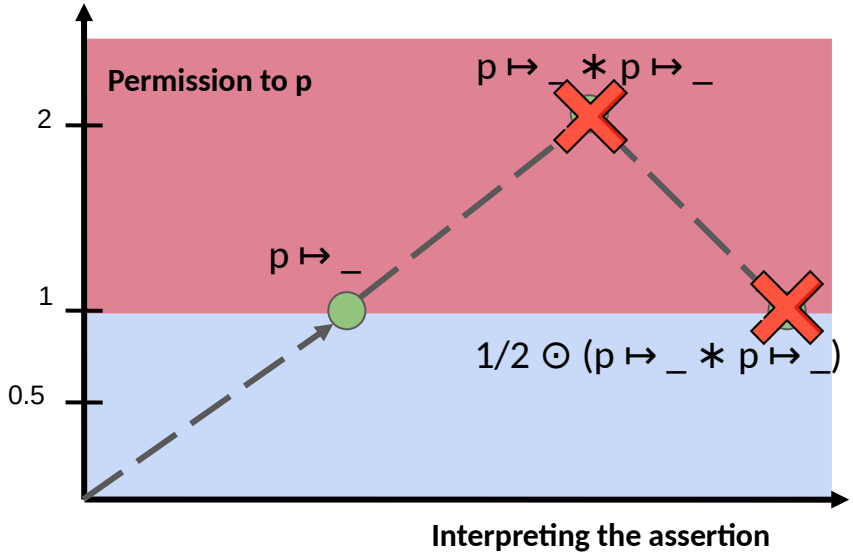
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$

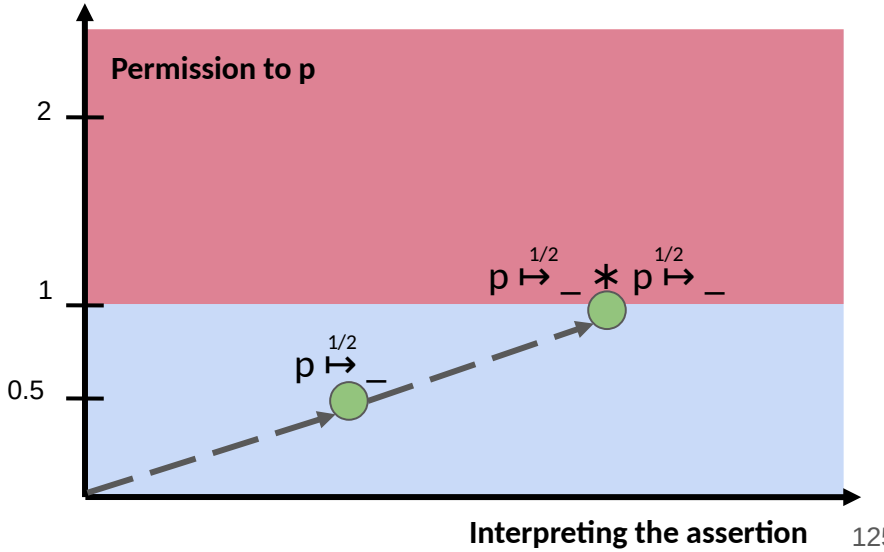
unsatisfiable

$\neq$

$p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

satisfiable





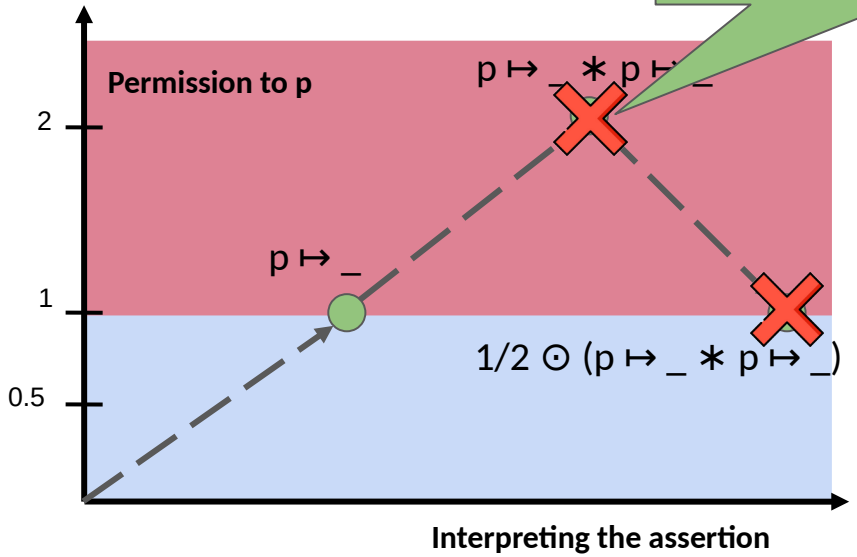
Fractional Predicates – Distribute and Factorize

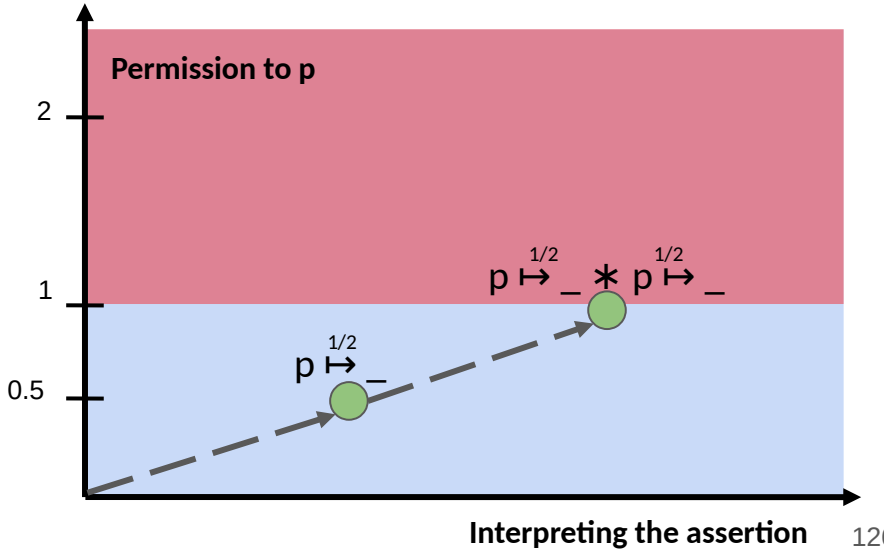
$1/2 \odot (p \mapsto \_ * p \mapsto \_)$ ≠ $p \overset{1/2}{\mapsto} \_ * p \overset{1/2}{\mapsto} \_$

unsatisfiable

satisfiable

Key idea: These states should be **temporarily allowed**





Fractional Predicates – Key Insights

	Split	Combine	Distribute	Factorize
Existing theory	✓	~	✓	✗
Our novel model	✓	✓	✓	✓

Fundamental **novel semantic model** for assertions:
Intermediate invalid states are allowed.

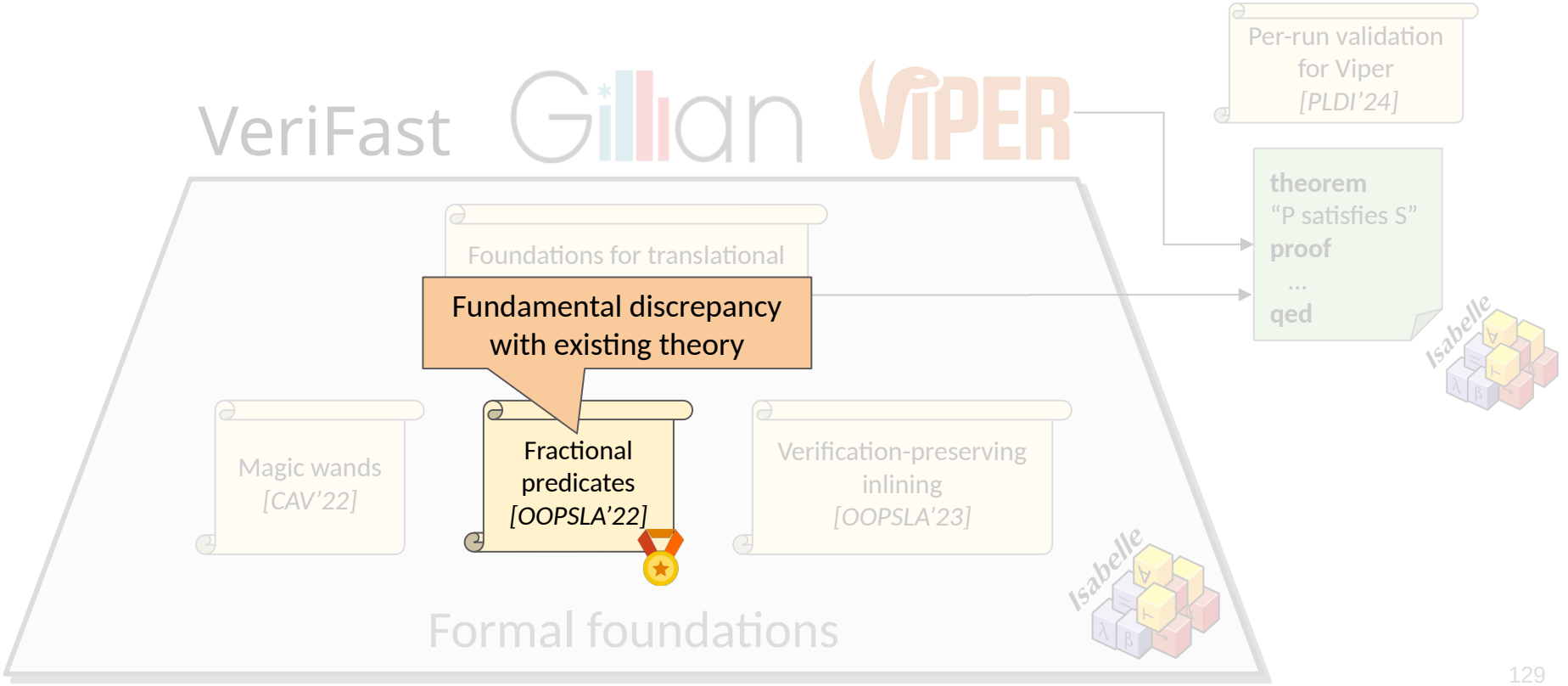
Fractional Predicates – Key Insights

	Split	Combine	Distribute	Factorize
Existing theory	✓	~	✓	✗
Our novel model	✓	✓	✓	✓

Fundamental **novel semantic model** for assertions: Intermediate invalid states are allowed.

Soundness of the **combine** rule proven via a **novel induction principle** for (co)inductive predicates.

Formal Foundations for Automated Separation Logic Verifiers



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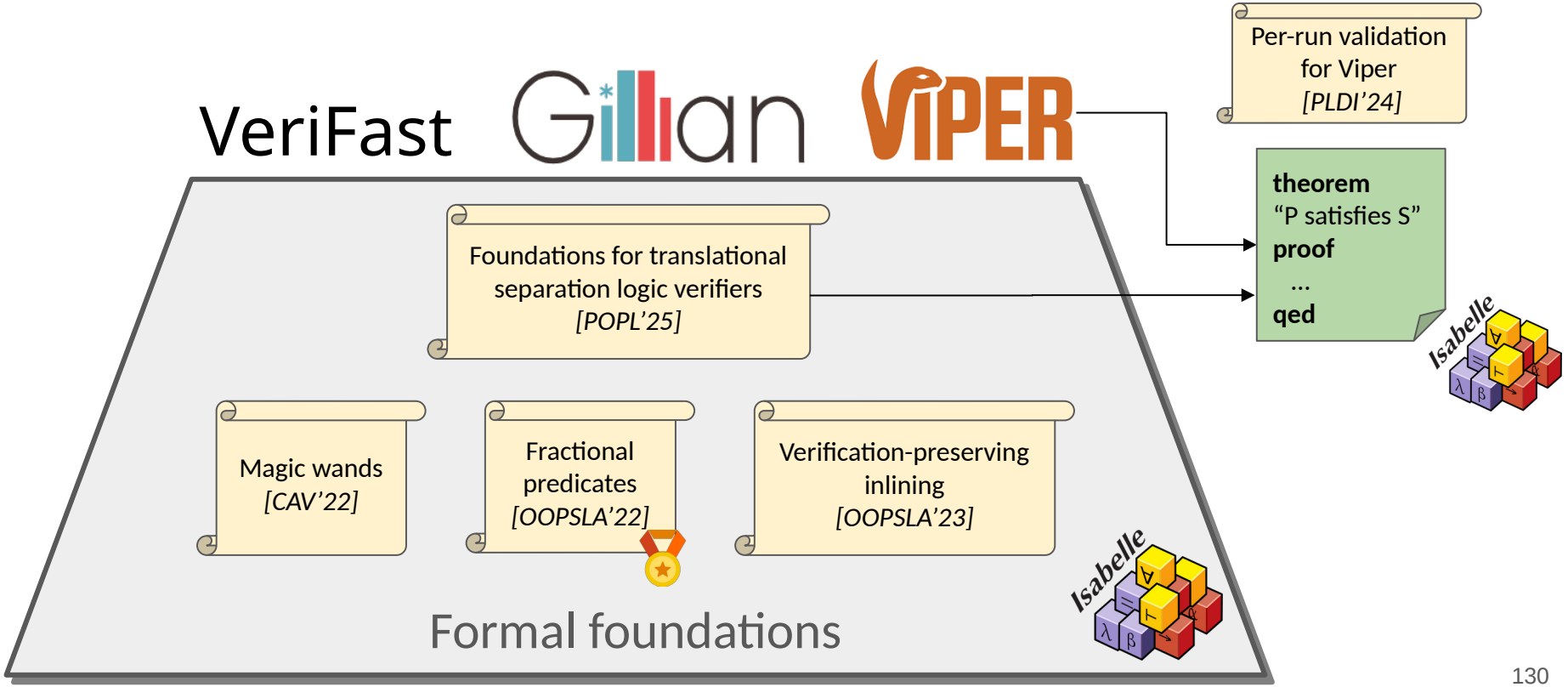


Formal Foundations for Automated Separation Logic Verifiers

Trustworthy verifier based on separation logic with **state-of-the-art automation**

VeriFast

Gillian

VIPER

Per-run validation for Viper *[PLDI'24]*

theorem
"P satisfies S"
proof
...
qed

Foundations for translational separation logic verifiers *[POPL'25]*

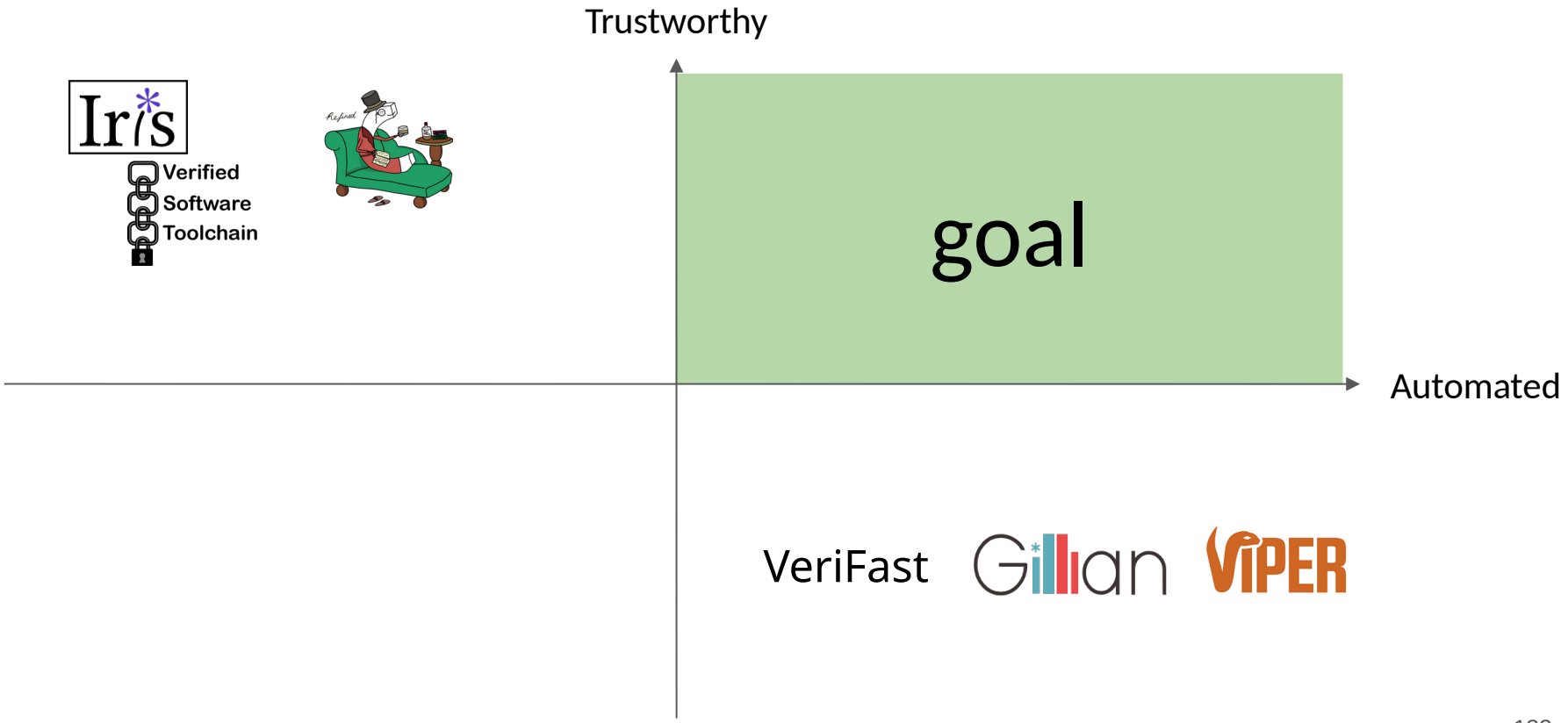
Magic wands *[CAV'22]*

Fractional predicates *[OOPSLA'22]*

Verification-preserving inlining *[OOPSLA'23]*

Formal foundations

Verifiers Based on Separation Logic



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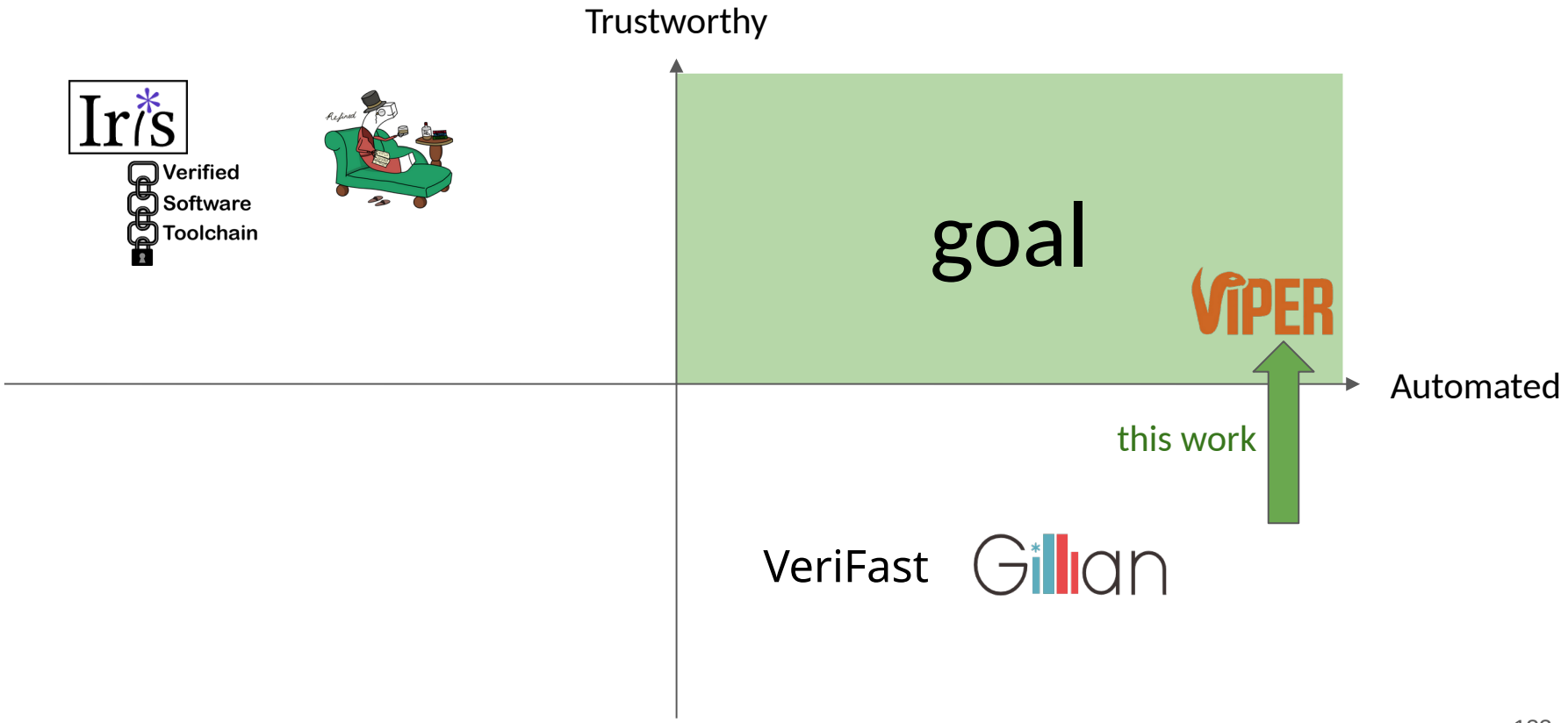

My Research

Build **provably sound** and **automated** deductive verifiers for **advanced properties**.

Problem 1
Trustworthiness

Provably sound and automated verifier based on *separation logic*

Problem 2
Expressiveness

Automated verifier for arbitrary *hyperproperties*

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Code error means that websites can leak user details including passwords through 'heartbeat' function used to secure connections

Log4shell software flaw threatens millions of servers as hackers scramble to exploit it

Internet

Sat 11 Dec 2021

The extreme ease the flaw allows an attacker to access a server is what experts say makes it so dangerous. *(Supplied: Accenture)*

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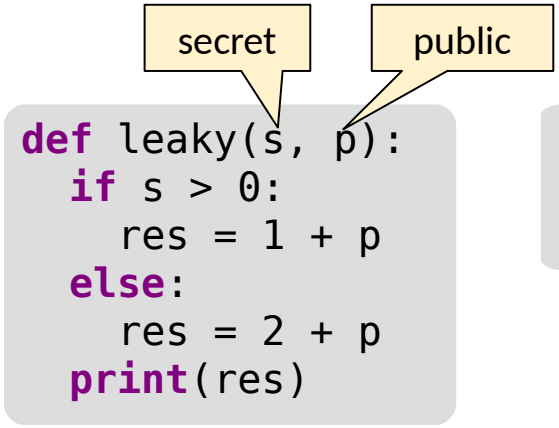


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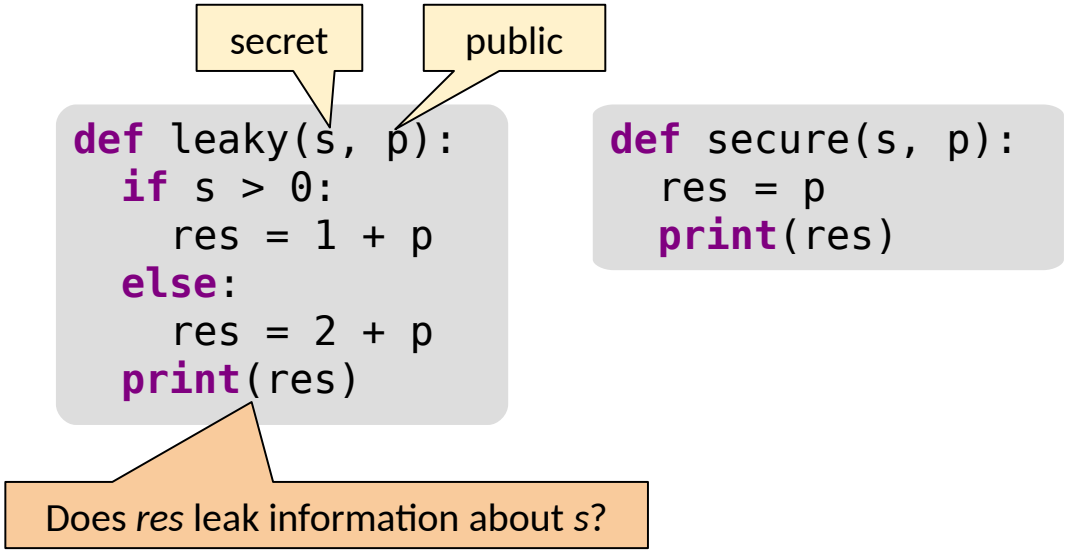

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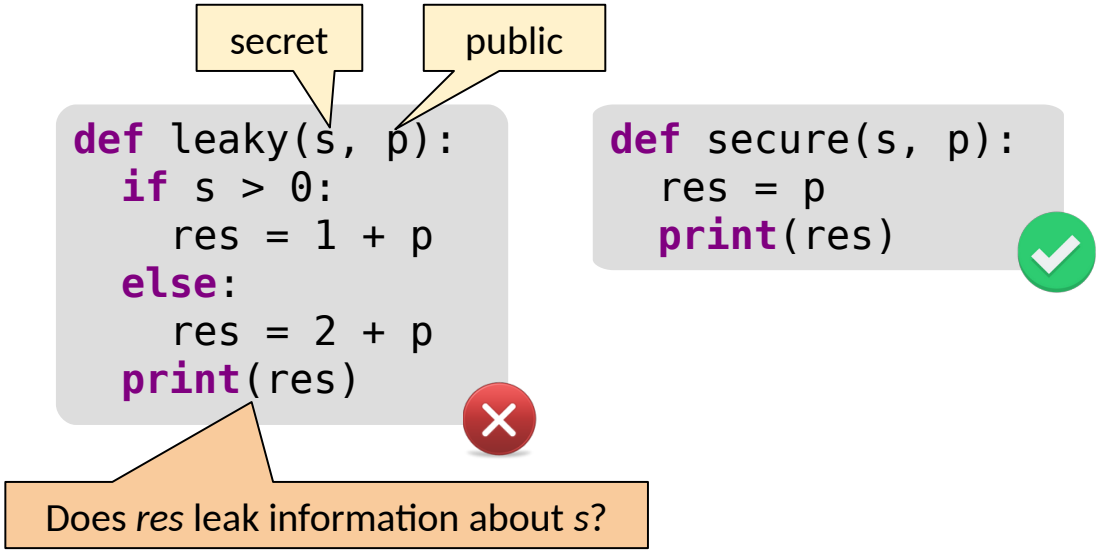

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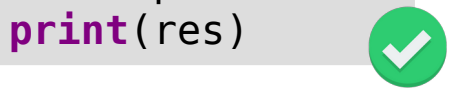

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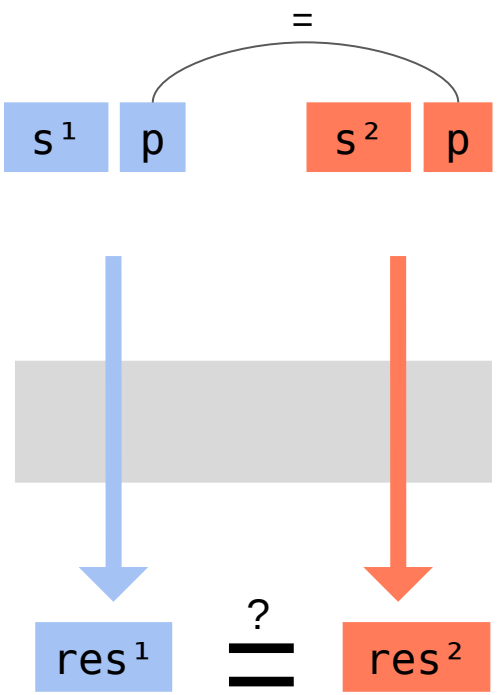

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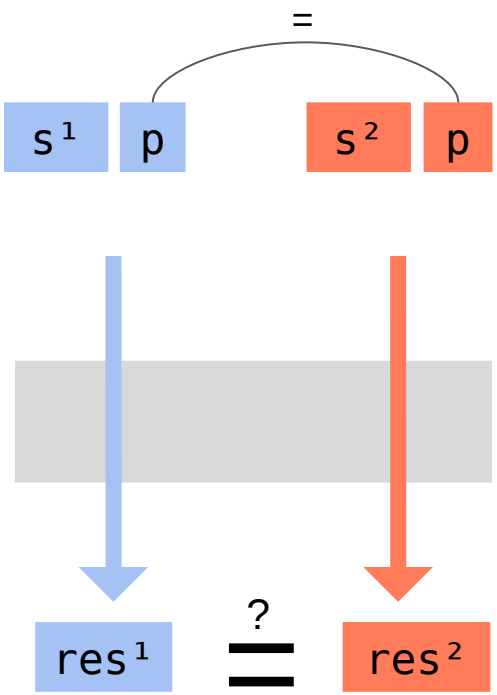

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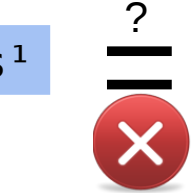

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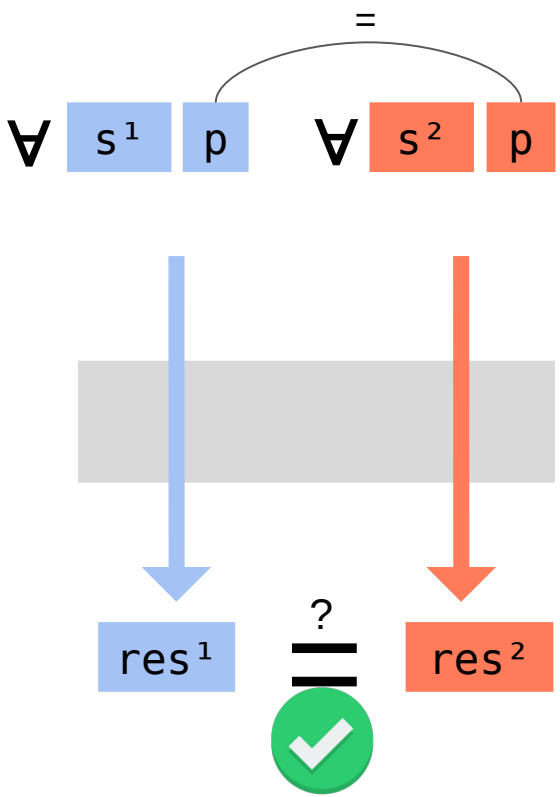

