(star) (no star)

Chalice to Boogie

Program Verification for Object-Oriented Programs

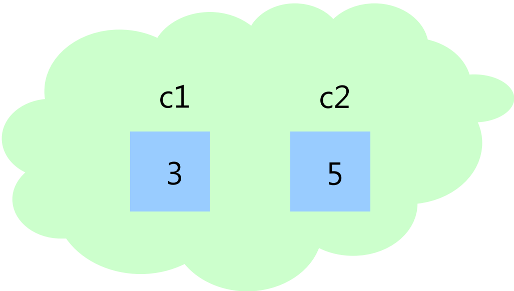
Chinmay Kakatkar

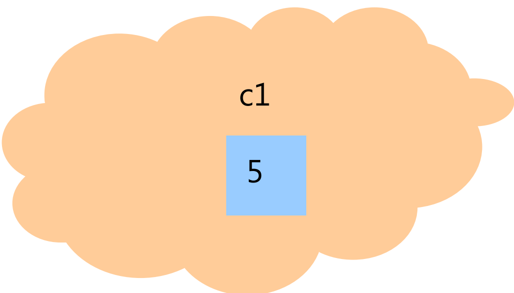
```
class Car
{
    int fuel;

    void refuel ( int amount )
    {
        this.fuel := amount;
    }

    void main ( )
    {
        ...
    }
}
```

```
class Car
{
    int fuel;

    void refuel ( int amount )
    {
        this.fuel := amount;
    }

    void main ( )
    {
        ...
    }
}
```

```
Car c1 := new Car ( );
Car c2 := new Car ( );
c1.refuel ( 3 );
c2.refuel ( 5 );
assert ( c1.fuel == 3 );
```

```
class Car
{
    int fuel;

    void refuel ( int amount )
    {
        this.fuel := amount;
    }

    void main ( )
    {
        ...
    }
}
```



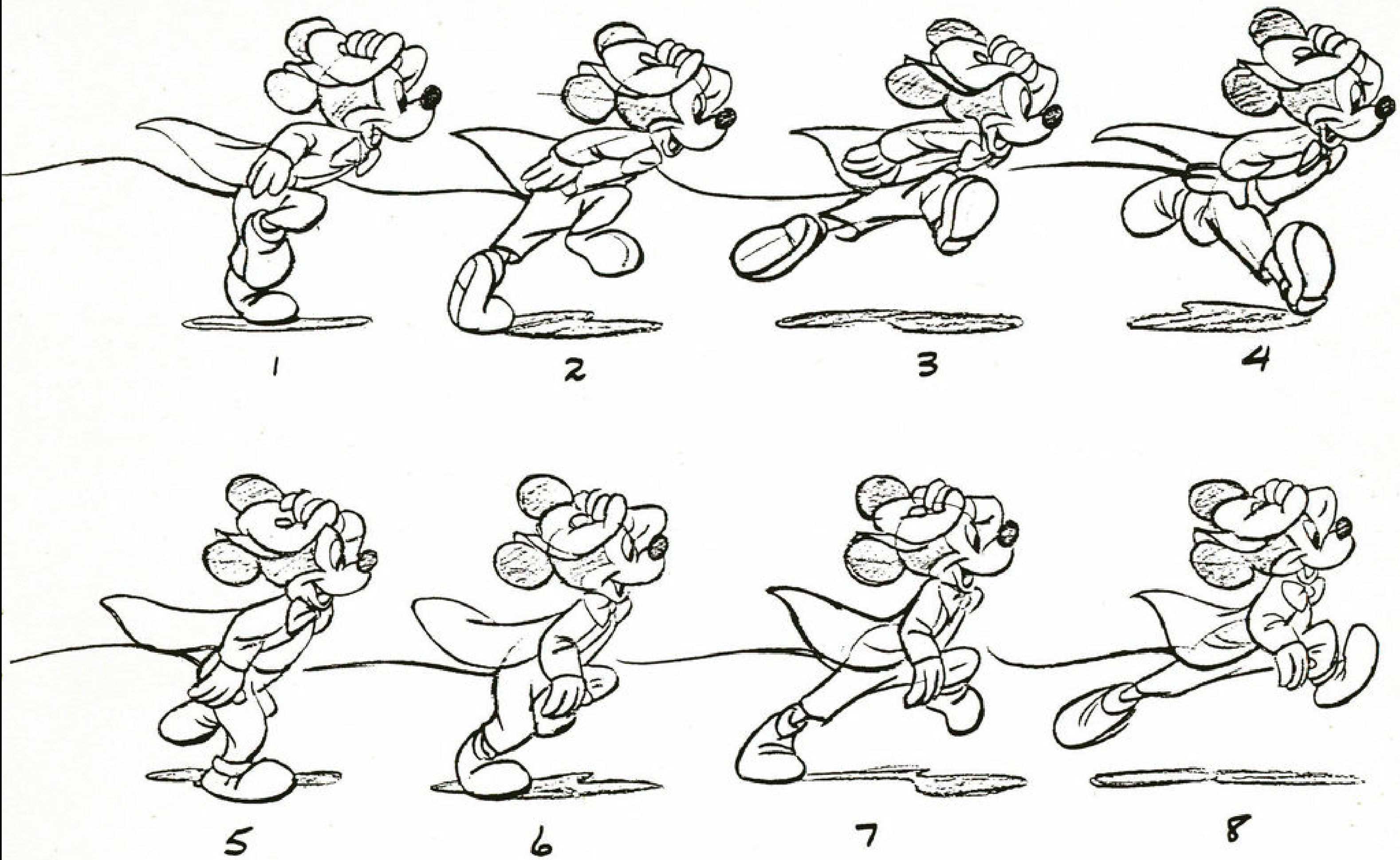



```
Car c1 := new Car ( );
Car c2 := new Car ( );
c1.refuel ( 3 );
c2.refuel ( 5 );
assert ( c1.fuel == 3 );
```

