Program Verification via an Intermediate Verification Language

K. Rustan M. Leino

Principal Researcher
Research in Software Engineering (RiSE), Microsoft Research, Redmond

Visiting Professor
Department of Computing, Imperial College London

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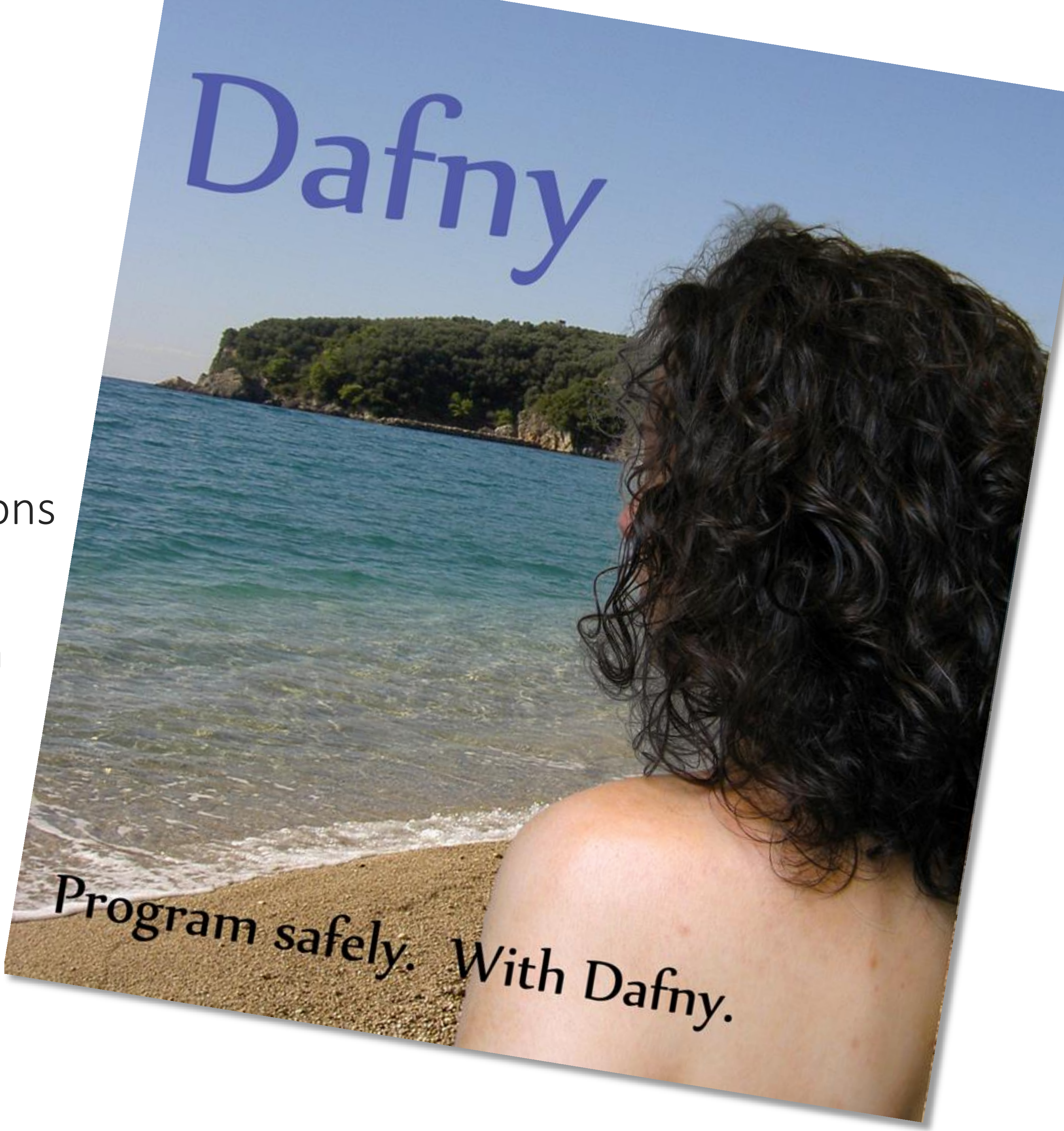
Static program verification

