Viper

A Verification Infrastructure for Permission-Based Reasoning

Uri Juhasz, Ioannis Kassios, Peter Müller, Milos Novacek, Malte Schwerhoff, Alex Summers (and several students)

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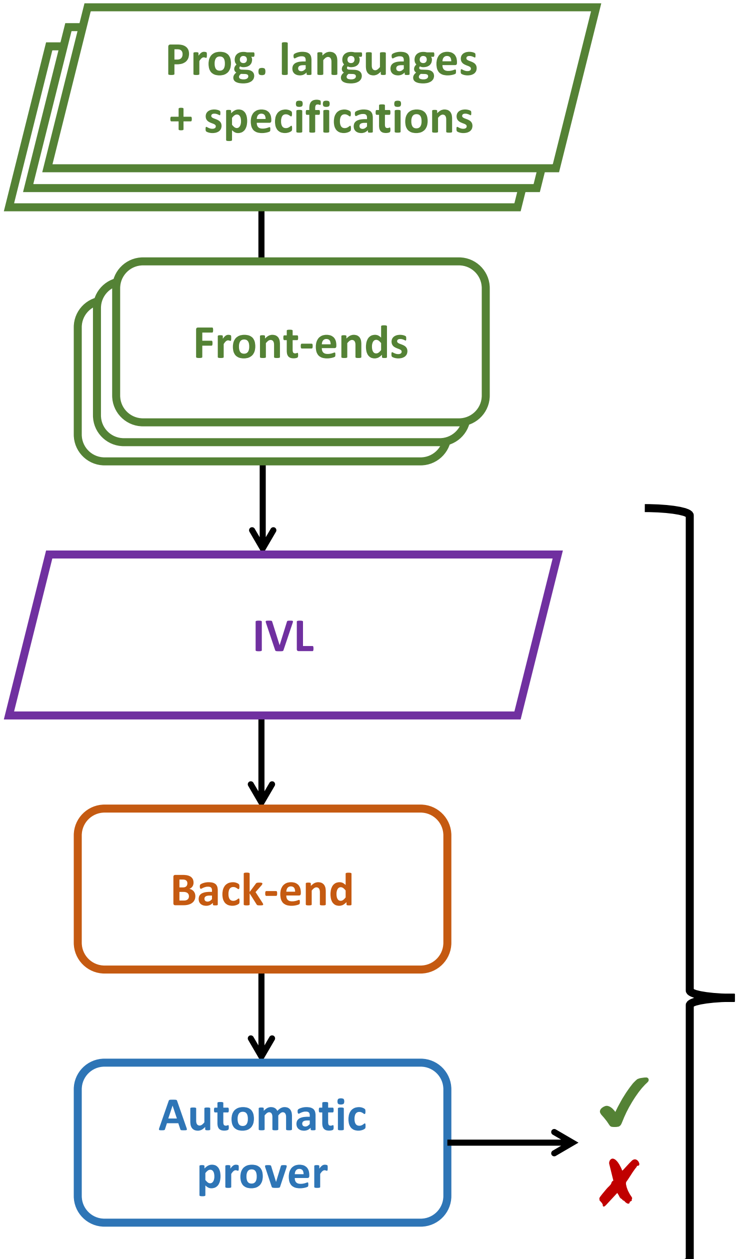
Our Vision

Automatic Program Verification

- Safety (memory accesses, non-null, …)
- Correctness (functional specs)
- Termination, message replies, …

Verification using Automatic Provers



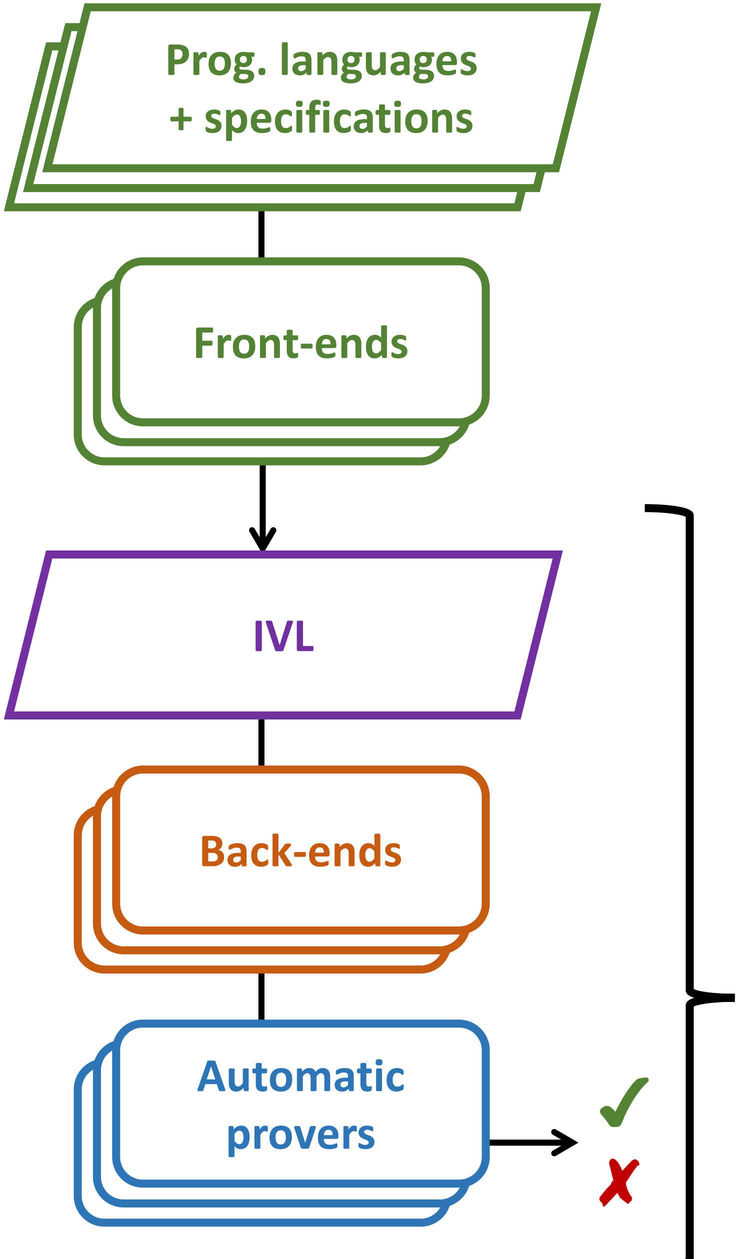
+ Automatic first-order logic tools – major progress in the last decade (SAT, SMT)

+ Intermediate verification languages - Boogie, Why, ...

+ Back-end: verifier (verification condition generator)