Formalizing Information Flow

Too restrictive for non-deterministic programs

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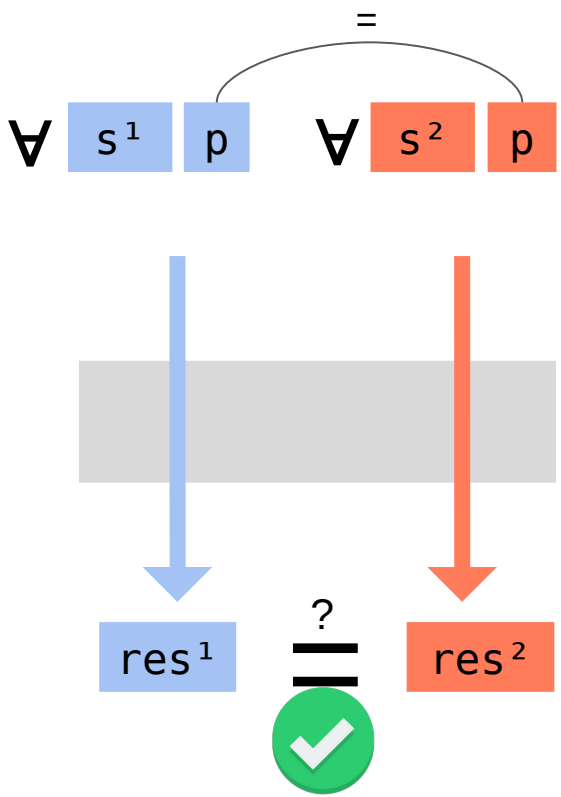

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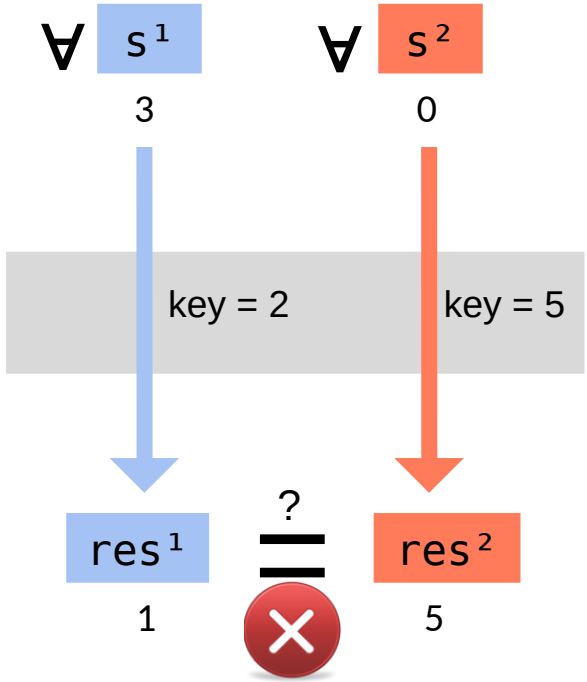

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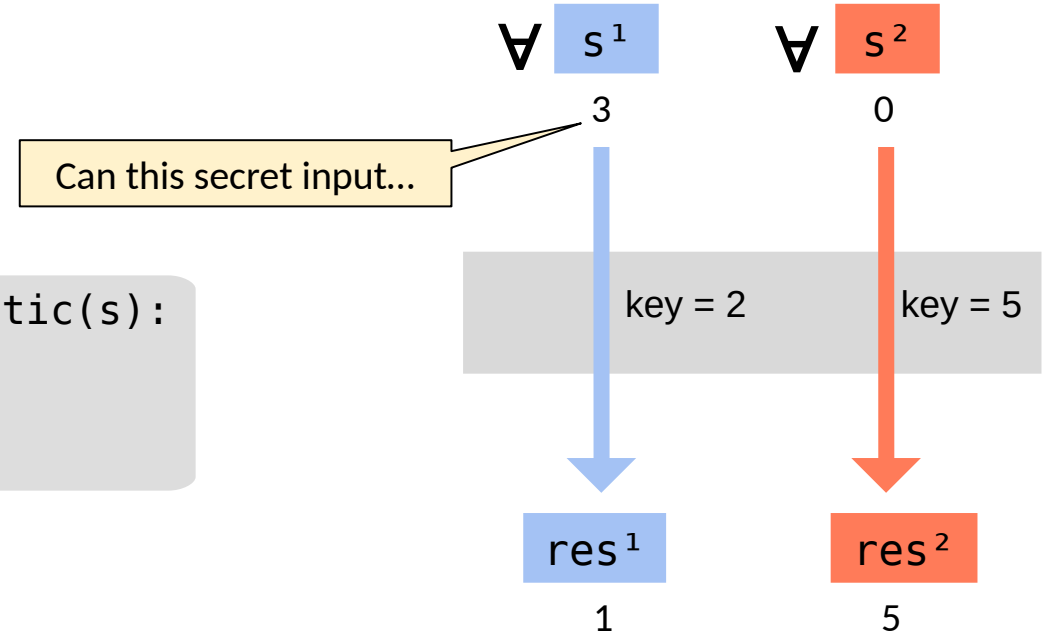

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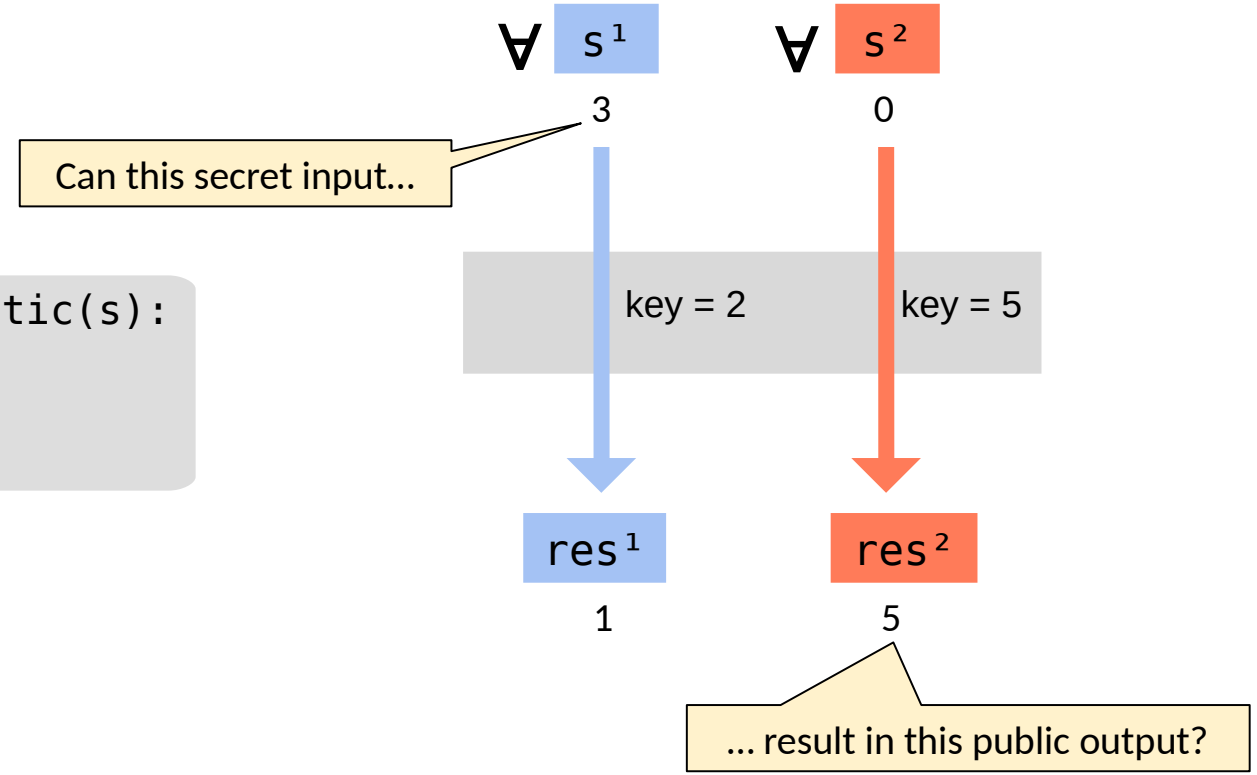

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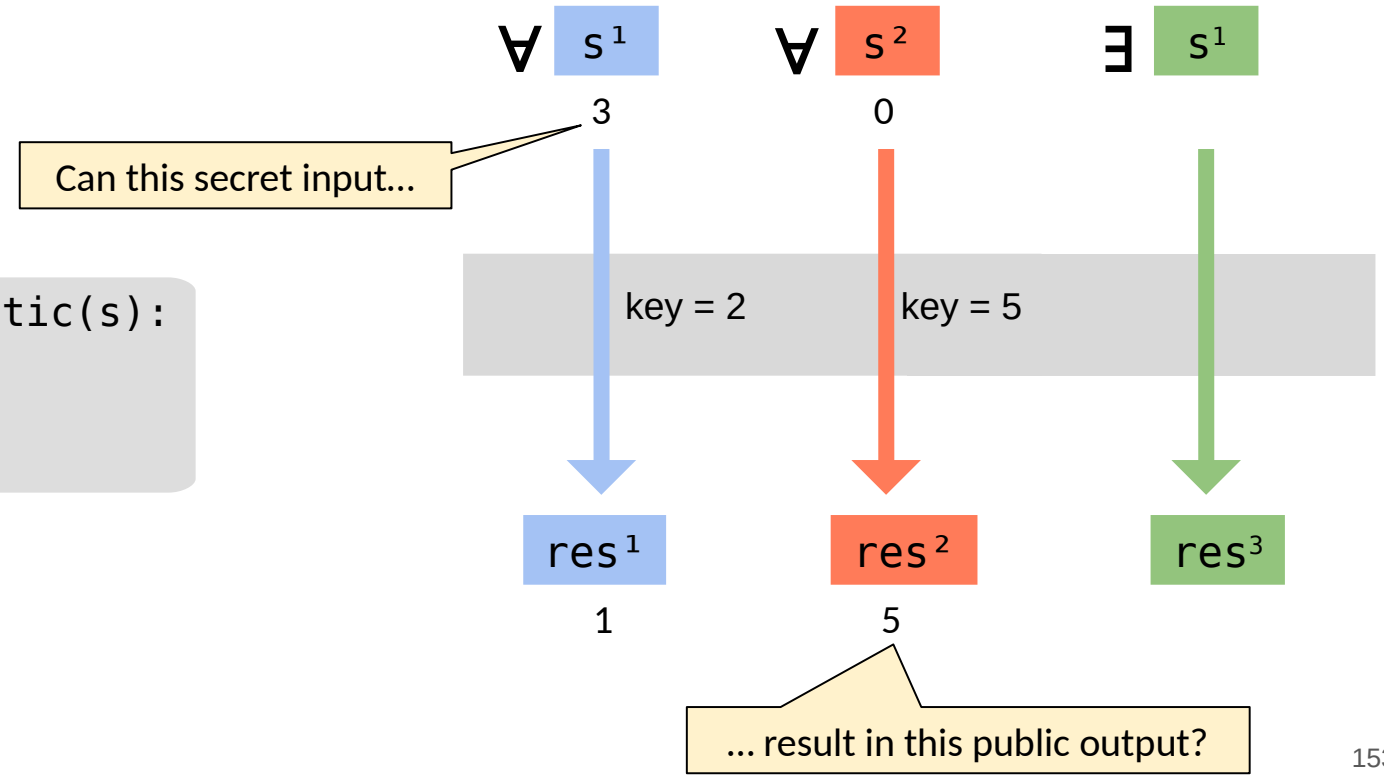

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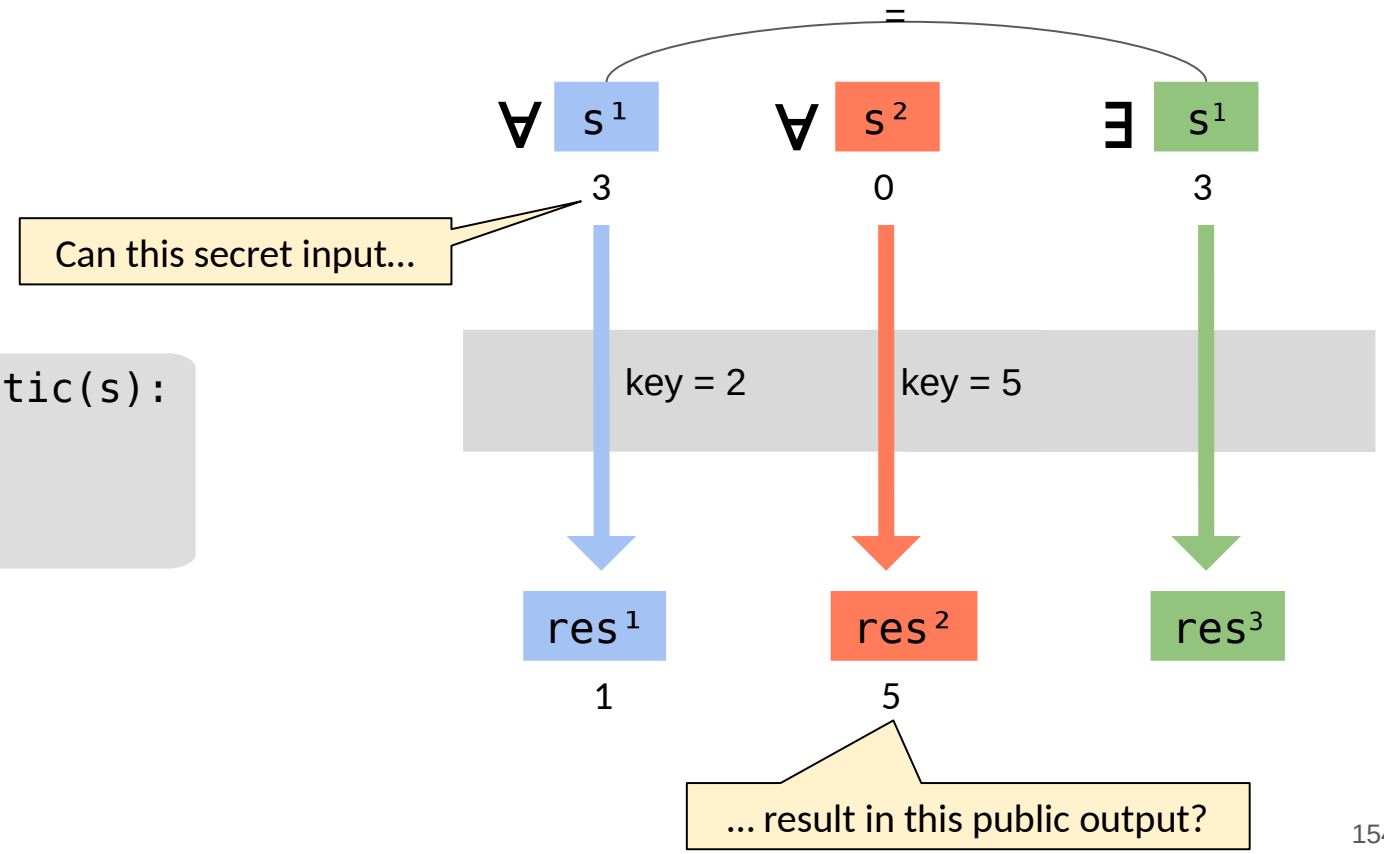

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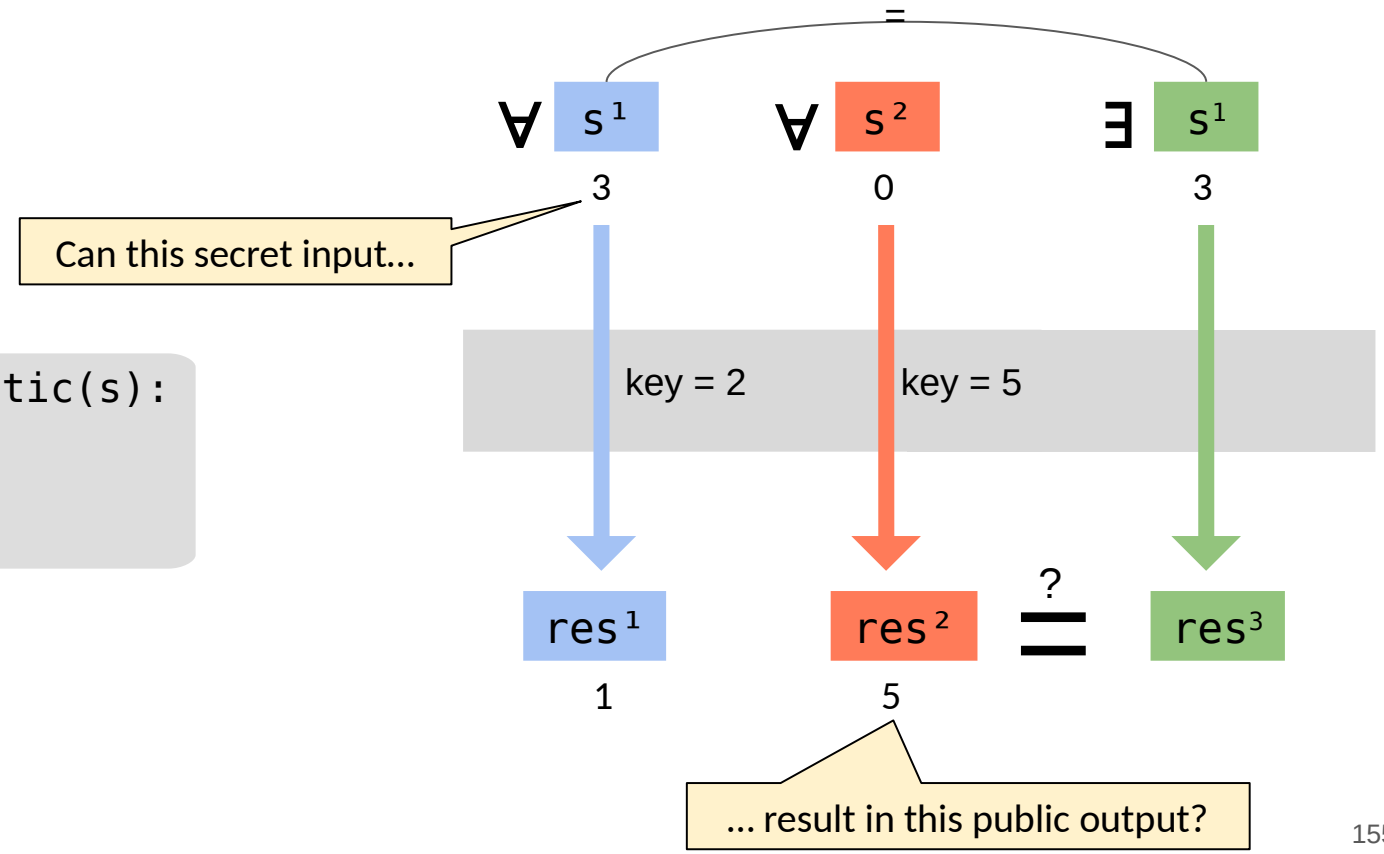

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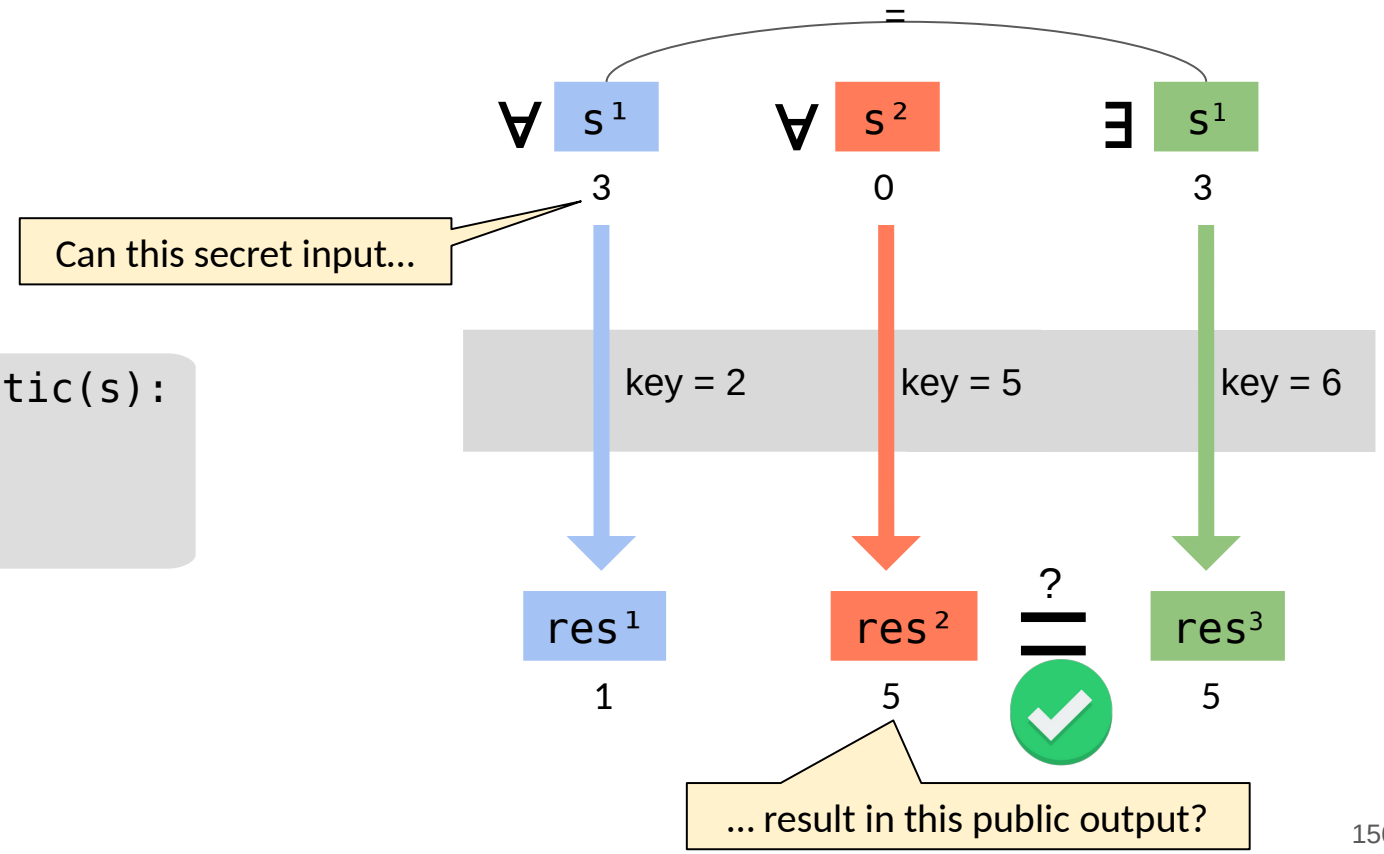

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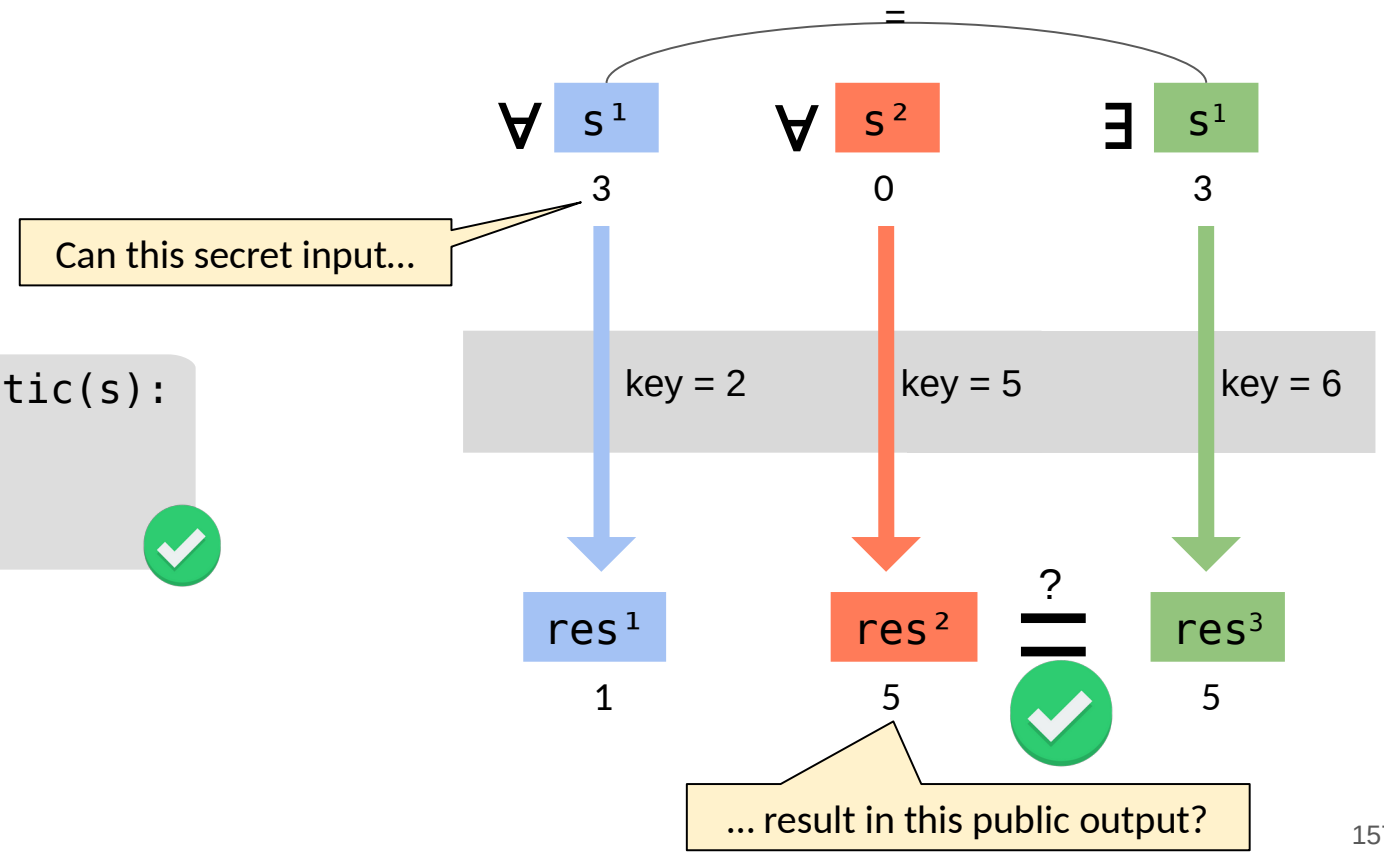

Hyperproperties

Hyperproperty $\triangleq$ property of a **set** of executions

	Type	Example use case
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"2-safety"

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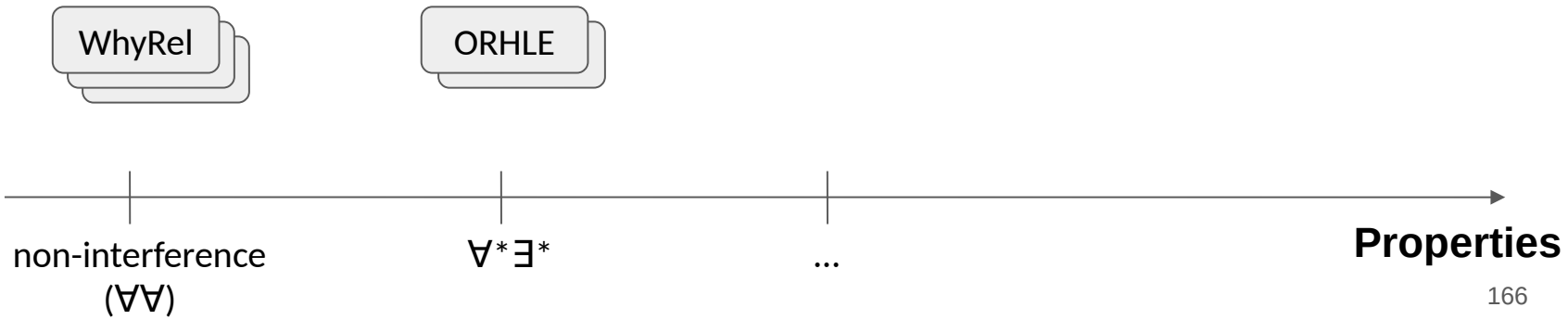
Contribution: The first automated verifier that can prove all these hyperproperties.

