Lightweight Support for Magic Wands in an Automatic Verifier

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Frame Problem

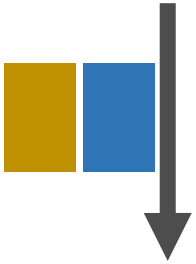
Modular, static verification of imperative programs
↳ Frame problem: Which memory locations change?

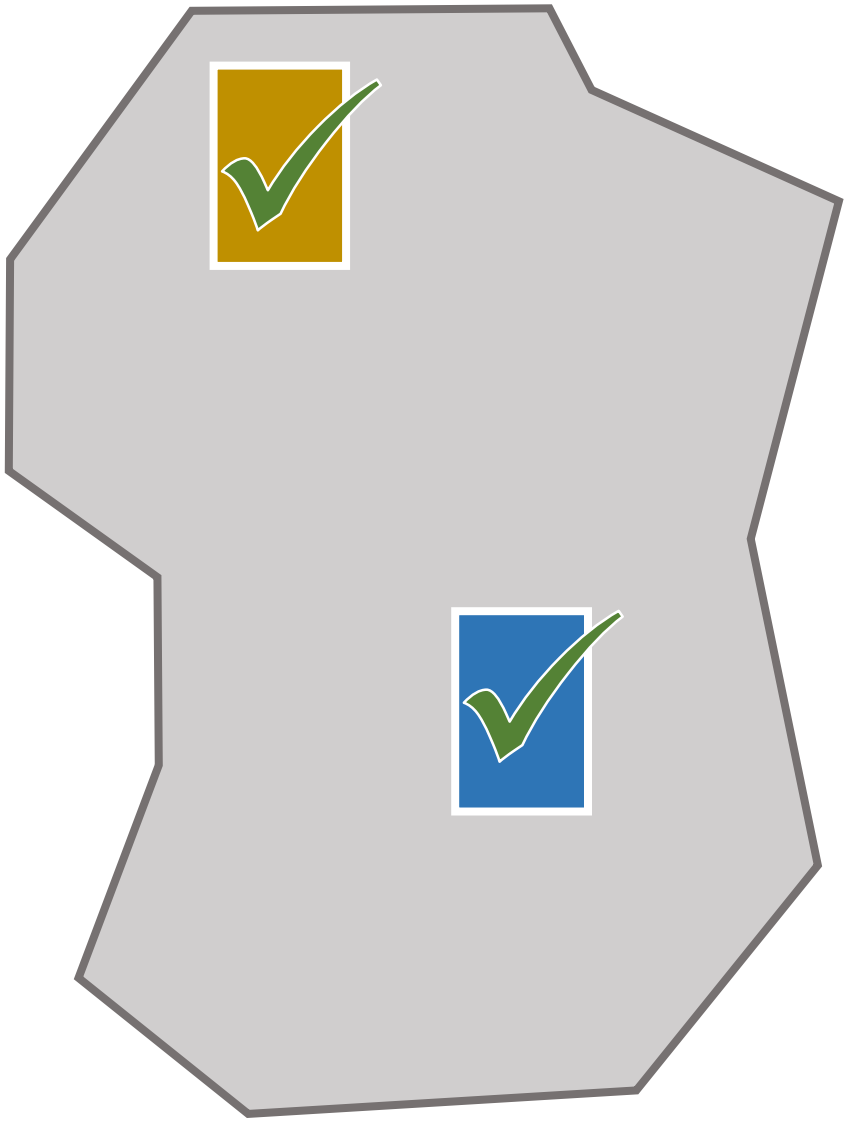
Automated verification: Pre-/Postconditions, invariants, ghost code

Well-known approach: Permissions (≈ Separation Logic)

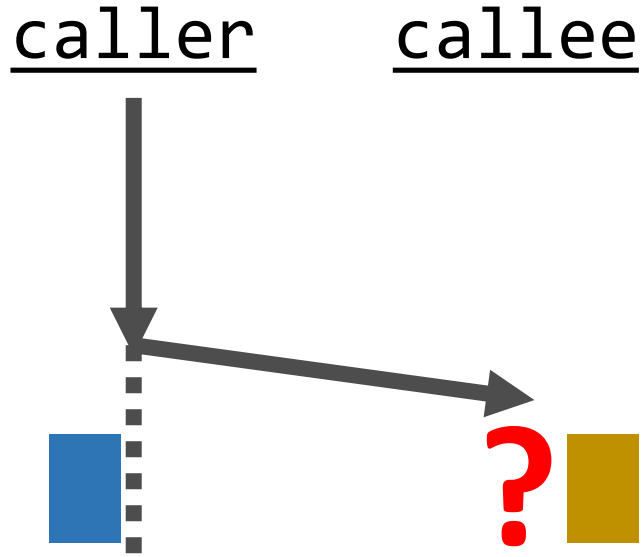
Permission Transfer

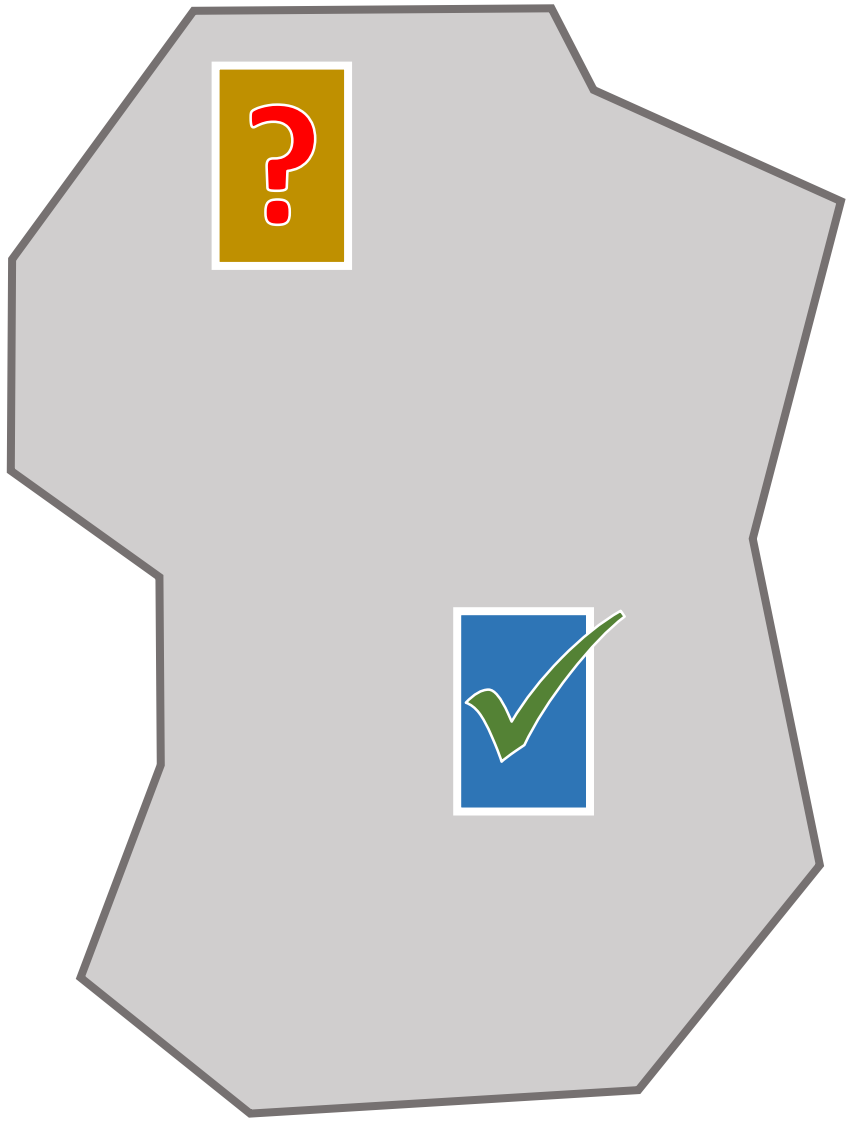
caller callee



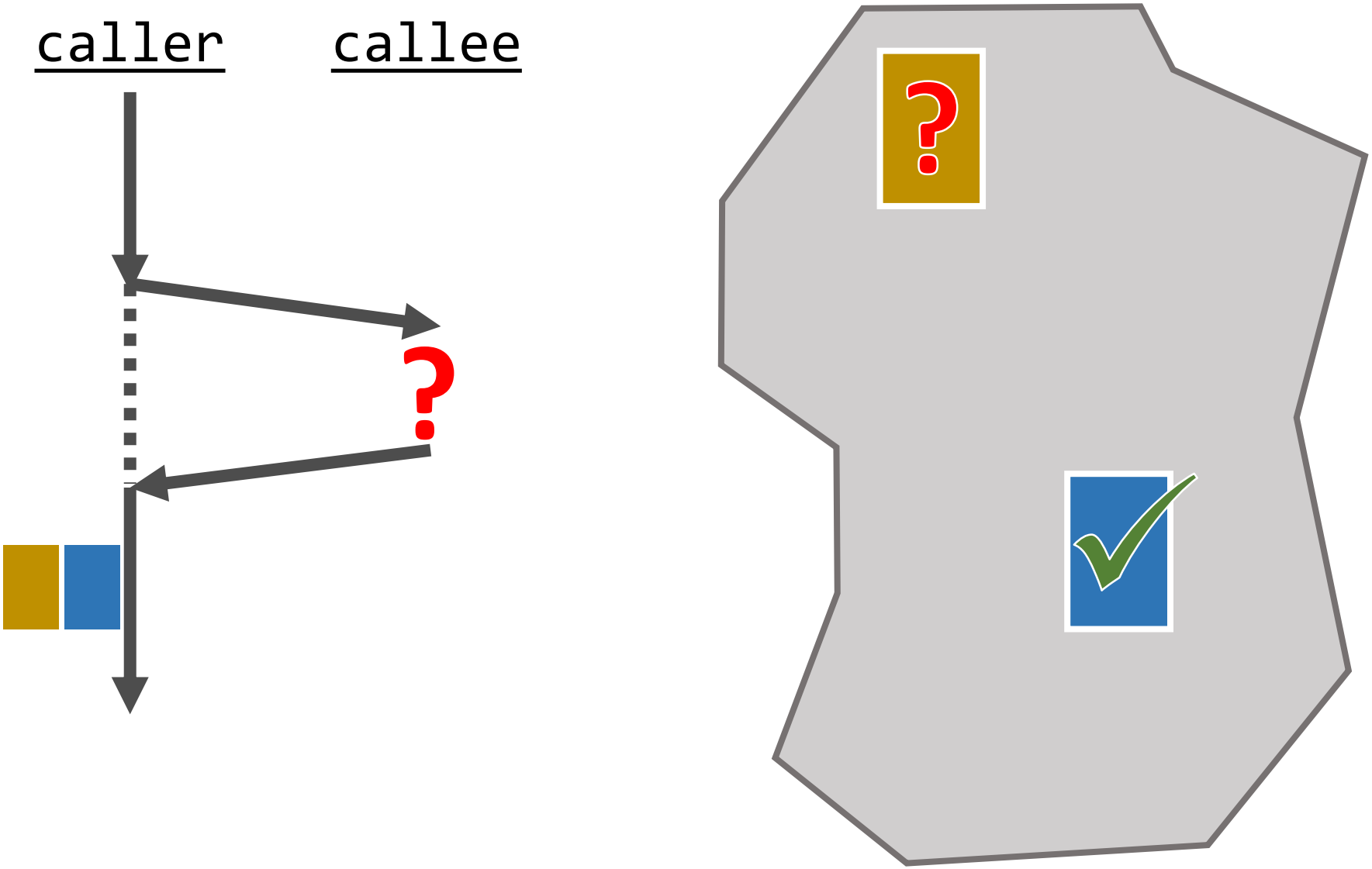


Permission Transfer





Permission Transfer



Syntax & Properties

Permissions (≈ Separation Logic)