= **Common infrastructure** for building front-end verifiers

Verification using Automatic Provers



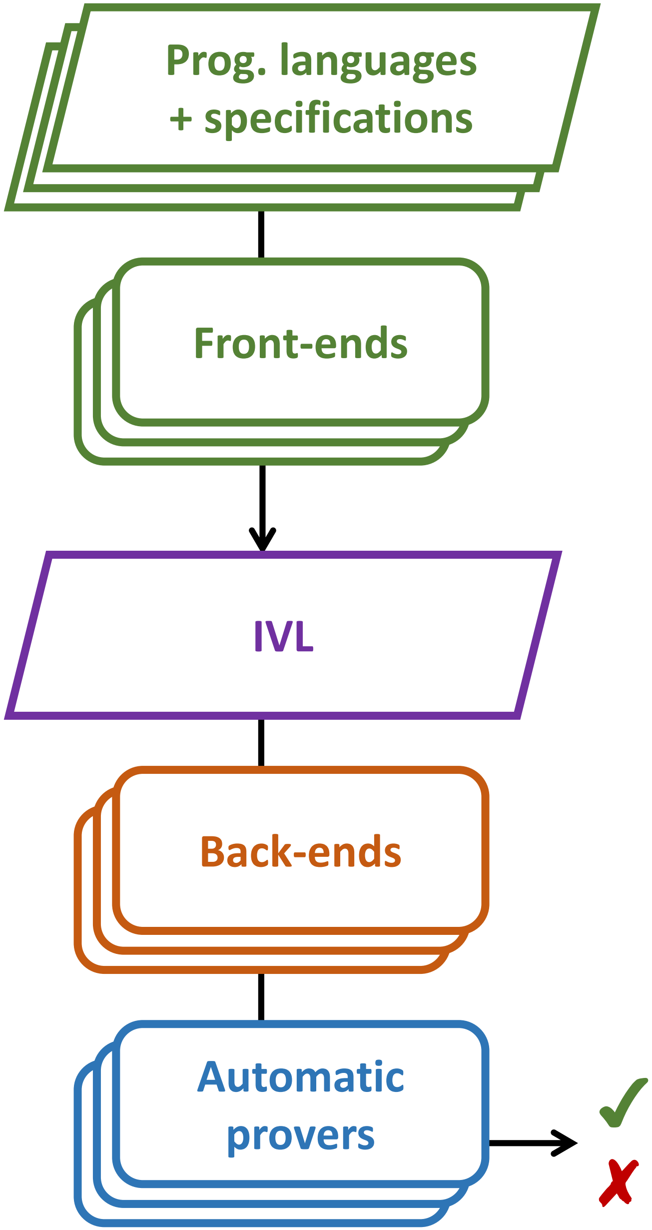
+ Automatic first-order logic tools – major progress in the last decade (SAT, SMT)

+ Intermediate verification languages - Boogie, Why, …

+ Back-ends: verifiers - but also inference engines, slicers, static analysers, …

= **Common infrastructure** for building front-end verifiers

Verification using Automatic Provers



Common infrastructure enabled many *success stories* and *tools*

- Microsoft Hypervisor (VCC)
- Device drivers (Corral)
- Spec#, Dafny
- Krakatoa, Jessie
- Frama-C, Why3
- …

Permission-Based Reasoning

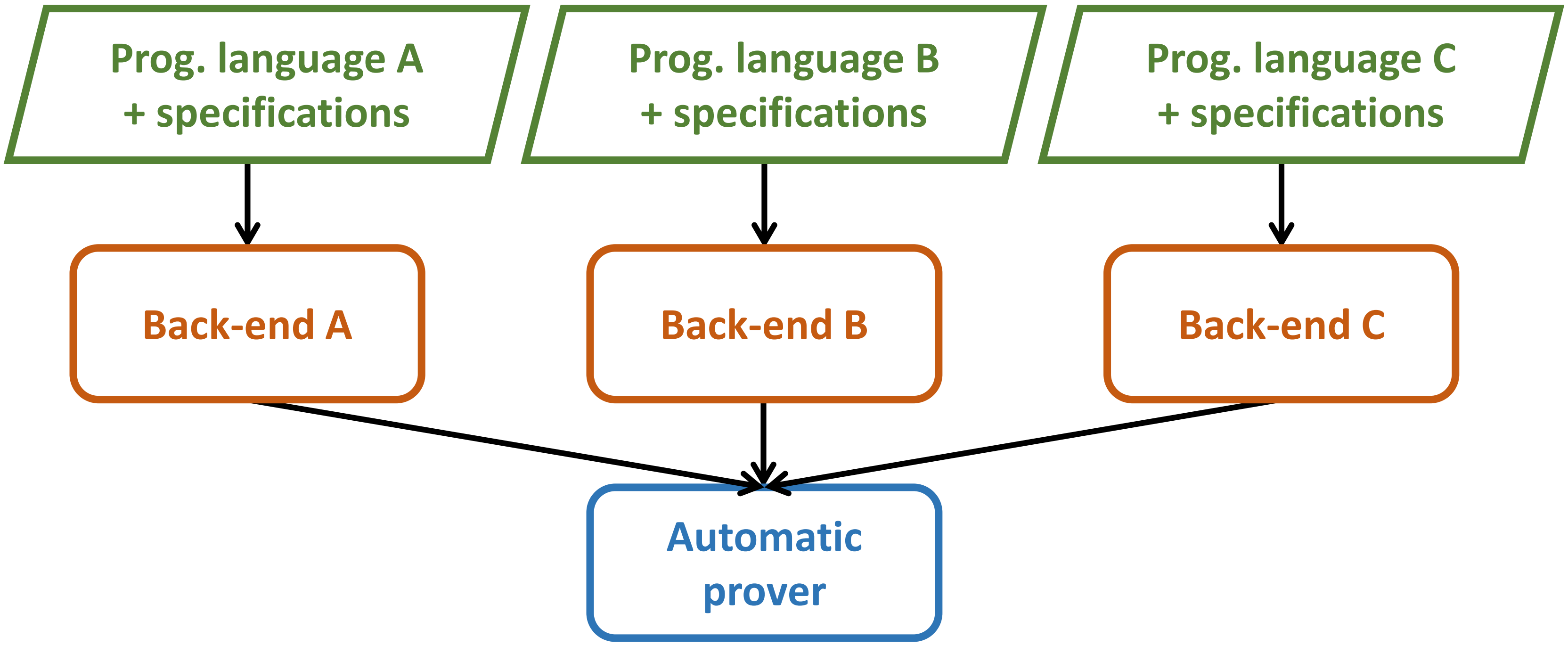
Separation logic and others *permission logics*:

- *Locally* reason about *shared mutable state*
- Many *successful applications*, including
  - Device driver safety (Microsoft)
  - Belgian Electronic Identity Card
- Many *ongoing developments*
  (esp. fine-grained concurrency)

Not a first-order logic
→ Significantly complicates using existing provers

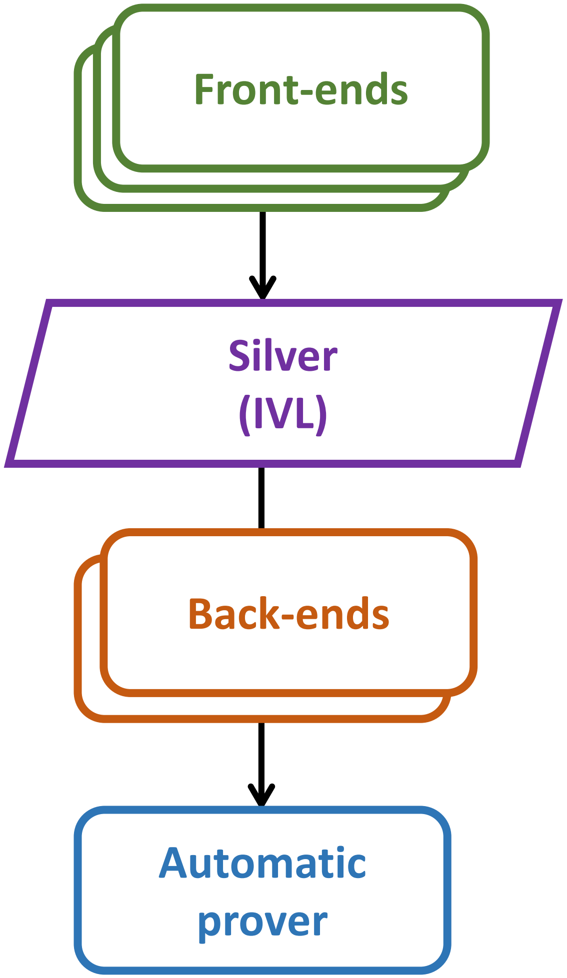
Permission-Based Reasoning

Consequence: many *custom verification engines* (usually based on symbolic execution): Smallfoot, VeriFast, jStar, …



Alternative: Encoding SL into FOL (e.g. Chalice)

Viper: Our Verification Infrastructure



Silver:

- *Native* support for permissions
- Few (but expressive) constructs
- Designed with verification and inference in mind

