Automated Software Verification with Implicit Dynamic Frames

Malte Schwerhoff, ETH Zürich/KU Leuven

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A long time ago, in a galaxy far, far away …

Outline

1. Implicit Dynamic Frames
2. Our Tool Chain
3. Supporting Magic Wands

Heap-Dependent Expressions

- SL: Points-to relations and logical variables

```
requires x.f |-> ?v &*& v > 0
```

- IDF: Access predicates and heap access

```
requires acc(x.f) && x.f > 0
```

- IDF-Assertions must be *self-framing*, i.e., only talk about locations to which access is requested

```
requires acc(x.f) && x.f > 0  ✓ self-framing
requires x.f > 0              ✗ not self-framing
requires x.f > 0 && acc(x.f)  ✗ neither (technical reason)
```

(SL-assertions are self-framing by design)

Example

Separation Logic

```
method inc(c: Cell)
  requires c.f |-> ?v &*& v > 0
  ensures  c.f |-> v + 1
{ c.f = c.f + 1 }
```

Implicit Dynamic Frames

```
method inc(c: Cell)
  requires acc(c.f) && c.f > 0
  ensures  acc(c.f) && c.f == old(c.f) + 1
 { c.f = c.f + 1 }
```

`old(`*e*`)` evaluates to the value *e* had in the pre-heap of the method call

SL: Abstract Predicates

```
predicate Cell(c: Cell; v: Int) { c.f |-> v}

method inc(c: Cell)
  requires Cell(c, ?v) &*& v > 0
  ensures  Cell(c, v + 1)
{
  open Cell(c, v)
  c.f = c.f + 1
  close Cell(c, v + 1)
}
```

- *Ghost statements* `open/close` guide the verifier; erased at runtime
- Opening a predicate instance means *consuming* the instance and *producing* its body (closing is the inverse operation)

IDF: Abstract Predicates and Pure Functions

```
predicate Cell(c: Cell) { acc(c.f) }

function get(c: Cell): Int
  requires acc(Cell(c))
{ unfolding Cell(c) in c.f }

method inc(c: Cell)
  requires acc(Cell(c)) && get(c) > 0
  ensures  acc(Cell(c) && get(c) == old(get(c)) + 1
{
  unfold Cell(c)
  c.f = c.f + 1
  fold Cell(c)
}
```

Ghost expression `unfolding` *P* `in` *e* makes the body of *P* temporarily available

Predicates and Functions

- SL: Predicates have *in-* and *out-parameters;* out-parameters are uniquely determined by the in-parameters and the predicate body

Separation Logic

```
predicate Cell(c: Cell; v: Int) = c.f |-> v
```

- IDF: Predicates have in-parameters, functions replace the out-parameters

Implicit Dynamic Frames

```
predicate Cell(c: Cell) { acc(c.f) }

function get(c: Cell): Int
  requires acc(Cell(c))
{ unfolding Cell(c) in c.f }
```

Predicates and Functions

Implicit Dynamic Frames

```
predicate Node(n: Node) {
  acc(n.val) && acc(n.nxt) && (n.nxt != null ==> acc(Node(n.nxt)))
}

function length(n: Node): Int
  requires acc(Node(n))
{ unfolding Node(n) in 1 + (n.nxt == null ? 0 : length(n.nxt)) }

function elems(n: Node): Seq[Int]
  requires acc(Node(n))
{ unfolding Node(n) in n.val :: (n.nxt == null ? Nil : elems(n.nxt)) }
```

- SL: `length` and `elems` could be out-parameters
    - Adding additional out-parameters later on potentially entails lots of code changes
    - Adding new functions in subclasses feels "natural"

- IDF: Separate heap shape description from abstractions

Functions

- IDF: Functions can be used in code, too!

Implicit Dynamic Frames

```
if (length(node) > 2) ...
```

- SL: Predicate arguments **and** methods are needed

Separation Logic

```
predicate Cell(c: Cell; v: Int) { c.f |-> v}

method length(c: Cell): Int
  requires Cell(c, ?v)
  ensures  result == v
{
  open Cell(c, v)
  return c.f
  close Cell(c, v)
}
```