Automated Deductive Verifiers for Hyperproperties



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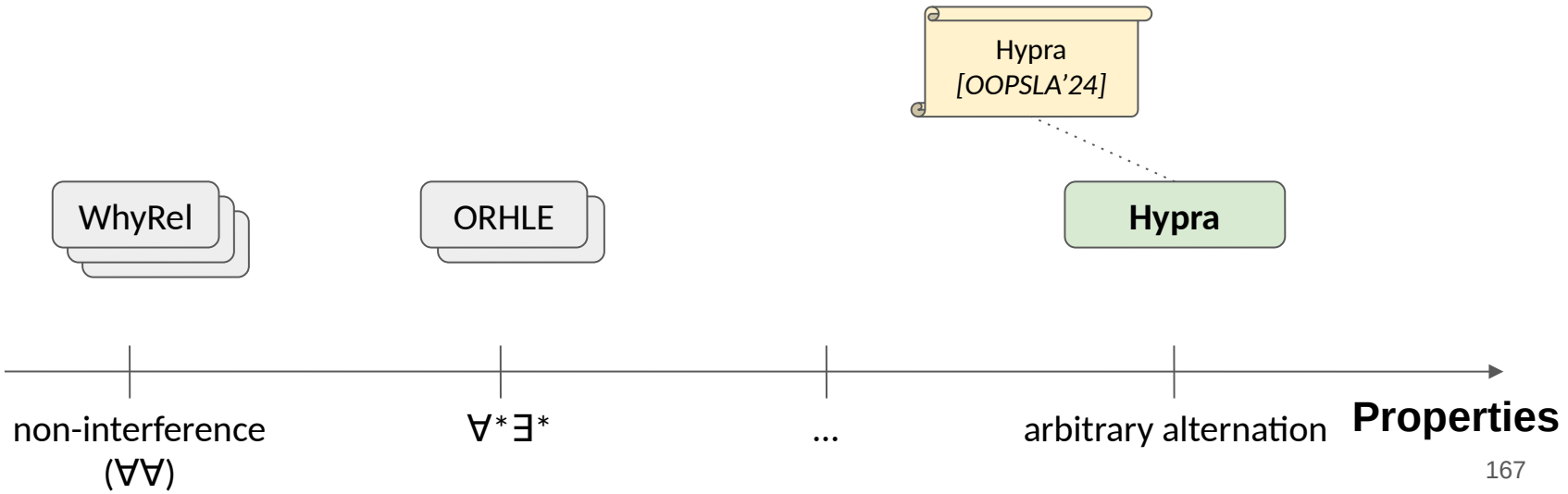

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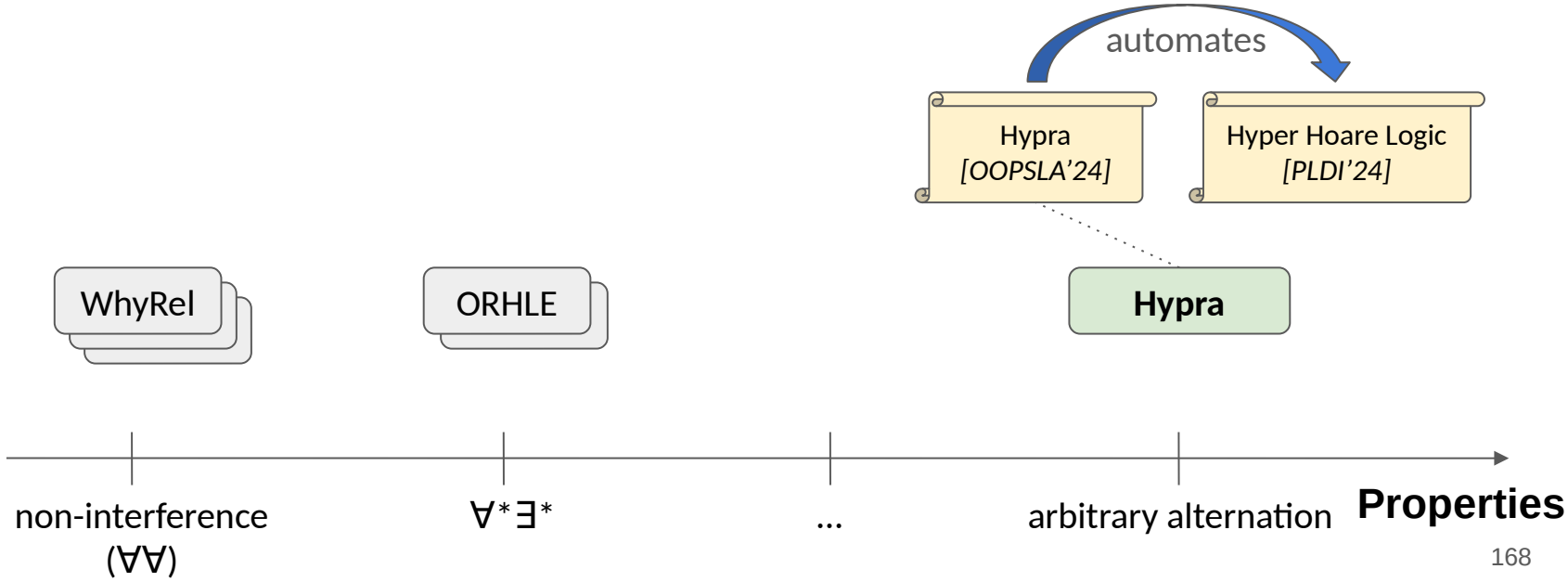

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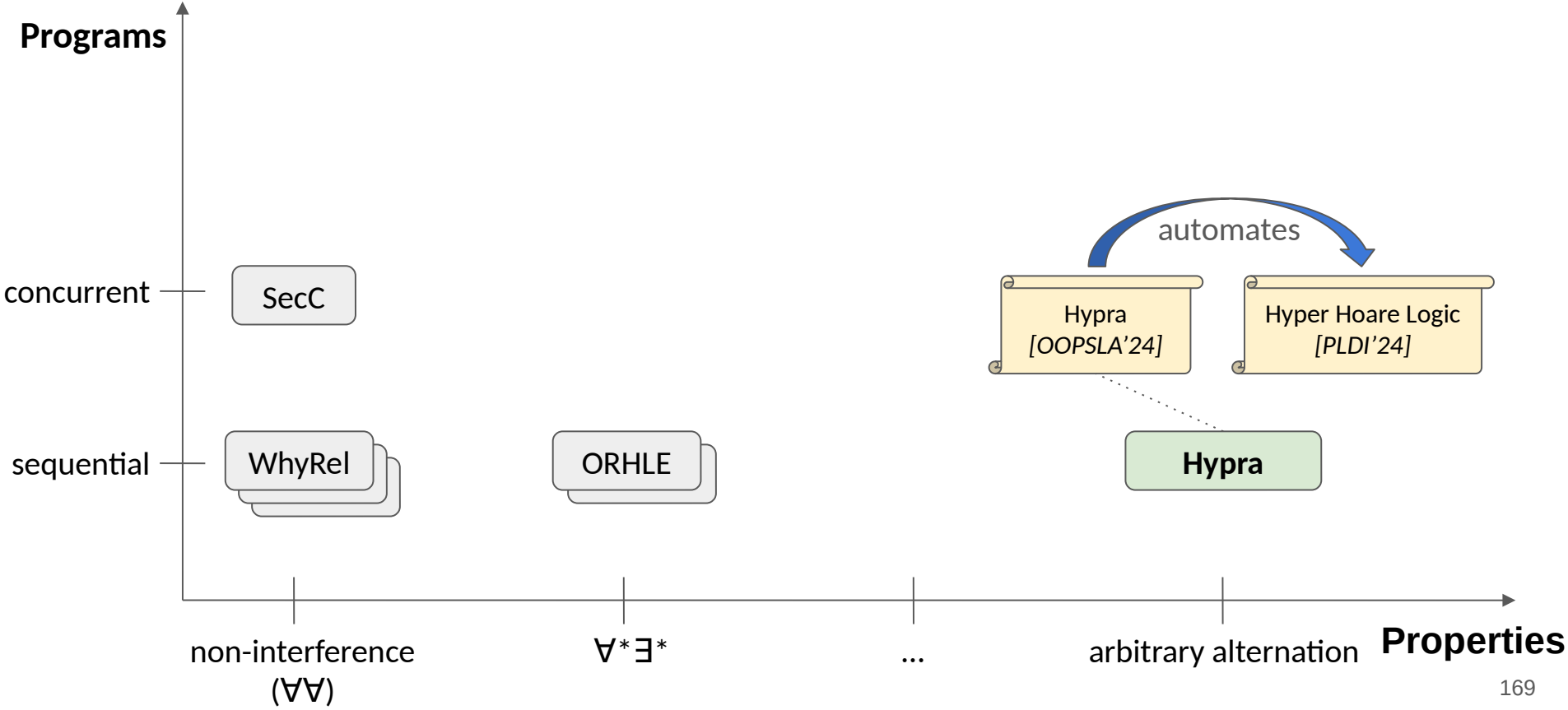

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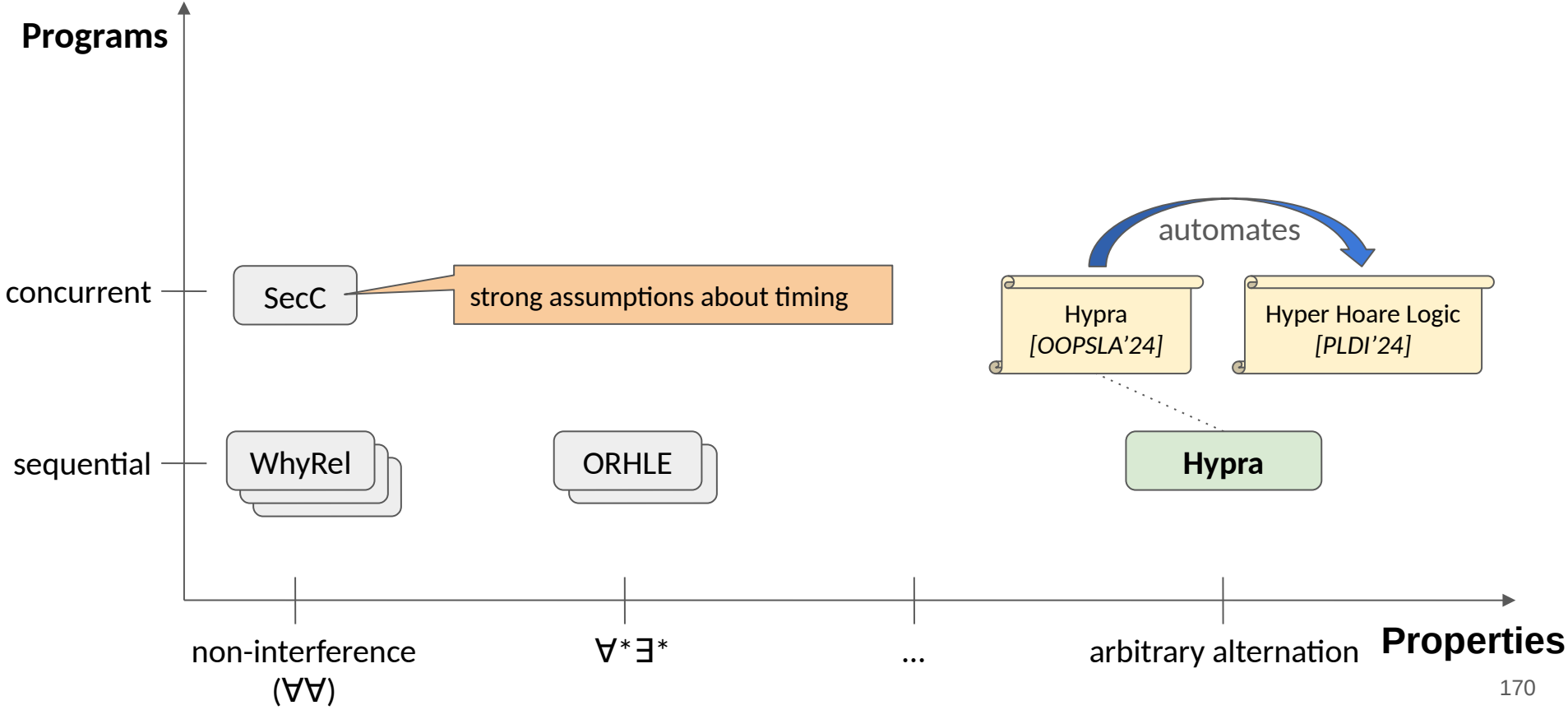

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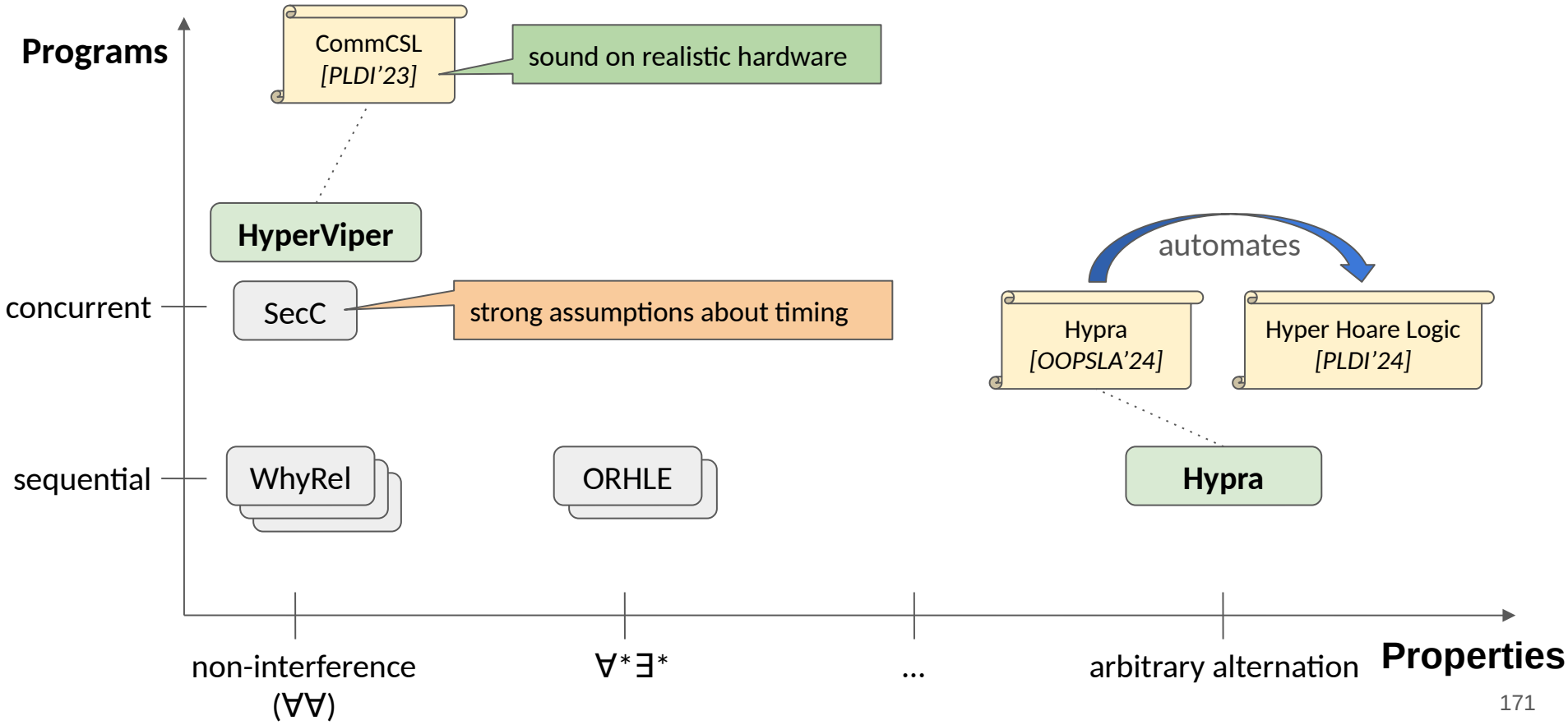

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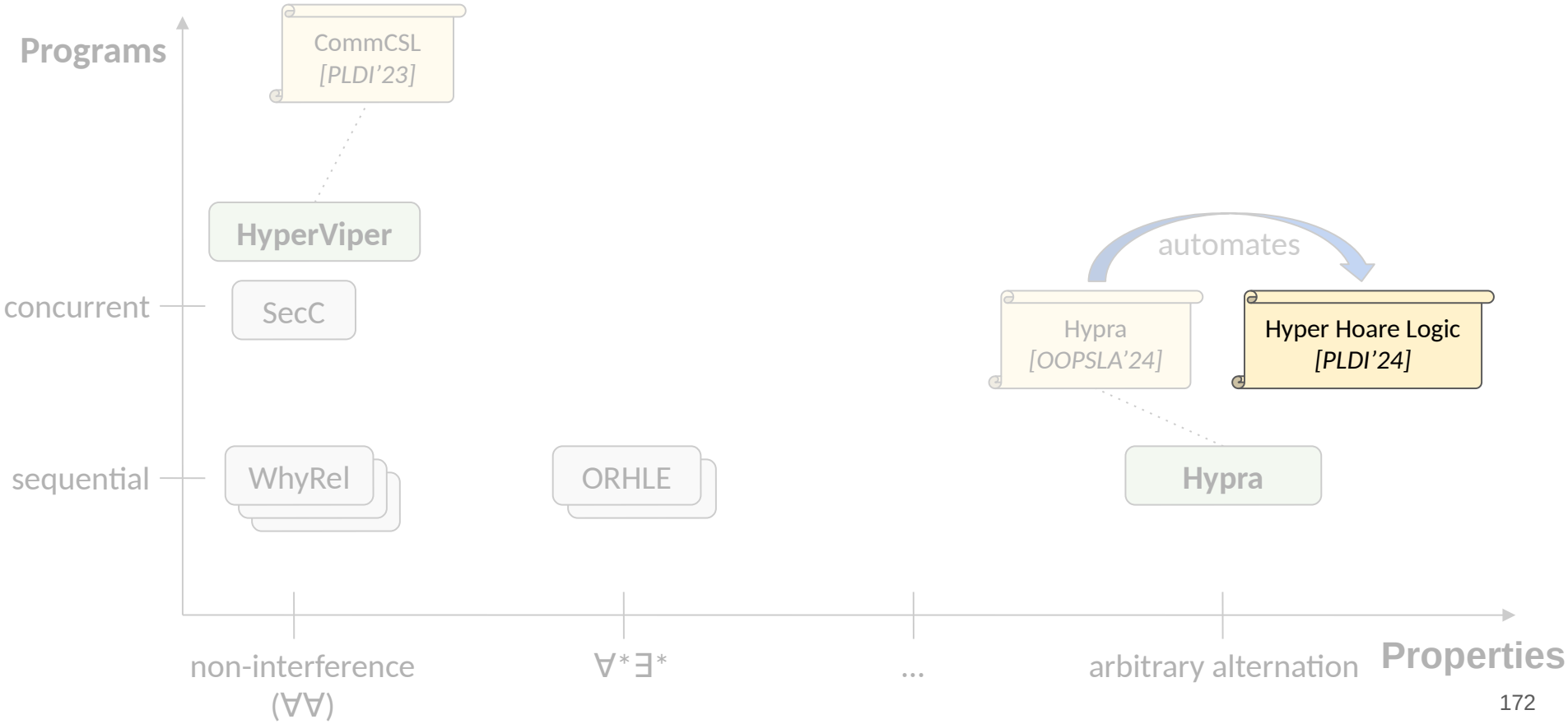
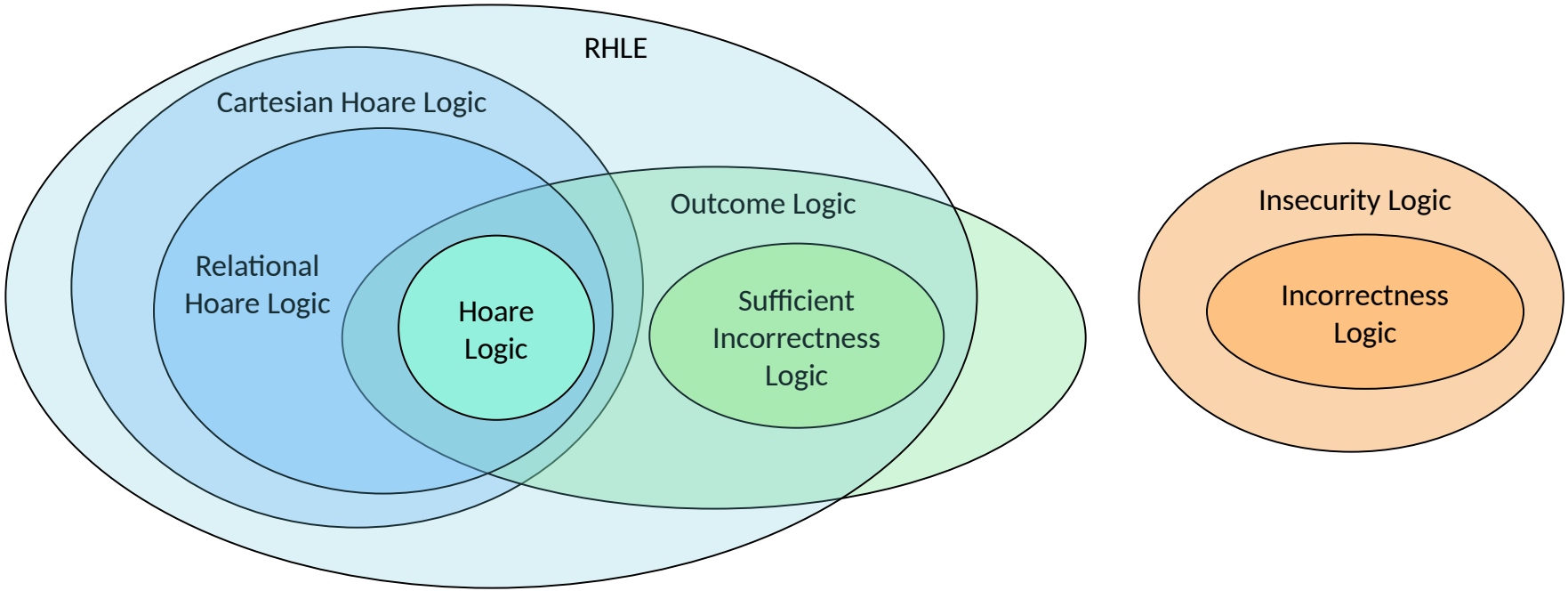


The Need for a Novel Foundation

Expressiveness of judgments restricted to a **single non-deterministic IMP** program (no heap or probabilities)



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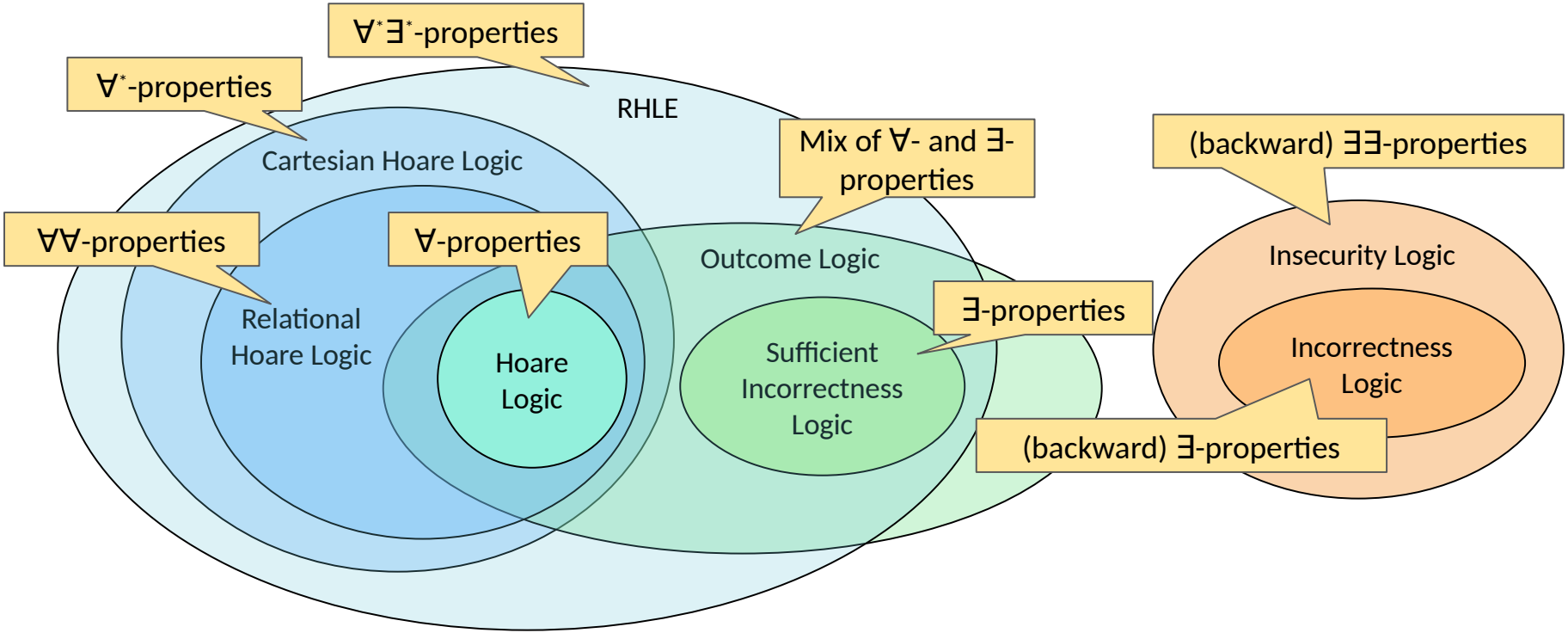

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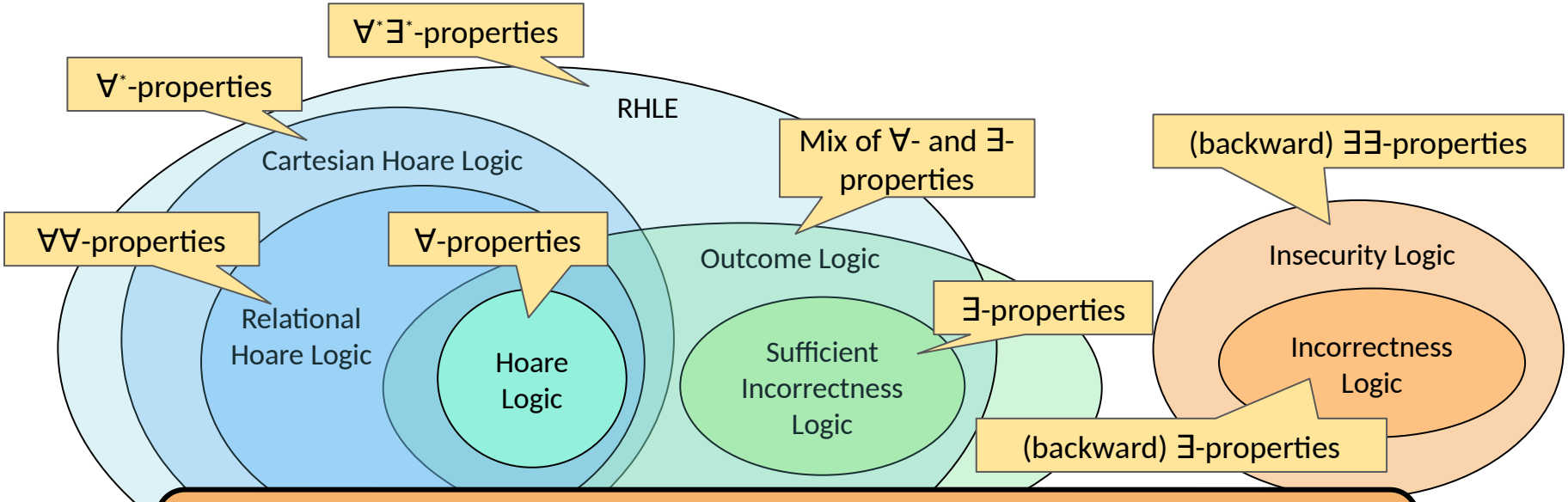

- Limited expressiveness (e.g., $\exists^*\forall^*$-properties)
- Limited compositionality (e.g., $\forall\forall$- and $\forall\exists$-properties)

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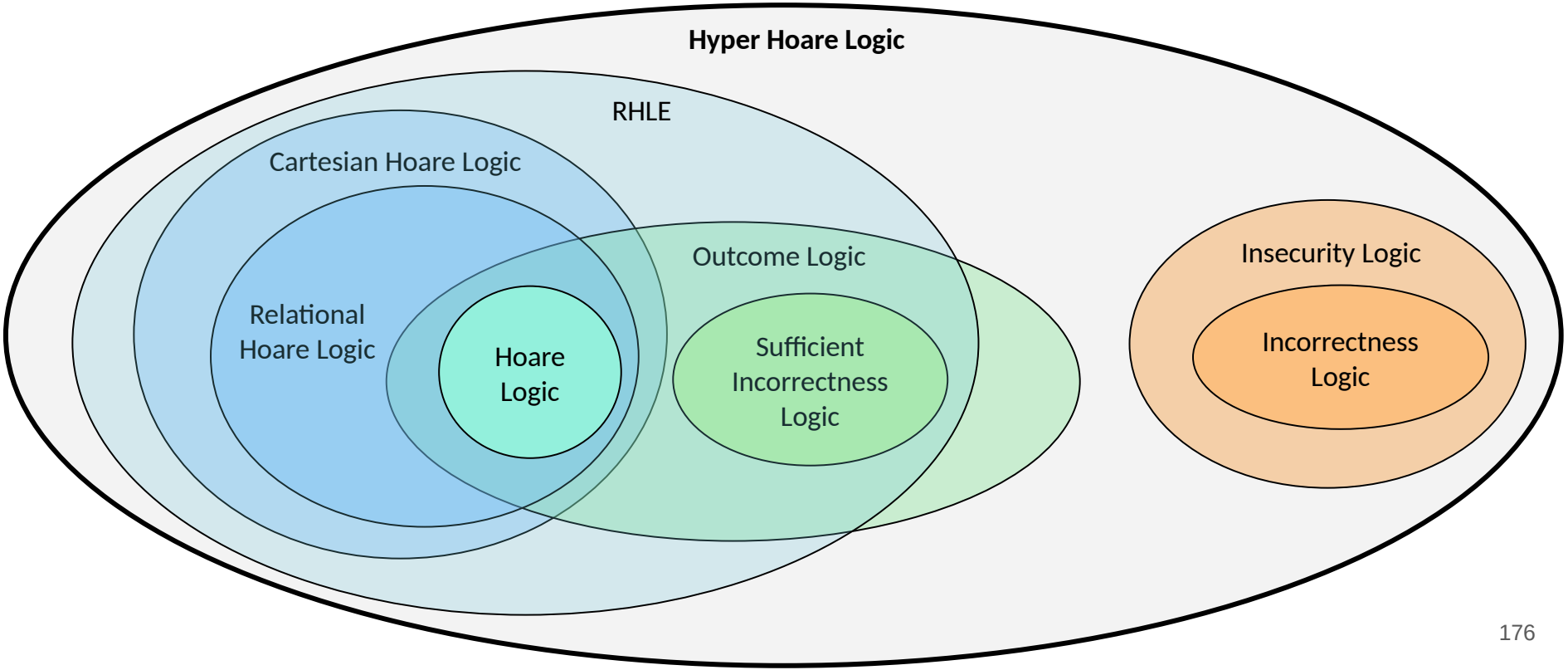