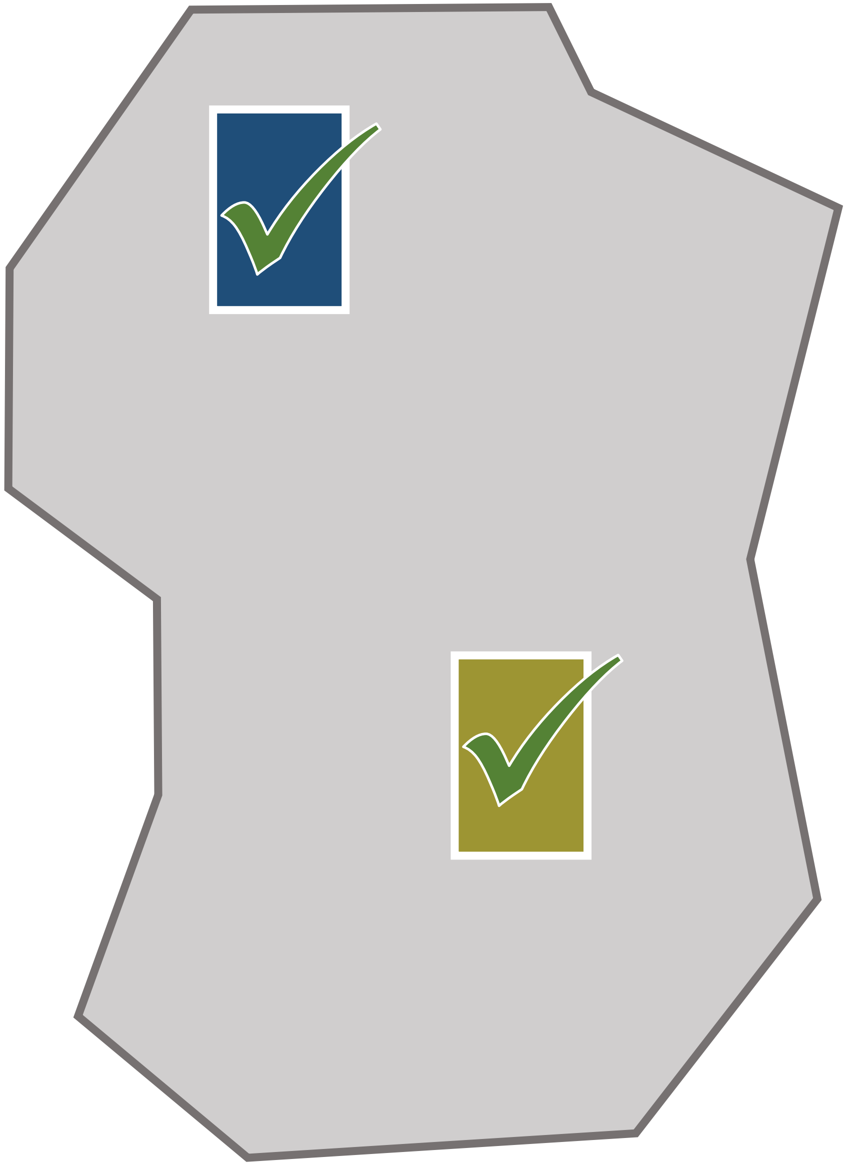
Back-ends: Two verifiers;
plans to develop inference, slicer

Front-ends (proof of concept):

- *Chalice* (concurrency research)
- *Scala* (very small subset)
- *Java* (VerCors, U Twente)
- *OpenCL* (VerCors, U Twente)

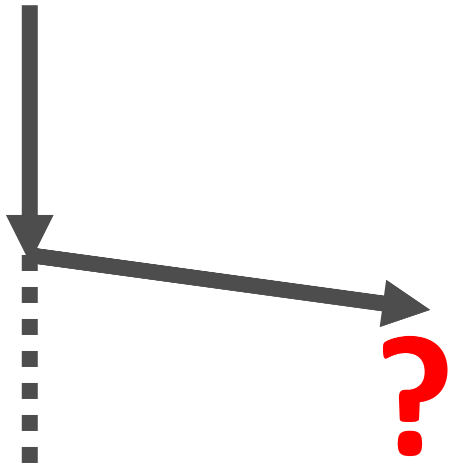
Modular Static Verification + Shared State