Logical properties


```
acc(x.f) * x.f == 0
```

(≈ `x.f ↦ 0`)

Disjointness: x ≠ y

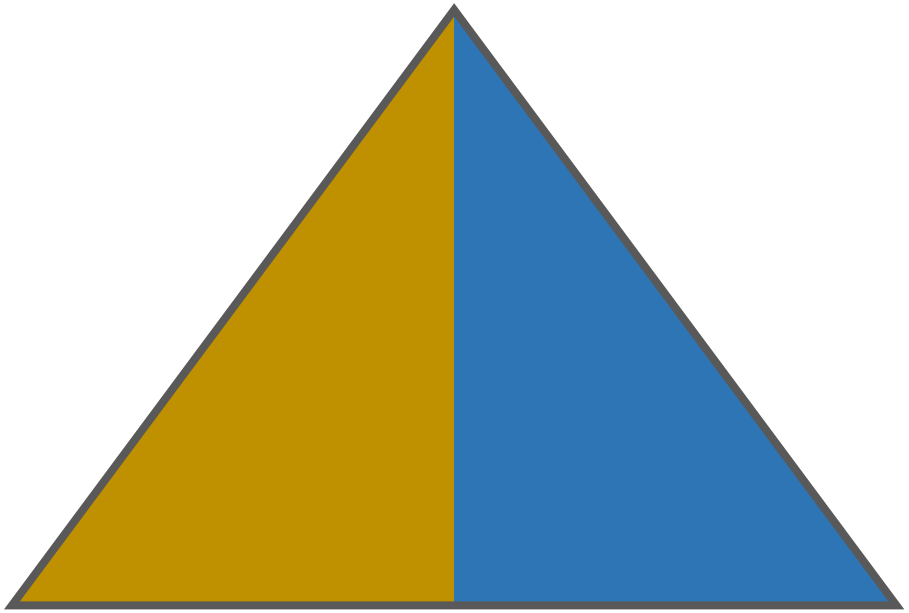
```
acc(x.f) * acc(y.f)
```

(≈ `x.f ↦ _ * y.f ↦ _`)

Separating Conjunction

$A * B$

describes the current state in terms of disjoint substates



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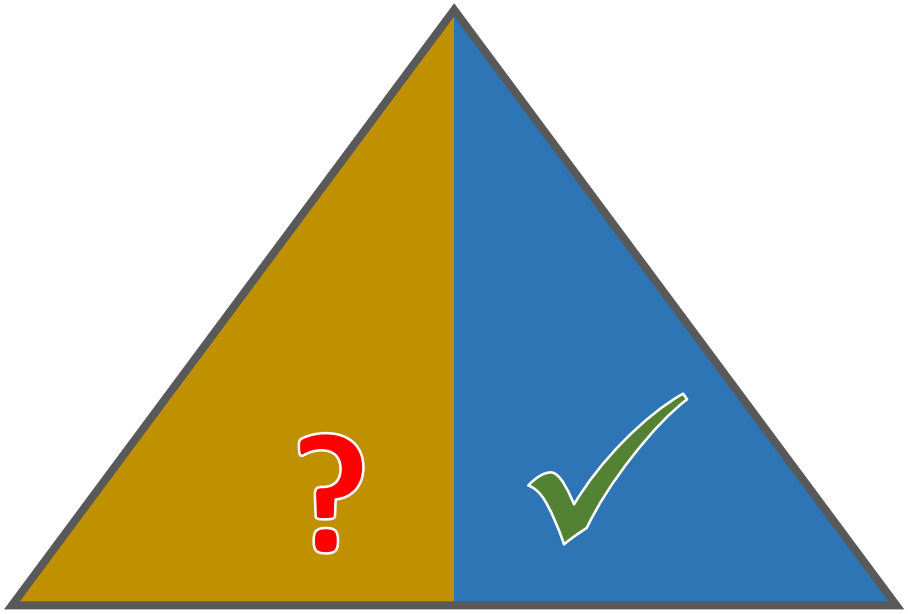


Is at the heart of verifiers based on separation logic

Magic Wands

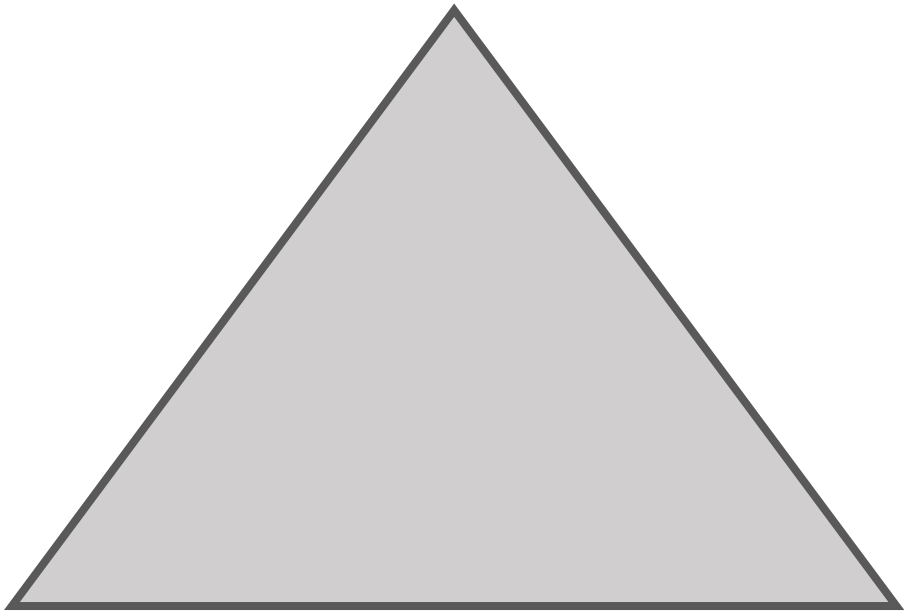
$$A \mathrel{-\!\!*} B$$

describes hypothetical states

Read as a promise: "In any state, if you provide A, then you will get B"

Partial Data Structures

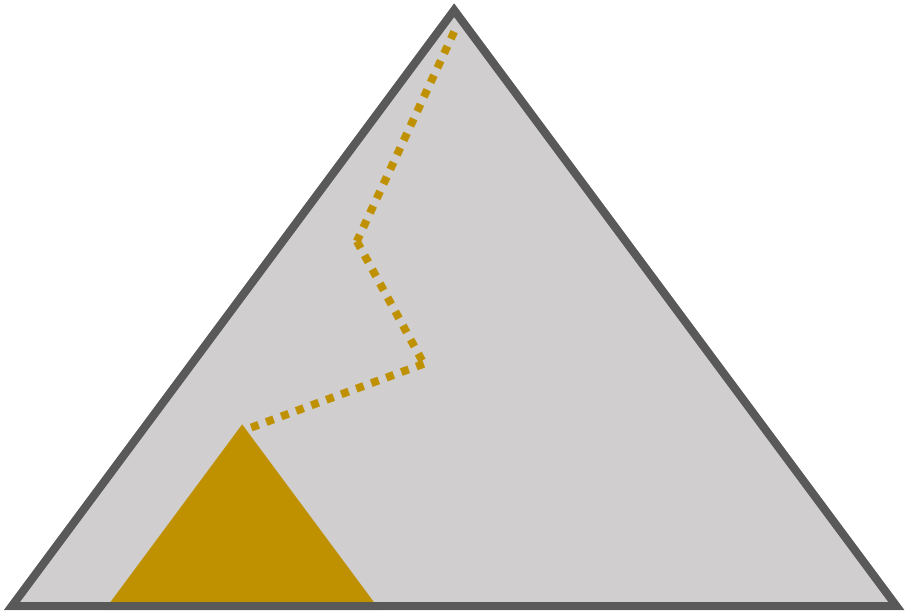
Scenario: Iteratively traverse a recursively defined tree (Verification Challenge at VerifyThis@FM'12)



Partial Data Structures

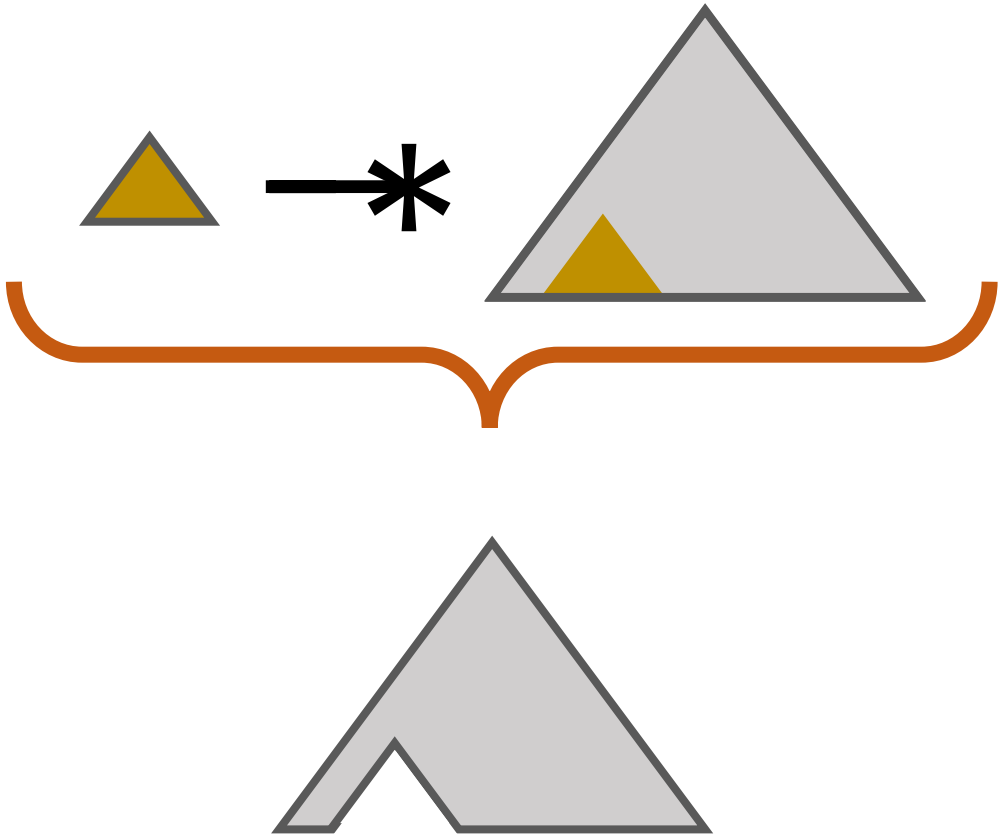
Scenario: Iteratively traverse a recursively defined tree