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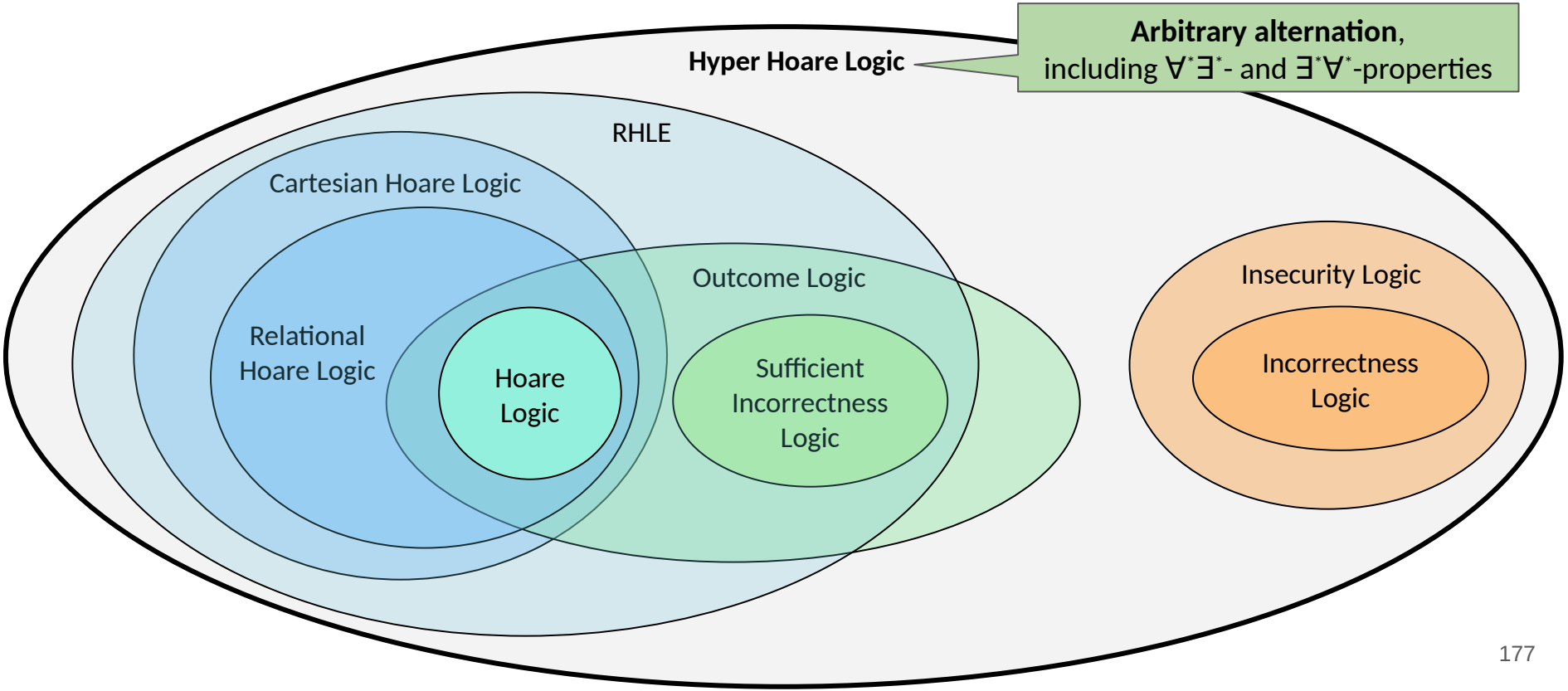
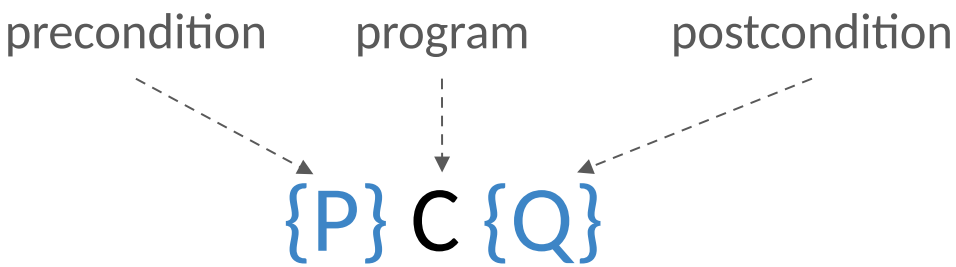


Hyper Hoare Logic – Key Insights



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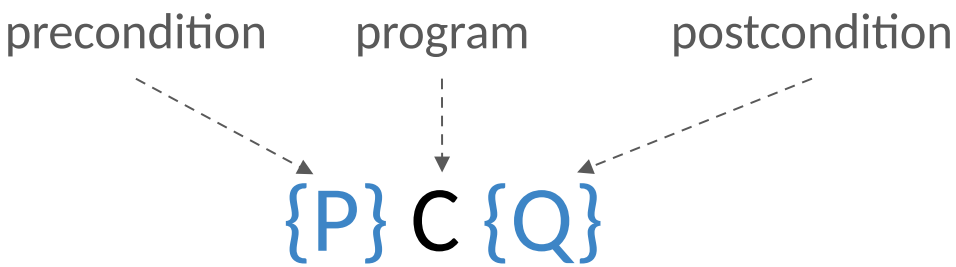
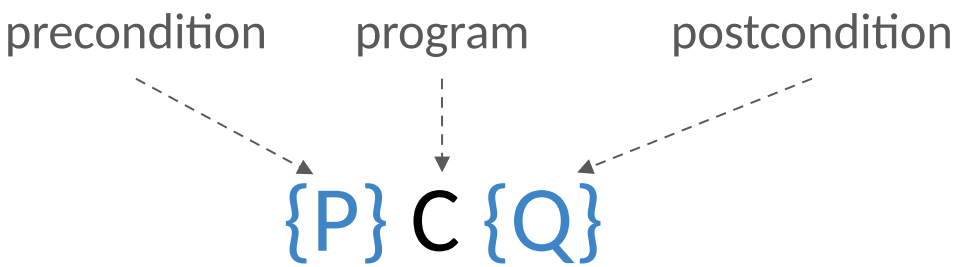


Pre-existing Hoare-like logics

Pre- and postconditions over **fixed** number of states

Hyper Hoare Logic – Key Insights



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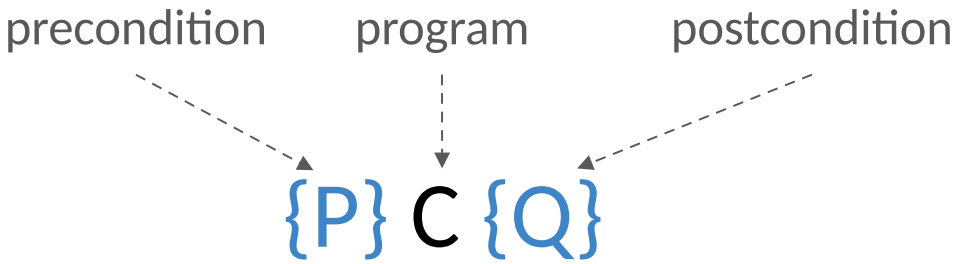
Quantification over executions **fixed**

Hyper Hoare Logic – Key Insights



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Pre- and postconditions over **sets** of reachable states

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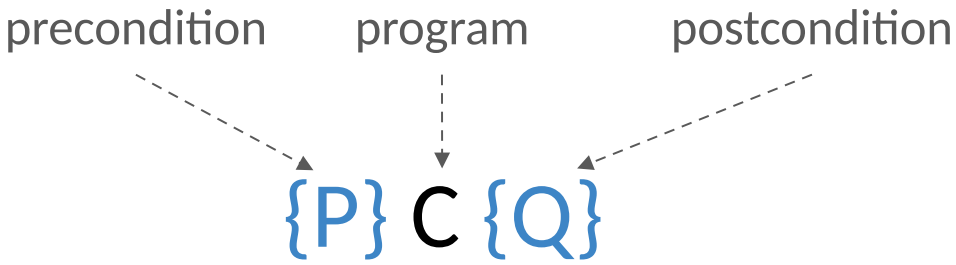

Pre-existing Hoare-like logics

Pre- and postconditions over **fixed** number of states

Quantification over executions **fixed**

Hyper Hoare Logic

Pre- and postconditions over **sets** of reachable states

Quantification over executions **explicit** in **assertions**

Hyper Hoare Logic – Non-Interference

$\{ \forall\langle\sigma_1\rangle.\ \forall\langle\sigma_2\rangle.\ \sigma_1(\mathrm{p}) = \sigma_2(\mathrm{p}) \}$ C $\{ \forall\langle\sigma_1\rangle.\ \forall\langle\sigma_2\rangle.\ \sigma_1(\mathrm{res}) = \sigma_2(\mathrm{res}) \}$

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initial states

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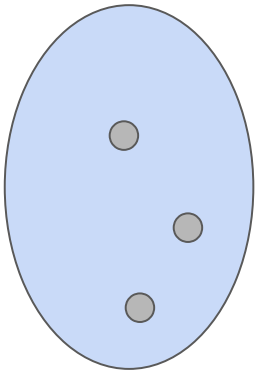

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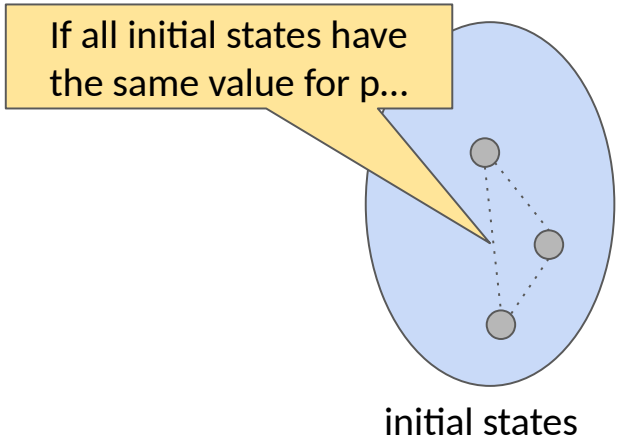

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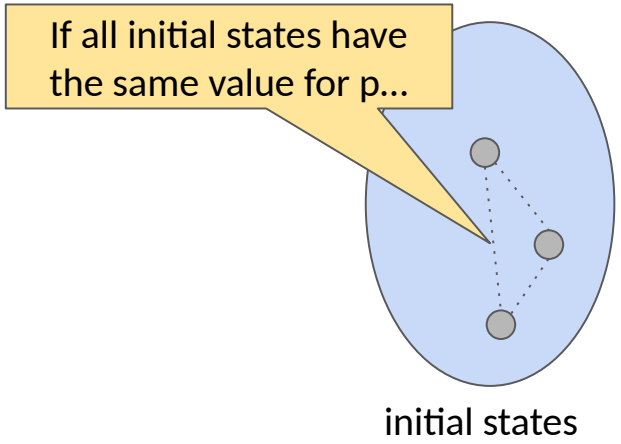
initial states

reachable states



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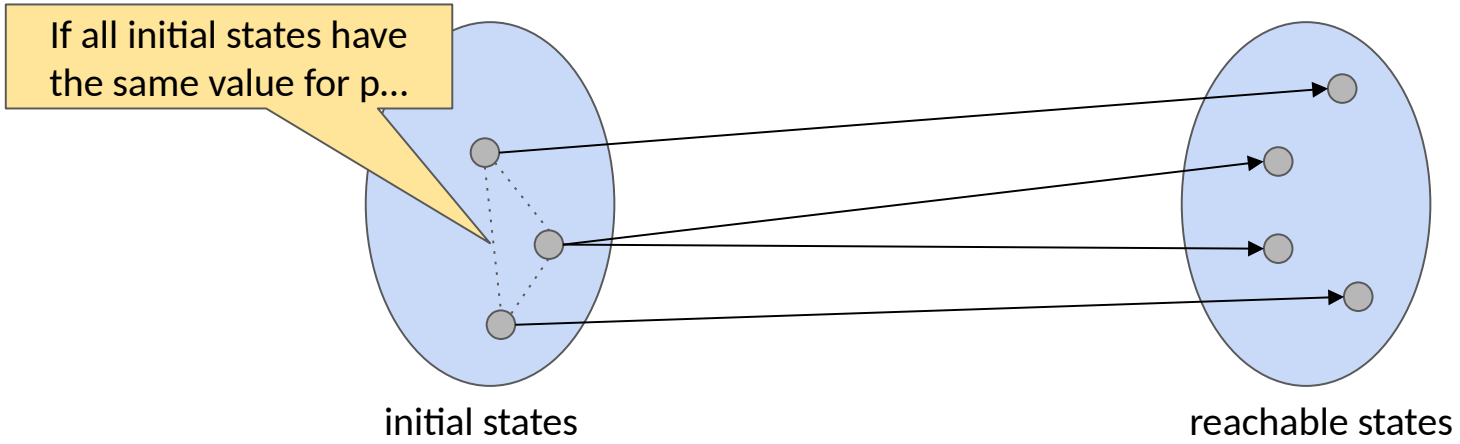

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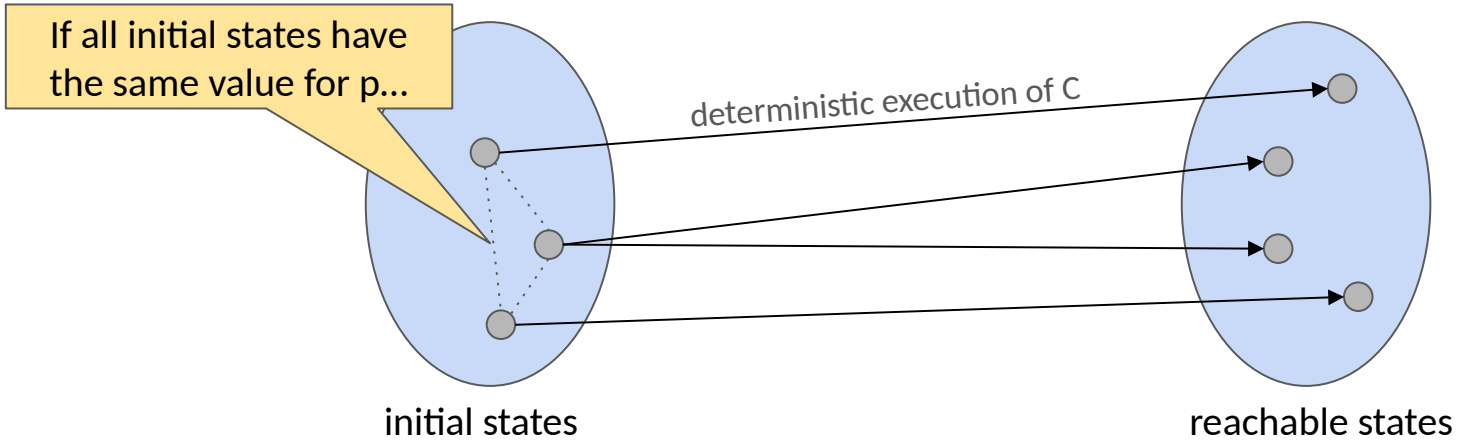

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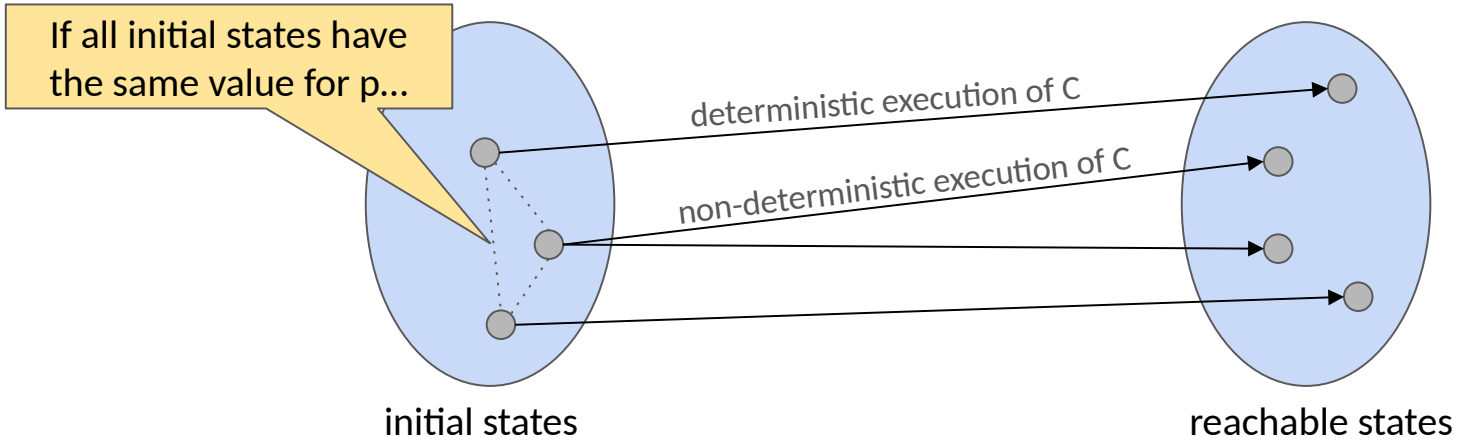

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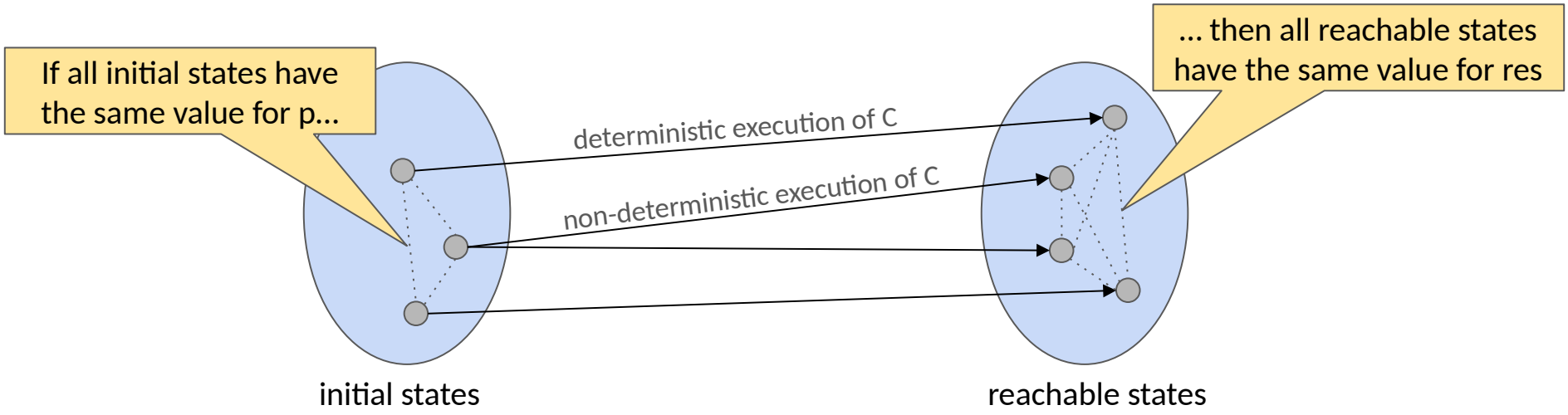
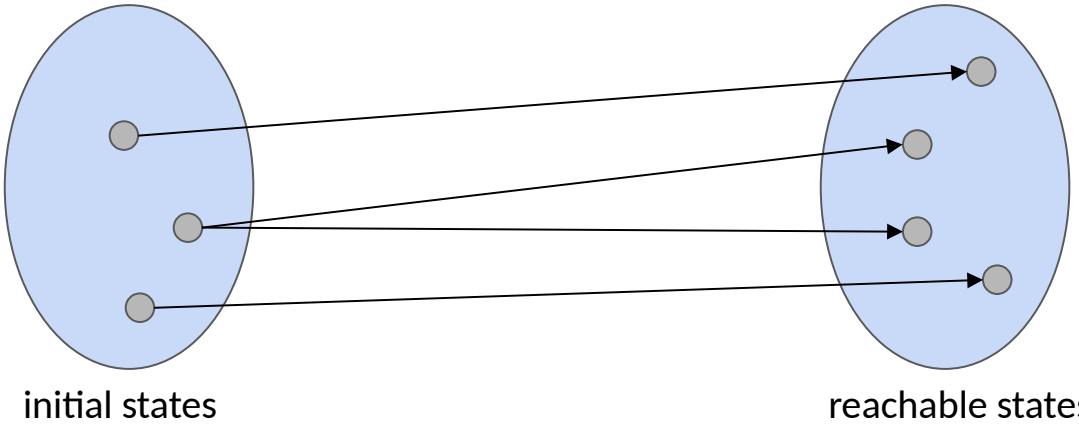


Hyper Hoare Logic – Generalized Non-Interference

$\{\forall\langle\sigma_1\rangle.\ \forall\langle\sigma_2\rangle.\ \sigma_1(\mathrm{p}) = \sigma_2(\mathrm{p})\}$ C $\{\forall\langle\sigma_1\rangle.\ \forall\langle\sigma_2\rangle.\ \exists\langle\sigma\rangle.\ \sigma(\mathrm{s}) = \sigma_1(\mathrm{s}) \wedge \sigma(\mathrm{res}) = \sigma_2(\mathrm{res})\}$



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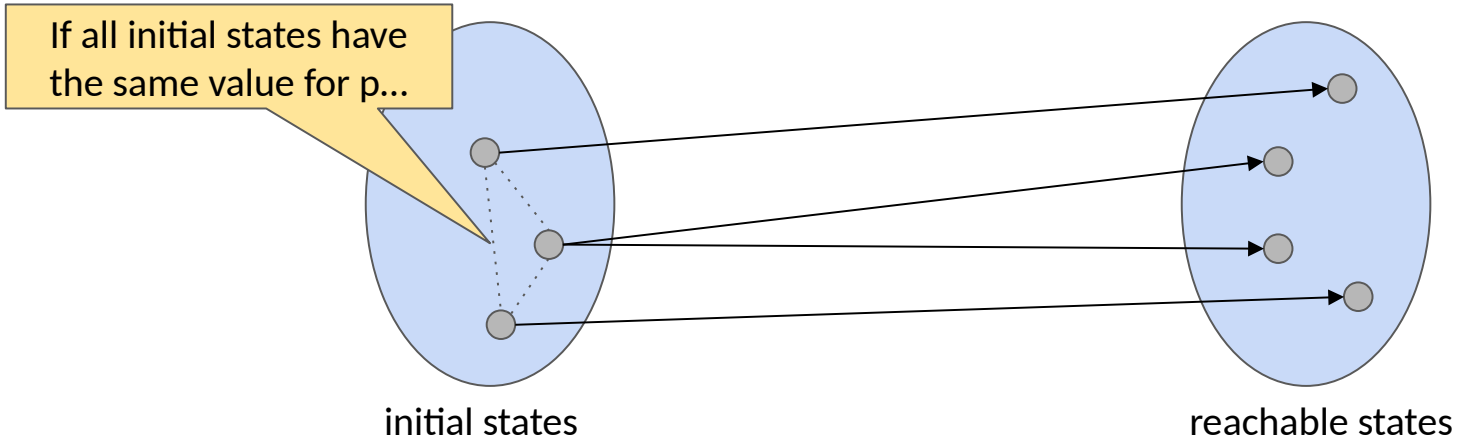

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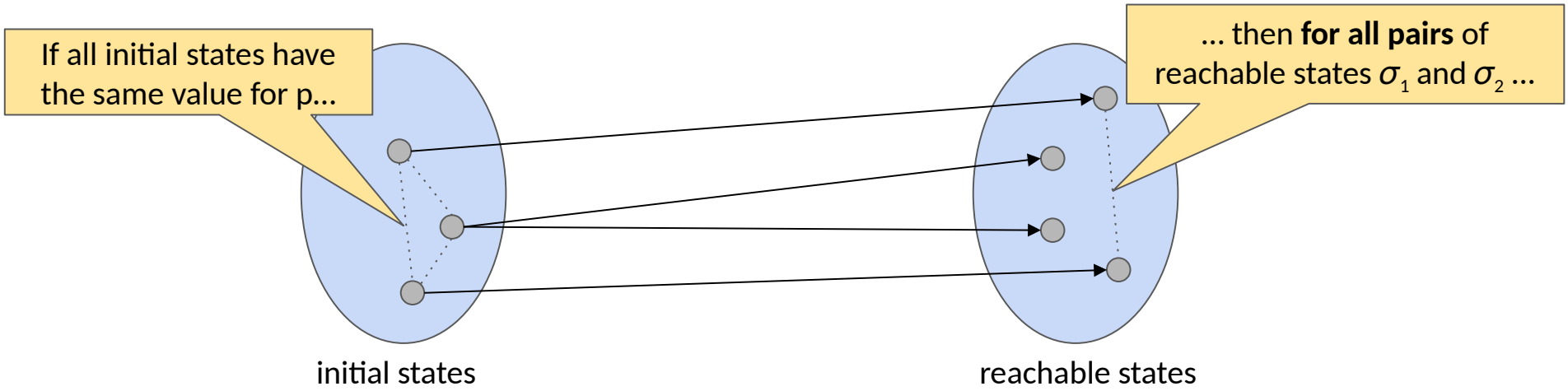

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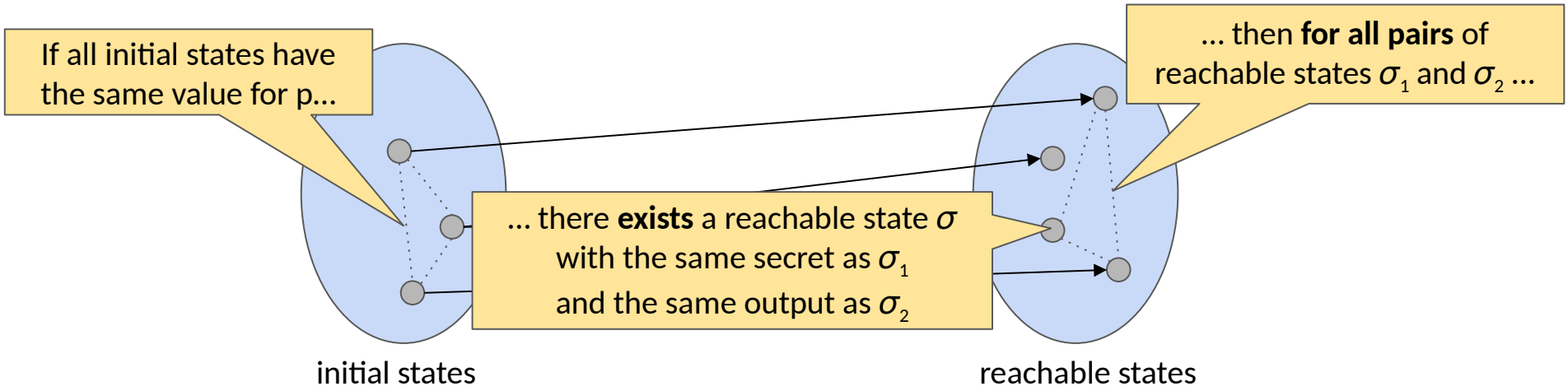

Hyper Hoare Logic – Rules

Minimal set of core rules
Complete

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Minimal set of core rules
Complete

Syntactic rules
Easy to use and automate

Hyper Hoare Logic – Rules

Minimal set of core rules
Complete

Compositionality rules
To compose different types of hyperproperties

Syntactic rules
Easy to use and automate

Hyper Hoare Logic – Rules

Minimal set of core rules
Complete

Compositionality rules
To compose different types of hyperproperties

Syntactic rules
Easy to use and automate

Loop rules
Capturing important proof principles

Hyper Hoare Logic – Rules

Minimal set of core rules
Complete

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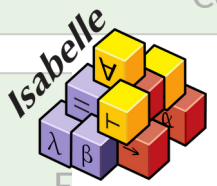


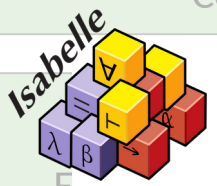
Hyper Hoare Logic: (Dis-)Proving Program Hyperproperties

THIBAULT DARDINIER, ETH Zurich, Switzerland
PETER MÜLLER, ETH Zurich, Switzerland

Hyper Hoare Logic – Rules

Hyper Hoare Logic – Rules

First automated verifier that can establish all previously-mentioned hyperproperties!