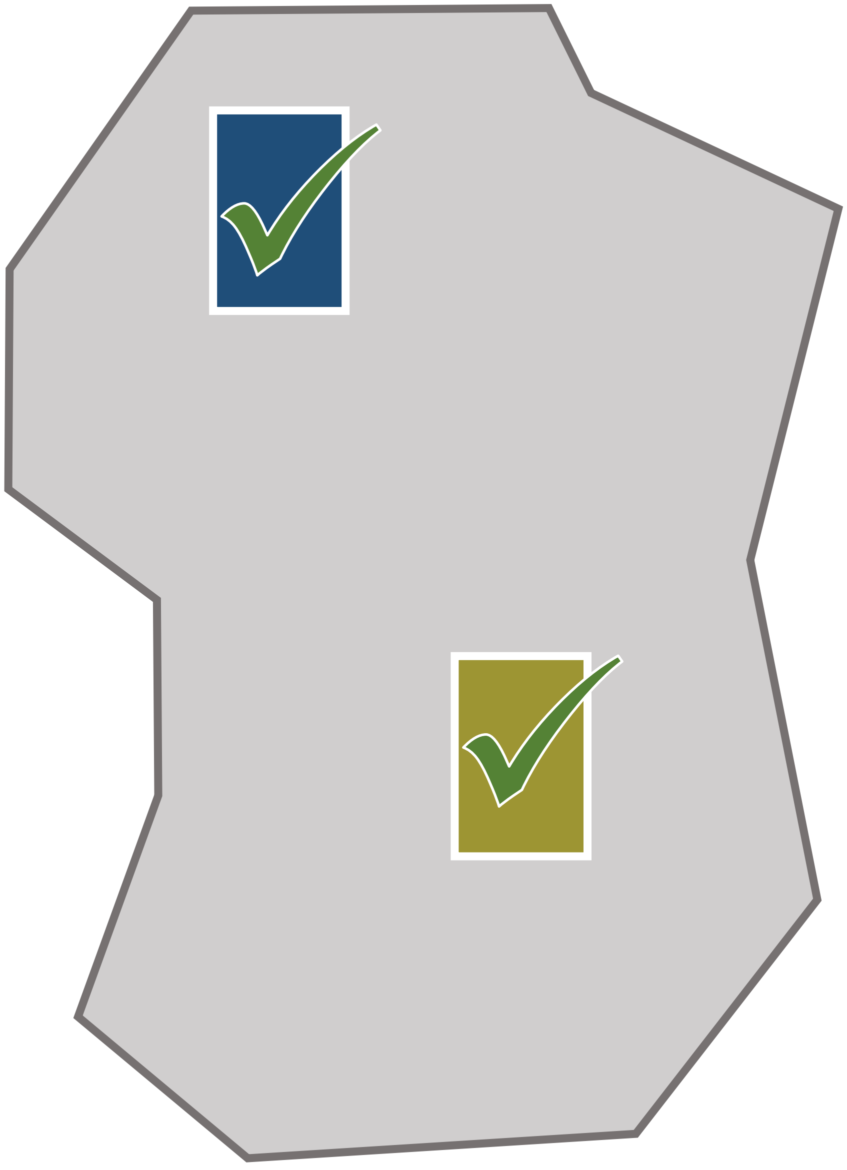
`foo(x)` `bar(x)`



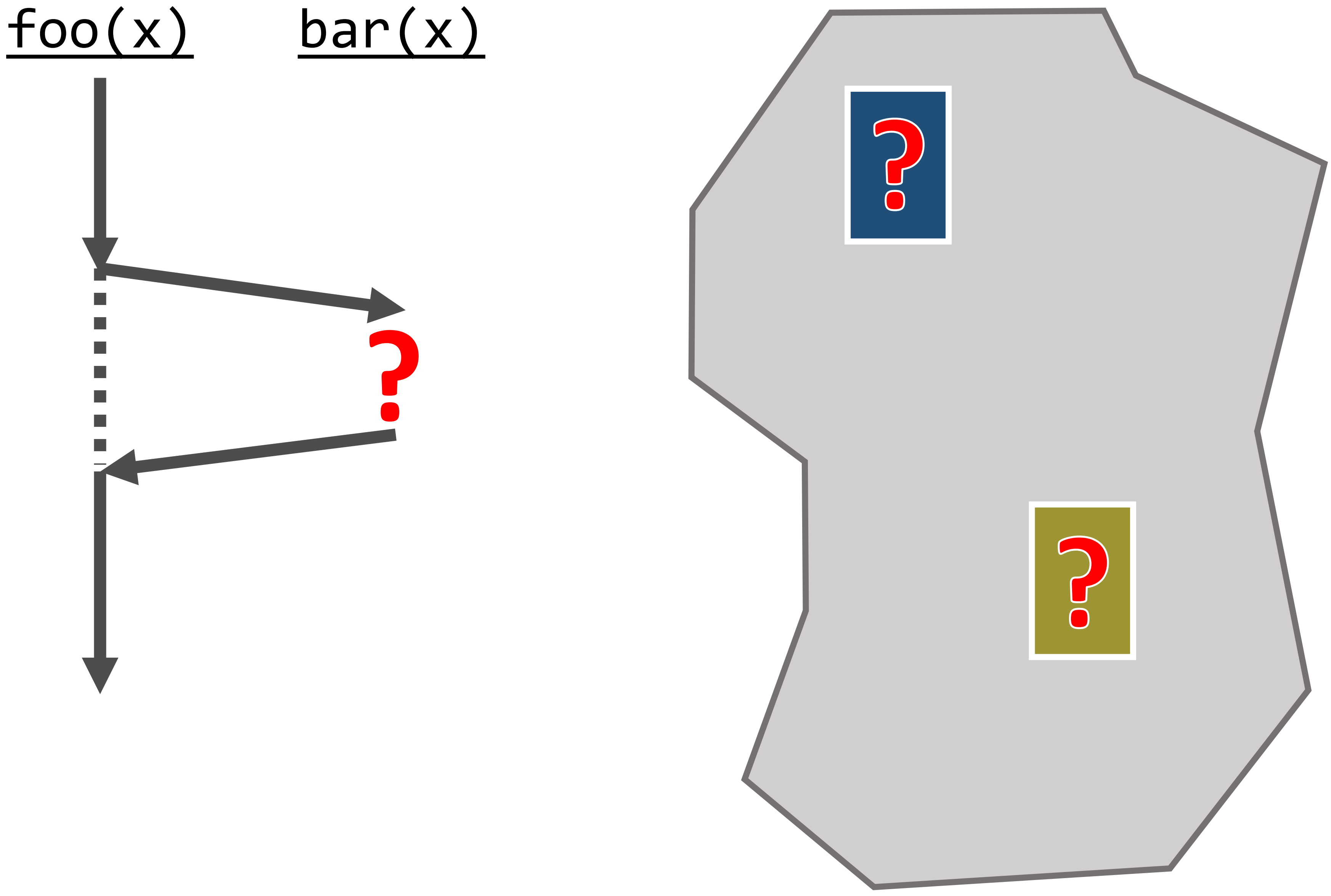
Modular Static Verification + Shared State