↳Loop invariant: Describe partial data structure



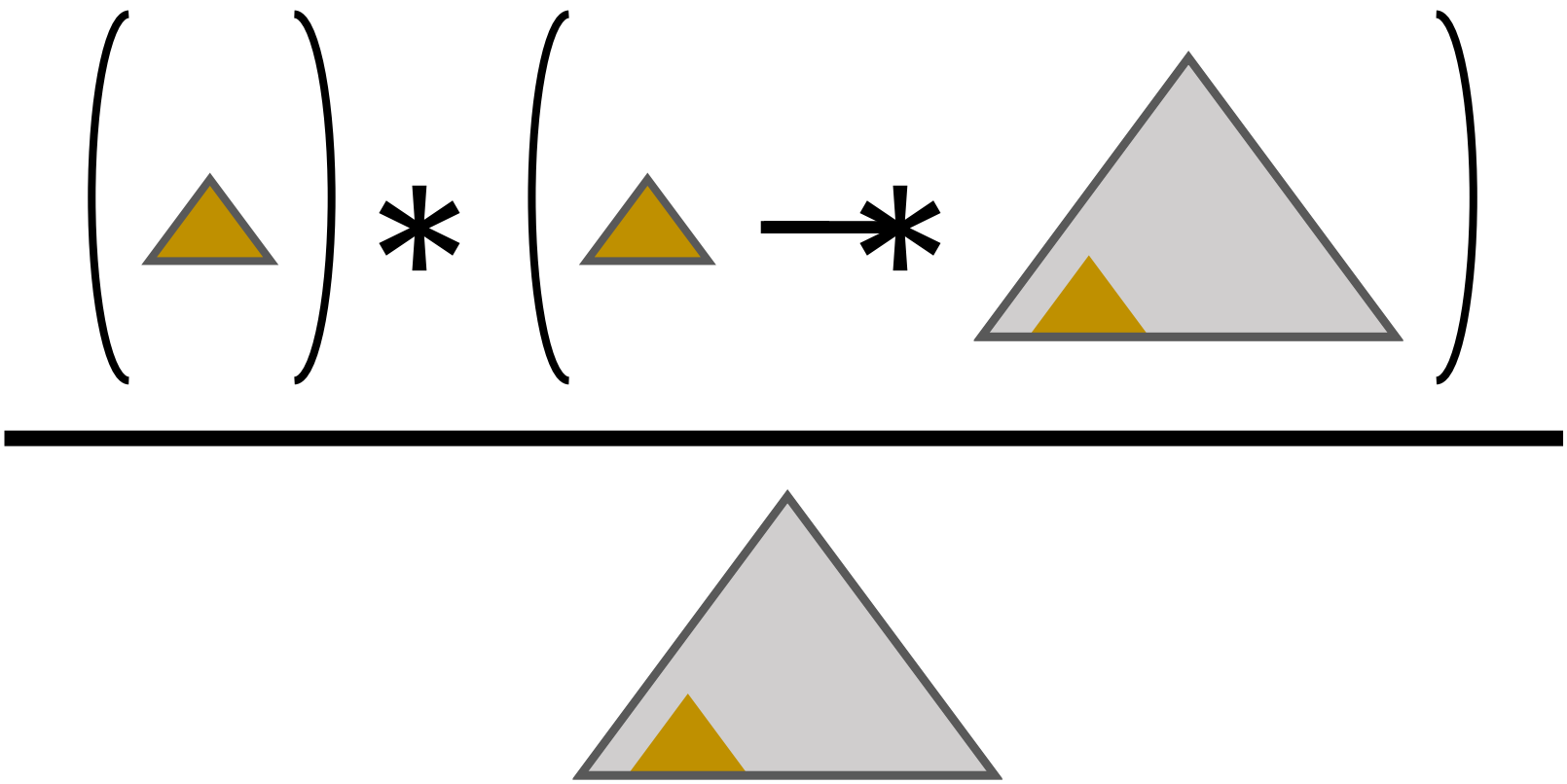
Partial Data Structures as Magic Wands

Indirectly describe partial data structure as a promise



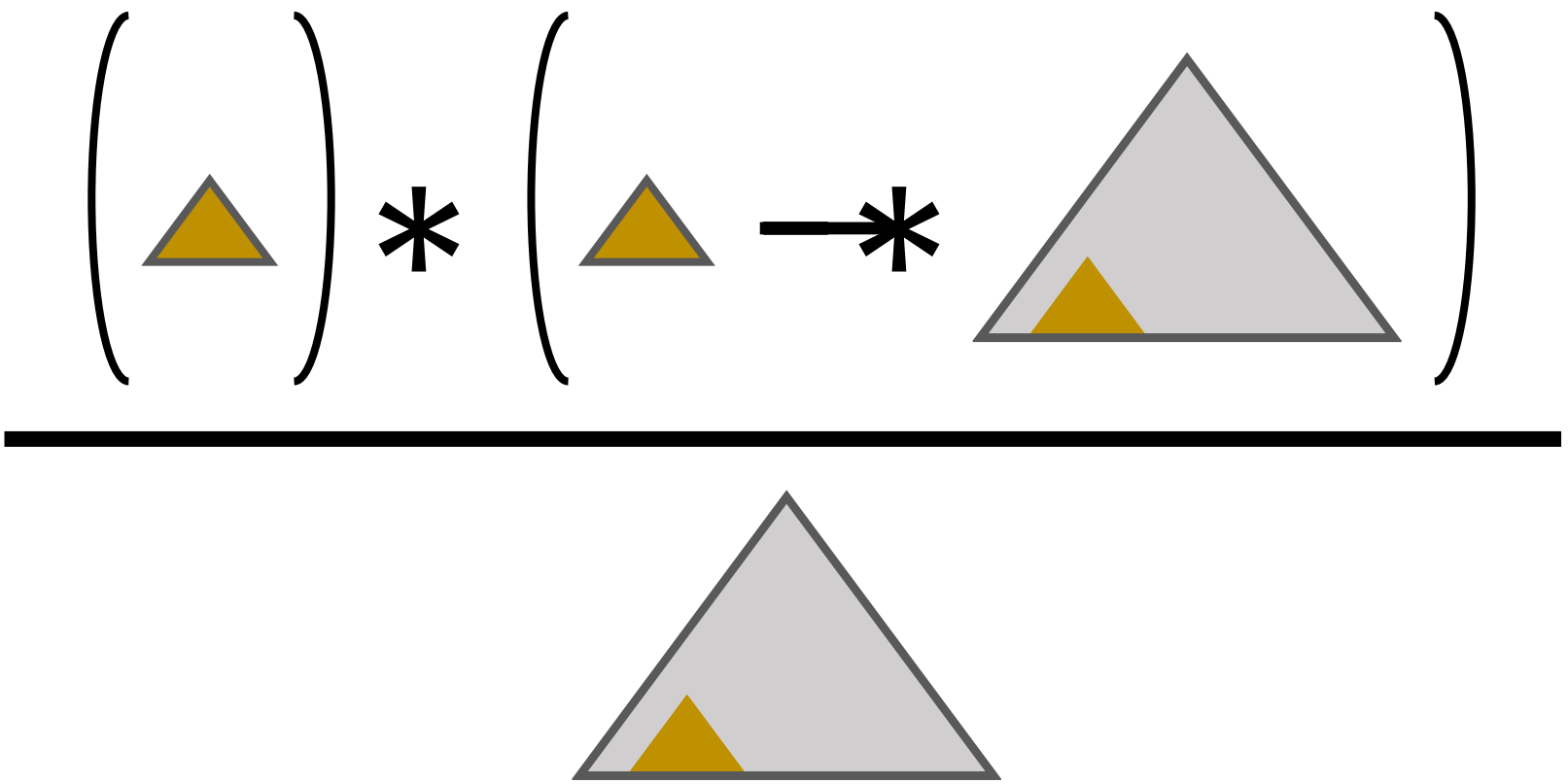
Partial Data Structures as Magic Wands

Modus-Ponens-like rule makes promise applicable



Partial Data Structures as Magic Wands

$$\sigma \vDash A \mathrel{-\!\!*} B \quad \Leftrightarrow \quad \forall\, \sigma' \cdot (\sigma' \vDash A \;\Rightarrow\; \sigma \uplus \sigma' \vDash B)$$



Magic Wands in Proofs and Tools

Used in various pen & paper proofs

- Partial data structures
- Usage protocols for data structures
- Synchronisation barriers
- …

Typically* not supported in automatic verifiers

$$\sigma \vDash A \mathrel{-\!\!*} B \quad \Leftrightarrow \quad \forall\, \sigma' \cdot (\sigma' \vDash A \;\Rightarrow\; \sigma \uplus \sigma' \vDash B)$$

* Only exception we are aware of is VerCors; developed in parallel

Automating Magic Wand Reasoning

Entailment of magic wand formulas is undecidable

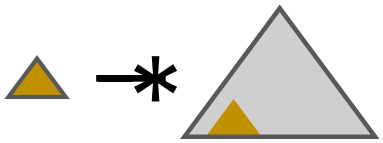
↳ Lightweight user guidance to direct verification

Guidance: Ghost Operations + Specifications

Make a promise

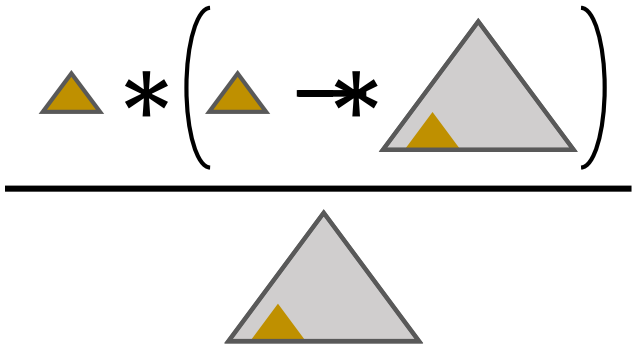
Pass it around

Use it



`package` $A \mathrel{-\!\!*} B$

Opaque resource; Specifications

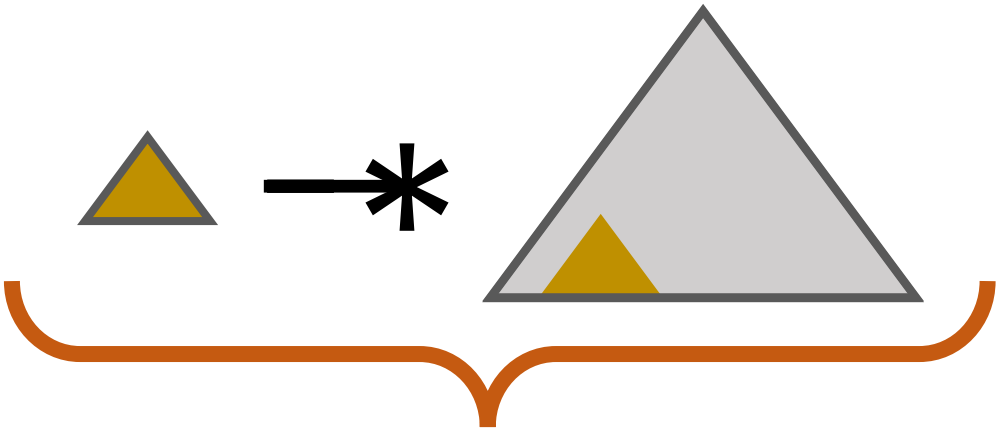


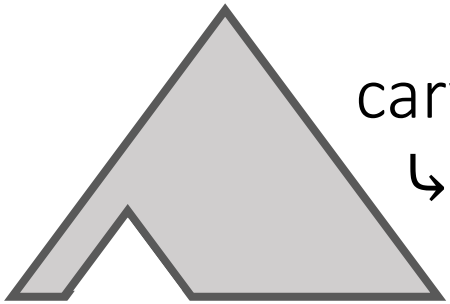
`apply` $A \mathrel{-\!\!*} B$

Guidance: Ghost Operations + Specifications

Footprints of $A \mathrel{-\!\!*} B$

Permissions guaranteeing that giving up $A * (A \mathrel{-\!\!*} B)$ and obtaining B is sound