The Problem is

Framing

MICKEY MOUSE / *run cycle*



(IN THIS ACTION — DRAWING NO 1 WOULD FOLLOW NO 8)

"We wish to ***logically represent how*** the execution of ***a command changes the state*** ***without having to explicitly say how the command does not change the state***."

One Solution is

Implicit Dynamic Frames *(IDF)*

Theory: **Kassios (2006), Smans (2008)**

Implementation: **ETH, Microsoft Research, Leuven**

Chalice

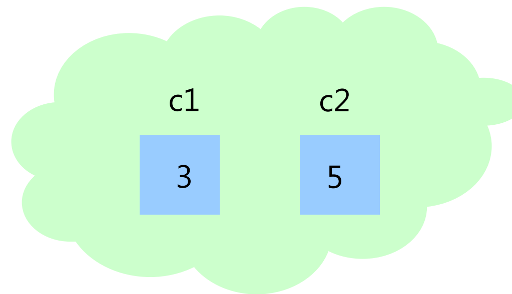
Car program in Chalice

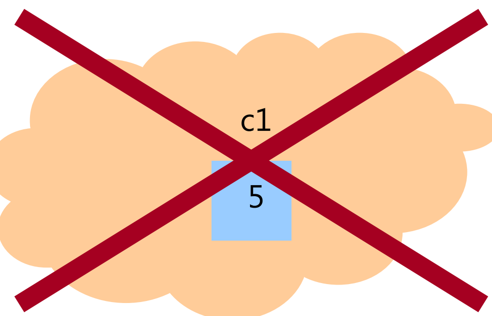
```
class Car
{
   var fuel : int;

   void refuel (amount :  int)
   requires acc (this.fuel );
   ensures acc (this.fuel ) &*& this.fuel == amount;
   {
      this.fuel := amount;
   }

   void main ( )
   {
      ...
   }
}
```

```
var c1 := new Car;
var c2 := new Car;
call c1.refuel ( 3 );
call c2.refuel ( 5 );
assert  c1.fuel == 3;
```