`foo(x)`   `bar(x)`



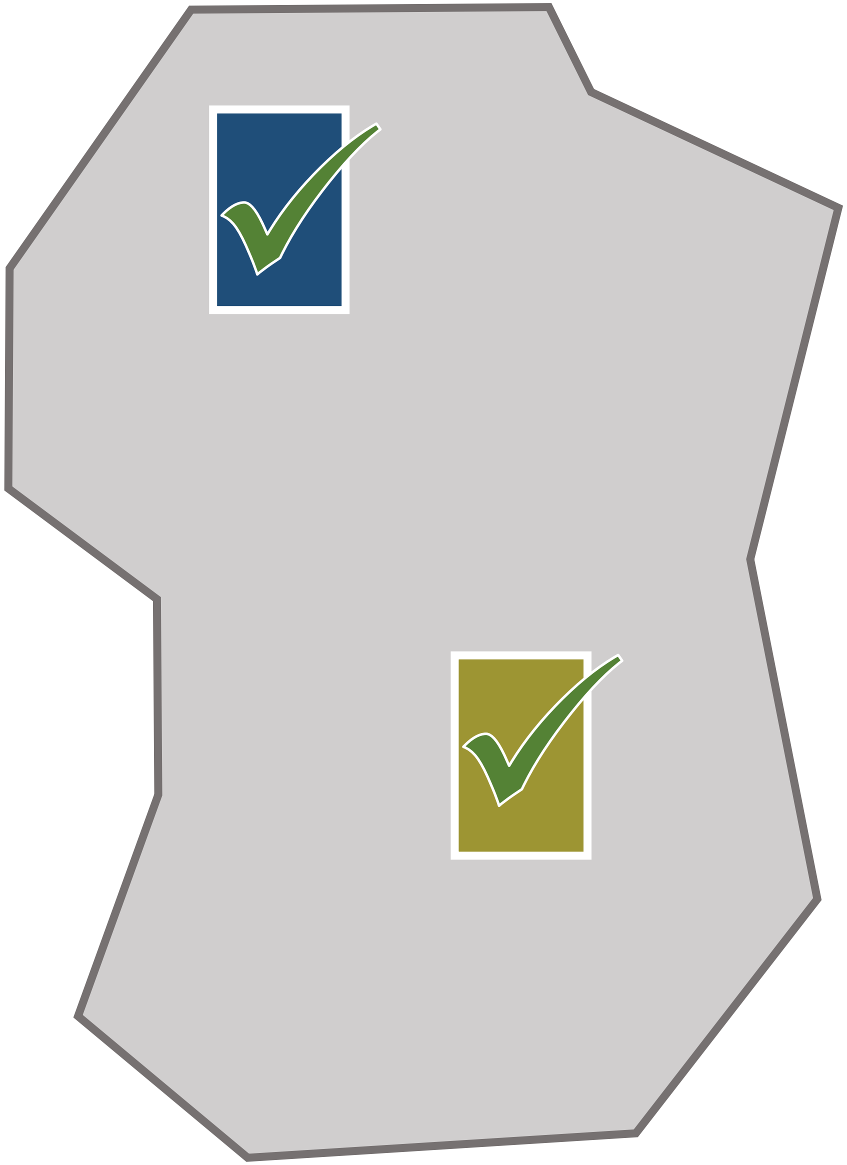


Modular Static Verification + Shared State

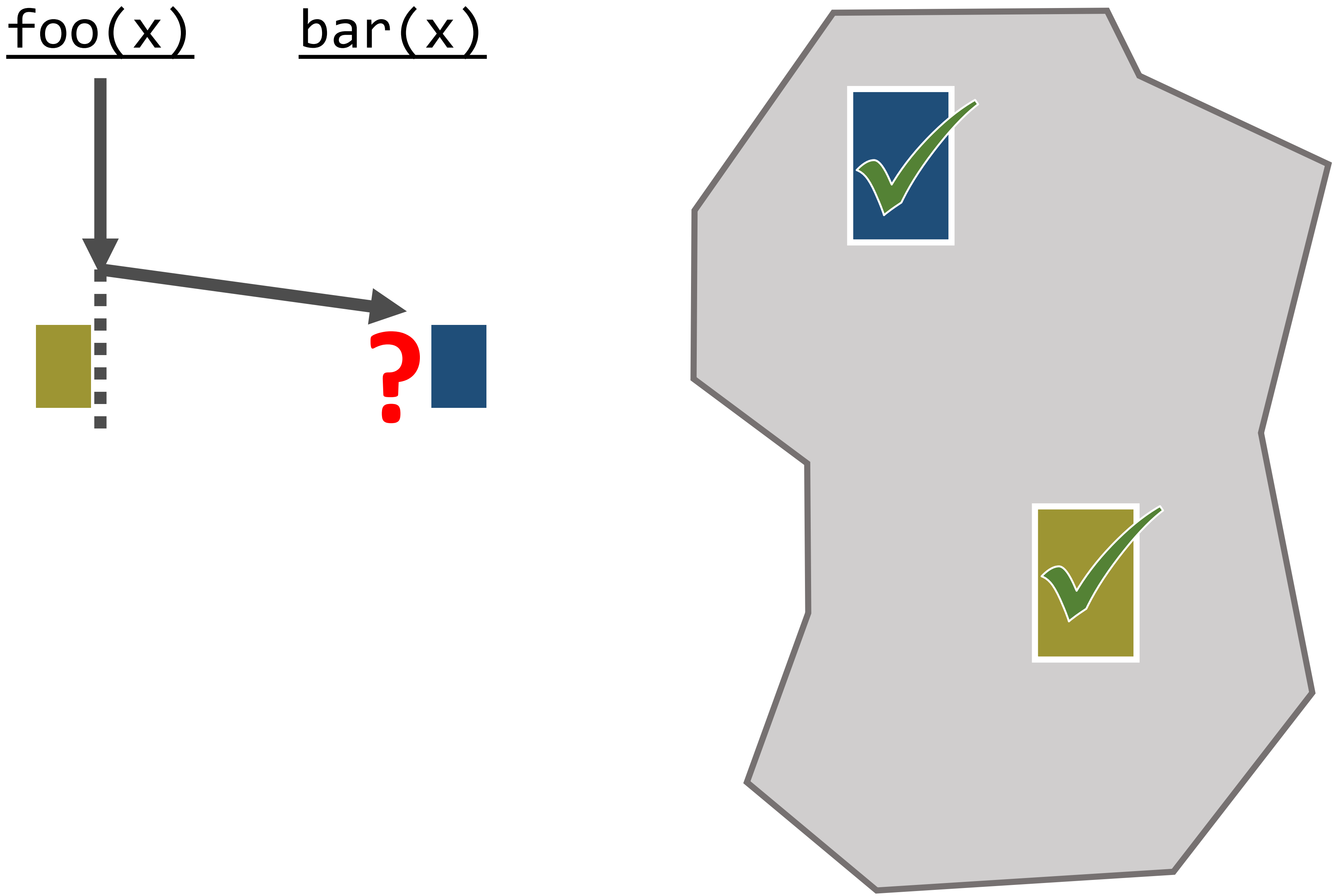


Permissions

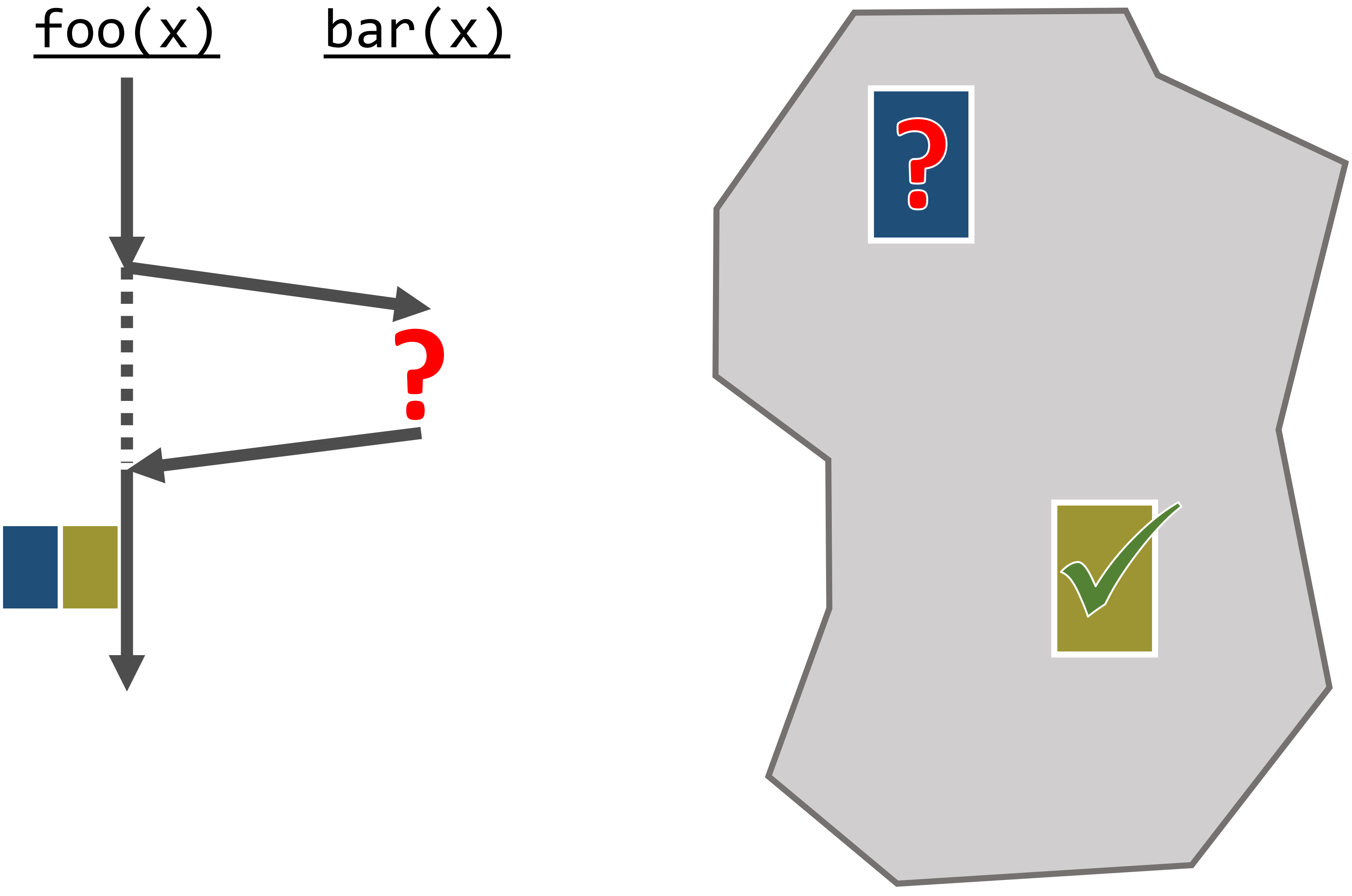
`foo(x)` `bar(x)`



Permission Transfer

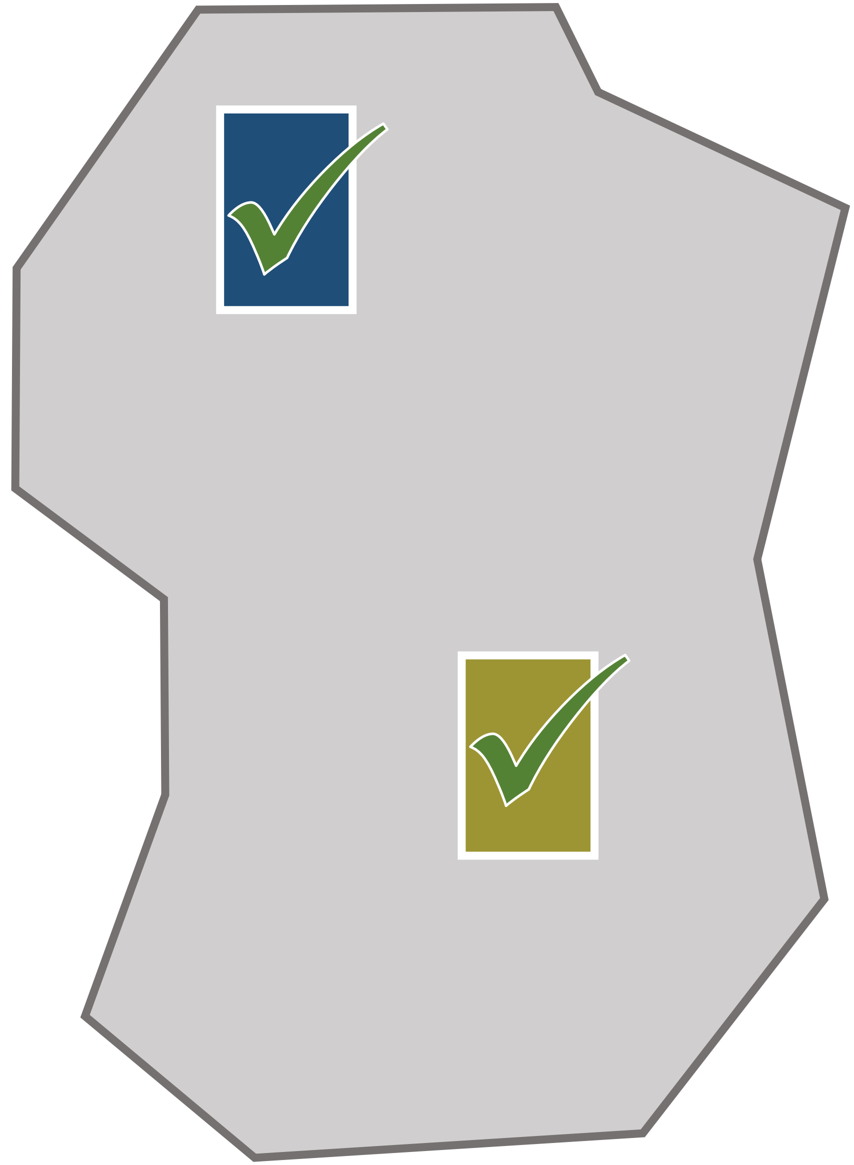


Permission Transfer

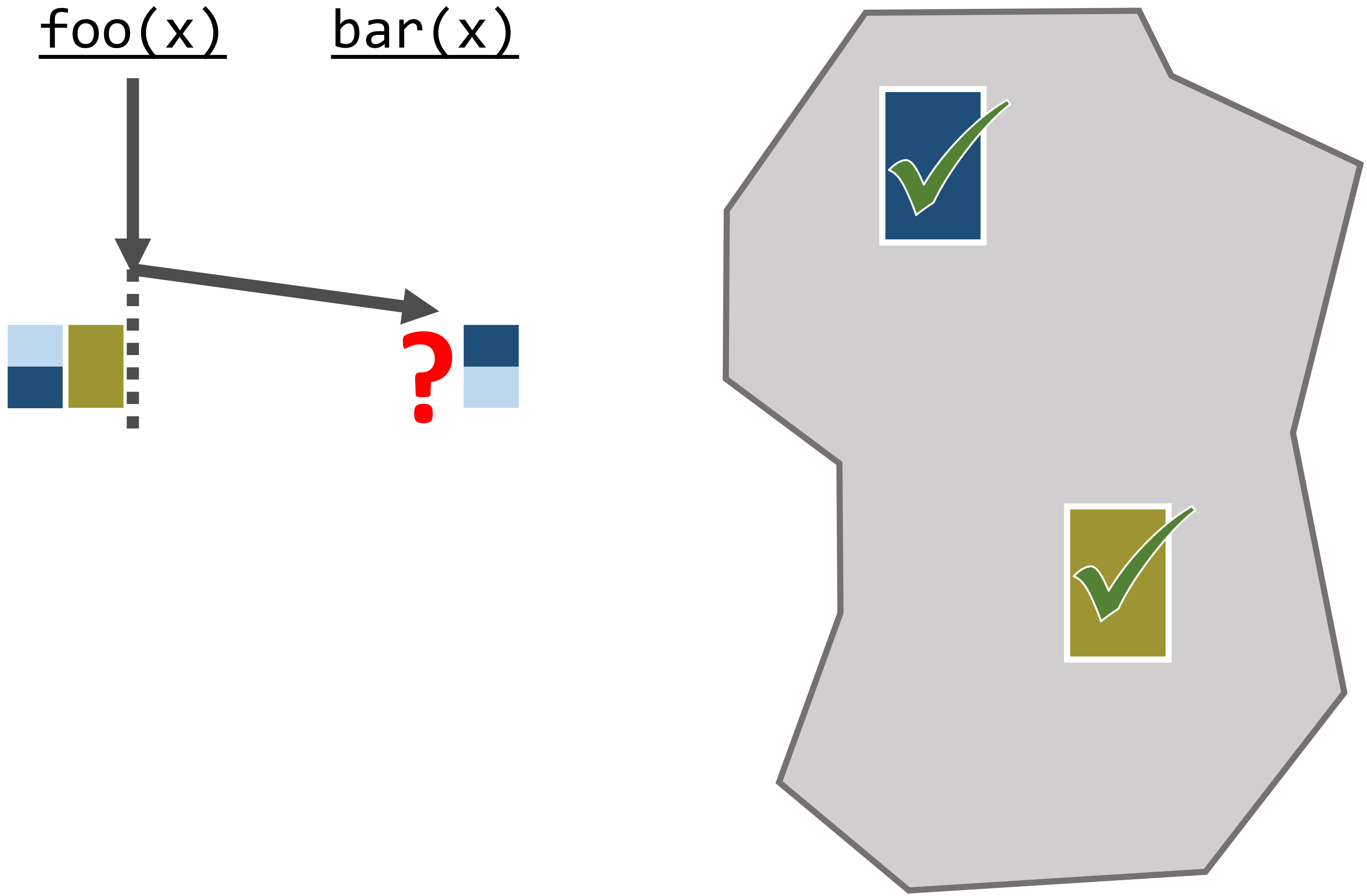


Fractional Permissions

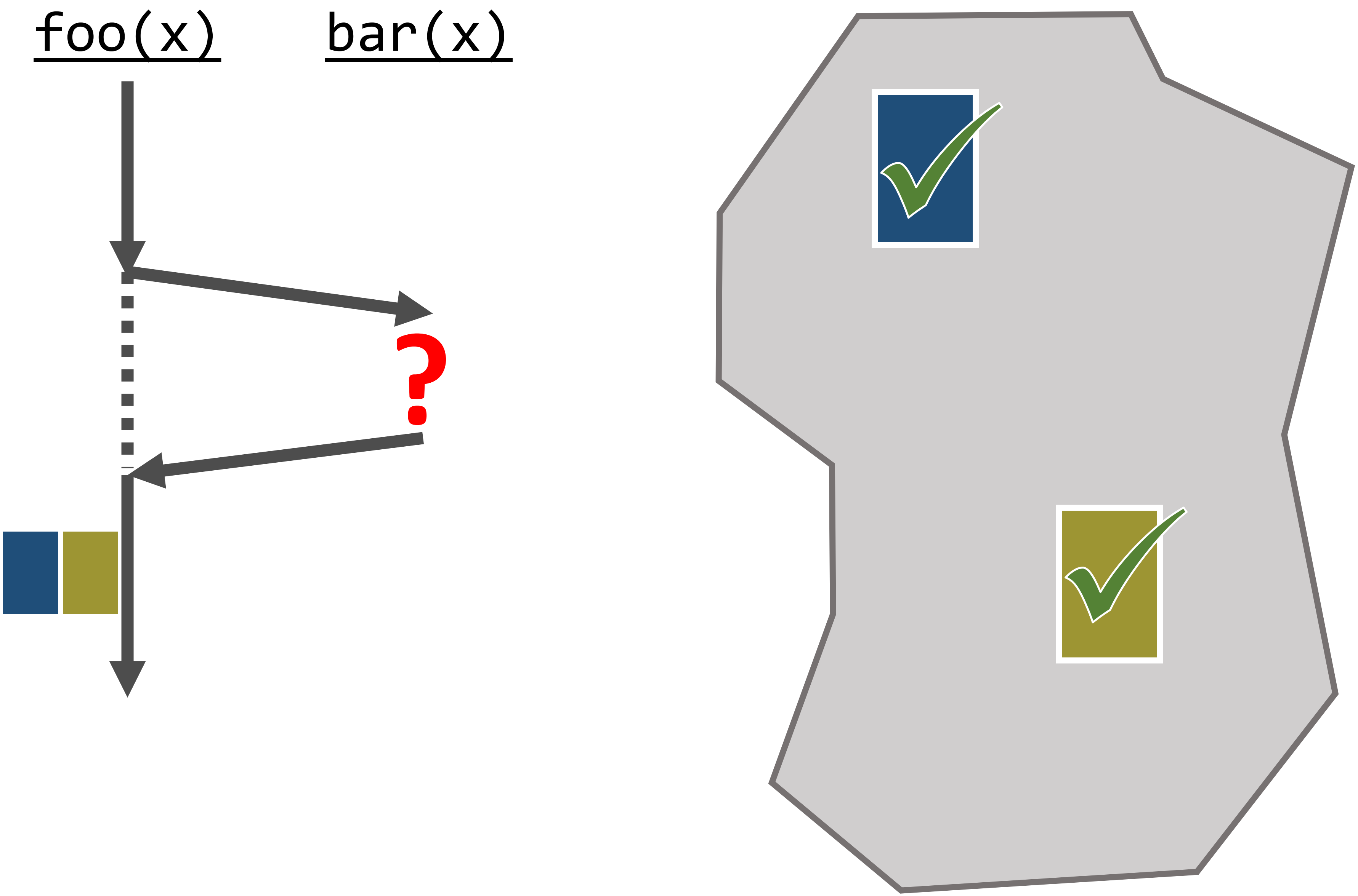
`foo(x)` `bar(x)`



Splitting Fractional Permissions



Merging Fractional Permissions



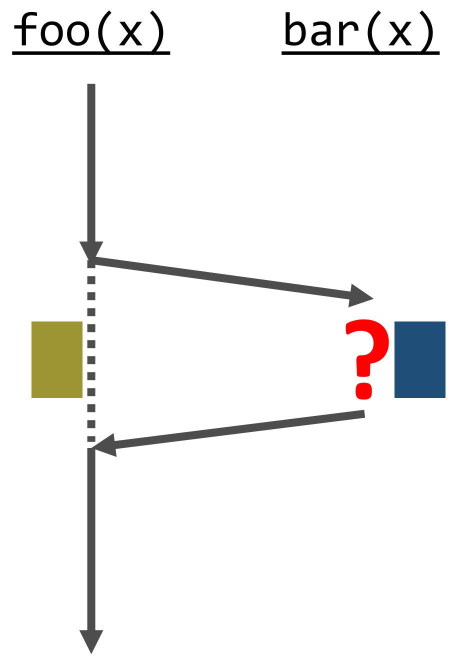
Permission Transfer

Idea of *permission transfer* generalises

- Fork-join (transfer between threads)
- Locks (transfer to/from lock invariant)
- Message passing (pass permissions)

Common operations

- Gain permissions
- Lose permissions



Silver: Inhale and Exhale Statements

Statement `exhale A` means

- Assert and remove permissions required by `A`
- Assert logical constraints in `A` (e.g. `c.f == 0`)
- Havoc locations to which all permissions is lost
  (i.e. forget their values)

Statement `inhale A` means

- Gain permissions required by `A`
- Assume logical constraints in `A`

Silver: Assertion Language Basics

Based on *implicit dynamic frames*

Accessibility predicates denote permissions

```
acc(c.f)
```

Assertions may be *heap-dependent*

```
acc(c.f) && c.f == 0
```

Fractional permissions

```
acc(c.f, ½)