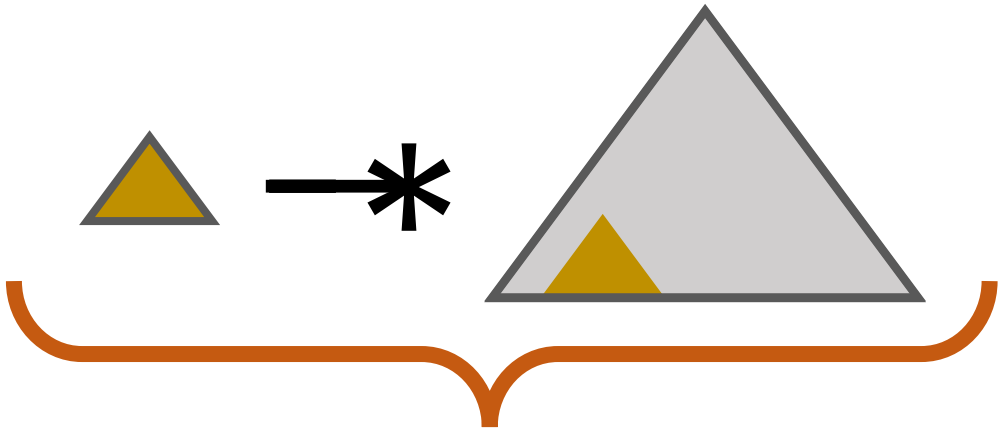


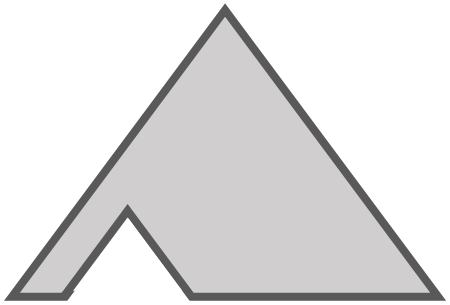
carved out

↳ effectively immutable

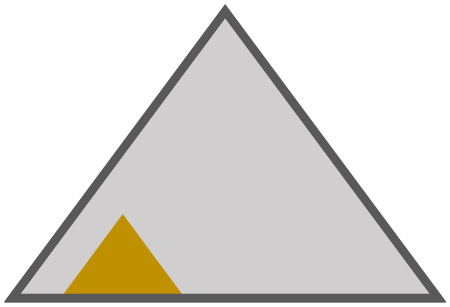
Footprints of $A \twoheadrightarrow B$

Footprints are not unique





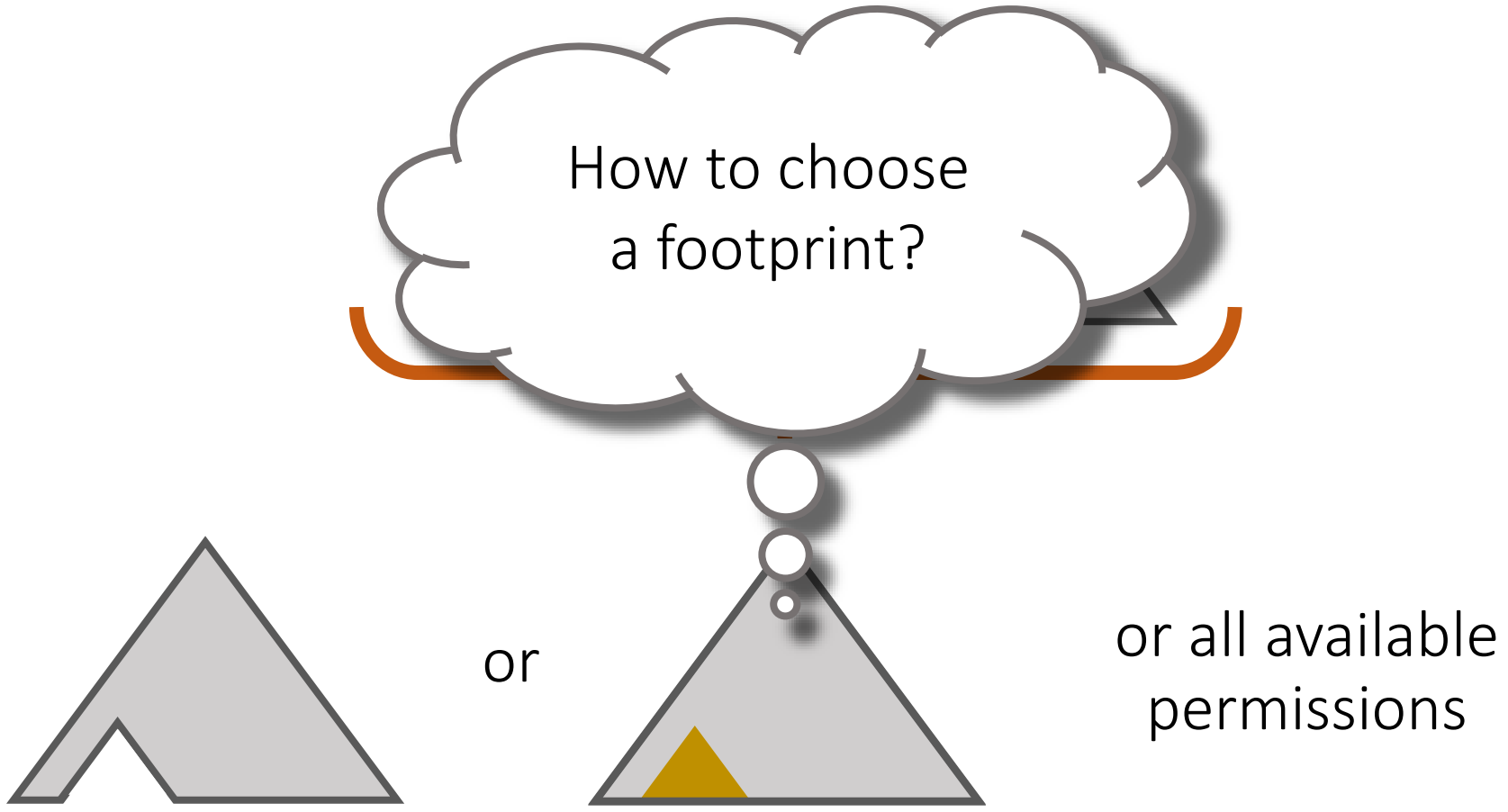
or



or all available permissions

Footprints of $A \twoheadrightarrow B$

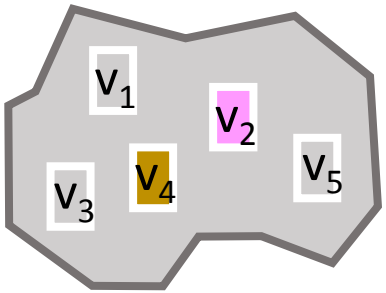
Footprints are not unique



Footprint Computation Algorithm: Setup

$$\texttt{package}\ \ A \twoheadrightarrow (B_1 * B_2 * \ldots * B_n)$$

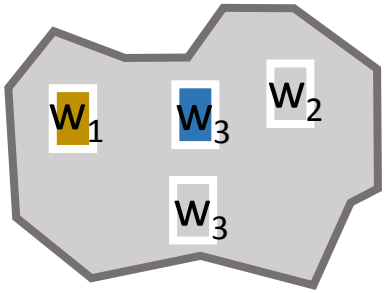
0. given current state



Footprint Computation Algorithm: Setup

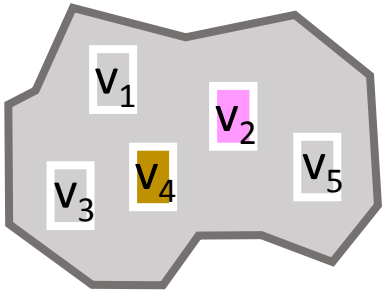
$$\texttt{package}\ \ A \twoheadrightarrow (B_1 * B_2 * \ldots * B_n)$$

1. create LHS state



$\models A$

current state

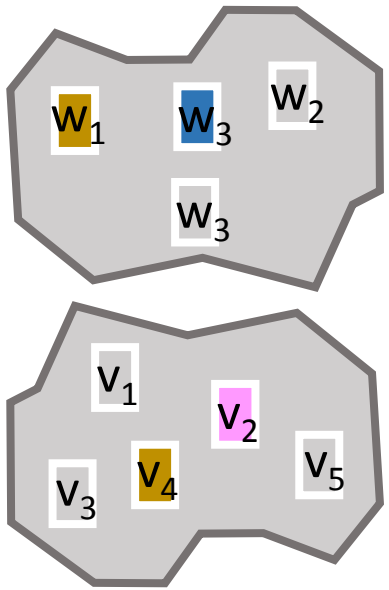


Footprint Computation Algorithm: Setup

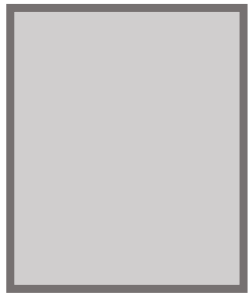
$$\texttt{package}\ \ A \twoheadrightarrow (B_1 * B_2 * \ldots * B_n)$$