Car program in Chalice

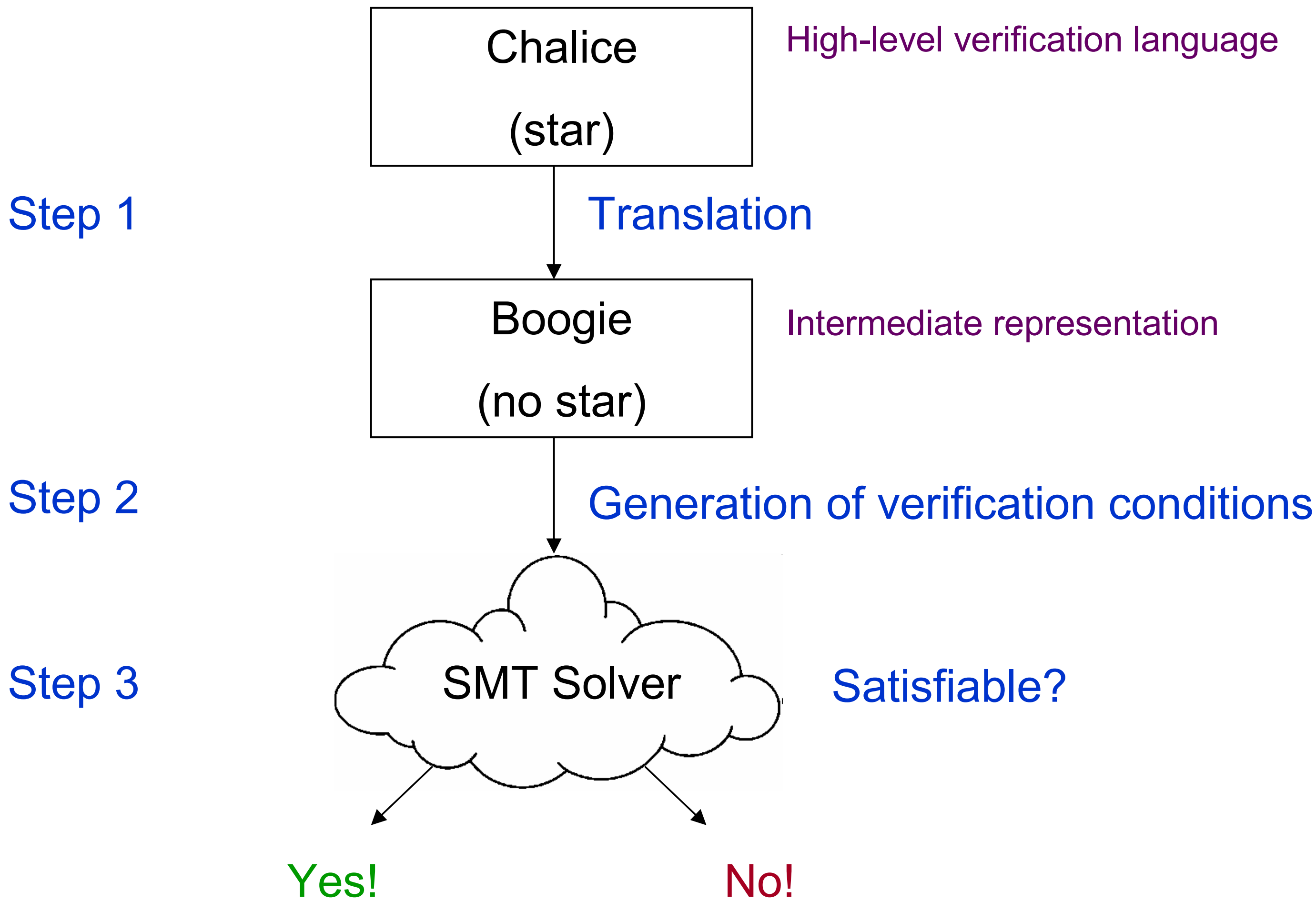
```
class Car
{
   var fuel : int;

   void refuel (amount :  int)
   requires acc (this.fuel );
   ensures acc (this.fuel ) &*& this.fuel == amount;
   {
      this.fuel := amount;
   }

   void main ( )
   {
      ...
   }
}
```