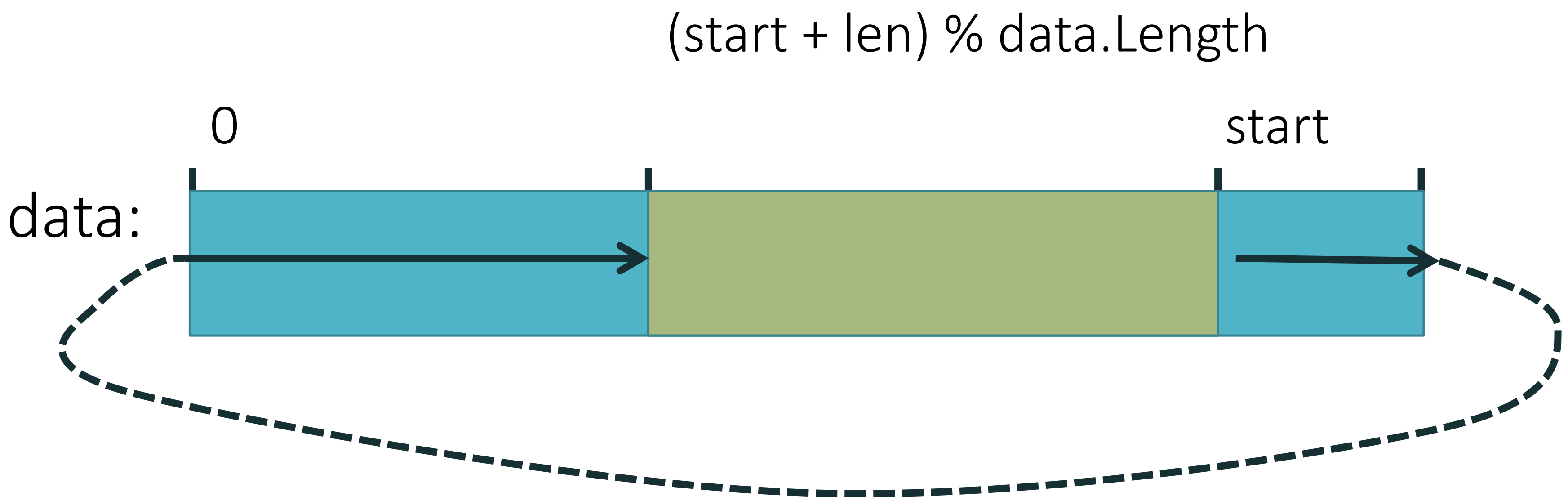
What is the state-of-art in program verifiers?

How to build a program verifier

Dafny

- Put reasoning about programs *first*
- Language aimed at reasoning
  - Constructs for recording design decisions
- Tool support
  - Static program verifier enforces design decisions
- Integrated development environment
  - Tools help in reasoning process
  - Verification is not an afterthought