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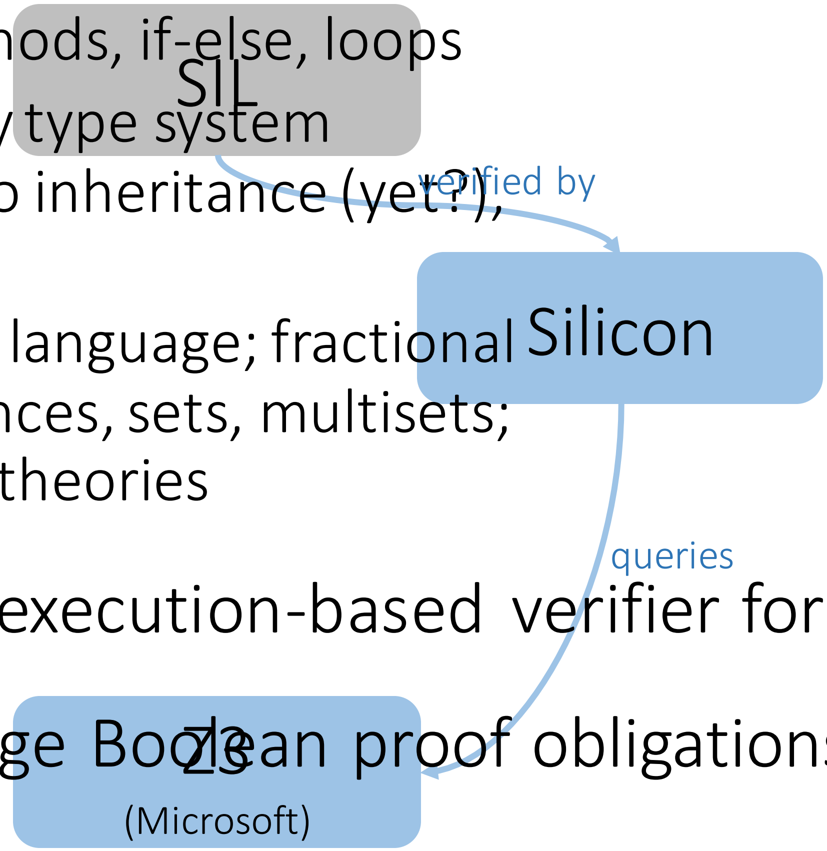
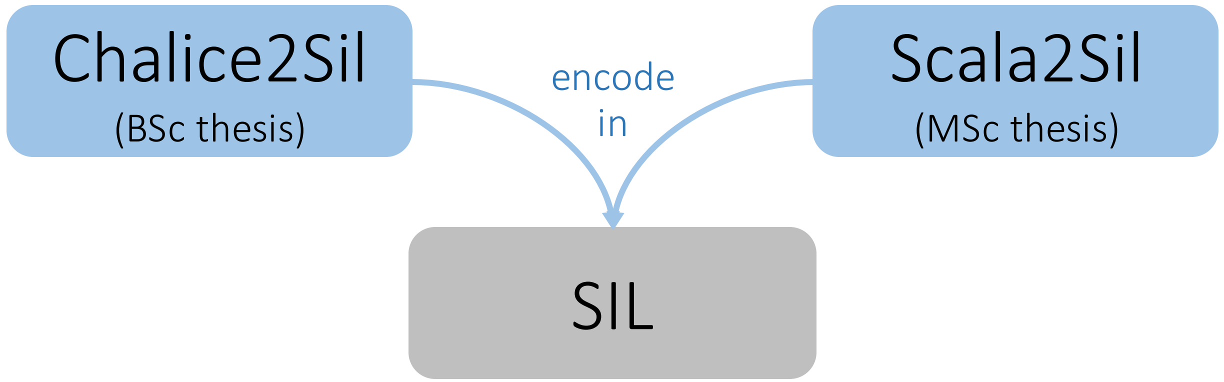
SIL and Silicon

- SIL is an *intermediate verification language;* programs with specifications can be encoded in SIL
  - Objects, fields, methods, if-else, loops
  - Simple: rudimentary type system (primitives + Ref), no inheritance (yet?), no concurrency
  - IDF-based assertion language; fractional permissions; sequences, sets, multisets; quantifiers; custom theories
- Silicon is a symbolic-execution-based verifier for SIL
- Z3 is used to discharge Boolean proof obligations