LHS state

current state



$\models A$

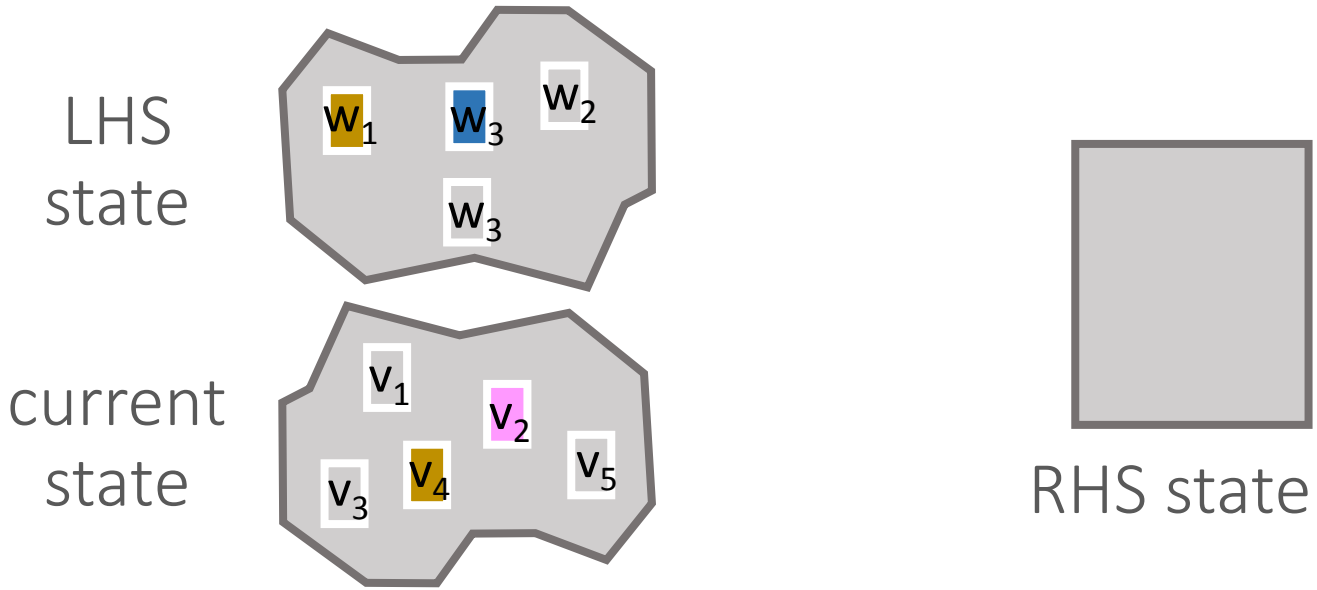


2. create empty RHS state

Footprint Computation Algorithm: Execution

$$\texttt{package}\ \ A \twoheadrightarrow (B_1 * B_2 * \ldots * B_n)$$

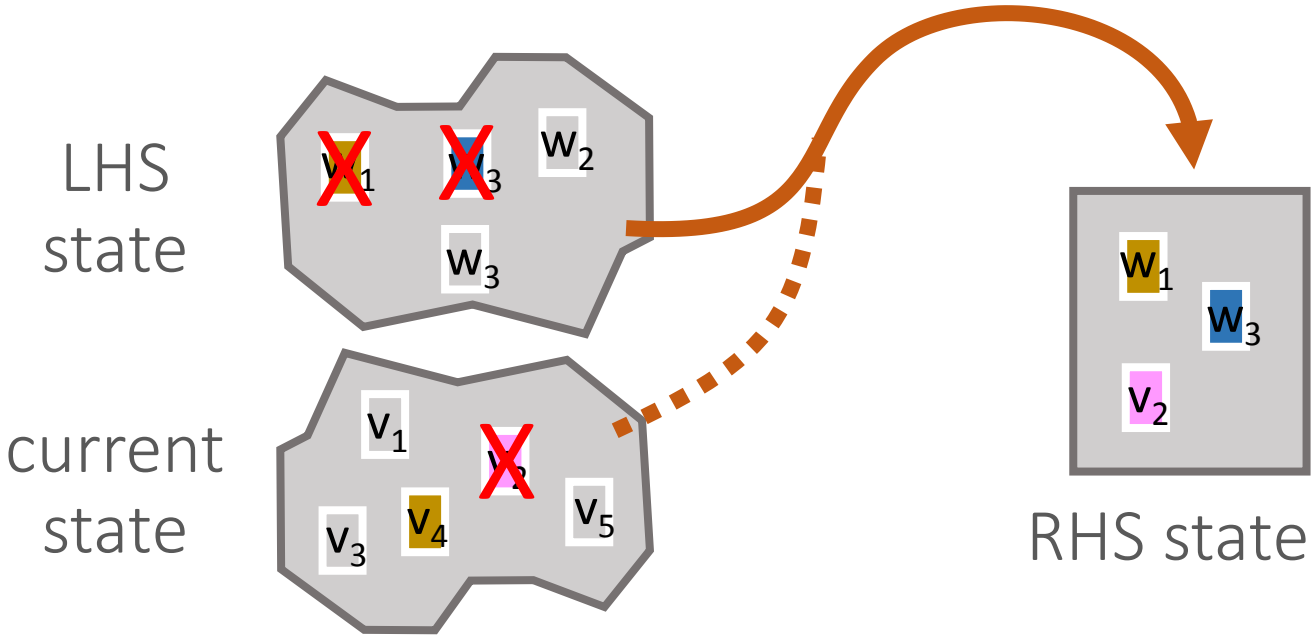
3. iterate over B_i's:



Footprint Computation Algorithm: Execution

$$\texttt{package}\ \ A \twoheadrightarrow (B_1 * B_2 * \ldots * B_n)$$

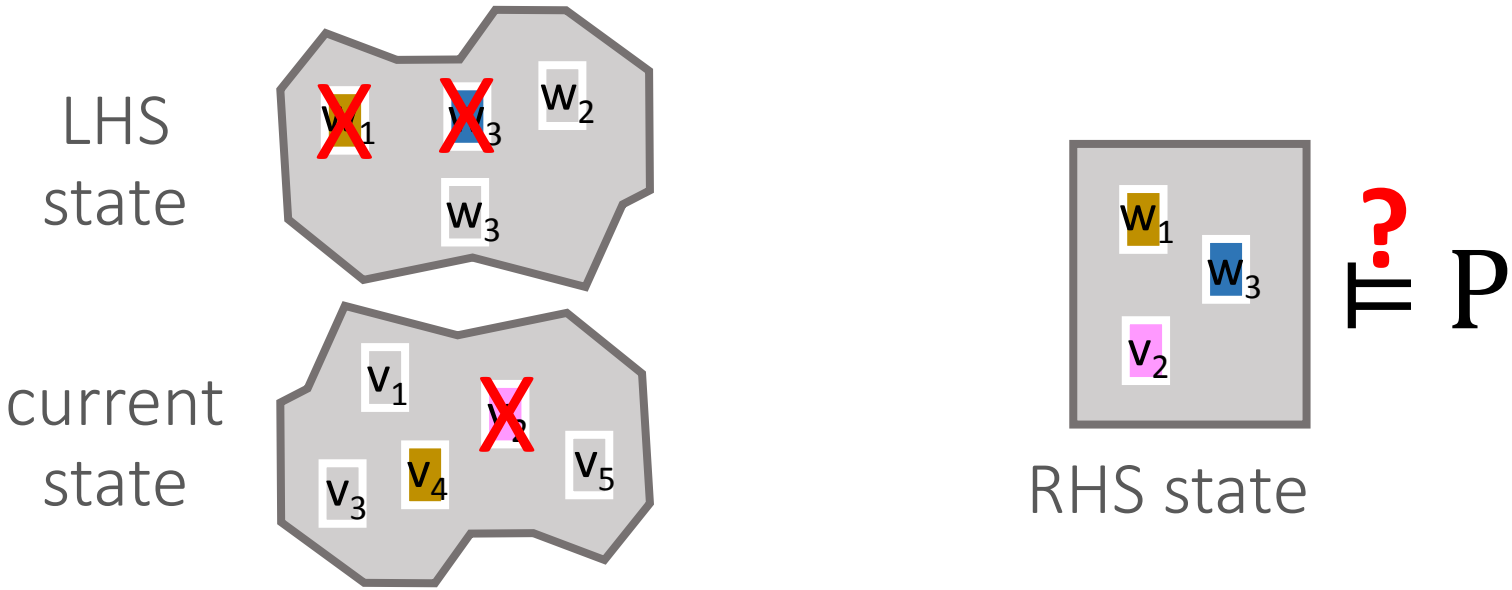
3. iterate over B_i's: If B_i is `acc(x.f)` then transfer permissions and assumptions



Footprint Computation Algorithm: Execution

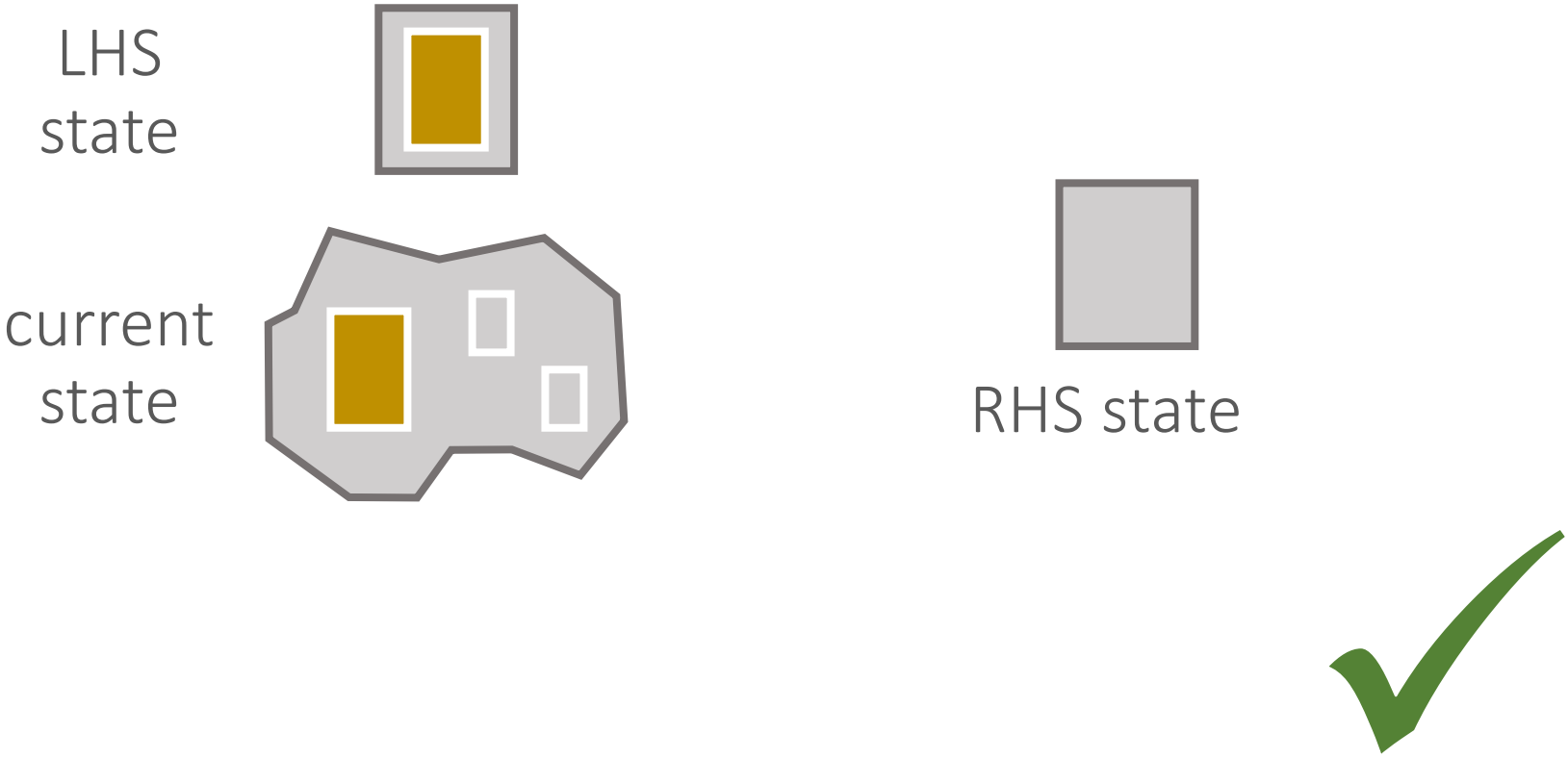
$$\texttt{package}\ \ A \twoheadrightarrow (B_1 * B_2 * \ldots * B_n)$$