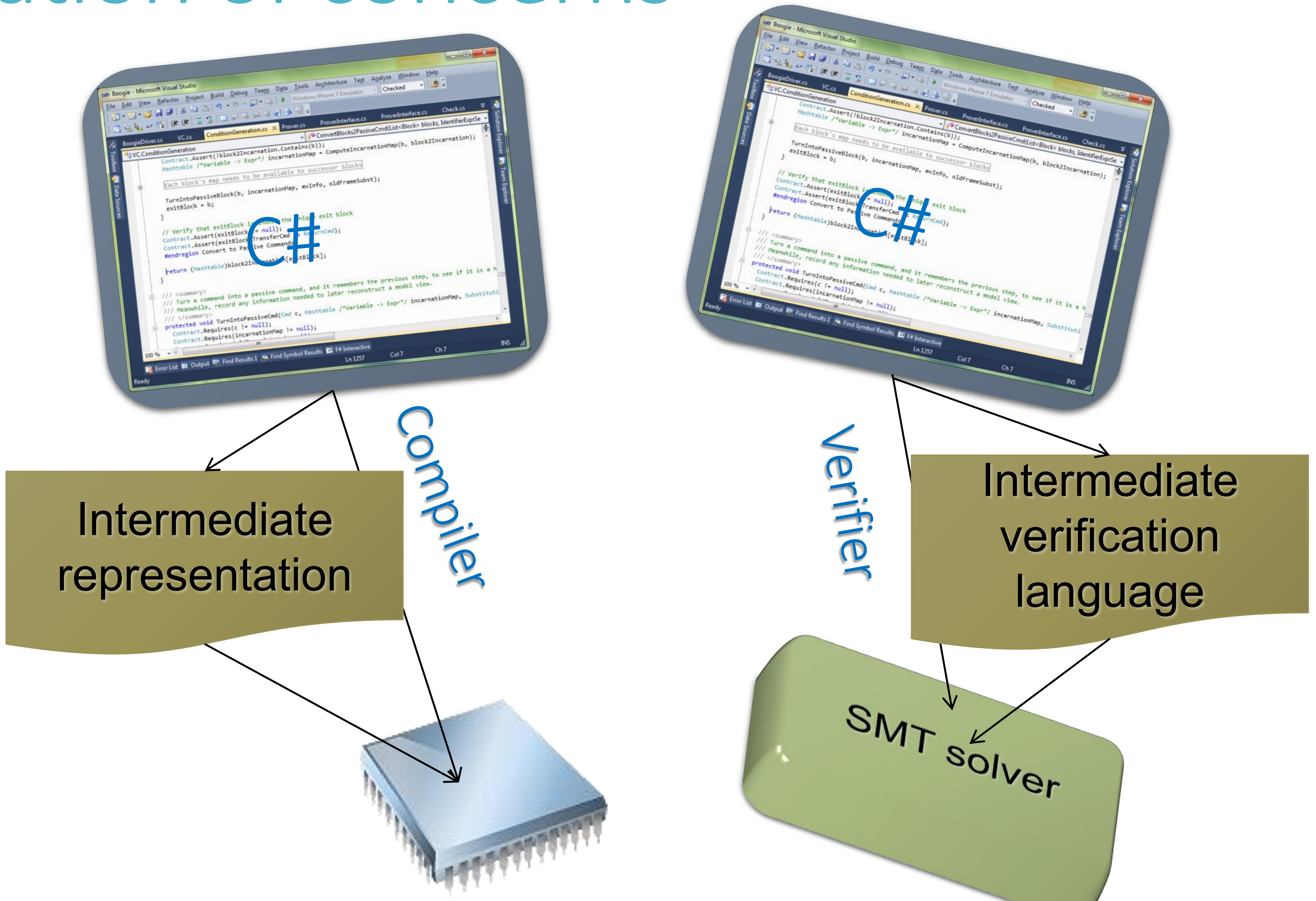


Enqueue at (start + len) % data.Length
Dequeue at start

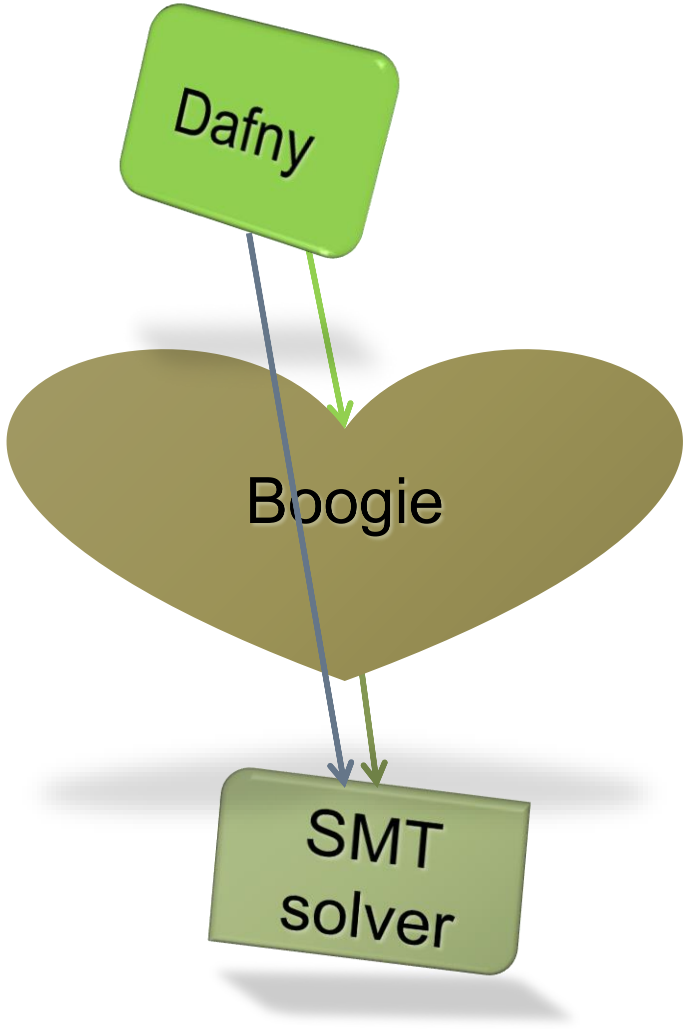
Demo

Queue implemented by a ring buffer