Hypra: A Deductive Program Verifier for Hyper Hoare Logic

THIBAULT DARDINIER*, ETH Zurich, Switzerland
ANQI LI*, ETH Zurich, Switzerland
PETER MÜLLER, ETH Zurich, Switzerland

Hyper Hoare Logic: (Dis-)Proving Program Hyperproperties

THIBAULT DARDINIER, ETH Zurich, Switzerland
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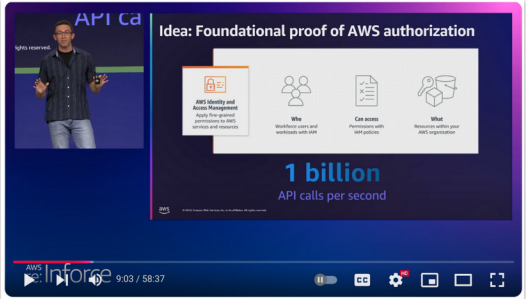
Summary



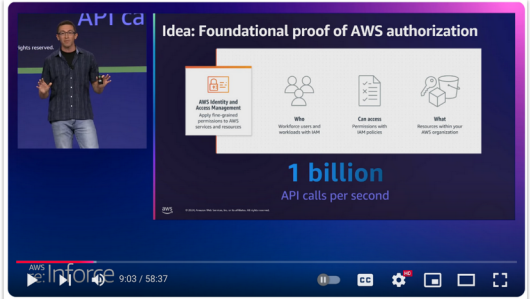
AWS re:Inforce 2024 - Proving the correctness of AWS authorization (IAM401)

1 billion times/second

~3,000 lines of code

~3x performance

Summary



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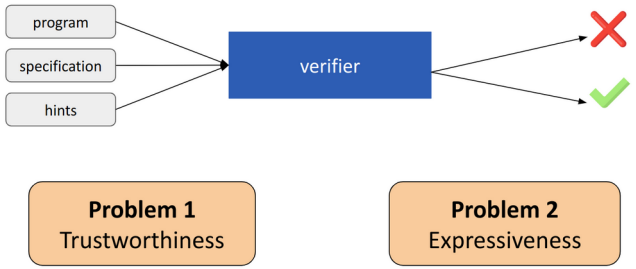

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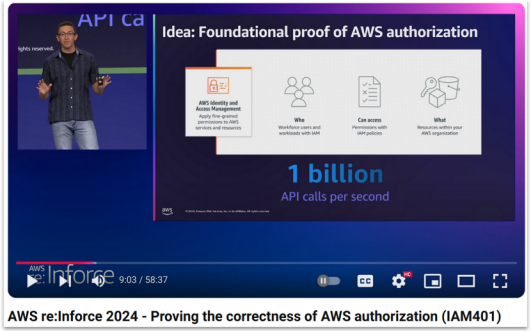

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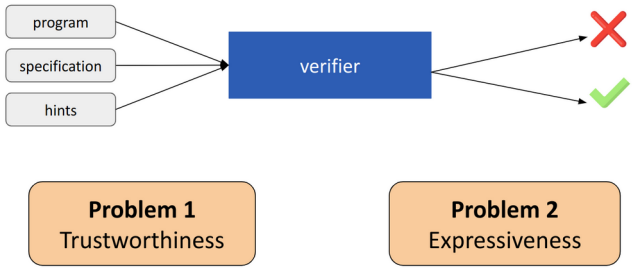

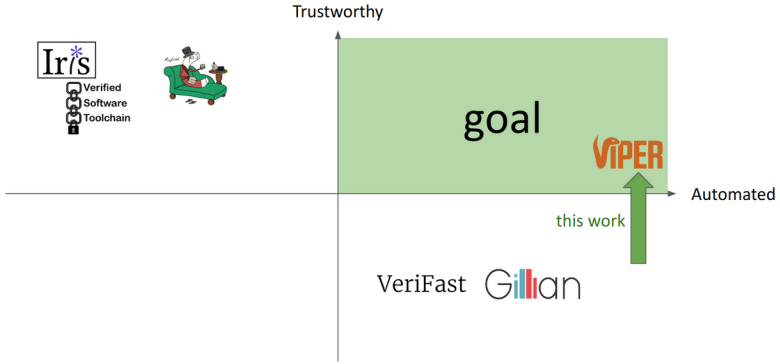

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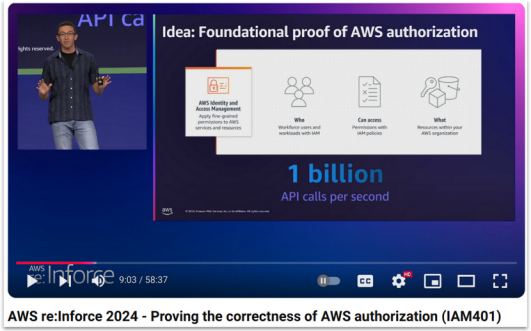

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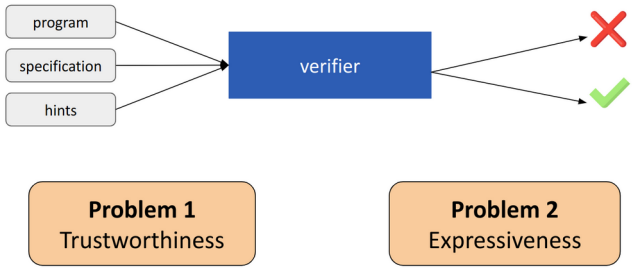
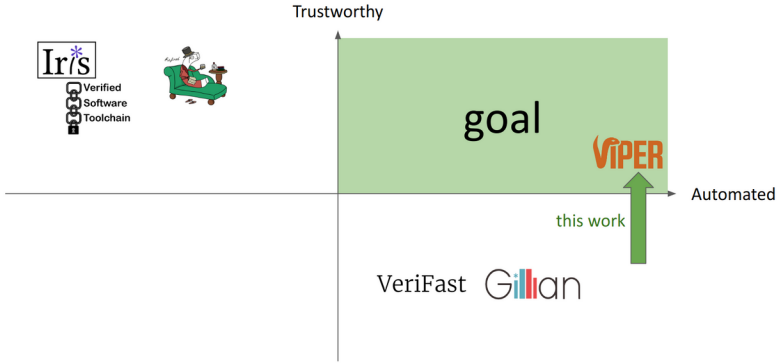
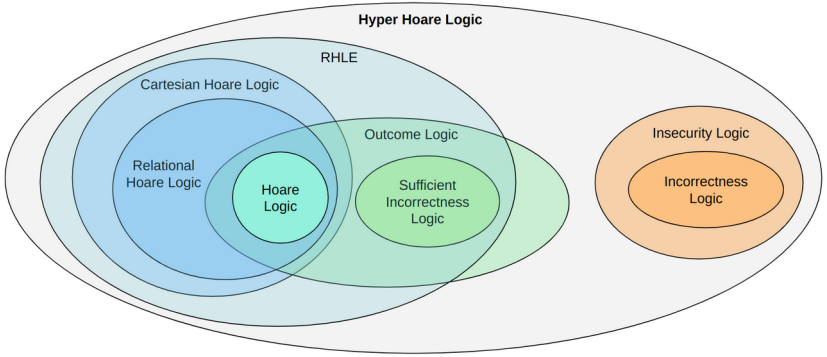






Past Research

Build **provably sound** and **automated** deductive verifiers for **advanced properties**.

Problem 1
Trustworthiness

Provably sound and automated verifier based on *separation logic*

Problem 2
Expressiveness

Automated verifier for arbitrary *hyperproperties*

Future Research Directions

Build **provably sound** and **automated** deductive verifiers for **advanced properties**.

Problem 1
Trustworthiness

Problem 2
Expressiveness

Future Research Directions

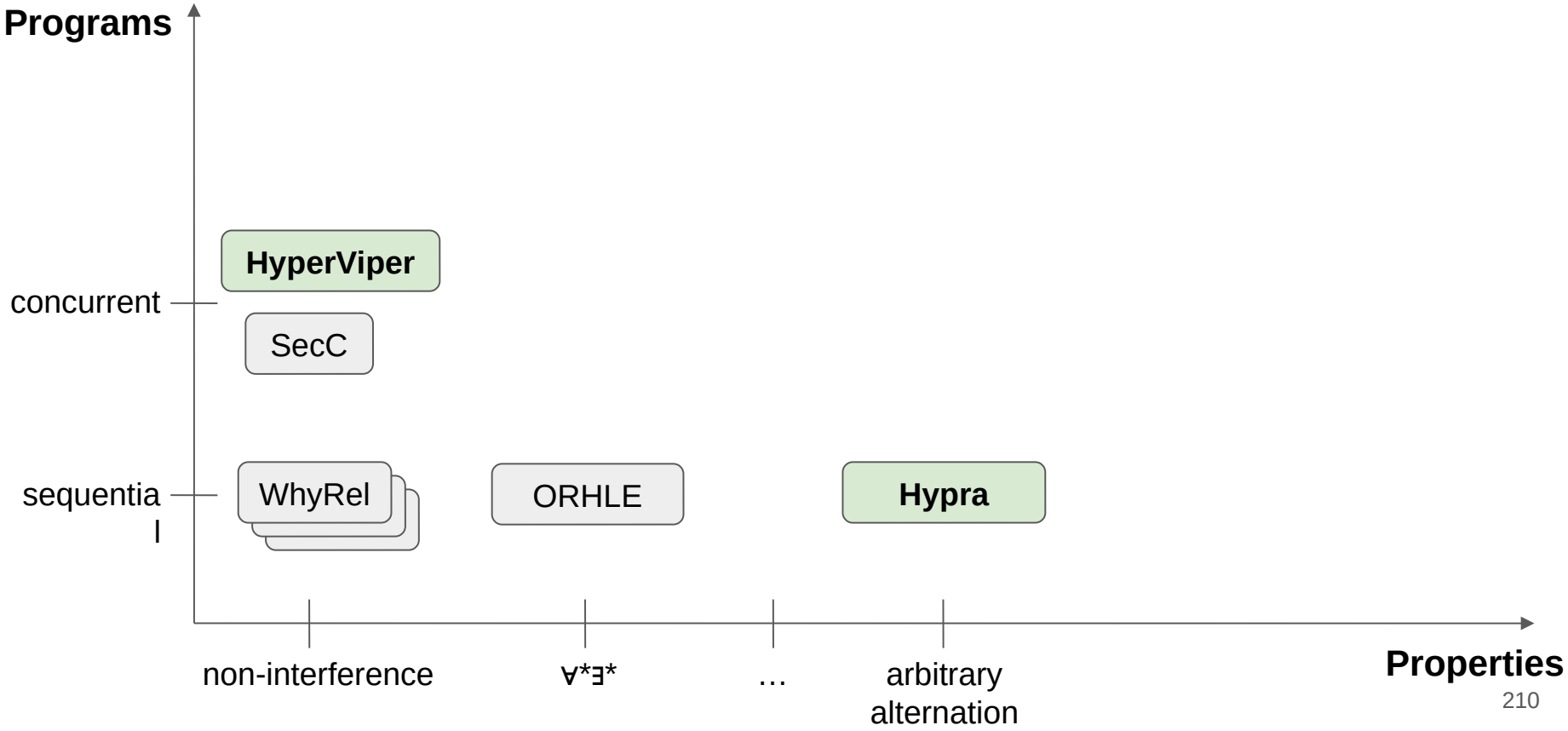
Build **provably sound** and **automated** deductive verifiers for **advanced properties**.

Problem 1
Trustworthiness

Problem 2
Expressiveness

General-purpose automated verifier for **security** and **privacy** properties

Automated Verifiers for Security and Privacy Properties



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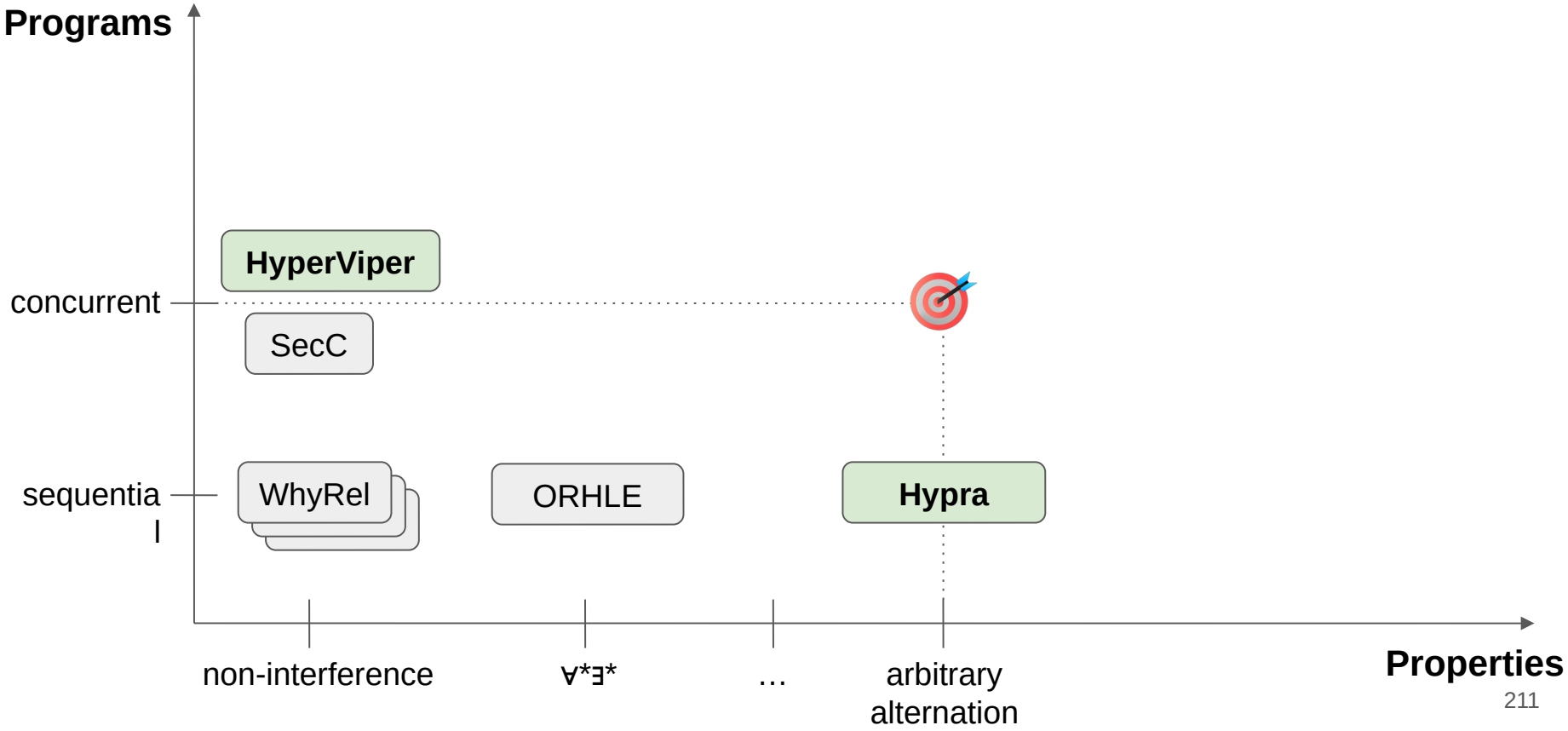

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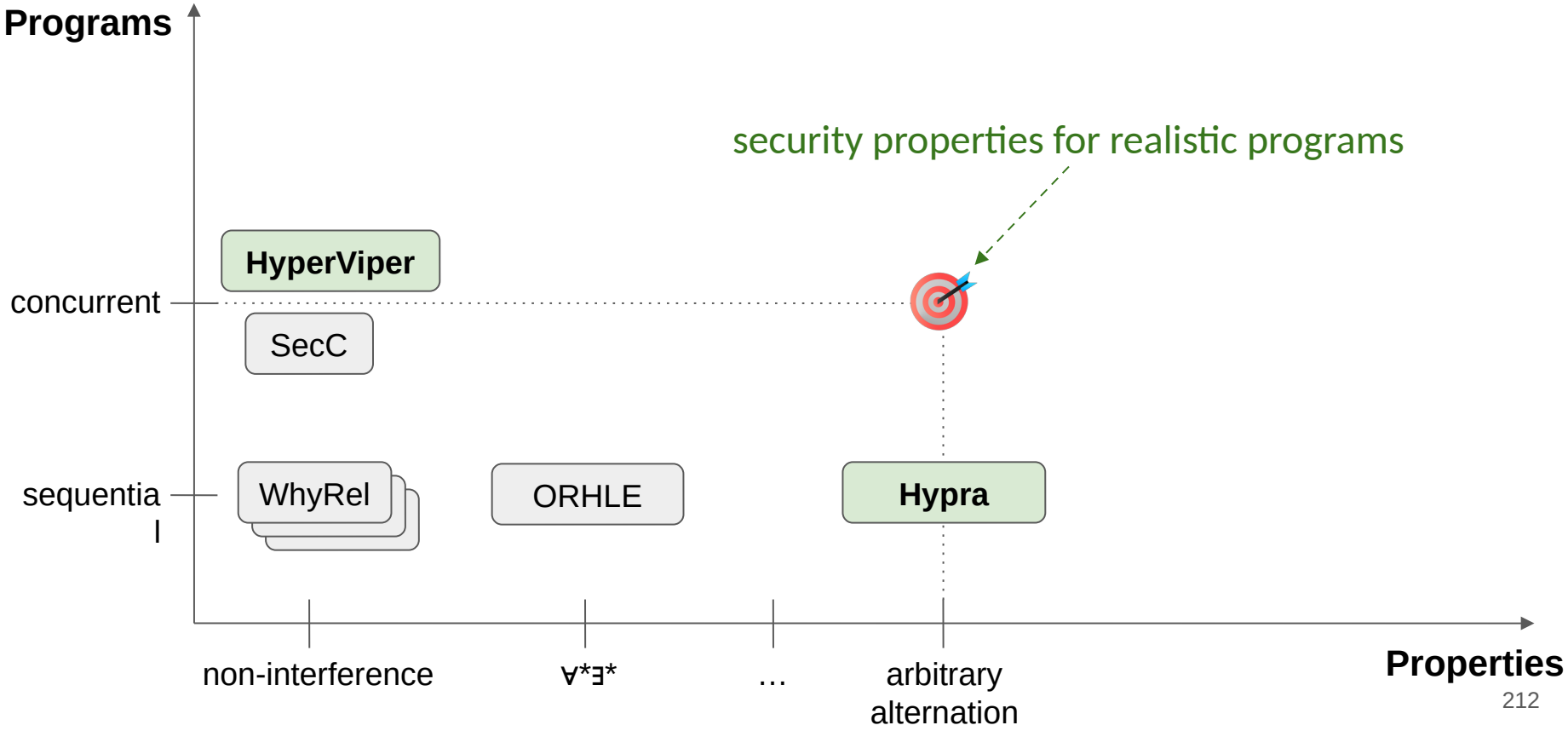

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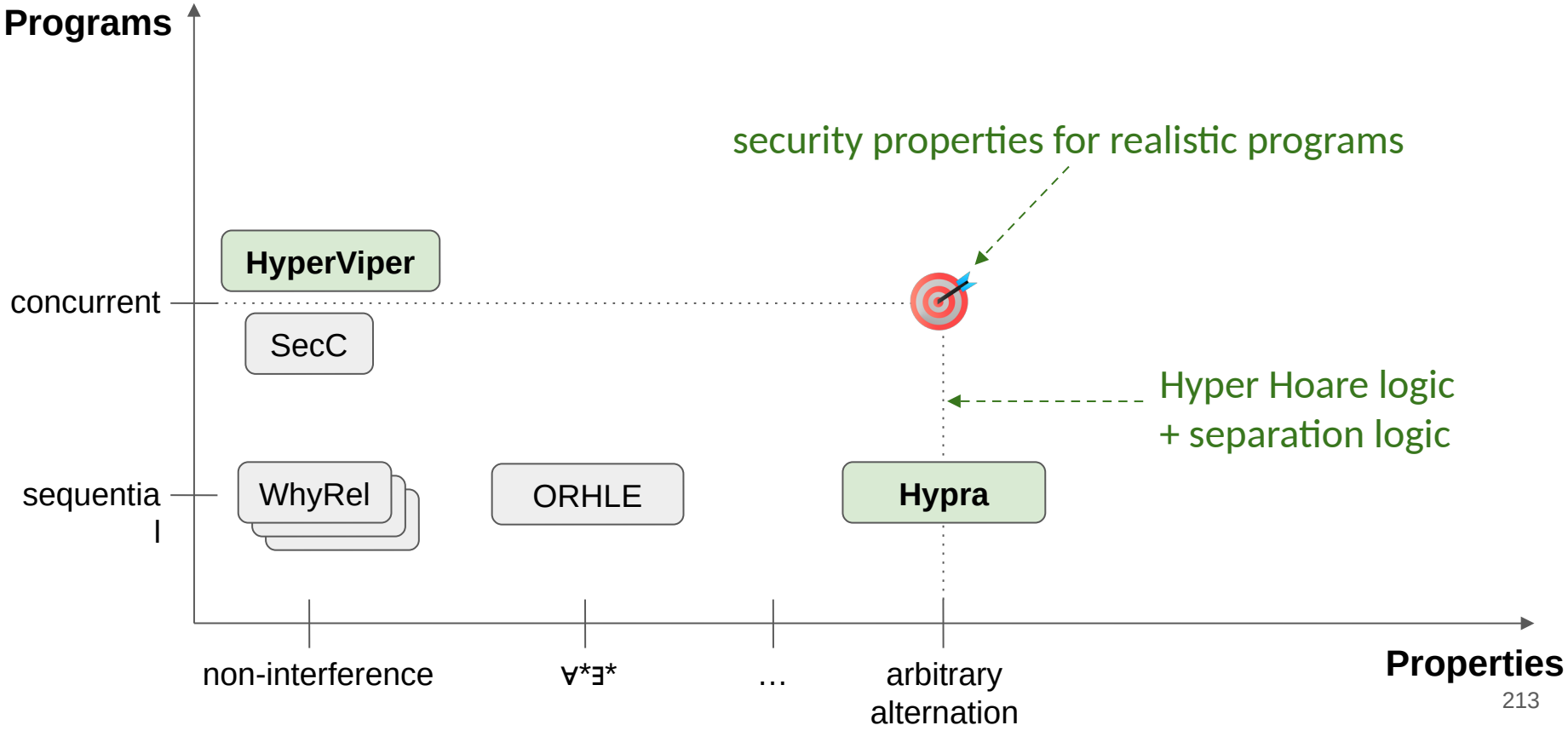

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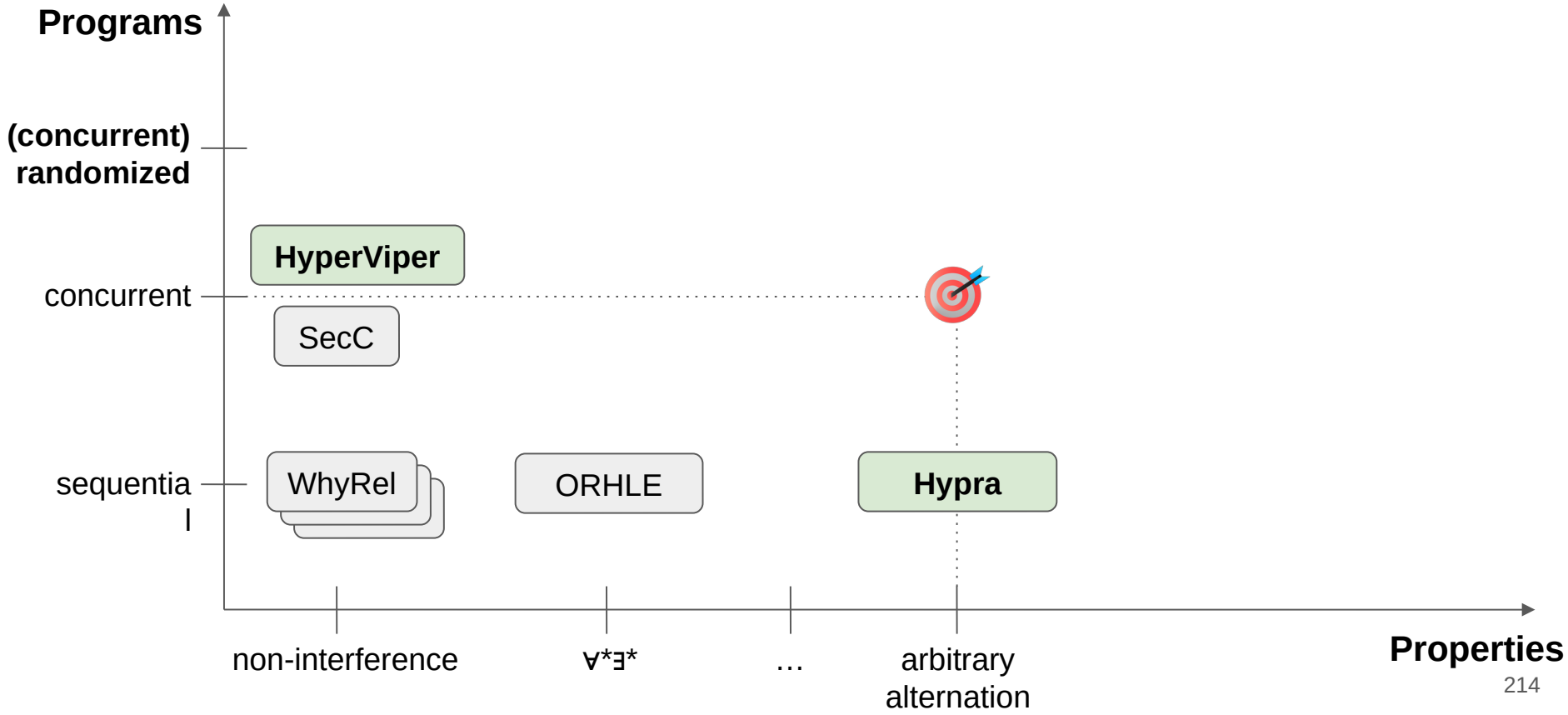

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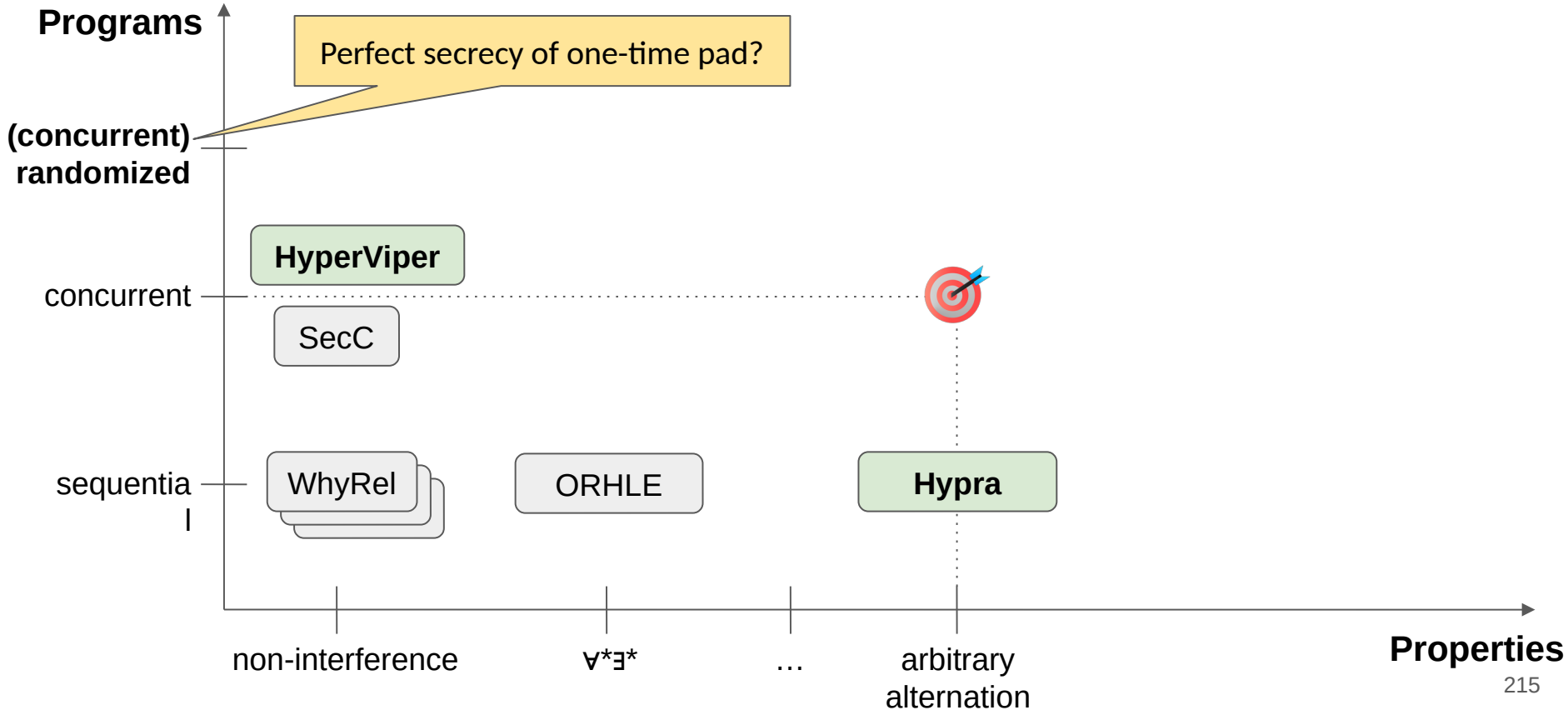
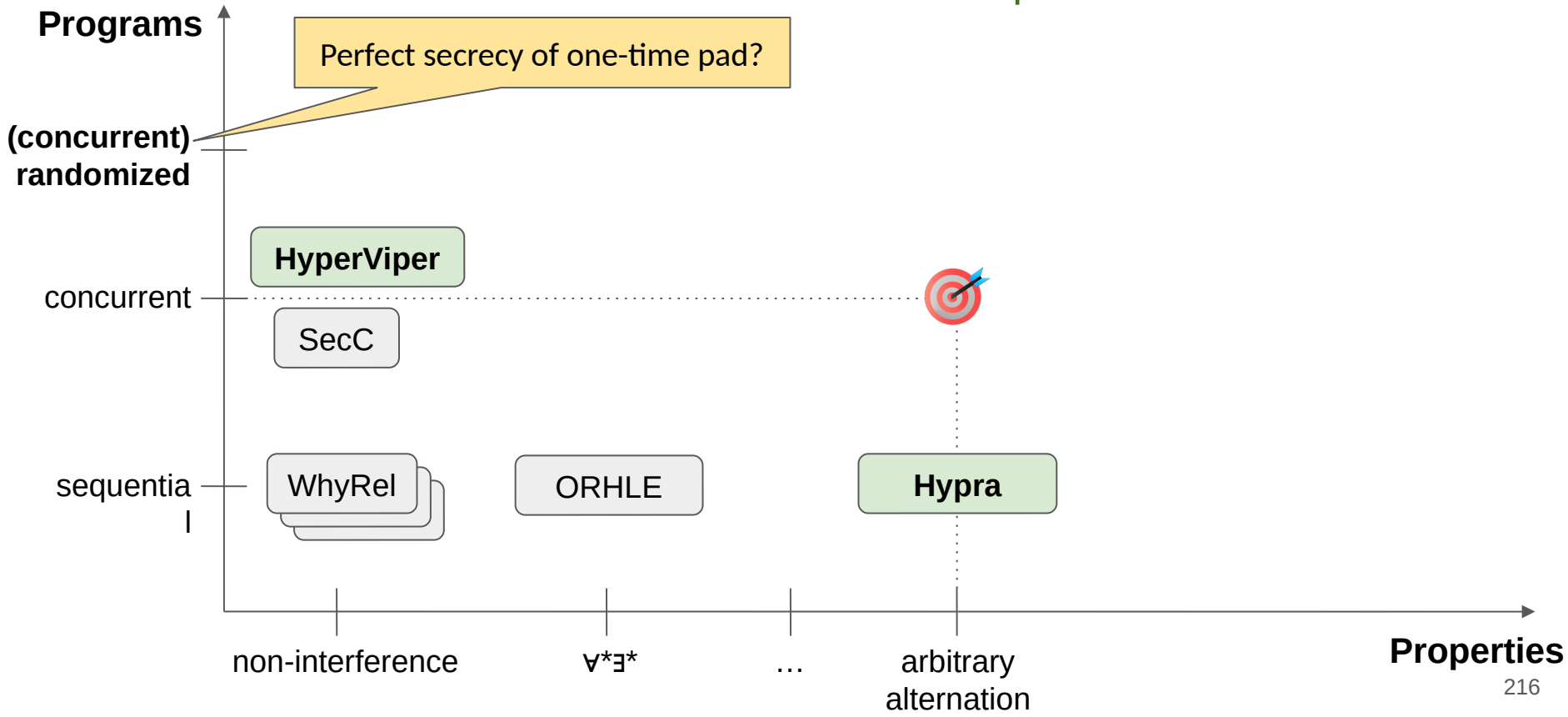