3. iterate over B_i's: If B_i is a logical property P,
e.g. `x.f == 0`, then check P



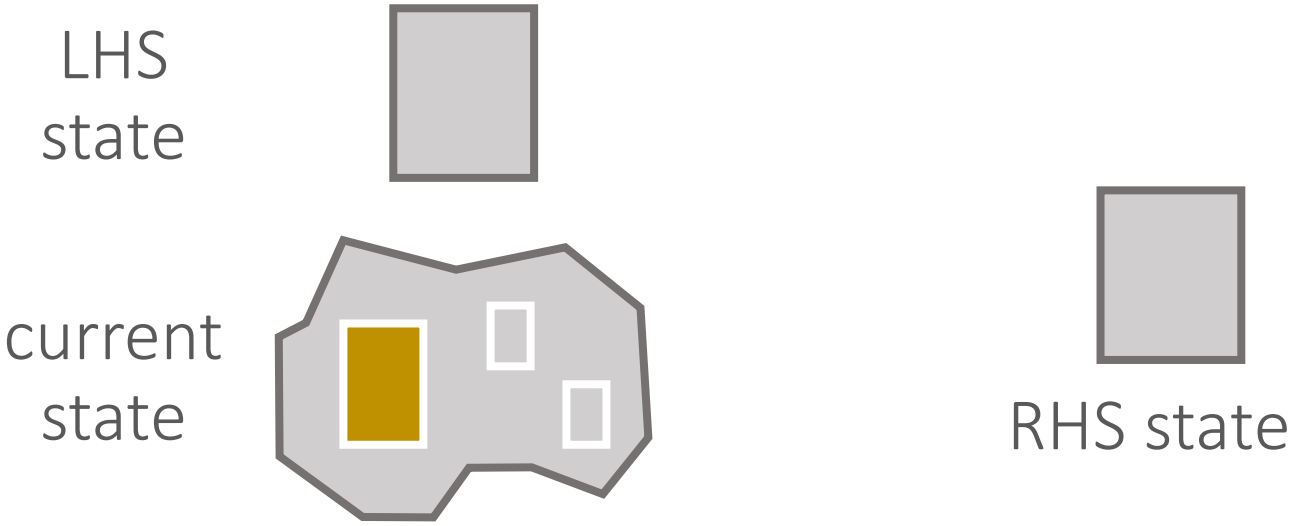
Examples

```
package acc(x.f) --* acc(x.f)
```



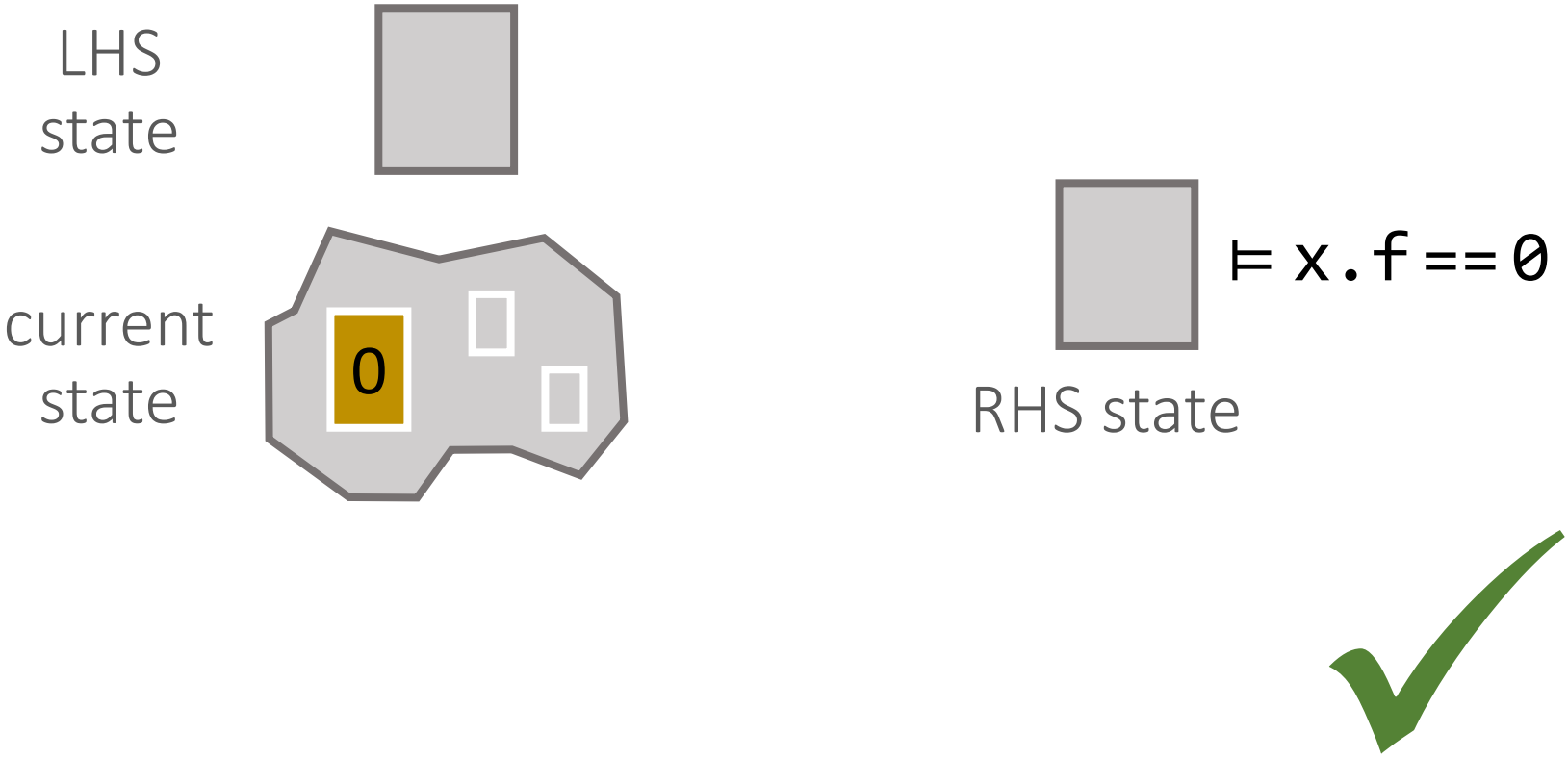
Examples

```
package true —∗ acc(x.f)
```



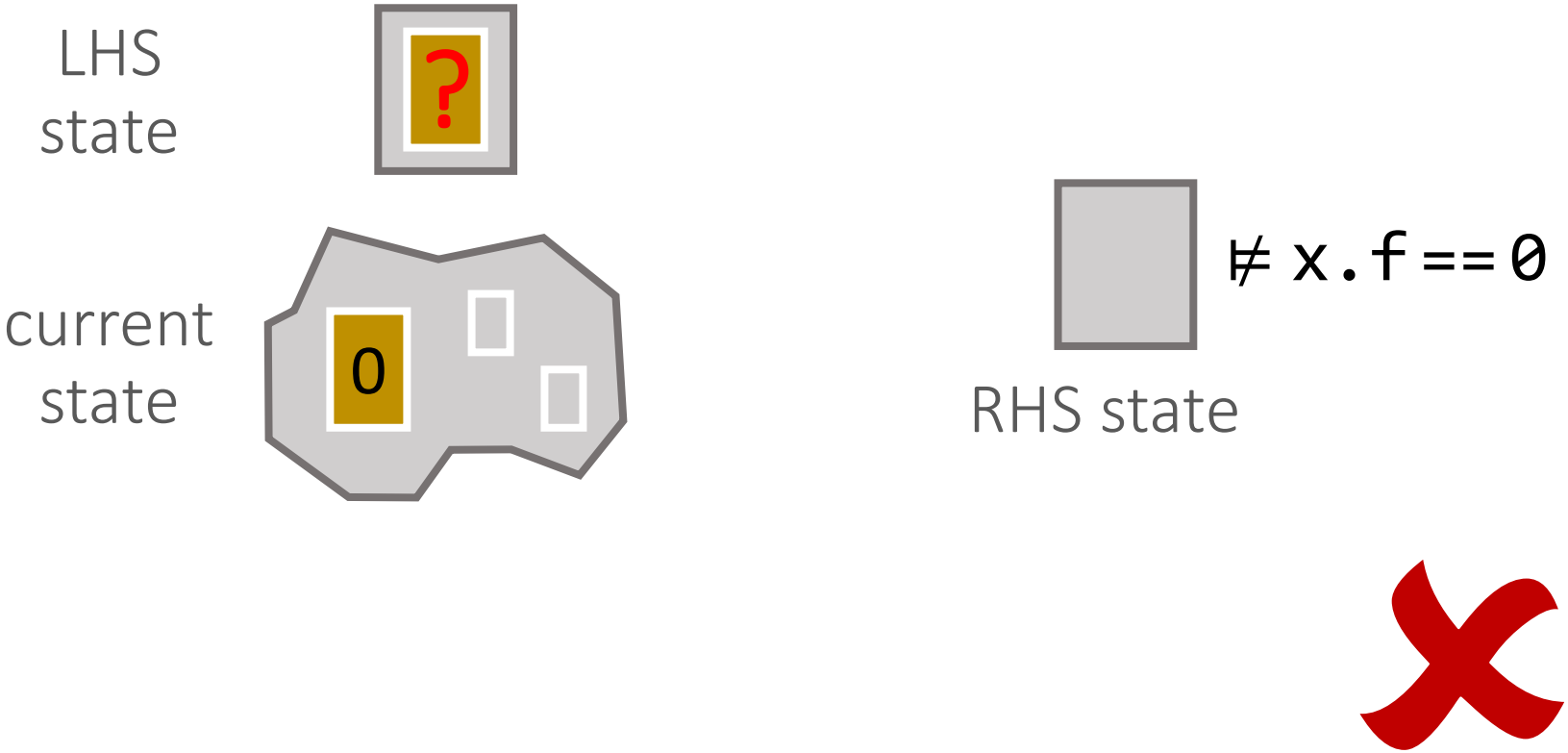
Examples

```
package true —∗ acc(x.f) ∗ x.f == 0
```