Encoding in SIL



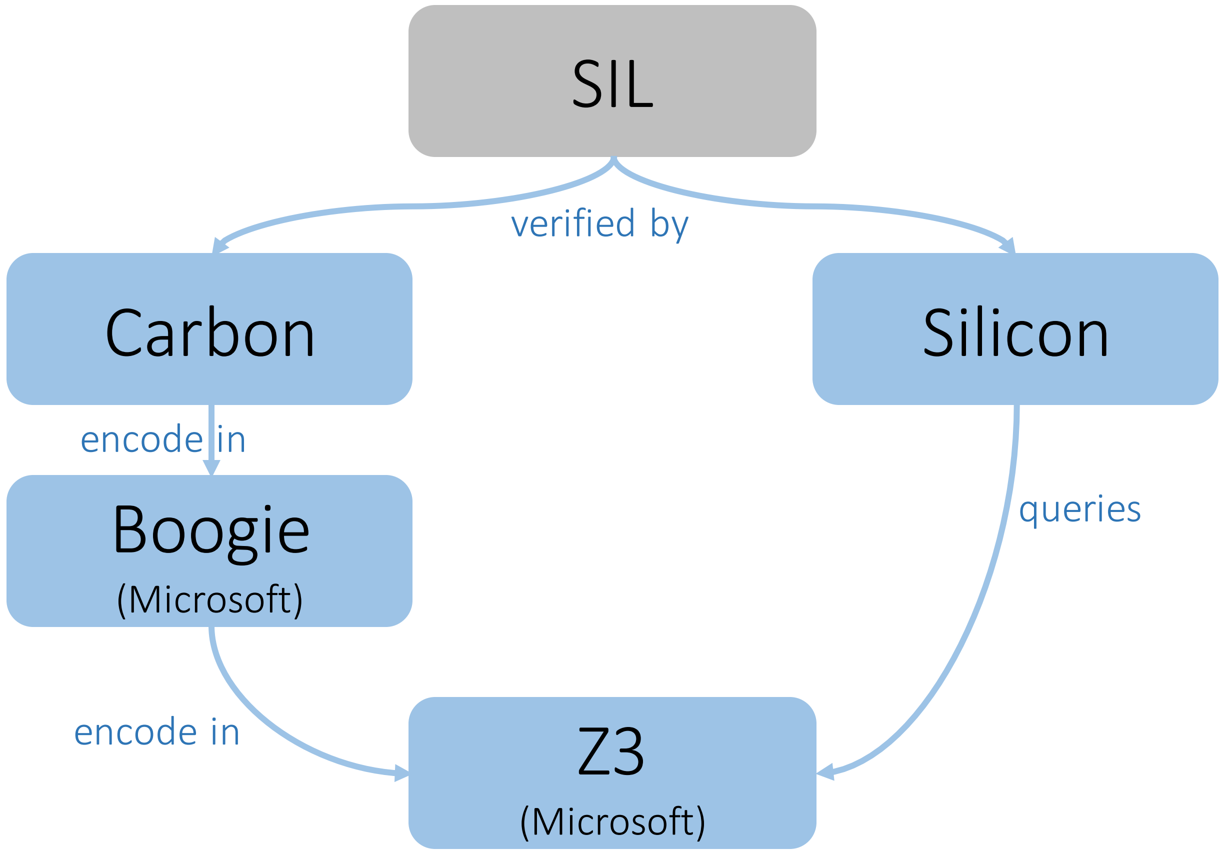
Chalice is a research language for concurrency

- Objects, fields, loops, ...
- Fork-join concurrency
- Communication via channels (message passing)
- Locking with lock invariants
- Deadlock-avoidance

Scala is a OO+FP hybrid language for the JVM

- ... with crazily many features
- Only translated basics, including
  - `val x = e` (≈ final fields in Java)
  - `lazy val x = e` (evaluated on first read)