Automated Verifiers for Security and Privacy Properties

+ probabilistic non-interference



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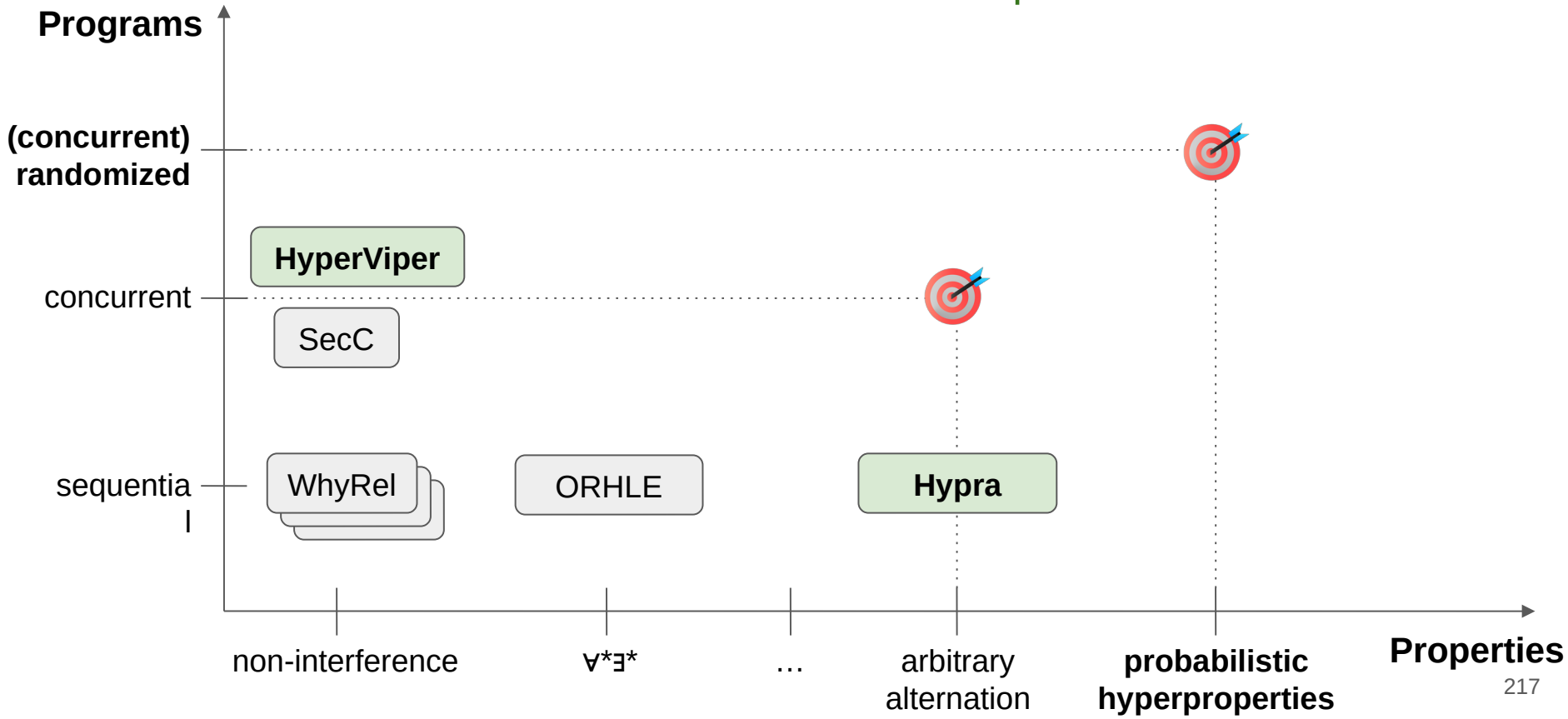
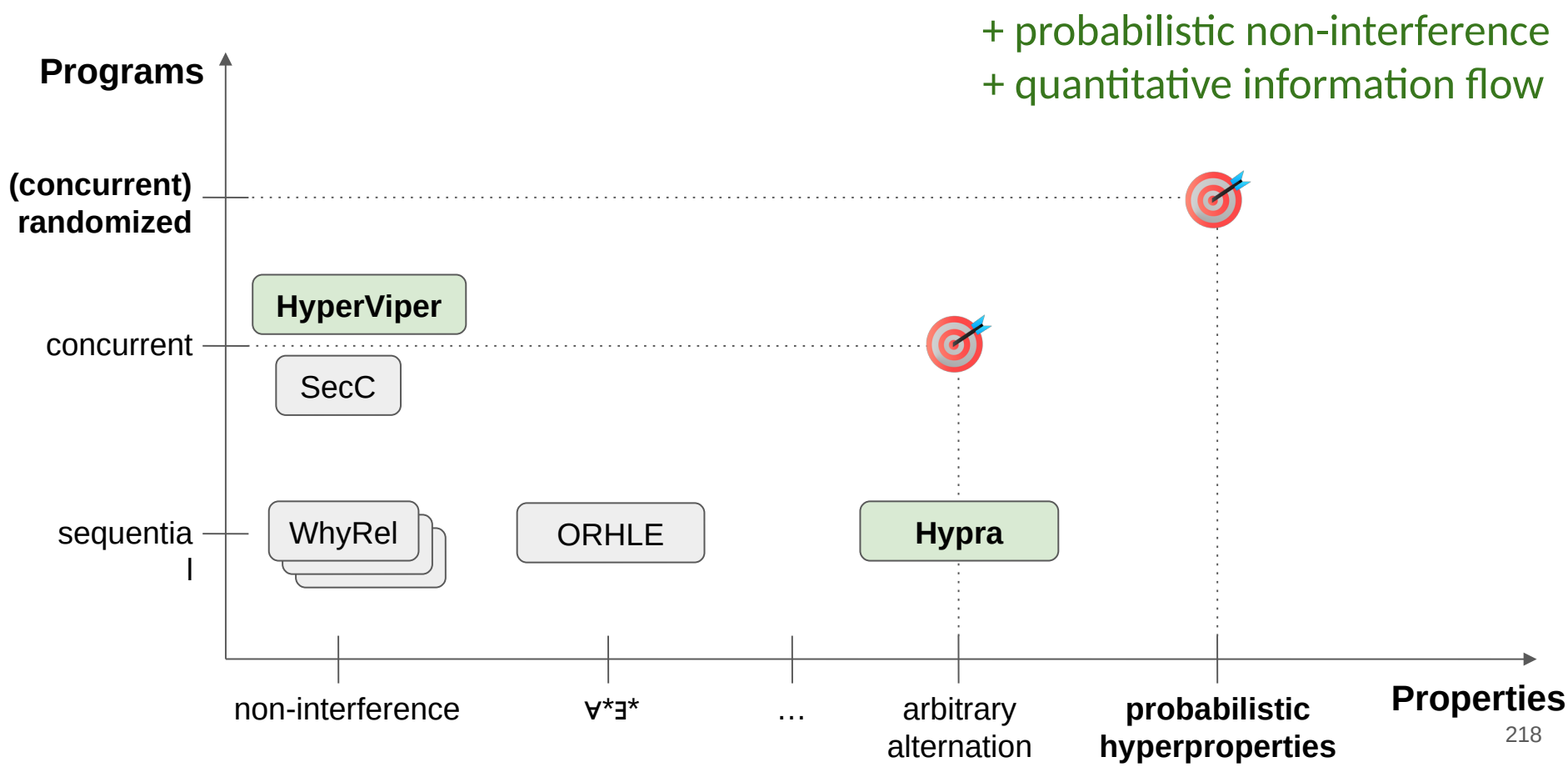


Automated Verifiers for Security and Privacy Properties



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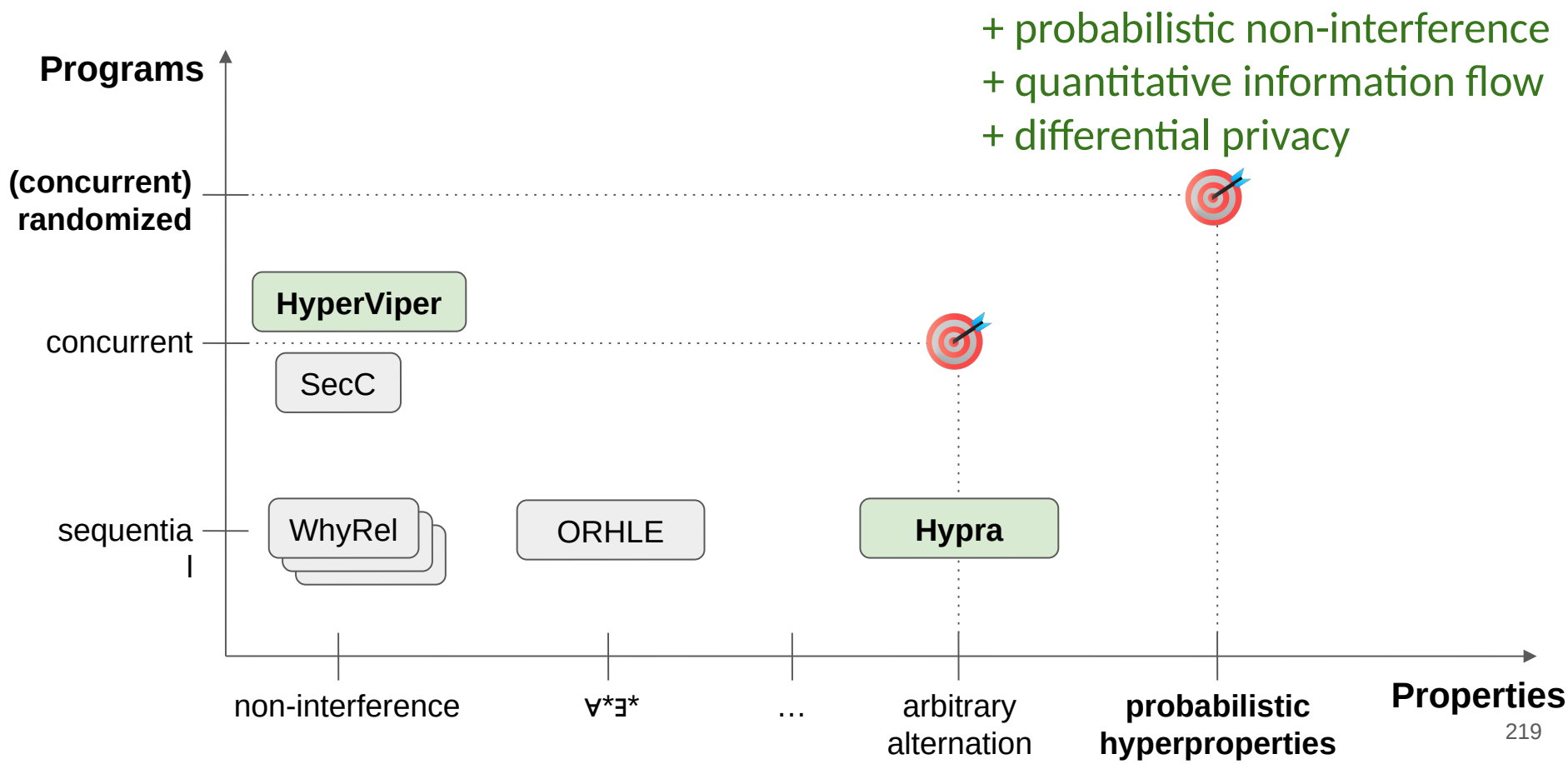

Future Research Directions

Build **provably sound** and **automated** deductive verifiers for **advanced properties**.

Problem 1
Trustworthiness

Problem 2
Expressiveness

General-purpose automated verifier for **security** and **privacy** properties

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Problem 1
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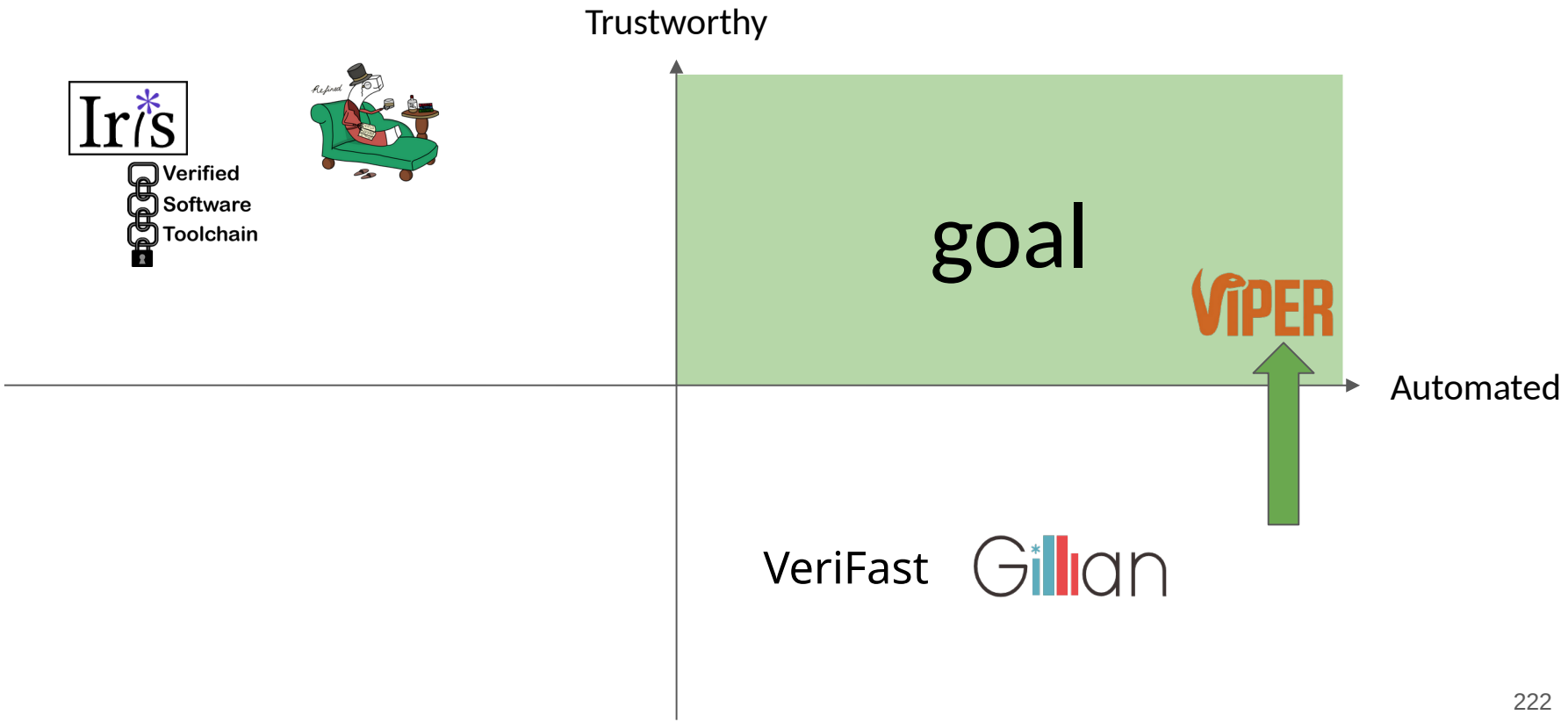
A **novel paradigm** to build sound automated verifiers

Problem 2
Expressiveness

General-purpose automated verifier for **security** and **privacy** properties

A Novel Paradigm to Build Sound Automated Verifiers



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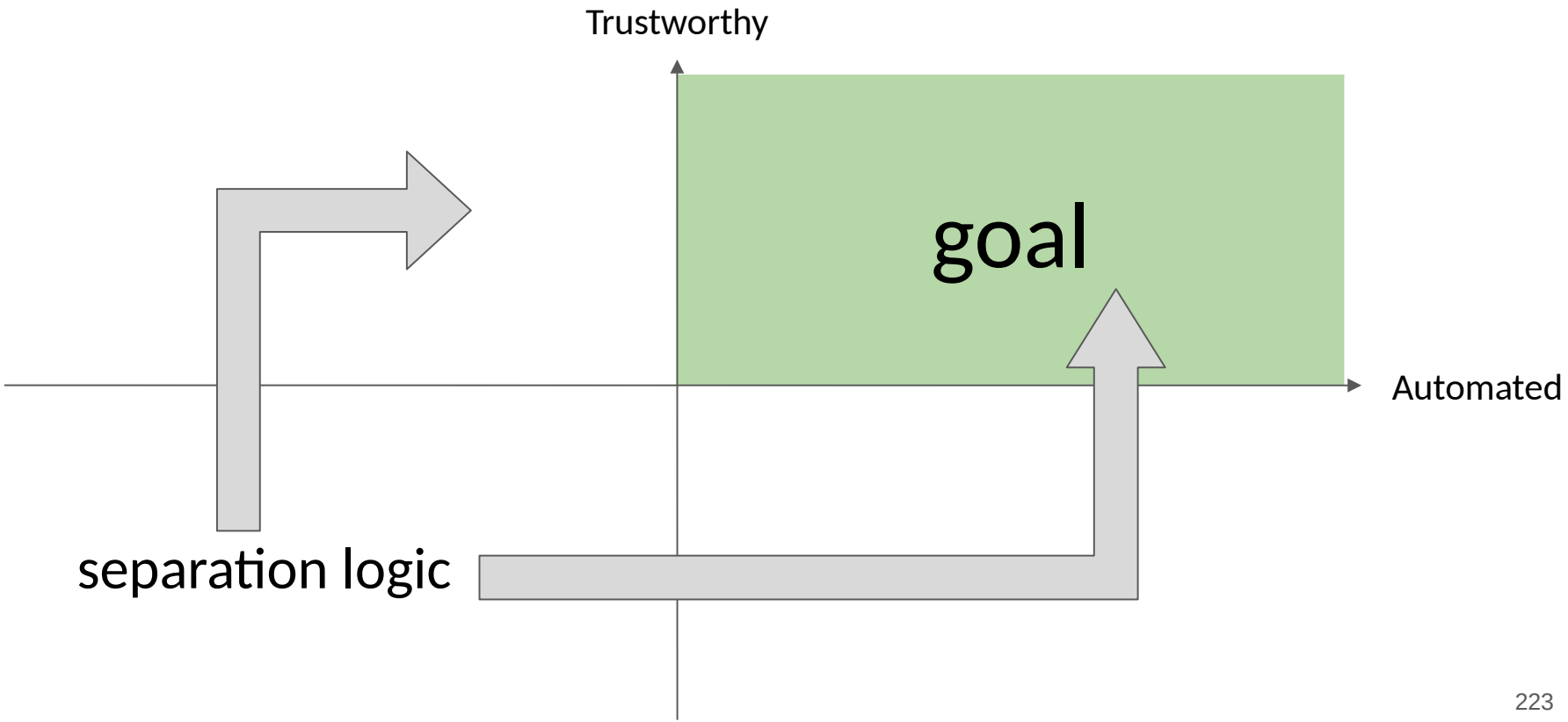

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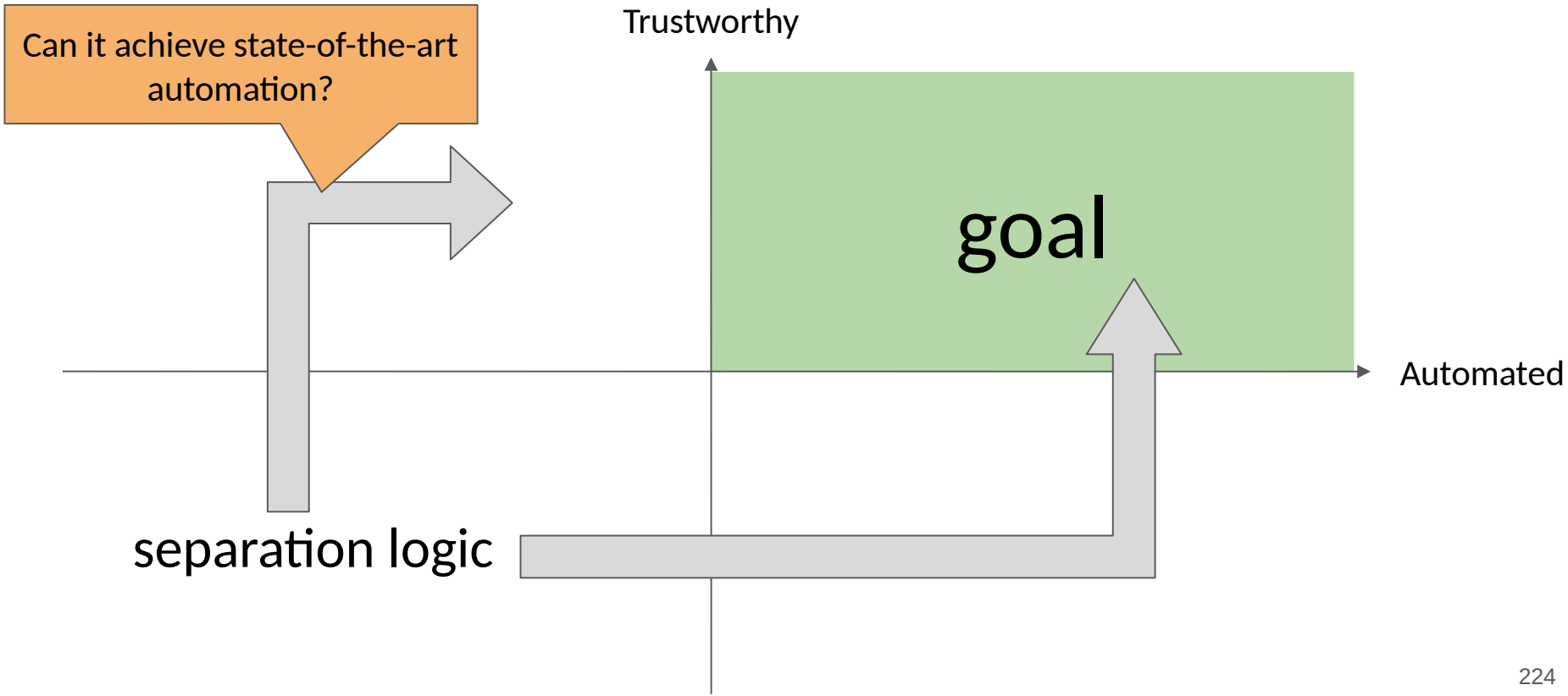

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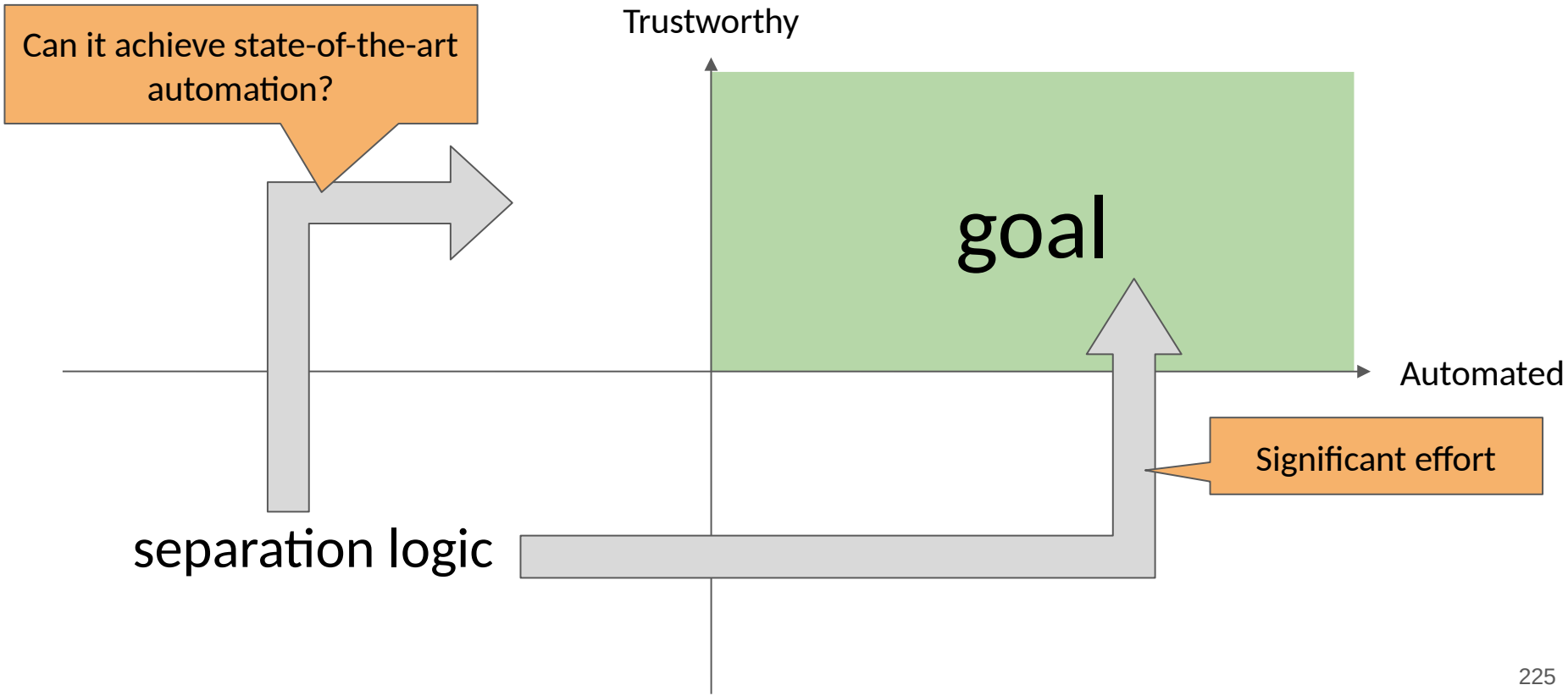

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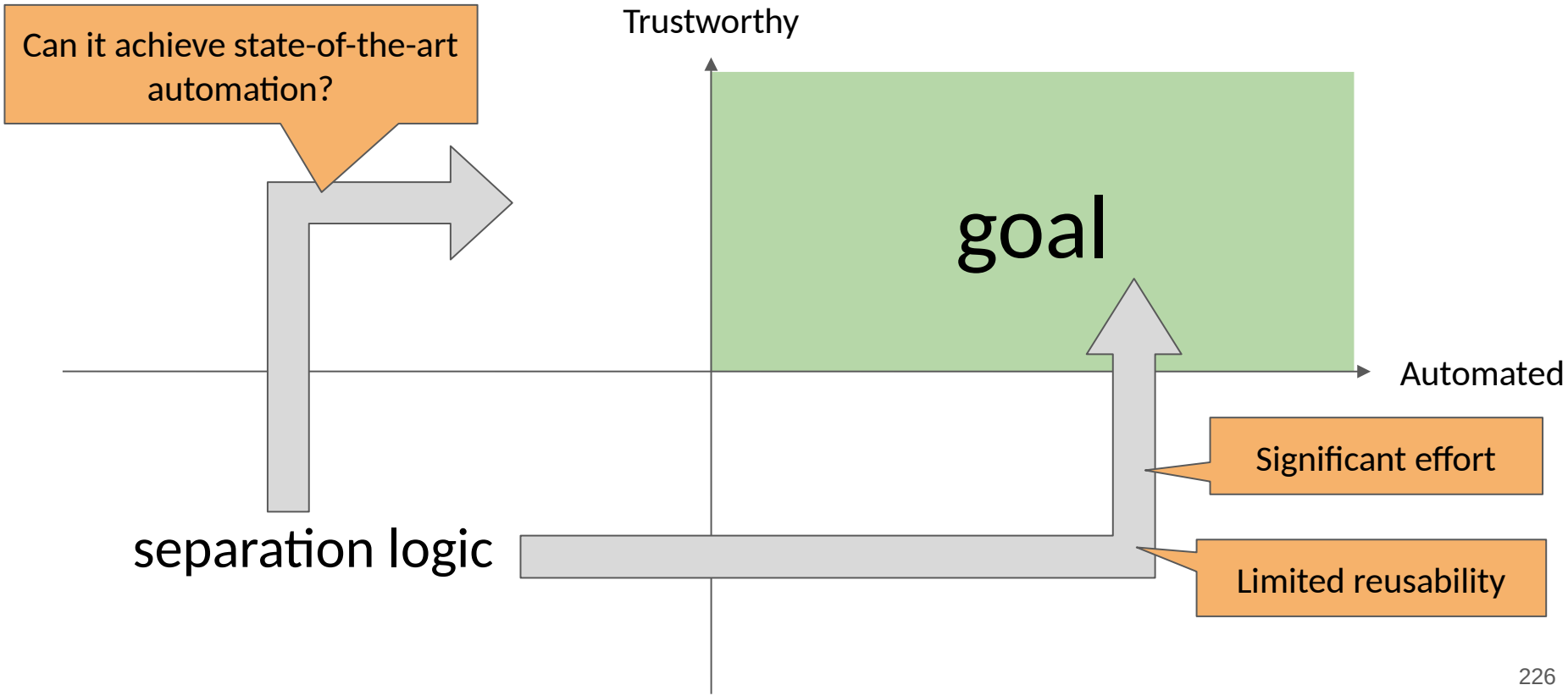