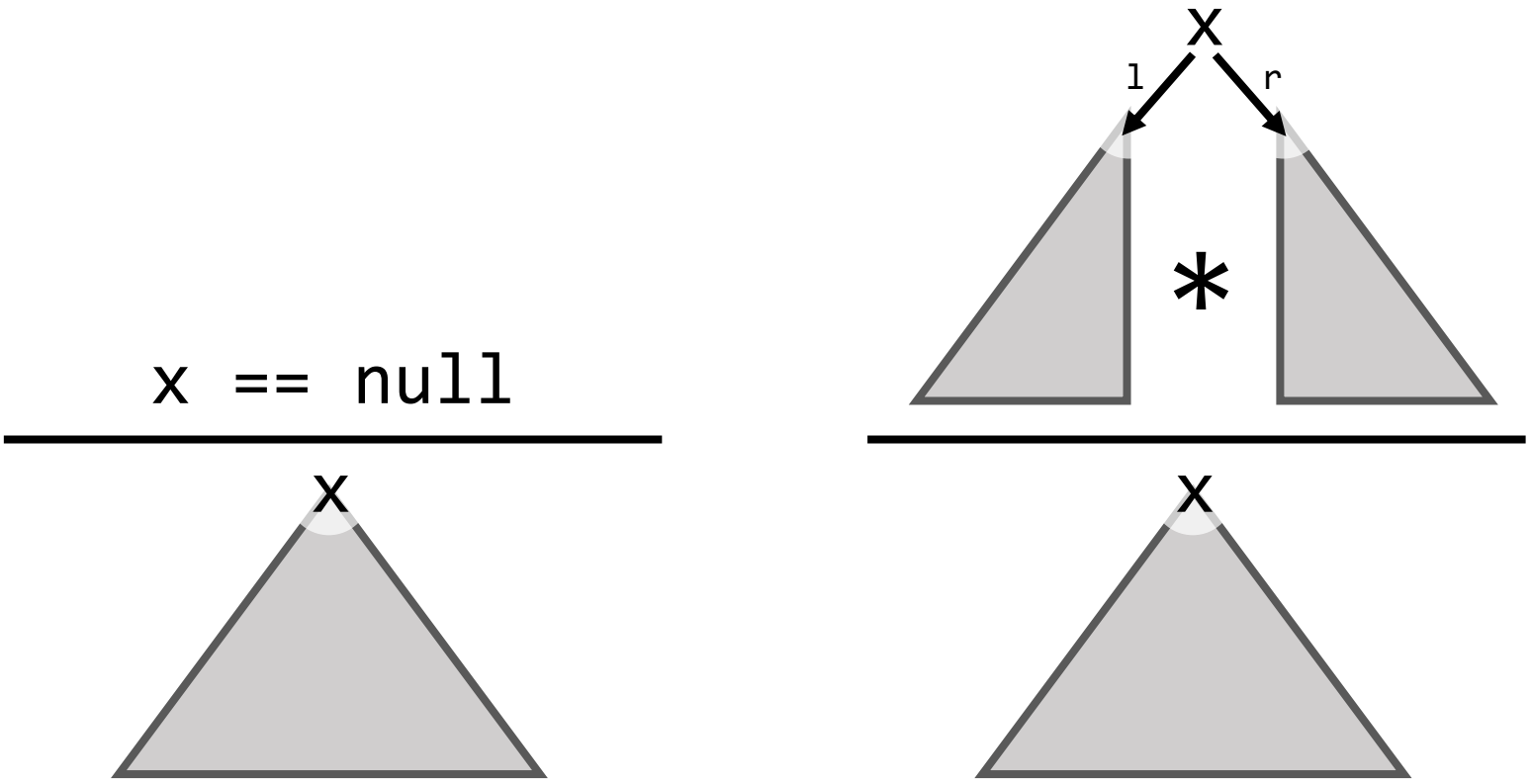
Examples

```
package acc(x.f) —∗ acc(x.f) ∗ x.f == 0
```



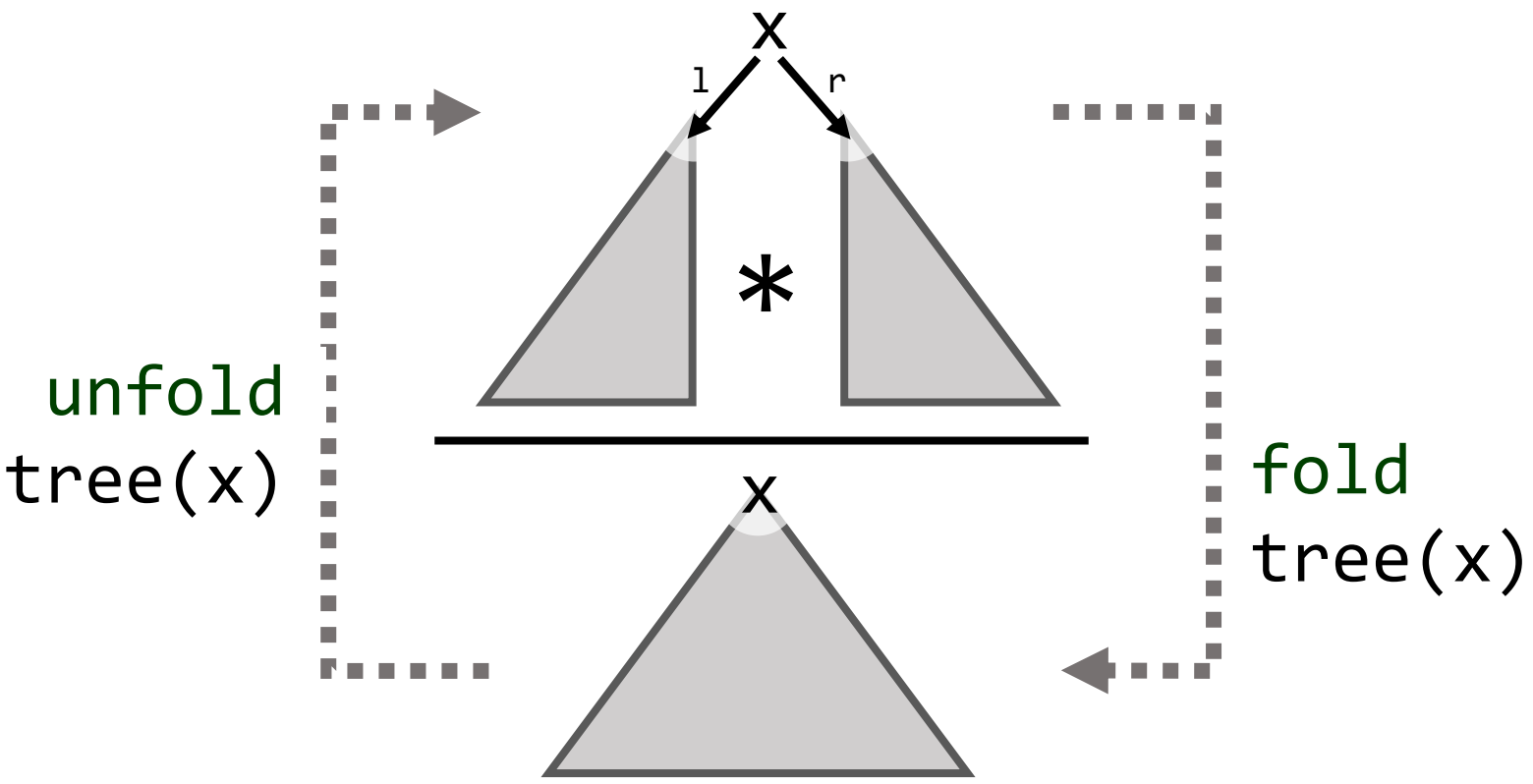
Existing Features

Abstract predicates for recursive data structures

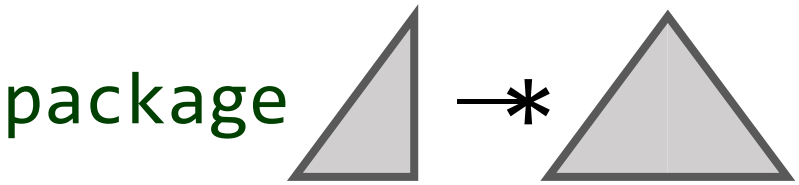


Existing Ghost Operations

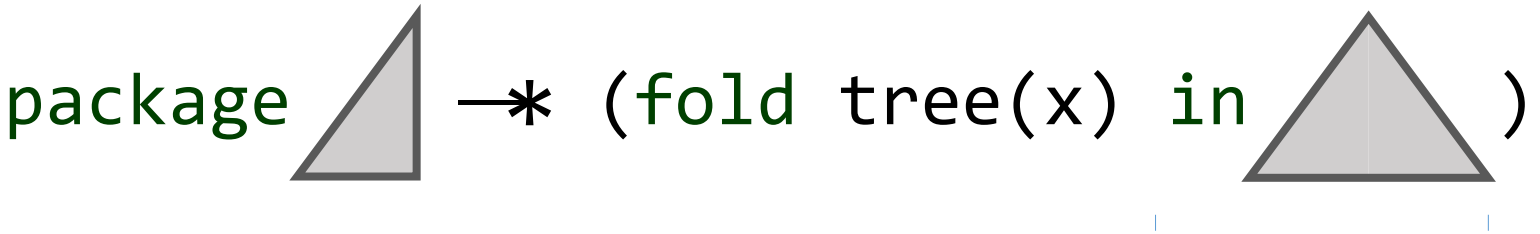
Abstract predicates plus ghost operations



Integrating Existing Ghost Operations



Integrating Existing Ghost Operations



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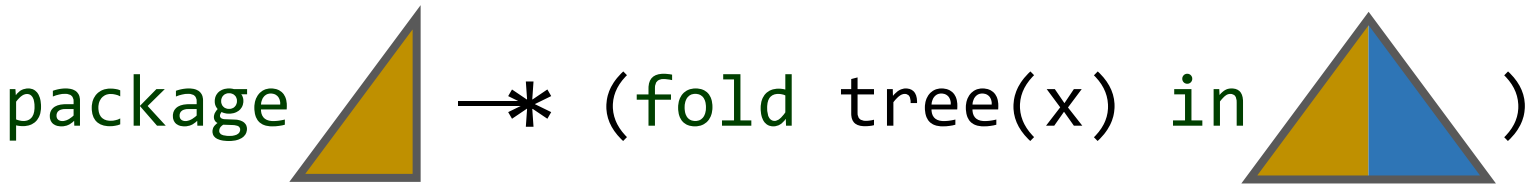

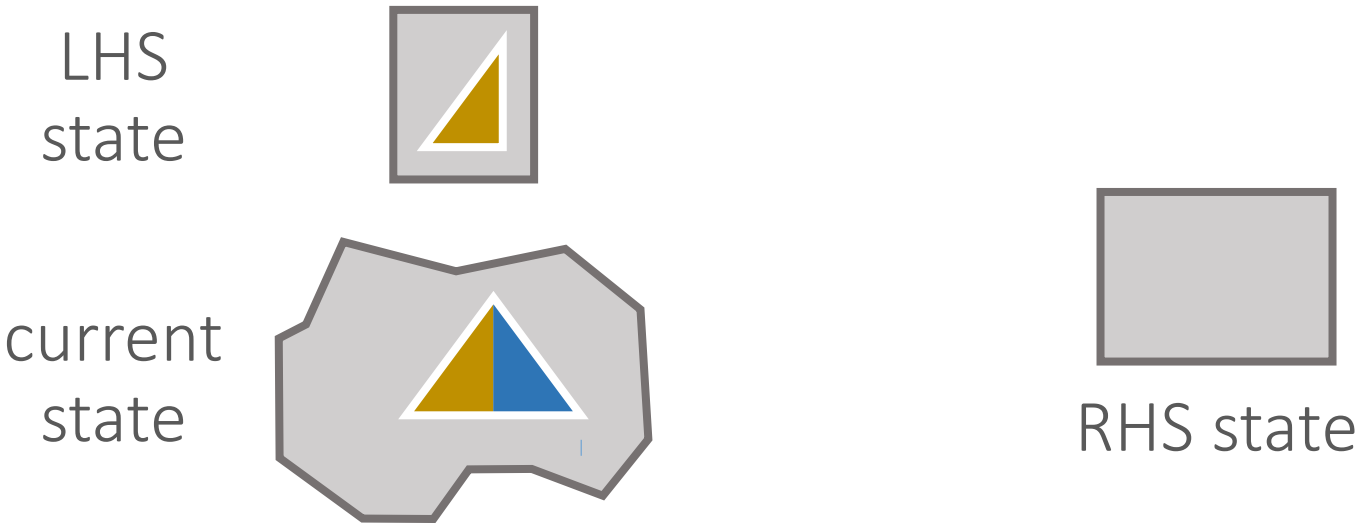

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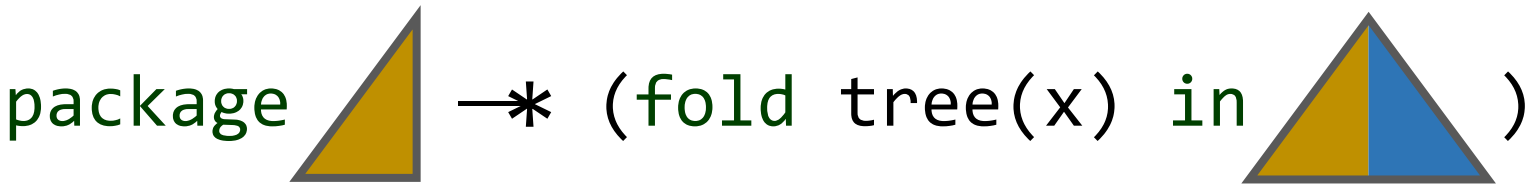