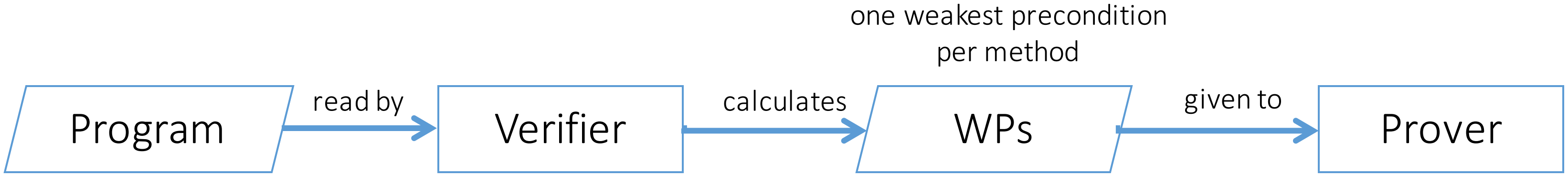
Verification of SIL code



Verification Condition Generation

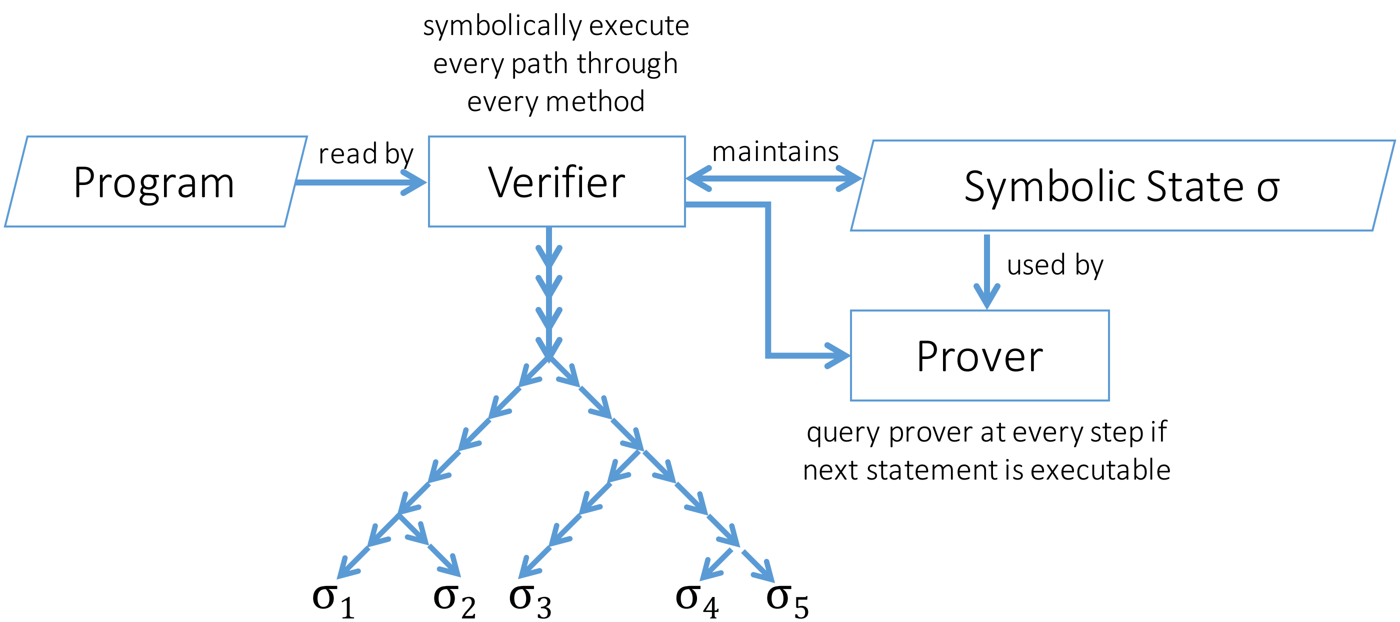
Symbolic Execution

Short deviation: VCG vs SE



Query prover once with full information (VeriCool)

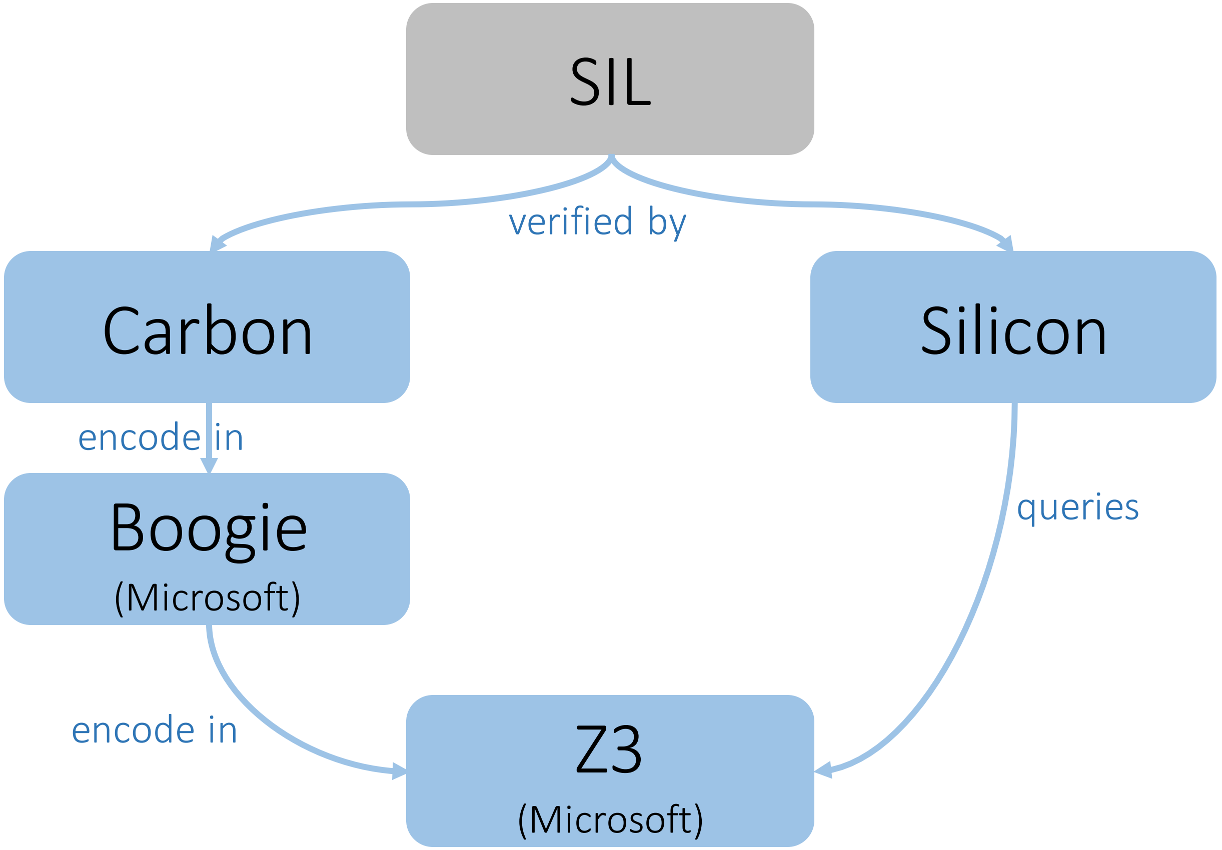
VCG



Query prover often with limited information (VeriFast)