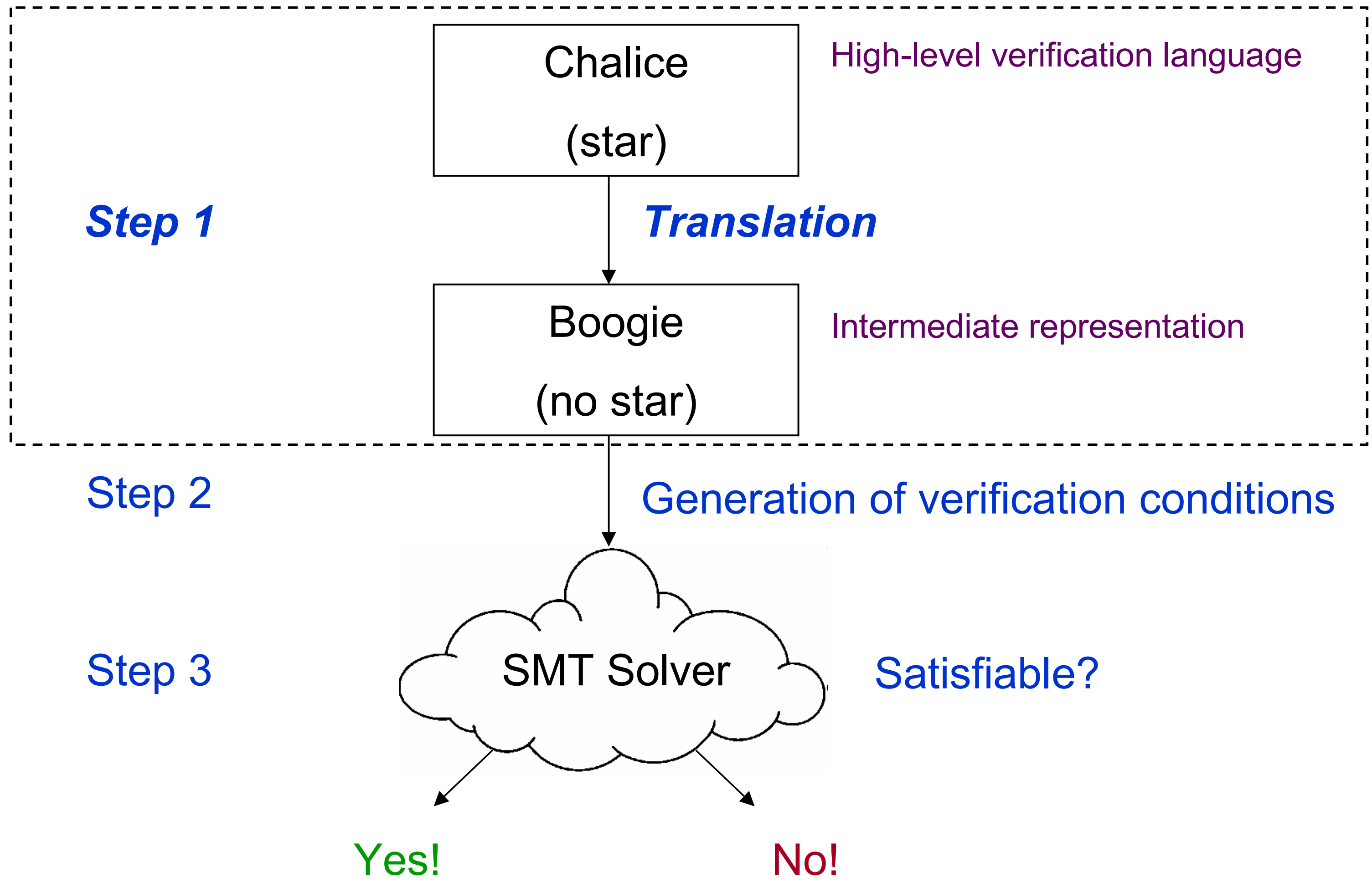



```
var c1 := new Car;
var c2 := new Car;
call c1.refuel ( 3 );
call c2.refuel ( 5 );
assert  c1.fuel == 3;
```

Verification Pipeline



Verification Pipeline



Contributions

1. Formalization of a Chalice subset
2. Formalization of a Boogie subset
3. Formalization of a subset translation from Chalice to Boogie
4. Proof of Soundness of Translation

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Chalice
(has star)

Our subset ignores concurrency features

We give:

- ***Operational semantics***
- ***Hoare logic*** { Pre } C { Post }
- ***Soundness proof of Hoare logic w.r.t. operational semantics***

"A Sip of the Chalice" (Drossopoulou & Raad, 2011)

Self-framing

Badly framed Car program in Chalice (1)

```
class Car
{
    var fuel : int;

    void refuel ( amount : int )
    requires true;
    ensures this.fuel == amount;
    {
        this.fuel := amount;  //ERROR: update is not framed
    }

    void main ( )
    {
        ...
    }
}
```

Badly framed Car program in Chalice (2)

```
class Car
{
    var fuel : int;

    void refuel ( amount : int )
    requires this.fuel == 0;  //ERROR: assertion not self-framing
    ensures acc ( this.fuel ) &*& this.fuel == amount;
    {
        this.fuel := amount;
    }

    void main ( )
    {
        ...
    }
}
```