LHS state

current state

RHS state

Implementation

Part of Viper verification infrastructure

- Implementation based on symbolic execution
- Rich logic: unrestricted abstract predicates, abstraction functions, quantifiers, sets, sequences, custom mathematical domains, flexible permission model, …

Set of interesting examples; 1.6 to 3 seconds

Verification challenge from VerifyThis'12

- Verifies in 3s
- VerCors:
  - 6 minutes (originally, using Chalice/Boogie)
  - 60 seconds (currently, using Viper)

Annotation Inference Heuristics

Simple heuristics to infer package and apply statements

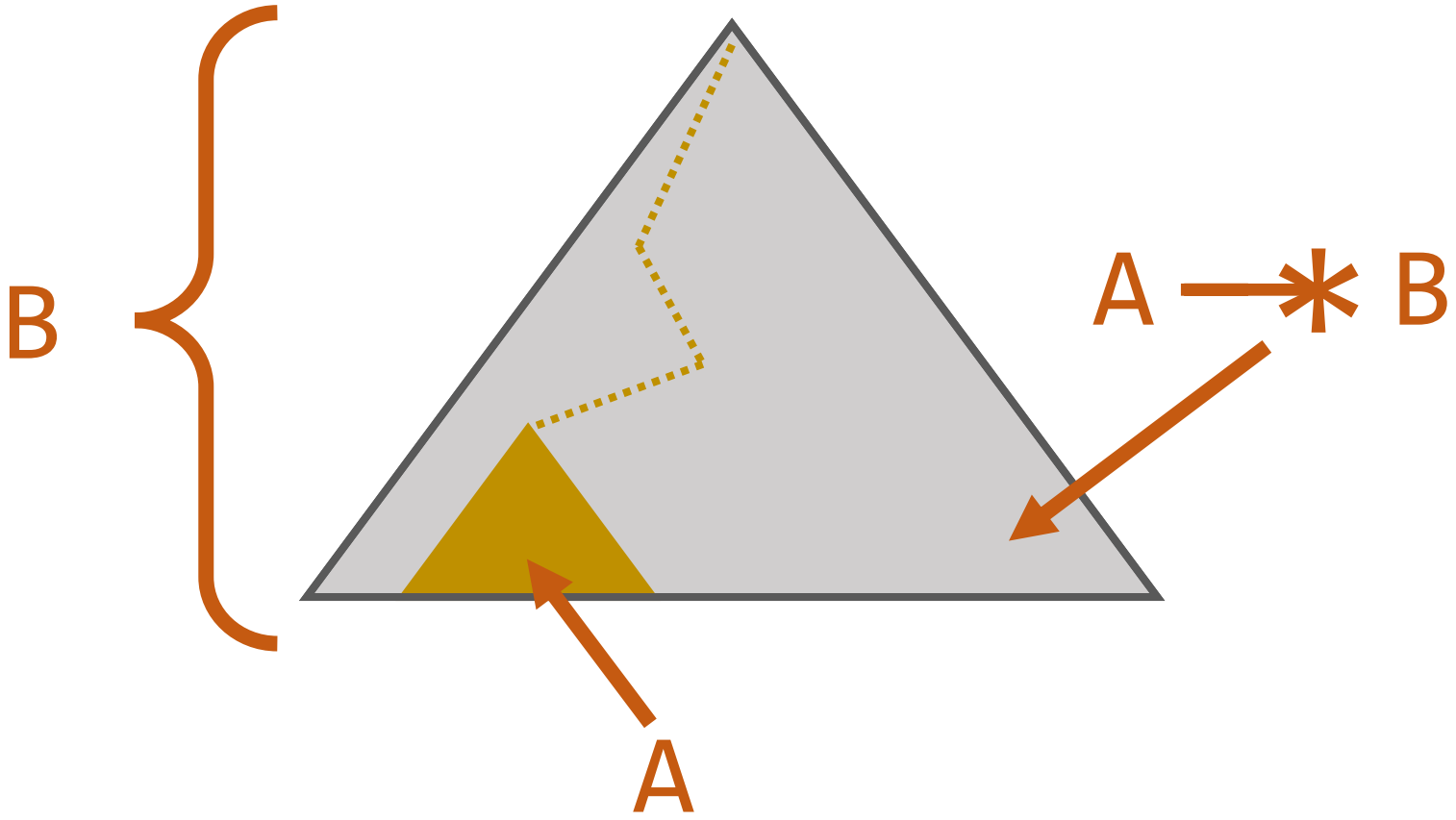
Infers all package and apply statements in our examples

Verification time: +0.5s or less

VerifyThis'12 Challenge Revisited

Scenario: Iteratively traverse a recursively defined tree

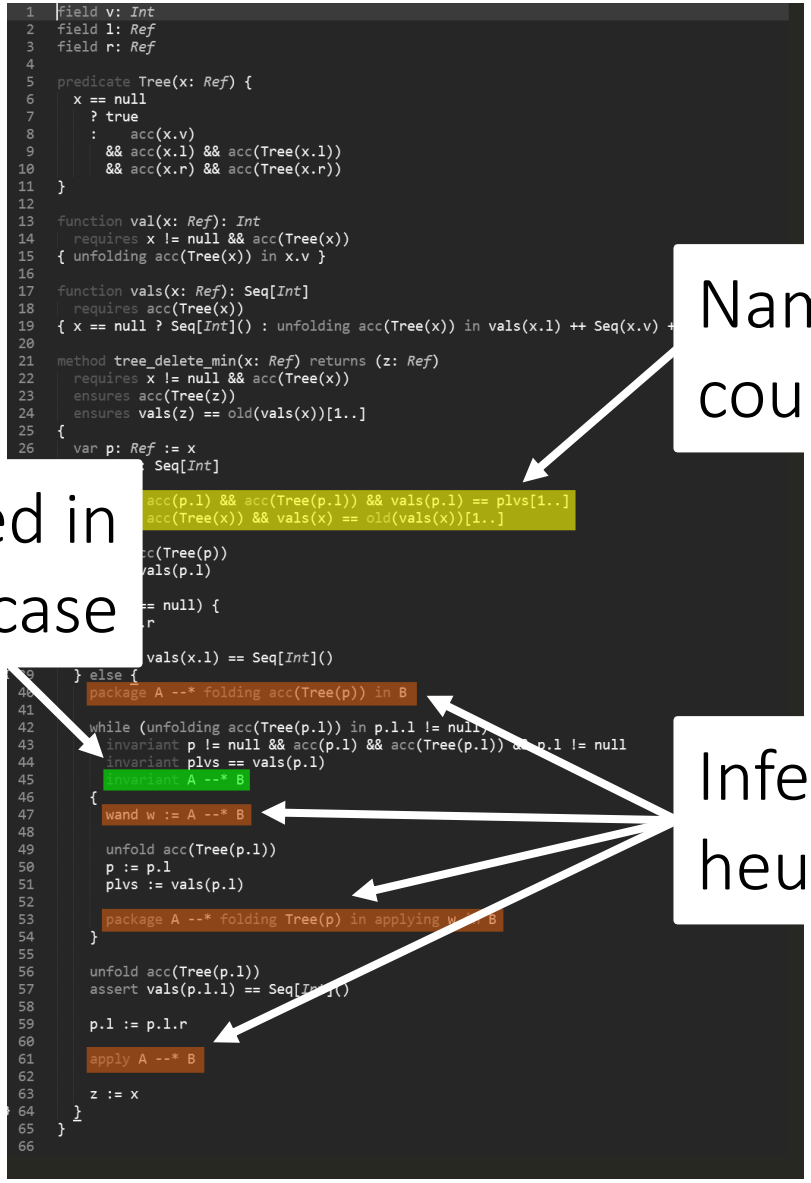
↳Loop invariant: Describe partial data structure



VerifyThis'12 Challenge Encoded

```
field v: Int
field l: Ref
field r: Ref

predicate Tree(x: Ref) {
  x == null
    ? true
    :     acc(x.v)
      && acc(x.l) && acc(Tree(x.l))
      && acc(x.r) && acc(Tree(x.r))
}

function val(x: Ref): Int
  requires x != null && acc(Tree(x))
{ unfolding acc(Tree(x)) in x.v }

function vals(x: Ref): Seq[Int]
  requires acc(Tree(x))
{ x == null ? Seq[Int]() : unfolding acc(Tree(x)) in vals(x.l) ++ Seq(x.v) ++ vals(x.r) }

method tree_delete_min(x: Ref) returns (z: Ref)
  requires x != null && acc(Tree(x))
  ensures acc(Tree(z))
  ensures vals(z) == old(vals(x))[1..]
{
  var p: Ref := x
  var plvs: Seq[Int]

  define A acc(p.l) && acc(Tree(p.l)) && vals(p.l) == plvs[1..]
  define B acc(Tree(x)) && vals(x) == old(vals(x))[1..]

  unfold acc(Tree(p))
  plvs := vals(p.l)

  if (p.l == null) {
    z := p.r

    assert vals(x.l) == Seq[Int]()
  } else {
    package A --* folding acc(Tree(p)) in B

    while (unfolding acc(Tree(p.l)) in p.l.l != null)
      invariant p != null && acc(p.l) && acc(Tree(p.l)) && p.l != null
      invariant plvs == vals(p.l)
      invariant A --* B
    {
      wand w := A --* B

      unfold acc(Tree(p.l))
      p := p.l
      plvs := vals(p.l)

      package A --* folding Tree(p) in applying w in B
    }

    unfold acc(Tree(p.l))
    assert vals(p.l.l) == Seq[Int]()

    p.l := p.l.r

    apply A --* B

    z := x
  }
}
```

VerifyThis'12 Challenge Encoded



Named shorthand, could be inlined

Required in either case

Inferred by heuristics

www.pm.inf.ethz.ch/research/viper.html

Algorithm for computing wand footprints

- Sound (proof sketch)
- Permissive and predictable

Formalised verifier-independently

Implementation

- Co-first* to support magic wands in an automatic verifier
- Lightweight user annotations
- Convincing initial results (expressiveness, performance)

* VerCors