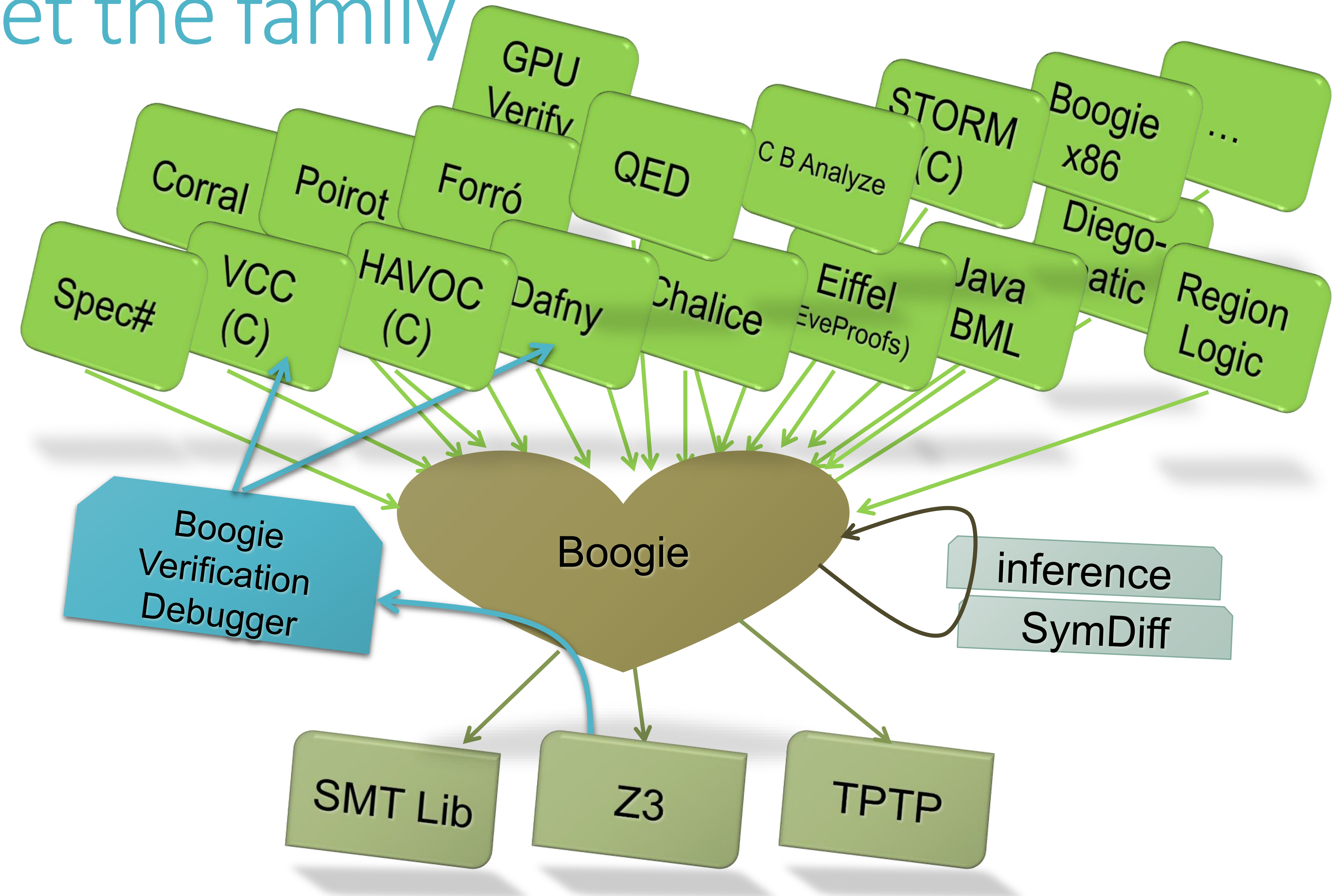
Separation of concerns



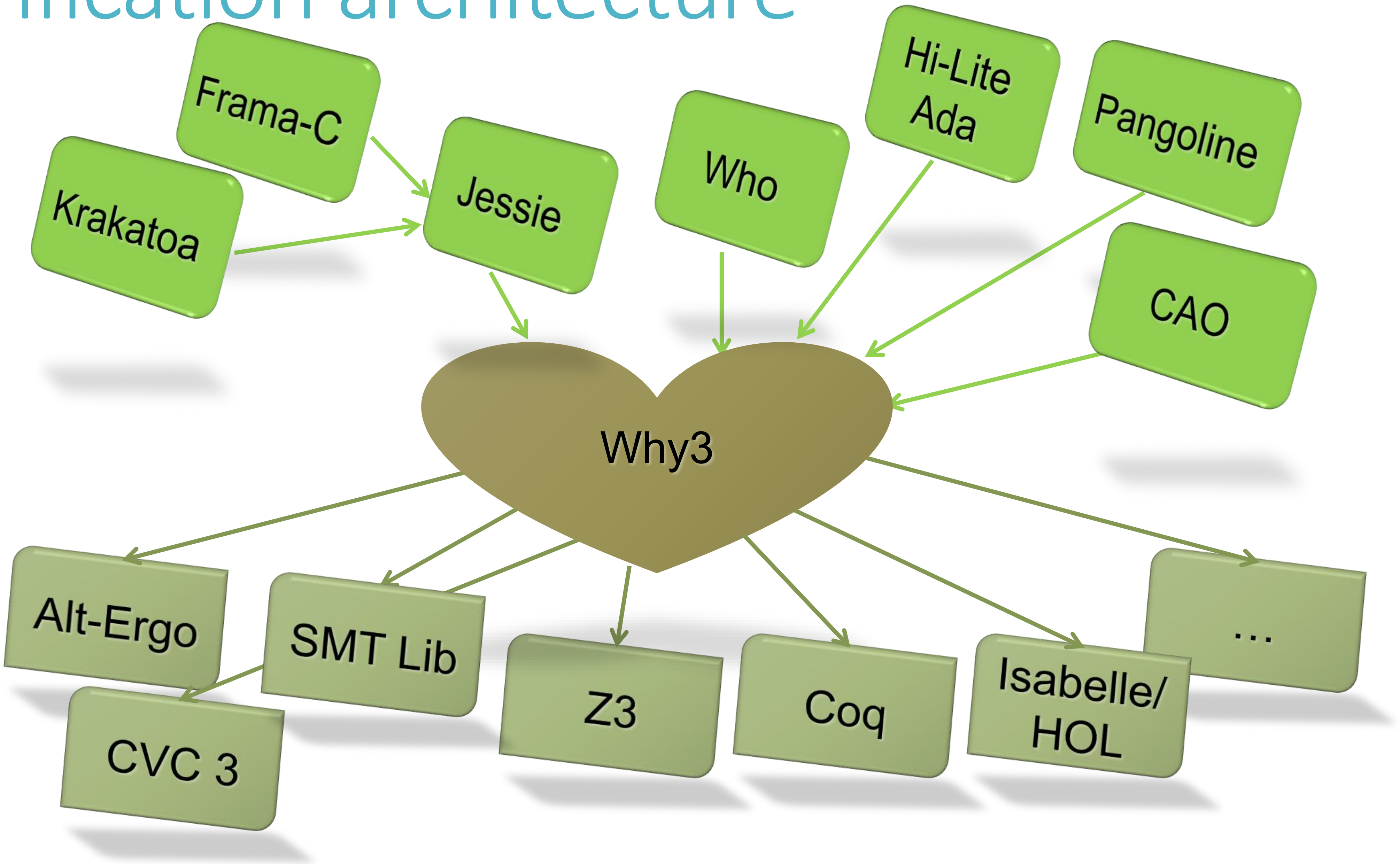
Verification architecture



Meet the family



Verification architecture



Boogie language overview

Mathematical features

```
type T
const x…
function f…
axiom E
```

Imperative features

```
var y…
procedure P… …spec…
implementation P… { …body… }
```