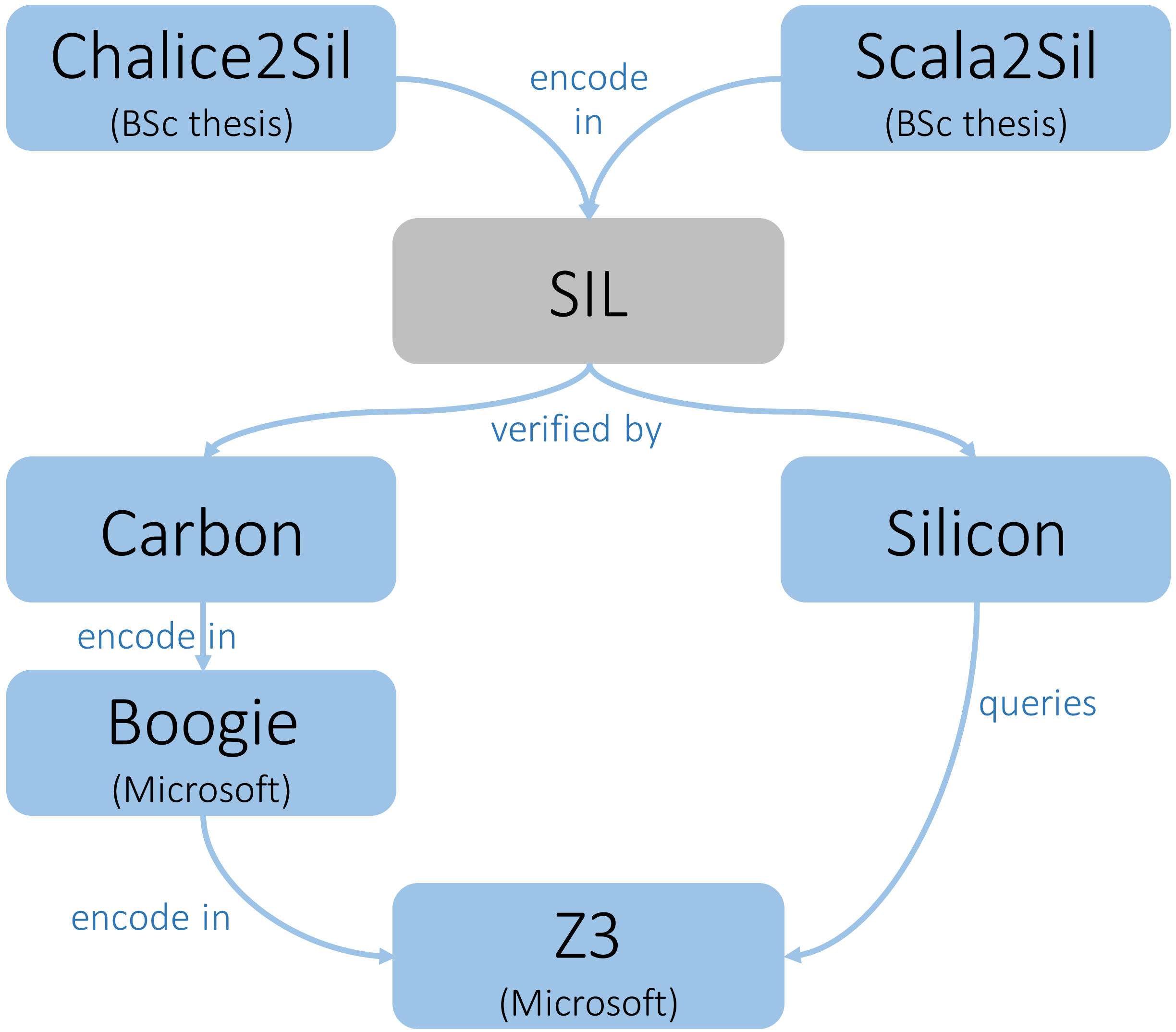
SE

Verification of SIL code



Parallel approach allows experimenting with new features and encodings; it helps uncovering weaknesses or performance problems

Overview



Chalice2Sil
(BSc thesis)
encode
in
Scala2Sil
(BSc thesis)
SIL
verified by
Carbon
Silicon
encode in
Boogie
(Microsoft)
queries
encode in
Z3
(Microsoft)

Outline

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   (joint work with Alexander J. Summers)

Magic Wands

- Boolean implication $\mathrm{A} \Rightarrow \mathrm{B}$
  "If A holds in the current state, then B also holds"

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

- Separating implication: $\mathrm{A} -\!\!* \mathrm{B}$
  "If A is added to the current state, then B also holds"

  (Kind of) Modus Ponens: $\mathrm{A} * (\mathrm{A} -\!\!* \mathrm{B}) \vDash \mathrm{B}$

- $\mathrm{A} -\!\!* \mathrm{B}$ Can be read as an exchange promise
  "If A is given up, then B is guaranteed to hold"

Magic Wands, Anyone?