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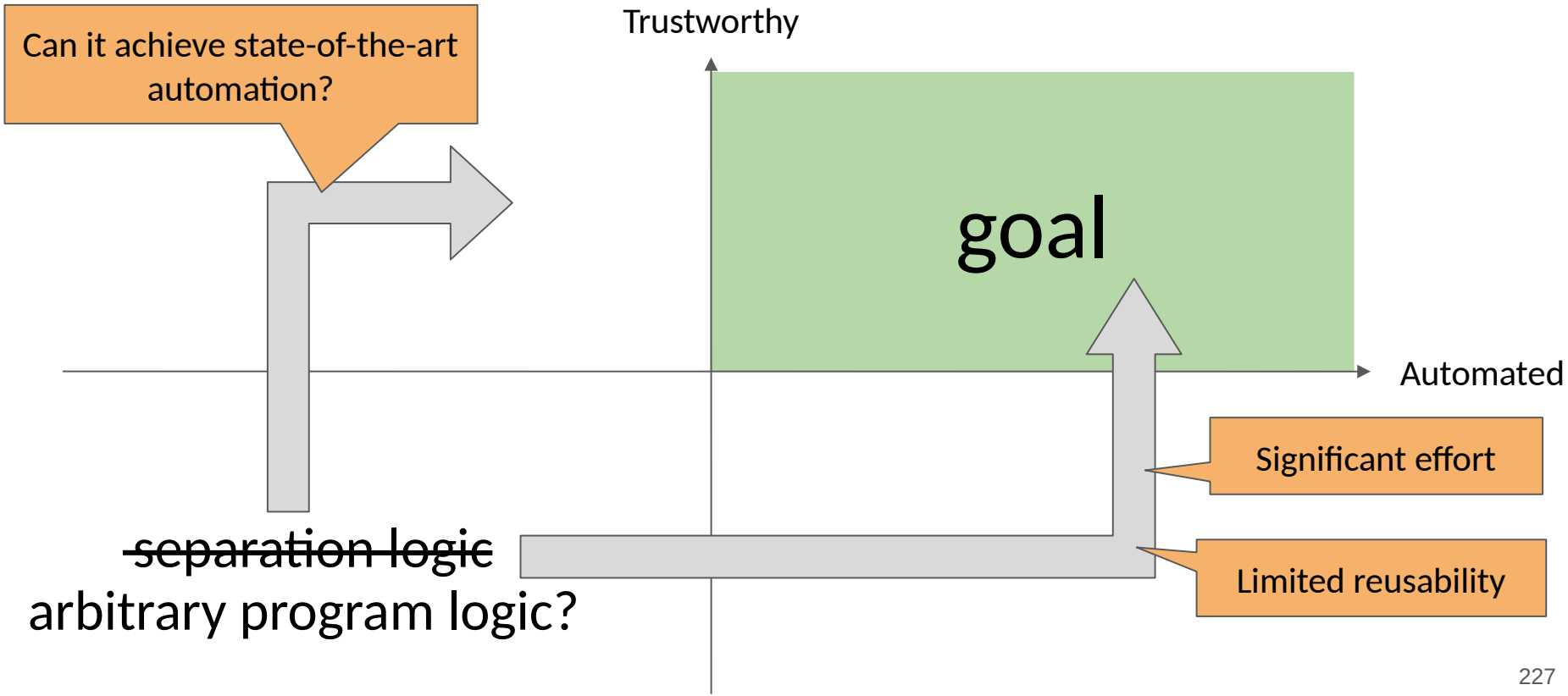

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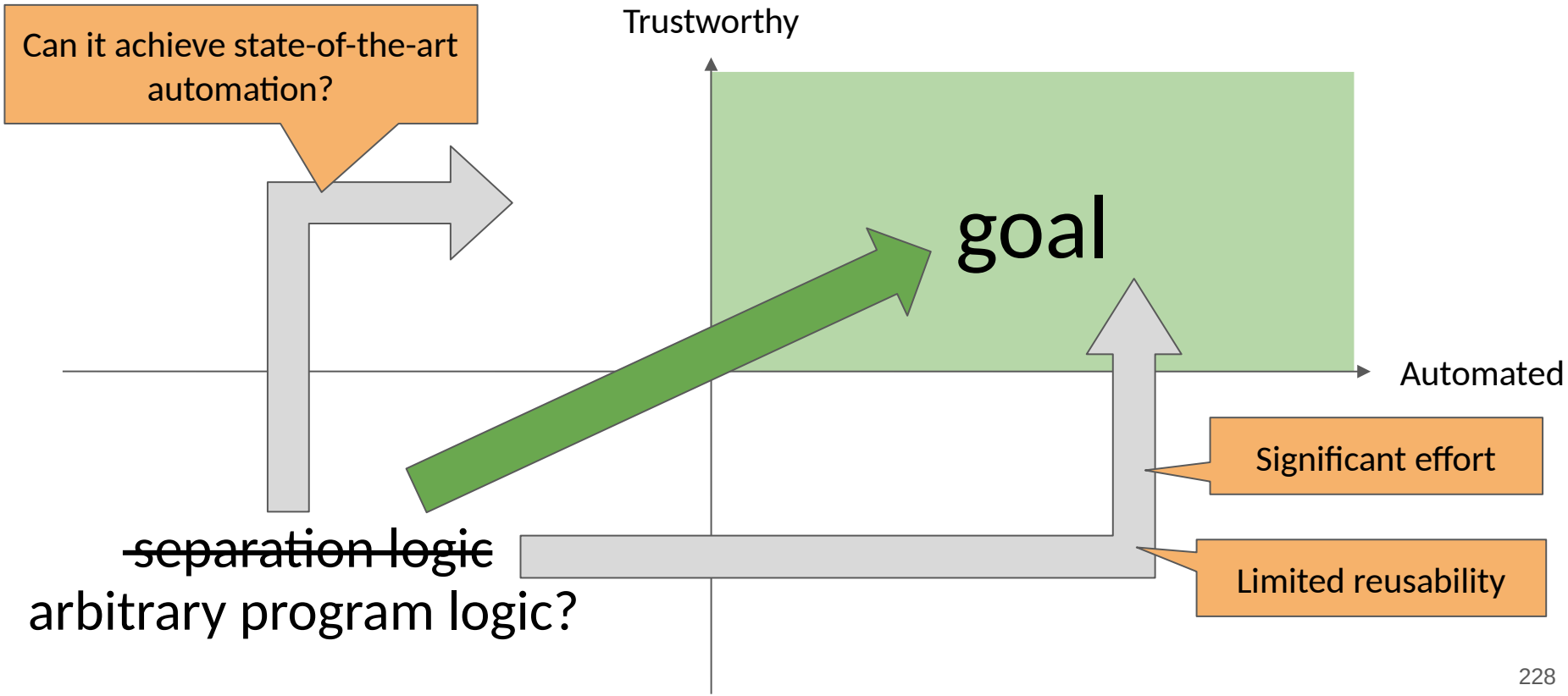

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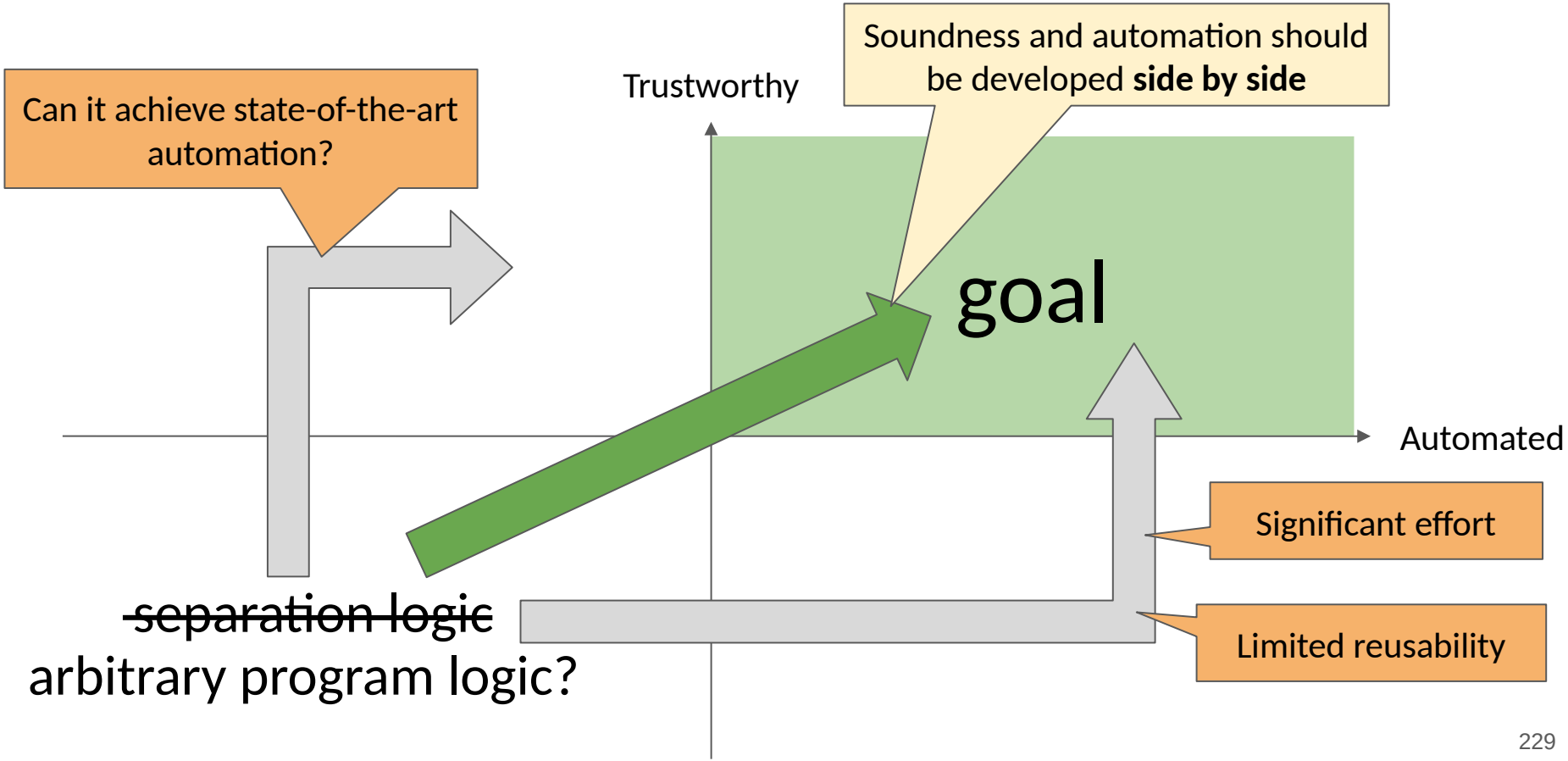
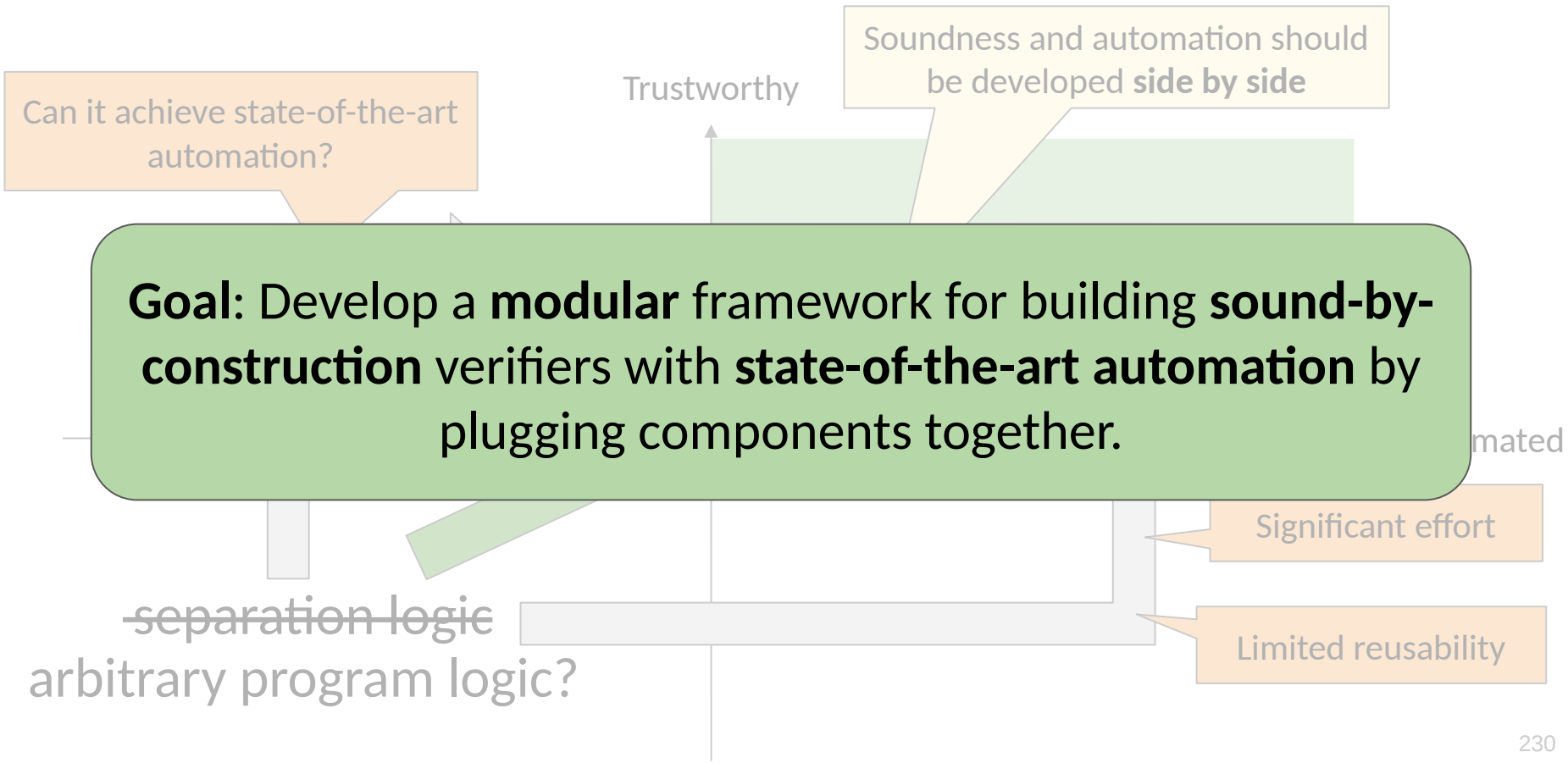


~~separation logic~~
arbitrary program logic?

A Novel Paradigm to Build Sound Automated Verifiers



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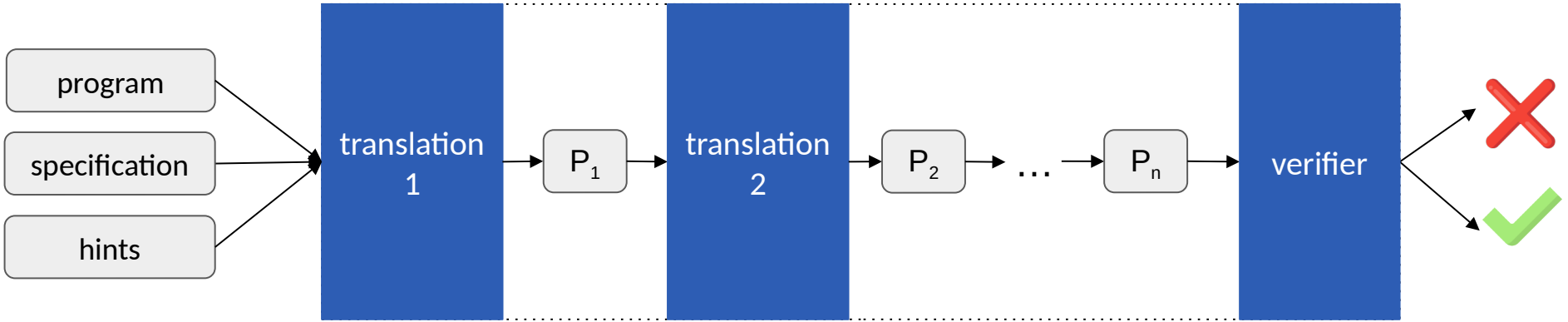

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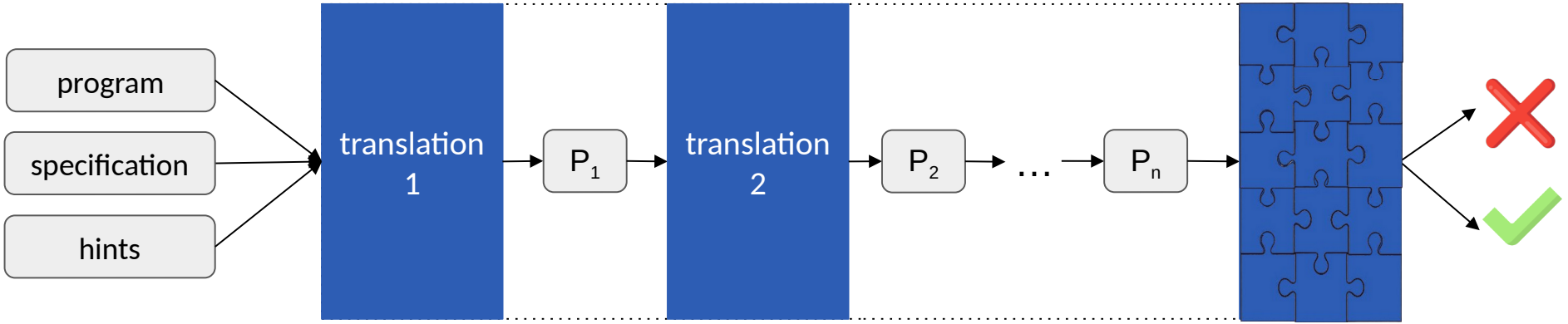

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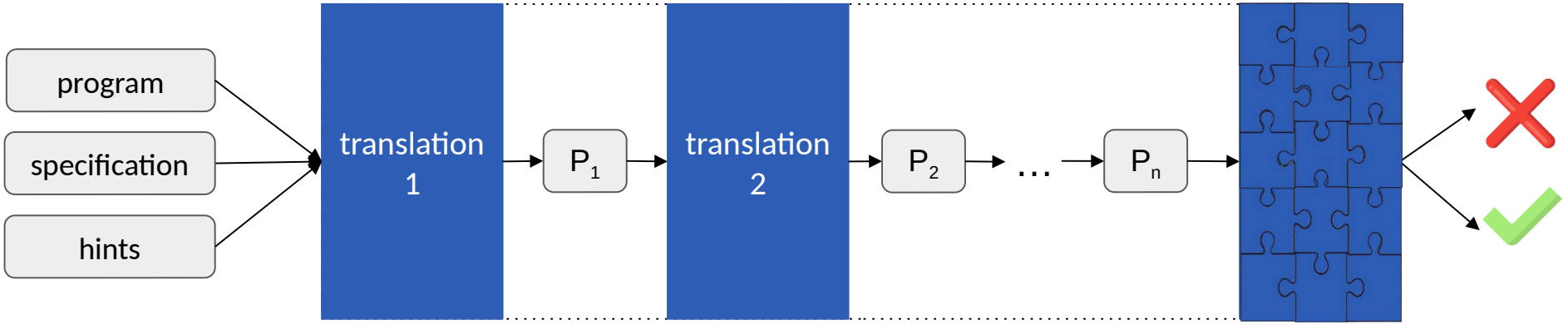

Modular framework to build **sound-by-construction** verifiers with **state-of-the-art automation** by plugging together components.

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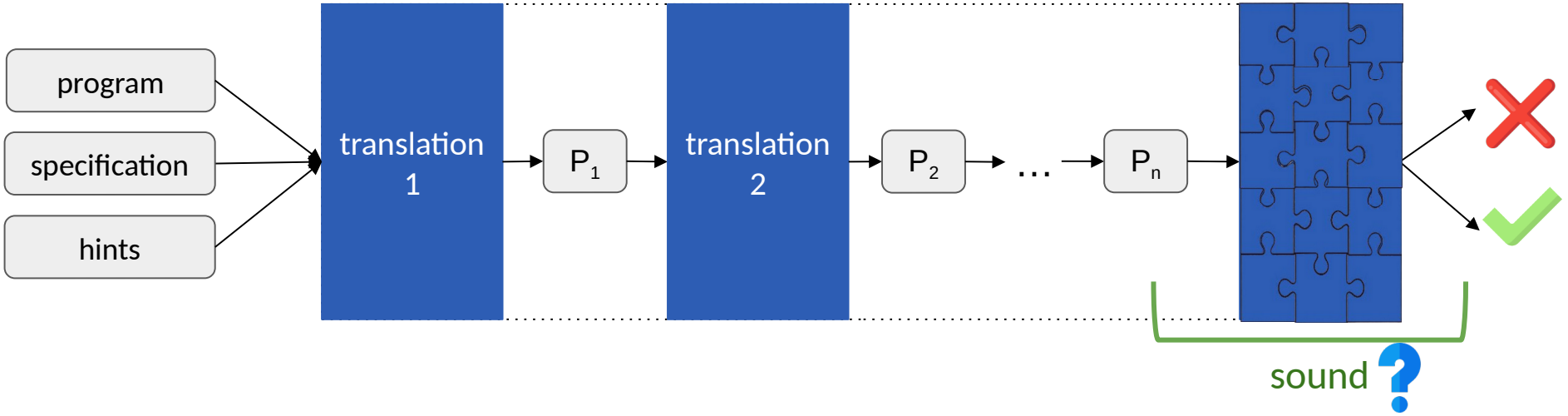

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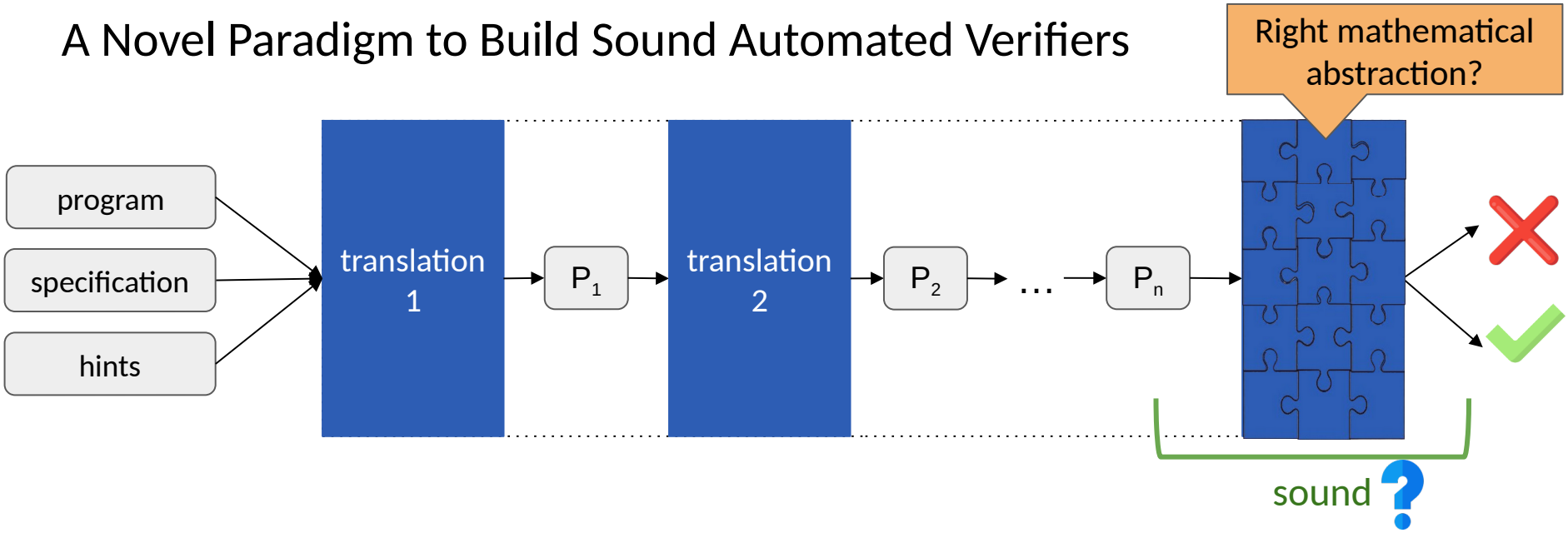

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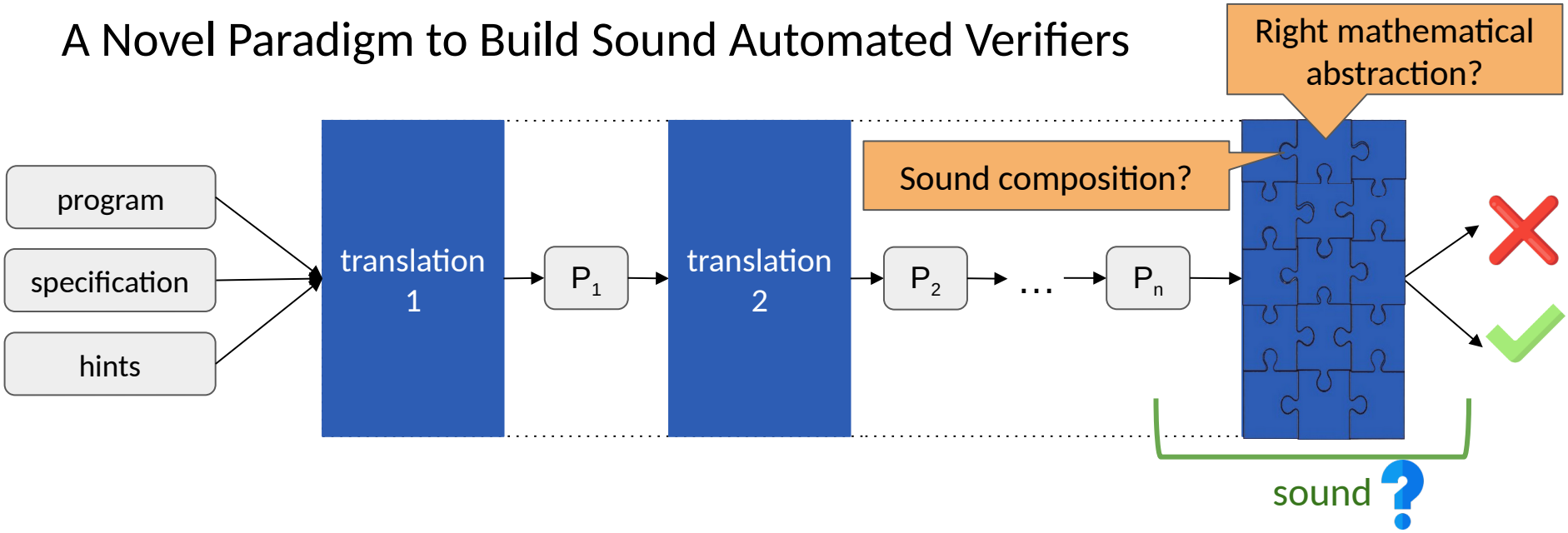

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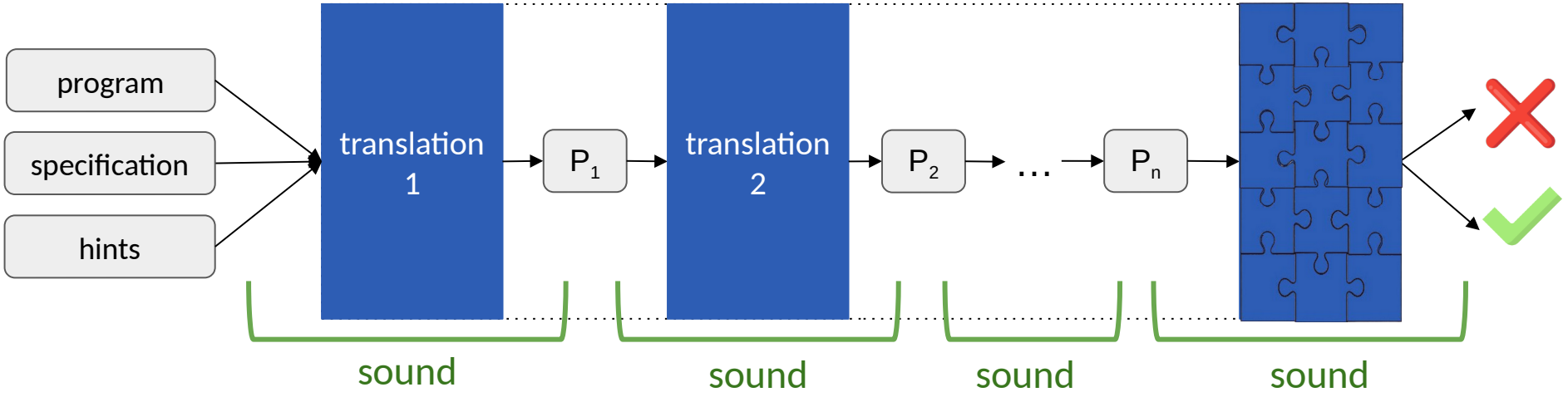