Statement outcomes

Terminate

Go wrong

Block

Diverge

Boogie statements

`x := E`

Evaluate `E` and change `x` to that value

`a[i] := E`

Same as `a := a[i := E]`

`havoc x`

Change `x` to an arbitrary value

`assert E`

If `E` holds, terminate; otherwise, go wrong

`assume E`

If `E` holds, terminate; otherwise, block

`call P()`

Act according to specification of `P`

```
if
while
break
label:
goto A, B
```

Translation basics

Ada

```
x : Integer;

procedure Update
   (y : Integer;
    r : out Integer) is
begin
  if x < y then
    x := y;
  end if;
  r := y;
end Update;

procedure Main is
begin
  Update(5, x);
end Main;
```

Boogie

```
var x: int;

procedure Update(y: int)
      returns (r: int)
  modifies x;
{
  if (x < y) {
    x := y;
  }
  r := y;
}

procedure Main()
  modifies x;
{
  call x := Update(5);
}
```

Unstructured control flow

.NET bytecode (MSIL)

```
.maxstack  2
.locals init ([0] int32 i,
              [1] bool CS$4$0000)
IL_0000:  nop
IL_0001:  ldc.i4.0
IL_0002:  stloc.0
IL_0003:  br.s      IL_000b
IL_0005:  nop
IL_0006:  ldloc.0
IL_0007:  ldc.i4.1
IL_0008:  add
IL_0009:  stloc.0
IL_000a:  nop
IL_000b:  ldloc.0
IL_000c:  ldarg.0
IL_000d:  clt
IL_000f:  stloc.1
IL_0010:  ldloc.1
IL_0011:  brtrue.s  IL_0005
IL_0013:  ret
```

Boogie

```
var i: int, CS$4$000: bool;
var $stack0i, $stack1i: int,
    $stack0b: bool;
IL_0000:
  $stack0i := 0;
  i := 0;
  goto IL_000b;
IL_0005:
  $stack1i := i;
  $stack0i := $stack0i + $stack1i;
  i := $stack0i;
IL_000b:
  $stack0i := i;
  $stack1i := n;
  $stack0b := $stack0i < $stack1i;
  CS$4$000 := $stack0b;
  $stack0b := CS$4$000;
  if ($stack0b) { goto IL_0005; }
IL_0013:
  return;
```

Reasoning about loops

Java + JML

```
//@ requires 0 <= n;
void m(int n)
{
  int i = 0;
  //@ loop_invariant i <= n;
  while (i < n) {
    i++;
  }
  //@ assert i == n;
}
```

Boogie

```
procedure m(n: int)
  requires 0 <= n;
{
  var i: int;
  i := 0;
  while (i < n)
    invariant i <= n;
  {
    i := i + 1;
  }
  assert i == n;
}
```

Custom operators: underspecification

C++

```cpp
void P() {
  int x;
  x = y << z;
  x = y + z;
}
```

Boogie

```
const Two^31: int;
axiom Two^31 == 2147483648;

function LeftShift(int, int): int;
axiom (forall a: int ::
  LeftShift(a, 0) == a);

function Add(int, int): int;
axiom (forall a, b: int ::
  -Two^31 <= a+b && a+b < Two^31
  ==>
  Add(a,b) == a+b);

procedure P() {
  var x: int;
  x := LeftShift(y, z);
  x := Add(y, z);
}
```

Definedness of expressions

F#

```
let x = y + z in
let w = y / z in
// ...
```

Boogie

```
// check for underflow:
assert -Two^31 <= y+z;
// check for overflow:
assert y+z < Two^31;
x := y + z;

// check division by zero:
assert z != 0;
w := Div(y, z);
```

Uninitialized variables

Pascal

```
var r: integer;
if B then
  r := z;
(* ... *)
if C then begin
  d := r
end
```

Boogie

```
var r: int;
var r$defined: bool;

if (B) {
  r, r$defined :=
     z, true;
}
// ...
if (C) {
  assert r$defined;
  d := r;
}
```

Loop termination

Eiffel

```
from
   Init
until
   B
invariant
   Inv
variant
   VF
loop
   Body
end
```