- Semantics of the Wand:

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

- Quantification over states, hence typically not supported in automated verifiers

- Used in proofs by hand, for example, when verifying linked lists with views (generalised iterators)

- The promise-interpretation lends itself to specifying partial data structures, for example,

  "Give up a list segment and you'll get back the whole linked list"

Iterating Over Recursively-Defined Data Structures

```
var val: Int
var next: Ref

predicate List(ys: Ref) {
  acc(ys.val) && acc(ys.next) && (ys.next != null ==> acc(List(ys.next)))
}

function sum_rec(ys: Ref): Int
  requires acc(List(ys))
{
  unfolding List(ys) in ys.val + (ys.next == null ? 0 : sum_rec(ys.next))
}

method sum_it(ys: Ref) returns (sum: Int)
  /* Iteratively compute the sum of the linked list s.t.
   * the result equals sum_rec(ys)
   */
```

Iterating Over Recursively-Defined Data Structures

```
method sum_it(ys: Ref) returns (sum: Int)
  requires ys != null && acc(List(ys))
  ensures acc(List(ys)) && sum == old(sum_rec(ys))
{
  var xs: Ref := ys   /* Pointer to the current node in the list */
  sum := 0            /* Sum computed so far */

  while (xs != null)
    invariant xs != null ==> acc(List(xs))
    invariant sum == old(sum_rec(ys)) - (xs == null ? 0 : sum_rec(xs))
  {
    var zs: Ref := xs
    unfold List(xs)
    sum := sum + xs.val
    xs := xs.next
    /* ??? */
  }
}
```

How to bookkeep permissions to the “list seen so far”?

—*

Our Solution

```
var xs: Ref := ys    /* Pointer to the current node in the list */
sum := 0             /* Sum computed so far */

/* Short-hands to keep the specifications concise */
define A xs != null ==> acc(List(xs))
define B acc(List(ys))
```

Here, $A \mathrel{-\!\!*} B$ reflects the promise

> "If you give up the current tail of the list (`xs`), then you'll get back the whole list (`ys`)"

Our Solution

```
define A xs != null ==> acc(List(xs))
define B acc(List(ys))

package A --* B

while (xs != null)
  invariant (xs != null ==> acc(List(xs))) && A --* B
  invariant sum == old(sum_rec(ys)) - (xs == null ? 0 : sum_rec(xs))
{
  wand w := A --* B /* Give magic wand instance the name w */

  var zs: Ref := xs
  unfold List(xs)
  sum := sum + xs.val
  xs := xs.next

  package A --* folding List(zs) in applying w in B
}

apply A --* B
```

Our Solution

```
define A xs != null ==> acc(List(xs))
define B acc(List(ys))

package A --* B
```

Establish wand

```
while (xs != null)
  invariant (xs != null ==> acc(List(xs))) && A --* B
  invariant sum == old(sum_rec(ys)) - (xs == null ? 0 : sum_rec(xs))
{
  wand w := A --* B /* Give magic wand instance the name w */

  var zs: Ref := xs
  unfold List(xs)
  sum := sum + xs.val
  xs := xs.next

  package A --* folding List(zs) in applying w in B
}

apply A --* B
```

Our Solution

```
define A xs != null ==> acc(List(xs))
define B acc(List(ys))

package A --* B

while (xs != null)
  invariant (xs != null ==> acc(List(xs))) && A --* B
  invariant sum == old(sum_rec(ys)) - (xs == null ? 0 : sum_rec(xs))
{
  wand w := A --* B /* Give magic wand instance the name w */

  var zs: Ref := xs
  unfold List(xs)
  sum := sum + xs.val
  xs := xs.next

  package A --* folding List(zs) in applying w in B
}

apply A --* B
```

Carry wand

Our Solution

```
define A xs != null ==> acc(List(xs))
define B acc(List(ys))

package A --* B

while (xs != null)
  invariant (xs != null ==> acc(List(xs))) && A --* B
  invariant sum == old(sum_rec(ys)) - (xs == null ? 0 : sum_rec(xs))
{
  wand w := A --* B /* Give magic wand instance the name w */

  var zs: Ref := xs
  unfold List(xs)
  sum := sum + xs.val
  xs := xs.next

  package A --* folding List(zs) in applying w in B
```

Update wand

```
apply A --* B
```

Our Solution

```
define A xs != null ==> acc(List(xs))
define B acc(List(ys))

package A --* B

while (xs != null)
  invariant (xs != null ==> acc(List(xs))) && A --* B
  invariant sum == old(sum_rec(ys)) - (xs == null ? 0 : sum_rec(xs))
{
  wand w := A --* B /* Give magic wand instance the name w */

  var zs: Ref := xs
  unfold List(xs)
  sum := sum + xs.val
  xs := xs.next

  package A --* folding List(zs) in applying w in B
}
```

```
apply A --* B
```

Use wand

Lifecycle

- Lifecycle of wand and predicate instances are similar
  - Created (packaged/folded)
  - Passed around (loop invariants, postconditions)
  - Destroyed (applied/unfolded)
- Unfolding a predicate gives assumptions about the heap
- Sound, because the permissions that *frame* these assumptions are consumed when the predicate is folded (and the assumptions are checked)
- These permissions are the *footprint* of a predicate
- What is the footprint of a wand?