```

Conjunction *sums up* permissions (similar to $*$ in separation logic)

```
acc(c.f,½) && acc(c.f,½)
```

Demo

Silver: Language Features

Objects and fields, if-then-else, methods (with pre/post specs), loops (with invariants)

No notion of concurrency (encode via `inhale`/`exhale`)

Simple type system

- `Int`, `Bool`, `Ref`, `Perm`
- Mathematical sets `Set[T]` and sequences `Seq[T]`

Silver: Unbounded Data Structures

Unbounded data structures via *recursive predicates*

```
predicate list(x: Ref) {
      acc(x.val) && acc(x.next)
  && (x.next != null ==> list(x.next))
}
```

`fold/unfold` statements exchange predicate instances for their bodies (not automatic due to recursion)

Heap-dependent, pure abstraction functions

```
function elems(x: Ref): Seq[Int]
  requires list(x)
{ unfolding list(x) in
    [x.val] ++ (x.next == null ? [] : elems(x.next))
}
```

Silver: Custom Mathematical Domains

D*omains* to specify custom mathematical types

- Type-parametric domains
- Domain functions
- Domain axioms

```
domain Pair[X,Y] {
 function pair(x: X, y: Y): Pair[X,Y]
 function first(p: Pair[X,Y]): X

 axiom forall x: X, y: Y • first(pair(x,y)) == x
}
...
method foo(x: Ref, p: Pair[Int, Int])
  requires acc(x.f)
{ x.f := first(p) }
```

Silver: Other Cool Features

Abstract read permissions

- Alternative to fractional permissions