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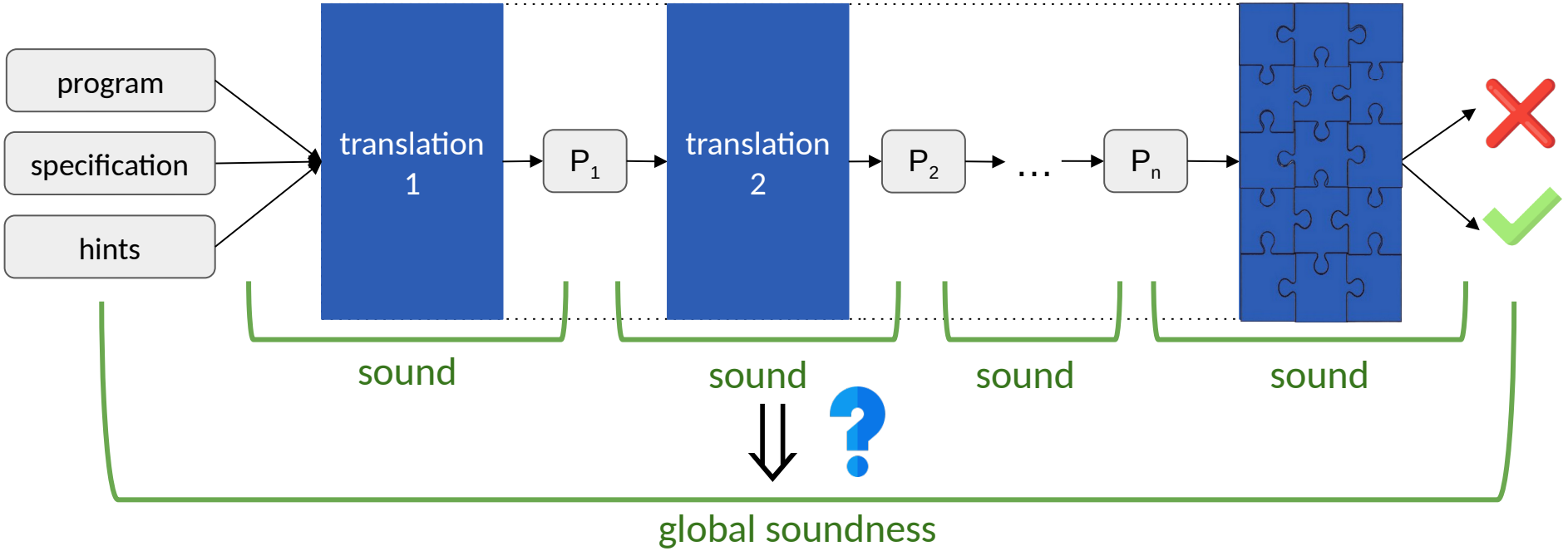

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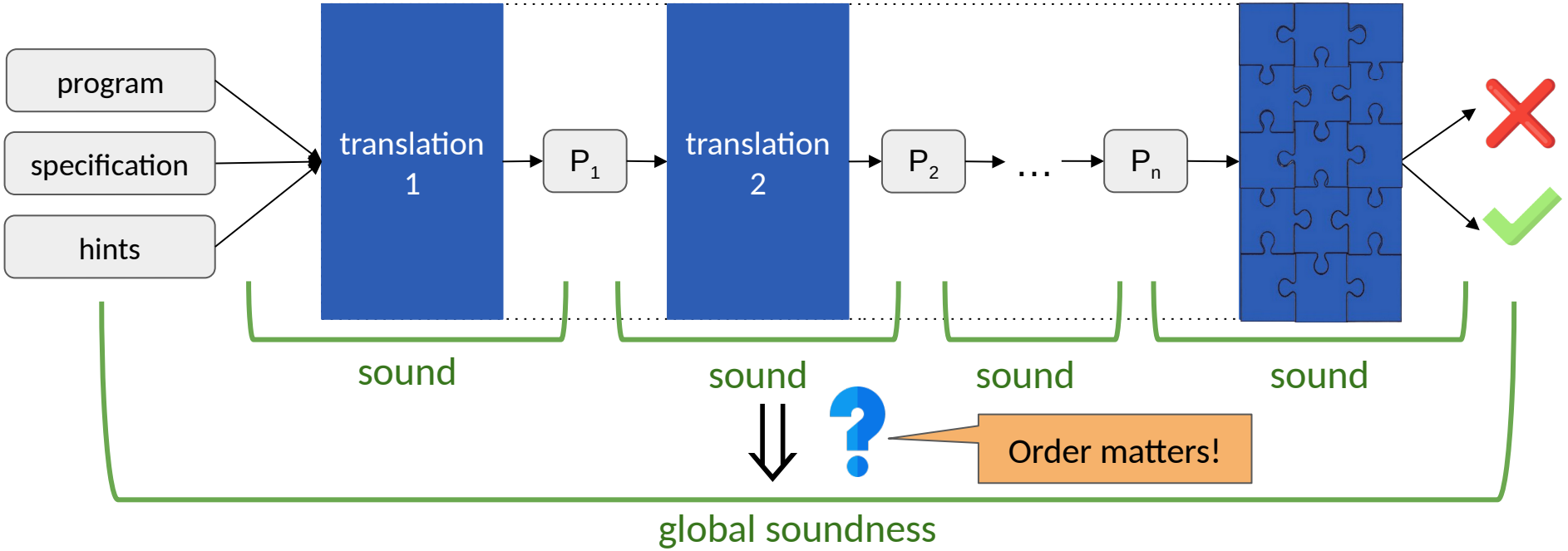

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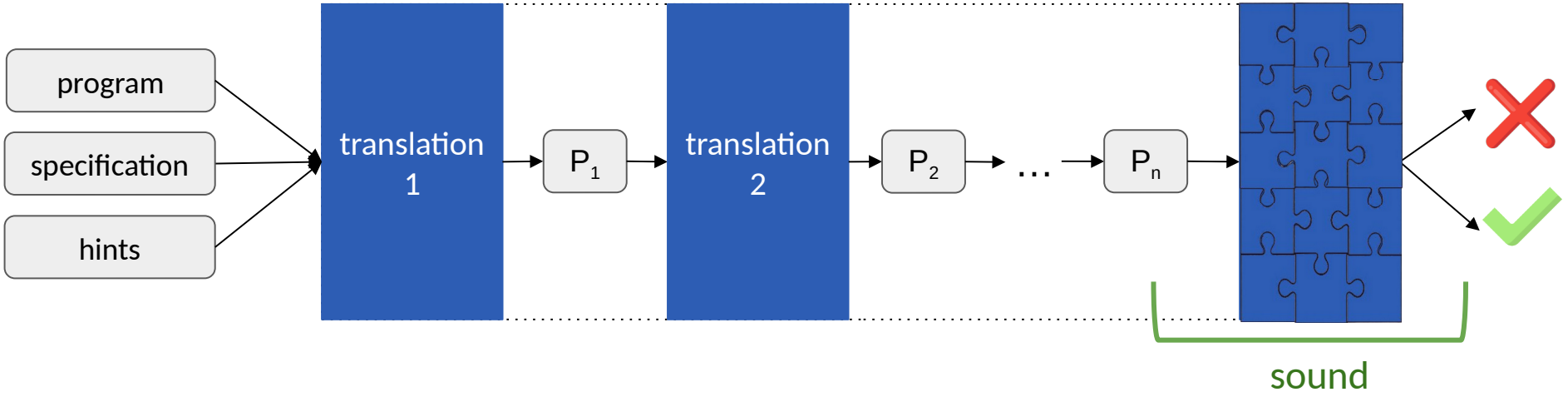
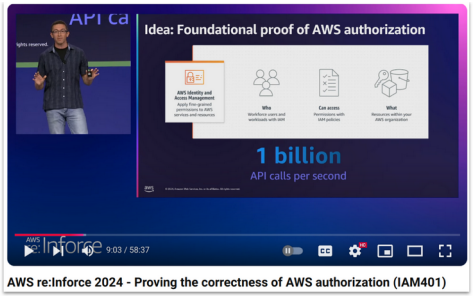


Modular framework to build **sound-by-construction** verifiers with **state-of-the-art automation** by plugging together components.

+ modular soundness
+ modular optimization
+ reusability
+ extensibility

Summary



AWS re:Inforce 2024 - Proving the correctness of AWS authorization (IAM401)

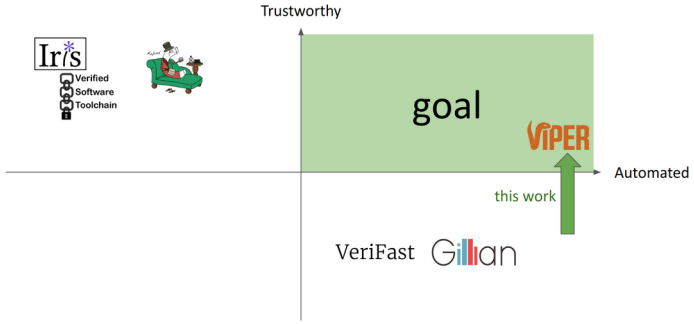
1 billion times/second

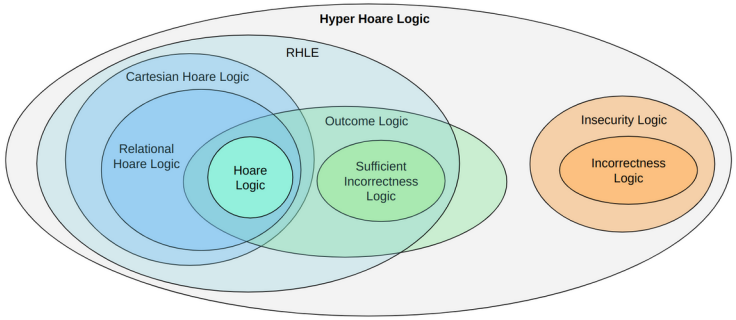
~3,000 lines of code

~3x performance

Problem 1
Trustworthiness

Problem 2
Expressiveness





CommCSL
[PLDI'23]

Hyper Hoare Logic
[PLDI'24]

Hypra *[OOPSLA'24]*

Magic wands
[CAV'22]

Fractional predicates
[OOPSLA'22]

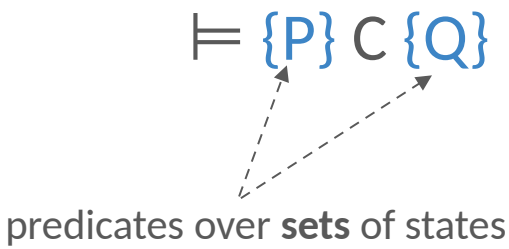
Verification-preserving inlining
[OOPSLA'23]

Per-run validation for Viper
[PLDI'24]

Foundations for translational separation logic verifiers
[POPL'25]

Backup Slides

Hyper Hoare Logic – Triples



Hyper Hoare Logic – Triples

$$\models \{P\}\ C\ \{Q\} \triangleq (\ \forall S.\ P(S) \Rightarrow Q(\text{reach}(C, S))\ )$$

predicates over **sets** of states

Hyper Hoare Logic – Triples

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set of initial states

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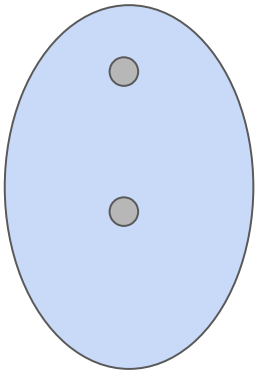
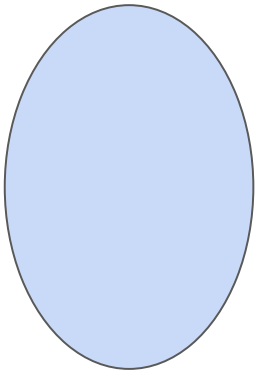


S



reach(C, S)

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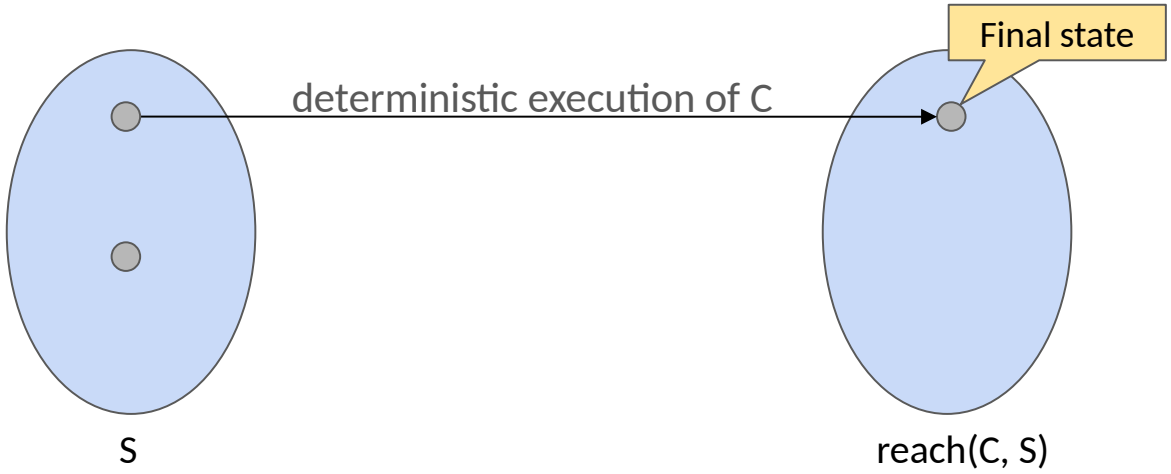

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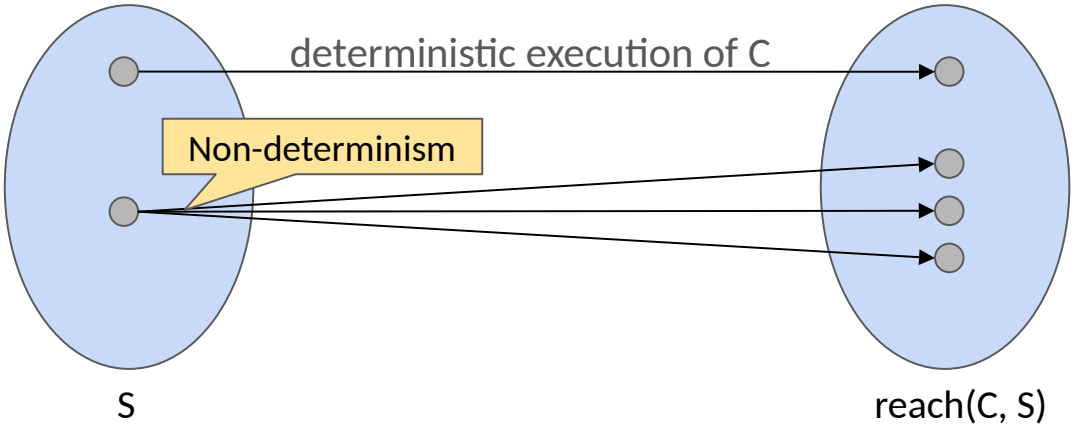

Information Flow Security: Probabilistic Non-Interference

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def badOneTimePad(s):
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   for i in range(9):
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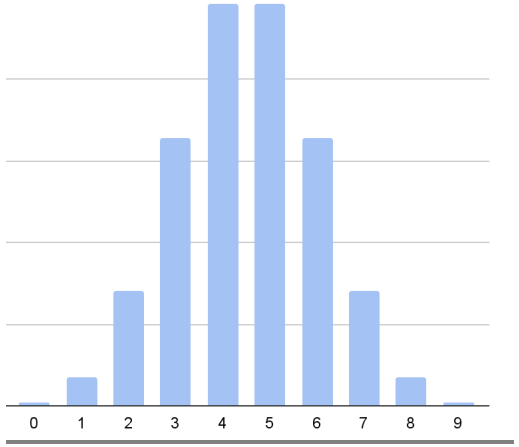

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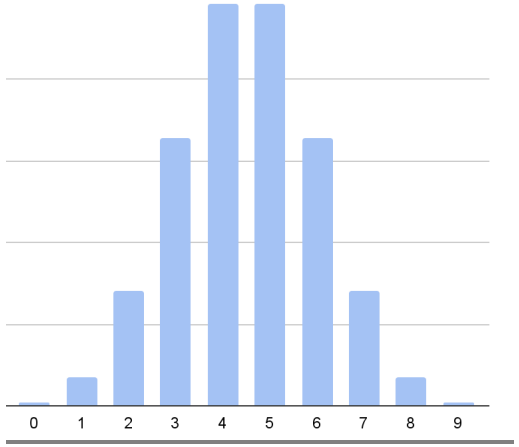

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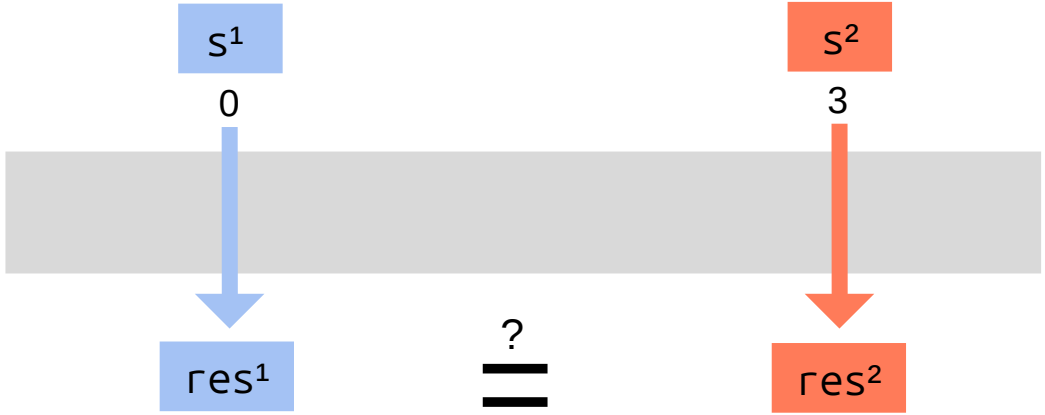

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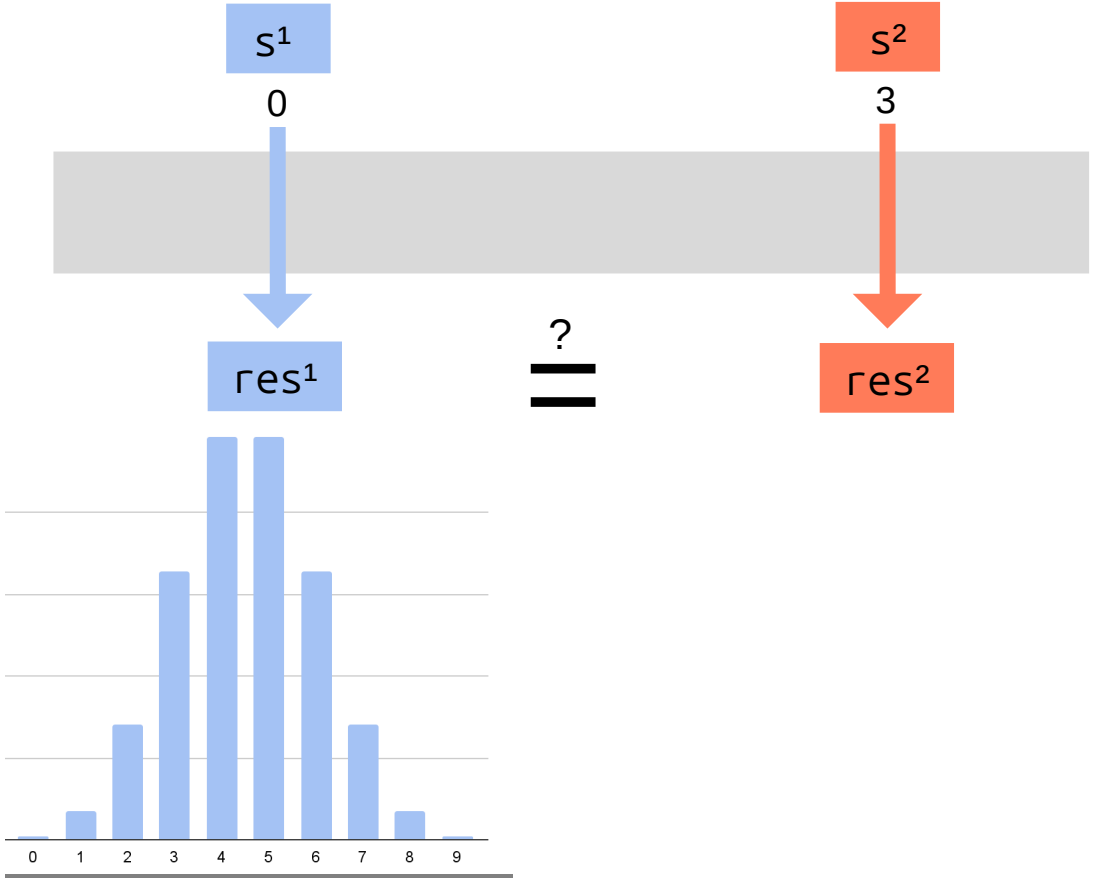

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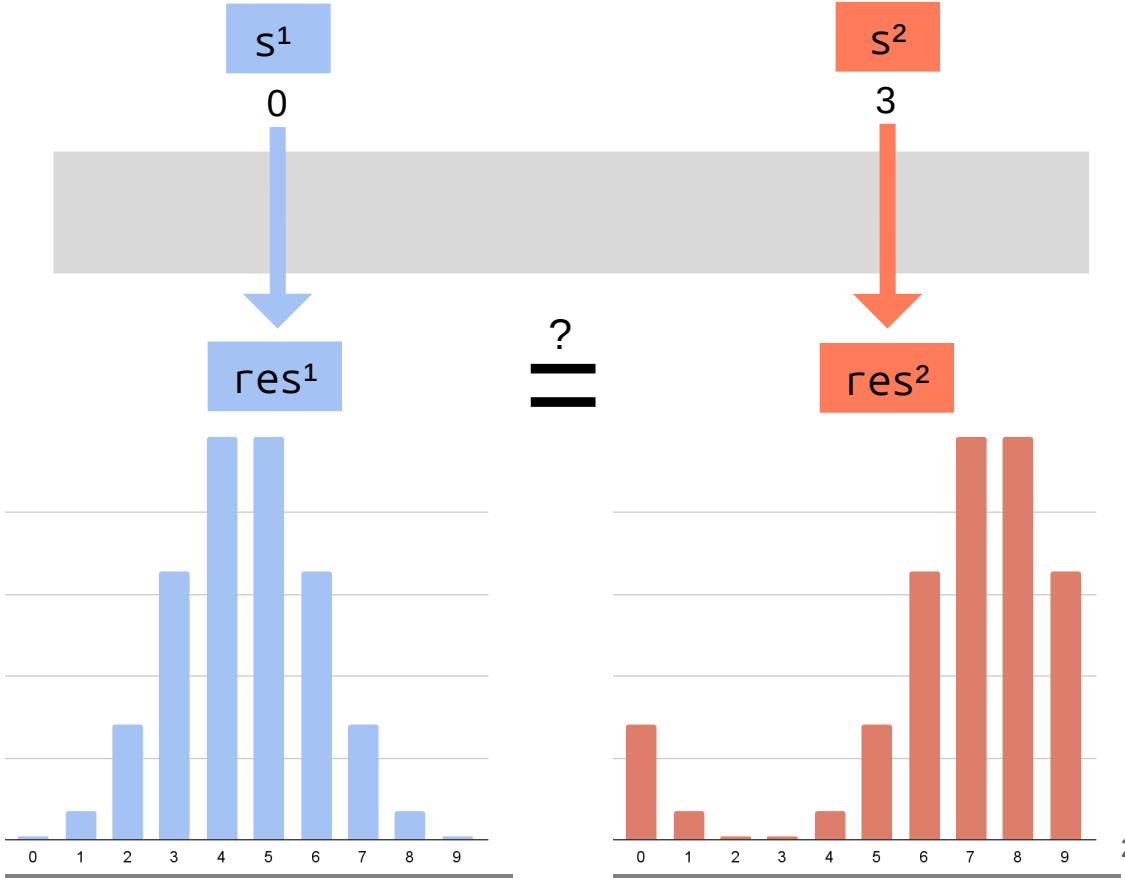

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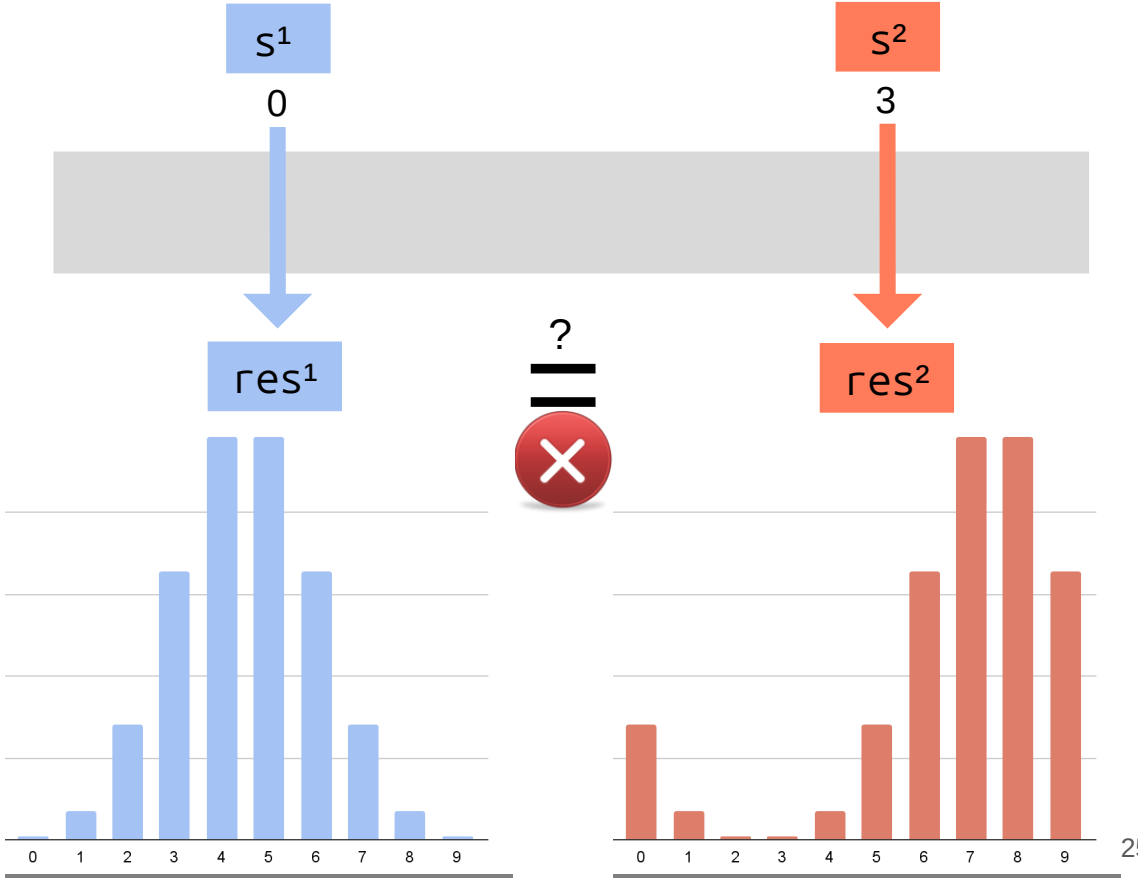

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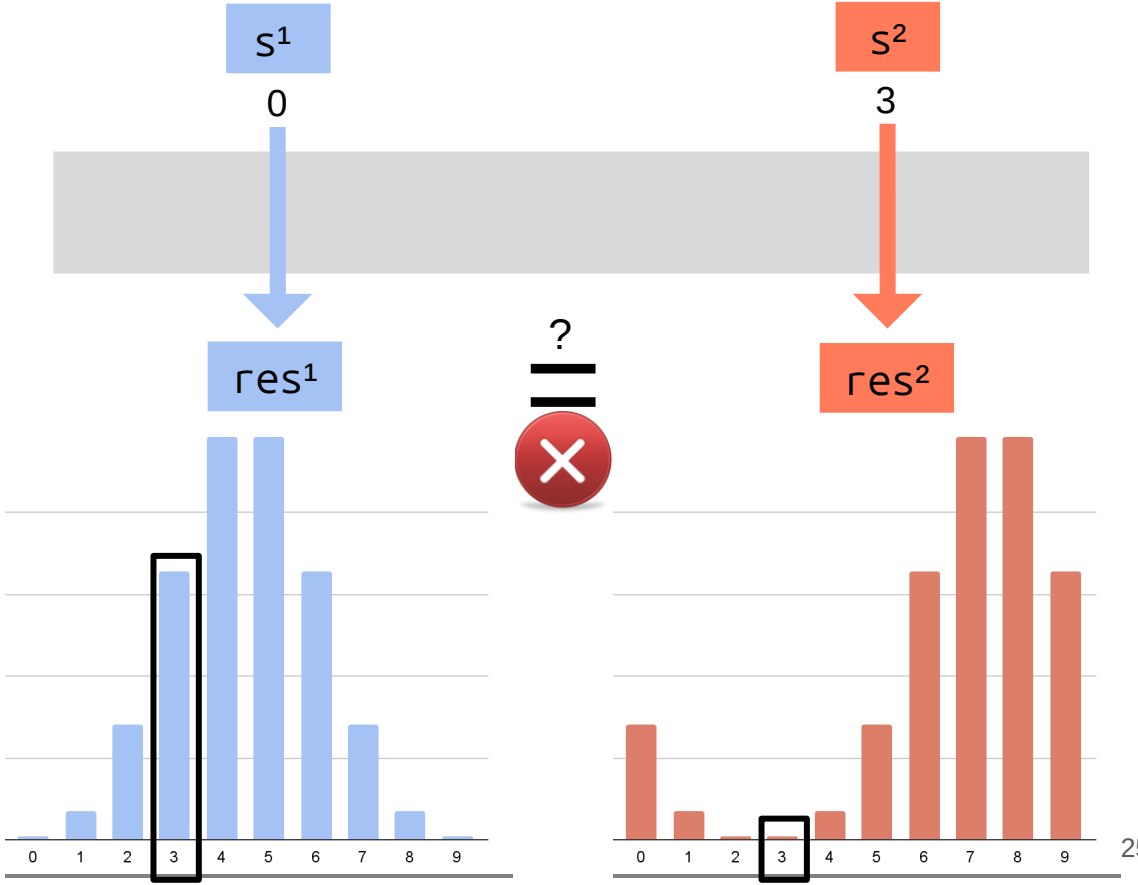

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