Footprints

- 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(x.g) | acc(x.g)
- The footprint of $A \mathrel{-\!\!*} B$ is the delta between A and B
- Consumed when $A \mathrel{-\!\!*} B$ is packaged and *produced* when $A \mathrel{-\!\!*} B$ is applied

Footprints and Assumptions

- Examples
  - σ: acc(x.f) && x.f = 1
    package true $-\!\!*$ acc(x.f) && x.f = 1 ✓
  - σ: acc(x.f) && x.f = 1
    package acc(x.f) $-\!\!*$ acc(x.f) && x.f = 1 ✗
  - σ: acc(x.f) && x.f = 1 && acc(x.g) && x.g = 2
    package acc(x.f) && x.f =2
    $-\!\!*$ acc(x.f) && acc(x.g) && x.f = x.g ✓
- When checking assumptions of the RHS, use the assumptions from the LHS, and those of the current state if framed by the footprint
- Claim: sound, regardless of the computed footprint

Footprints and Assumptions

- Circularity problem
  - Footprint is determined by permissions requested by the RHS (and not provided by the LHS)
  - Permissions might be conditionally requested (if-then-else)
  - Guards of these conditionals might be determined by the current heap
  - Assumptions about the current heap can only be used if framed by the footprint
  - ... which we currently try to compute :-(

Our Solution

- Compute footprint in parallel with checking the RHS
  - Setup
    - Let $\boldsymbol{\sigma}_{\mathrm{curr}}$ be the current heap
    - Let $\boldsymbol{\sigma}_{\mathrm{foot}}$ be the initially empty footprint state
    - Produce the LHS into $\mathbf{emp}$ to get $\boldsymbol{\sigma}_{\mathrm{lhs}}$
  - Algorithm
    - Consume permissions requested by the RHS from $\boldsymbol{\sigma}_{\mathrm{lhs}}$, and **only** from $\boldsymbol{\sigma}_{\mathrm{curr}}$ if $\boldsymbol{\sigma}_{\mathrm{lhs}}$ does not provide sufficient permissions
    - If taken from $\boldsymbol{\sigma}_{\mathrm{curr}}$, move effected permissions (and move/copy assumptions) into $\boldsymbol{\sigma}_{\mathrm{foot}}$
    - Check assumptions made by the RHS in the combination of $\boldsymbol{\sigma}_{\mathrm{lhs}}$ and $\boldsymbol{\sigma}_{\mathrm{foot}}$

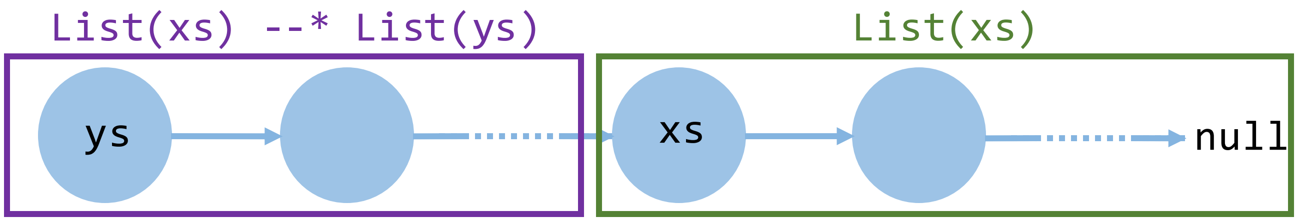
Back to the Code

```
define A xs != null ==> acc(List(xs))
define B acc(List(ys))

package A --* B

while (xs != null)
  invariant (xs != null ==> acc(List(xs))) && A --* B
  invariant sum == old(sum_rec(ys)) - (xs == null ? 0 : sum_rec(xs))
{
  wand w := A --* B /* Give magic wand instance the name w */

  var zs: Ref := xs
  unfold List(xs)
  sum := sum + xs.val
  xs := xs.next

  package A --* folding List(zs) in applying w in B
```