- No need to commit to concrete fractions, e.g. ½

```
method foo(x: Ref, p: Perm)
  requires 0 < p && acc(x.f, p)
{
  // read x.f
  if (*) {
    var q: Perm
    constraining (q) {
      foo(x, q) // give away q < p
    }
  }
}
```

Allows *unbounded splitting and counting*

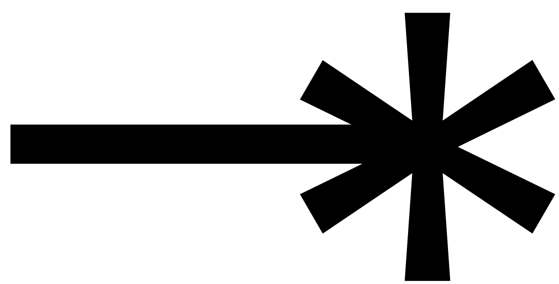
Silver: Other Cool Features

Paired assertions `[A, B]`

- When inhale, **A** is used
- When exhaled, **B** is used
- Asymmetry justified elsewhere
  (type system, soundness proof, induction schema, ...)

```
[
 forall x: Nat • P(x),

 forall x: Nat •
   (forall y: Nat • y < x ==> P(y)) ==> P(x)
]
```

Magic Wands



Magic Wands Primer

Boolean implication $\mathrm{A} \Rightarrow \mathrm{B}$

Modus Ponens $\mathrm{A} \wedge (\mathrm{A} \Rightarrow \mathrm{B}) \vDash \mathrm{B}$

Separating implication $\mathrm{A} \mathrel{-\!\!*} \mathrm{B}$

Modus Ponens $\mathrm{A} * (\mathrm{A} \mathrel{-\!\!*} \mathrm{B}) \vDash \mathrm{B}$

$\mathrm{A} \mathrel{-\!\!*} \mathrm{B}$ can be understood as an *exchange promise*

“If A and $\mathrm{A} \mathrel{-\!\!*} \mathrm{B}$ are given up,
then B is guaranteed to hold“

Magic Wands Primer

Semantics of the magic wand:

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

Quantification over state; typically not supported in automated verifiers

Used in proofs by hand (e.g. data structure modifications, barrier synchronization)