Boogie

```
Init;
while (!B)
   invariant Inv;
   // check boundedness:
   invariant 0 <= VF;
{
   tmp := VF;
   Body;
   // check decrement:
   assert VF < tmp;
}
```

Modeling memory

C#

```
class C {
  C next;
  void M(C c)
  {
    C x = next;
    c.next = c;
  }
}
```

Boogie

```
type Ref;
const null: Ref;

type Field;
const unique C.next: Field;

var Heap: [Ref,Field]Ref;
        // Ref * Field --> Ref

procedure C.M(this: Ref, c: Ref)
  requires this != null;
  modifies Heap;
{
  var x: Ref;

  assert this != null;
  x := Heap[this, C.next];

  assert c != null;
  Heap[c, C.next] := y;
}
```

More about memory models

Encoding a good memory model requires more effort

Boogie provides many useful features

- Polymorphic map types
- Partial commands (`assume` statements)
- Free pre- and postconditions
- `where` clauses

Demo

RingBuffer translated

Verification-condition generation

0. passive features: assert, assume, ;
1. control flow: goto (no loops)
2. state changes: :=, havoc
3. loops

Weakest preconditions

The *weakest precondition* of a statement S with respect to a predicate Q on the post-state of S, denoted wp(S,Q), is the set of pre-states from which execution:

does not go wrong, and

if it terminates, terminates in Q

VC generation: passive features

wp(assert E, Q) =

$E \wedge Q$

wp(assume E, Q) =

$E \Rightarrow Q$

wp(S; T, Q) =

wp(S, wp(T, Q))

VC generation: acyclic control flow

For each block A, introduce a variable A_{ok} with the meaning: A_{ok} is true iff every program execution starting in the current state from block A does not go wrong

The verification condition for the program:

A: S; goto B or C

…

is:

$$(A_{ok} \equiv wp(S, B_{ok} \wedge C_{ok})) \wedge$$

…

$$\Rightarrow$$

$$A_{ok}$$

VC generation: state changes

Replace definitions and uses of variables by definitions and uses of different *incarnations* of the variables

{x→x0, y→y0} x := E(x,y)
x1 := E(x0,y0) {x→x1, y→y0}

{x→x0, y→y0} havoc x
skip {x→x1, y→y0}

VC generation: state changes (cont.)

Given:

{x→x0 ,y→y0} S S' {x→x1, y→y0}

{x→x0, y→y0} T T' {x→x2, y→y0}

then we have:

{x→x0, y→y0} if E(x,y) then S else T end

```
if E(x0,y0) then
        S' ;  x3 := x1
else
        T' ;  x3 := x2
end
```

{x→x3, y→y0}

VC generation: state changes (cont.)

Replace every assignment

    x := E

with

    assume x = E

VC generation: loops

loop head:

assert LoopInv(x) ;

after loop:

assume ¬Guard(x) ;

loop body:

assume Guard(x) ;

x := …

VC generation: loops

assert P
=
assert P ; assume P

loop head:

assert LoopInv(x) ;
assume LoopInv(x);

after loop:

assume ¬Guard(x) ;

loop body:

assume Guard(x) ;
x := ...

VC generation: loops

```
assert LoopInv( x ) ;
```

loop head:

```
assert LoopInv( x ) ;
assume LoopInv( x );
```

after loop:

```
assume ¬Guard( x ) ;
```

loop body:

```
assume Guard( x ) ;
x := …
assert LoopInv( x ) ;
```

VC generation: loops

assert LoopInv(x) ;

loop head:

havoc x ;

assume LoopInv(x);

loop target

after loop:

assume ¬Guard(x) ;

loop body:

assume Guard(x) ;

x := …

assert LoopInv(x);

VC generation: loops

assert LoopInv(x) ;

loop head:

havoc x ;
assume LoopInv(x);

after loop:

assume ¬Guard(x) ;

loop body:

assume Guard(x) ;
x := …
assert LoopInv(x);
assume false;

Demo

/traceverify

Take-home messages

To build a verifier, use an intermediate verification language (IVL)

- An IVL is a thinking tool
- An IVL helps you separate concerns
- IVL lets you reuse and share infrastructure

Try Dafny and Boogie in your browser at rise4fun.com

Watch Verification Corner on YouTube

Verification Corner