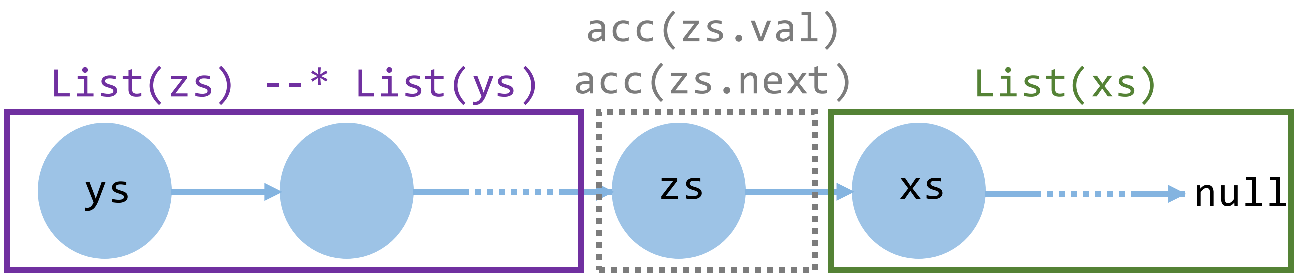
Update wand

```
apply A --* B
```

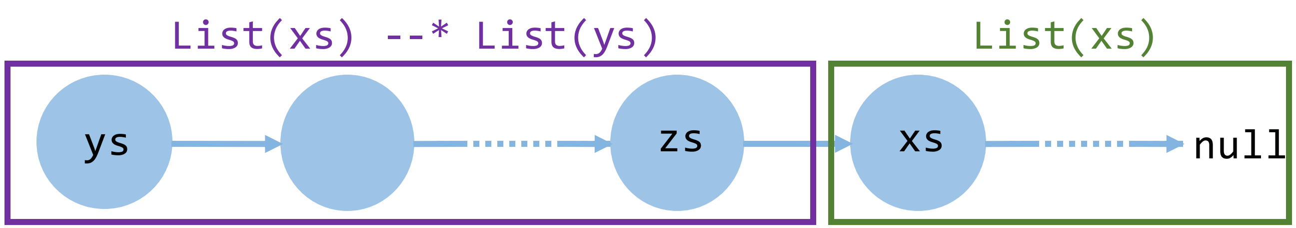
Packaging Wands with Ghost Operations



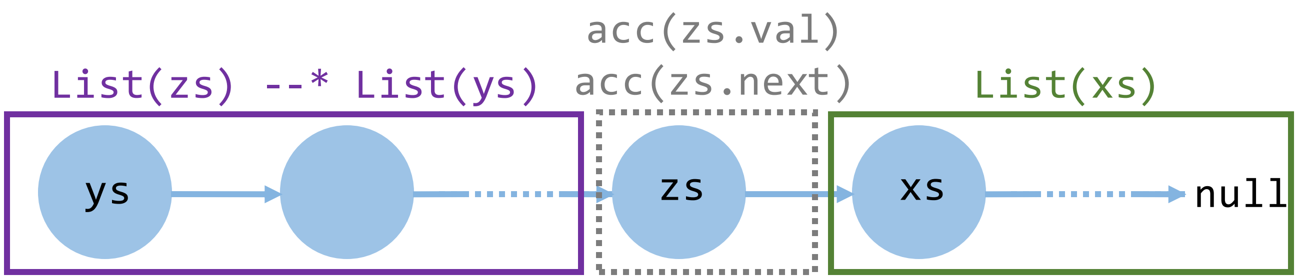

```
var zs := xs;  unfold List(xs);  xs := xs.next
```




```
package List(xs) --*

                    List(ys)
```



Packaging Wands with Ghost Operations




```
package List(xs) --* folding List(zs) in
                     applying List(zs) --* List(ys) in
                     List(ys)
```

- Interaction with the footprint: delta between permissions produced/consumed by ghost operations
- Prover hints only, created wand instance is **`List(xs) --* List(ys)`**
- Nicely blend into SIL, which has **`unfolding`** already

Code (Last Time, I Promise)

```
define A xs != null ==> acc(List(xs))
define B acc(List(ys))

package A --* B

while (xs != null)
  invariant (xs != null ==> acc(List(xs))) && A --* B
  invariant sum == old(sum_rec(ys)) - (xs == null ? 0 : sum_rec(xs))
{
  wand w := A --* B /* Give magic wand instance the name w */

  var zs: Ref := xs
  unfold List(xs)
  sum := sum + xs.val
  xs := xs.next

  package A --* folding List(zs) in applying w in B
}

apply A --* B
```

Conclusion

- Implicit Dynamic Frames
  - Allows for (relatively) nice specifications
  - Simplifies contrasting VCG and SE
- Intermediate Verification Language SIL
  - Potential to encode other languages into it looks promising
  - VCG and SE backends facilitate experiments
- Magic Wands
  - Useful for specifying partial data structures
  - Lightweight support that nicely integrates into IDF

Future Work

- Tool Chain
  - Polish it (documentation, IDE, debugger)
  - Release it (and merge various branches)
  - Continue Scala2Sil
- Magic Wands
  - Demonstrate other applications
  - More examples
  - Support in VCG?

Questions?

malte.schwerhoff@inf.ethz.ch
http://www.pm.inf.ethz.ch/