Permission Bookkeeping and Recursive Predicates

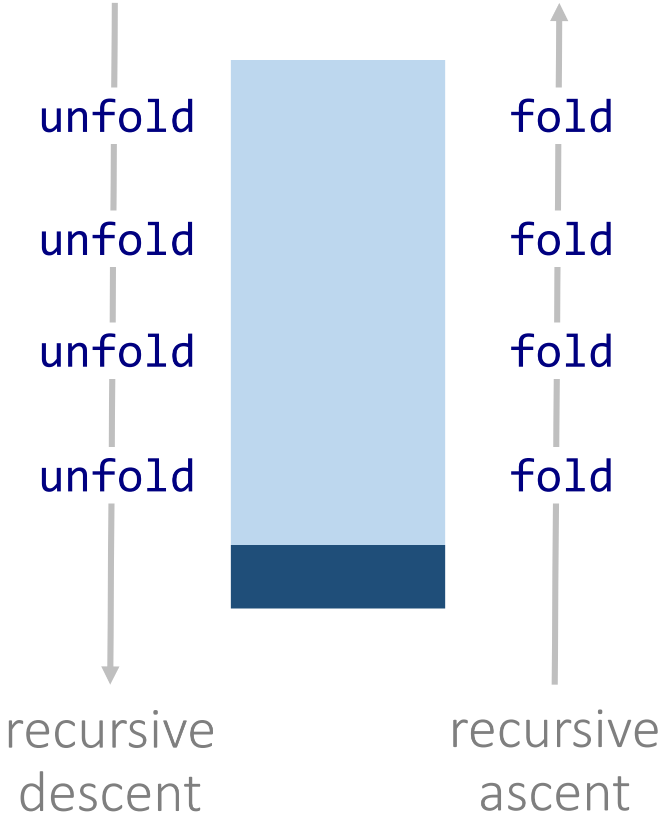
```
predicate list(xs: Ref) {
  acc(xs.next) && (xs.next != null ==> list(xs.next))
}
```

```
method rec(xs: Ref)
  requires list(xs)
  ensures list(xs)
{
  unfold list(xs)
  rec(xs.next)
    // Ignoring base case
  unfold list(xs)
}
```

Permission Bookkeeping and Recursive Predicates

```
predicate list(xs: Ref) {
  acc(xs.next) && (xs.next != null ==> list(xs.next))
}
```

```
method rec(xs: Ref)
  requires list(xs)
  ensures list(xs)
{
  unfold list(xs)
  rec(xs.next)
    // Ignoring base case
  fold list(xs)
}
```

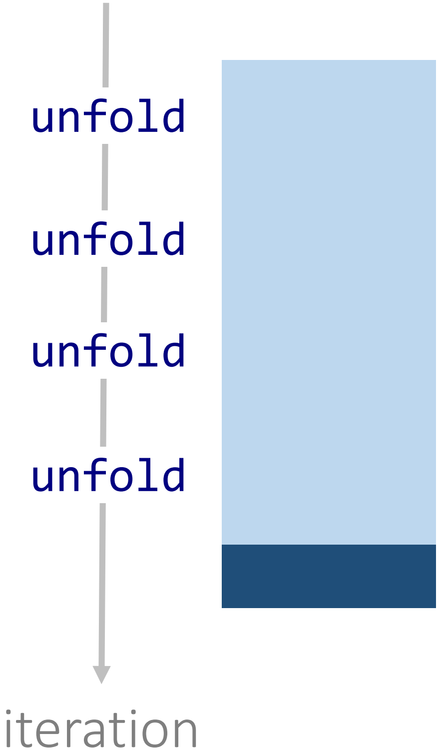


Bookkeeping *implicitly* done by the *call stack*

Permission Bookkeeping and Recursive Predicates

```
predicate list(xs: Ref) {
  acc(xs.next) && (xs.next != null ==> list(xs.next))
}
```

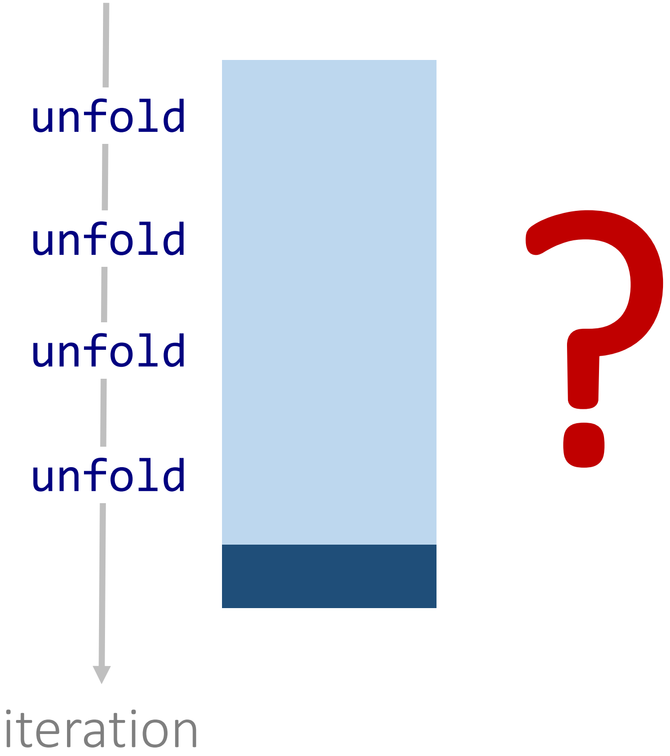
```
method it(xs: Ref)
  requires list(xs)
  ensures list(xs)
{
  var cur := xs
  while (*)

  {
    unfold list(cur)
    cur := cur.next
  }

}
```



Permission Bookkeeping and Recursive Predicates

```
predicate list(xs: Ref) {
  acc(xs.next) && (xs.next != null ==> list(xs.next))
}
```

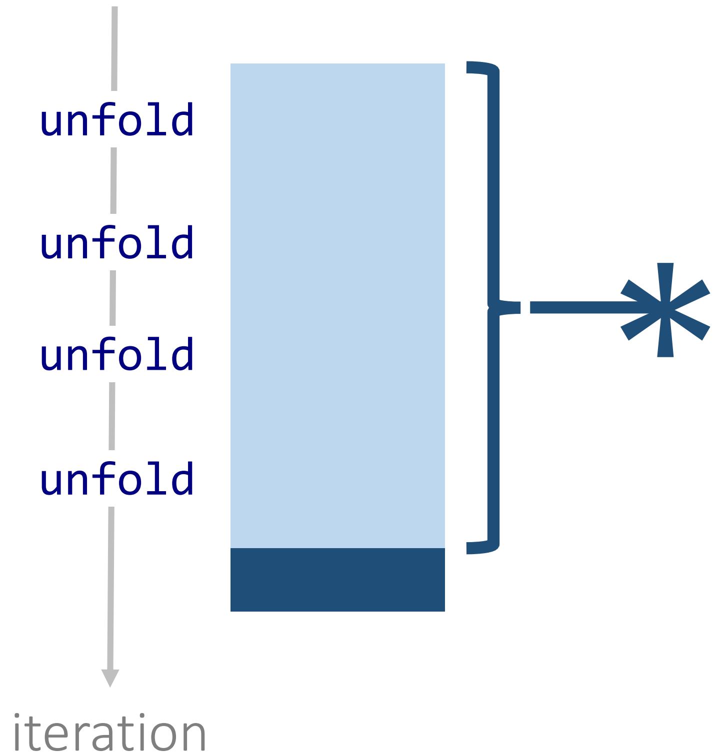
```
method it(xs: Ref)
  requires list(xs)
  ensures list(xs)
{
  var cur := xs
  while (*)
    inv ???
  {
    unfold list(xs)
    cur := cur.next
  }
  ???
}
```



Permission Bookkeeping and Recursive Predicates

```
predicate list(xs: Ref) {
  acc(xs.next) && (xs.next != null ==> list(xs.next))
}
```

```
method it(xs: Ref)
  requires list(xs)
  ensures list(xs)
{
  var cur := xs
  while (*)
    inv list(cur) --* list(xs)
  {
    unfold list(xs)
    cur := cur.next
    // Update wand
  }
  // Get list(xs) from wand
}
```



Magic Wands in Silver

Specifying *partial data structures* is just one application

We support arbitrary* wands

Main contribution: *automatic footprint computation*

- Recall $A * (A \mathrel{-\!\!*} B) \models B$
- Footprint = permission delta between A and B

Examples

– true $\mathrel{-\!\!*}$ acc(x.f)	acc(x.f)
– acc(x.f) $\mathrel{-\!\!*}$ acc(x.f)	emp
– acc(x.f, 1/3) $\mathrel{-\!\!*}$ acc(x.f, 1/1)	acc(x.f, 2/3)
– acc(x.f) $\mathrel{-\!\!*}$ acc(y.f)	x != y ==> acc(y.f)

Demo

http://bitbucket.org/viperproject/