Our approach to self-framing

An assertion *A* is ***self-framing***

if and only if

All heap references in *A* are sufficiently framed by the access predicate.

$$\mathit{A} = \underbrace{\text{acc (x.f)}}_{\text{Rights}} \;\&{*}\&\; \ldots \;\&{*}\&\; \underbrace{\text{x.f == 100}}_{\text{Access}}$$

A is self-framing

if and only if

Access (*A*) $\subseteq$ Rights (*A*)

To be or not to be self-framing

A	Access (*A*)	Rights (*A*)	
acc(x.f) &*& x.f == 100	{ x.f }	{ x.f }	✓
acc(x.f) &*& y.f == 90	{ y.f }	{ x.f }	✗
acc(x.f) &*& x.g == 101	{ x.g }	{ x.f }	✗
acc(x.f)	{ }	{ x.f }	✓

Our approach to self-framing

is intuitive,

provides an operational angle,

and simplifies proof of soundness.

Challenges

- Scoping & Simplification
- Design choices
- Formalization of method calls

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Boogie
(no star)

Our Boogie subset mirrors our Chalice subset

We give an operational semantics for our Boogie subset

Motivated in Rustan Leino's talk at Imperial College London (2012)

$$\frac{\varphi(mask)(r, C.f) = v}{[\![\texttt{CanAccess}(mask, r, f)]\!]_\varphi = v}$$

$$\frac{\forall r : ObjectReference, f : FieldId.(\varphi(mask)(r, C.f) \in \{0, 1\})}{[\![\texttt{IsGoodMask}(mask)]\!]_\varphi = 1}$$

$$\frac{\begin{array}{l}\forall r : ObjectReference, f : FieldId.(\texttt{CanAccess}(mask, r, f) \\ \Rightarrow \varphi(h_i)(r, C.f) = \varphi(h)(r, C.f))\end{array}}{[\![\texttt{IsGoodInhaleState}(h_i, h, mask)]\!]_\varphi = 1}$$

$$\frac{}{[\![mask[r, C.f]]\!]_\varphi = \varphi(mask)(r, C.f)} \qquad \frac{}{[\![h[r, C.f]]\!]_\varphi = \varphi(h)(r, C.f)}$$

$$\frac{\varphi \models B}{\texttt{assume}\ \ B, \varphi \rightsquigarrow \varphi} \qquad \frac{\varphi \models B}{\texttt{assert}\ \ B, \varphi \rightsquigarrow \varphi}$$

$$\frac{}{\texttt{havoc}(x), \varphi \rightsquigarrow \varphi[x \mapsto v]} \qquad \frac{\varphi \not\models B}{\texttt{assert}\ \ B, \varphi \rightsquigarrow ERROR}$$

$$\frac{\varphi(mask)(r, C.f) = v}{[\![\texttt{CanAccess}(mask, r, f)]\!]_\varphi = v}$$

$$\frac{\forall r : ObjectReference, f : FieldId.(\varphi(mask)(r, C.f) \in \{0, 1\})}{[\![\texttt{IsGoodMask}(mask)]\!]_\varphi = 1}$$

$$\frac{\begin{array}{l}\forall r : ObjectReference, f : FieldId.(\texttt{CanAccess}(mask, r, f) \\ \Rightarrow \varphi(h_i)(r, C.f) = \varphi(h)(r, C.f))\end{array}}{[\![\texttt{IsGoodInhaleState}(h_i, h, mask)]\!]_\varphi = 1}$$

$$\frac{}{[\![mask[r, C.f]]\!]_\varphi = \varphi(mask)(r, C.f)} \qquad \frac{}{[\![h[r, C.f]]\!]_\varphi = \varphi(h)(r, C.f)}$$

$$\frac{\varphi \models B}{\texttt{assume}\ \ B, \varphi \rightsquigarrow \varphi} \qquad \frac{\varphi \models B}{\texttt{assert}\ \ B, \varphi \rightsquigarrow \varphi}$$

$$\frac{}{\texttt{havoc}(x), \varphi \rightsquigarrow \varphi[x \mapsto v]} \qquad \frac{\varphi \not\models B}{\texttt{assert}\ \ B, \varphi \rightsquigarrow ERROR}$$

Challenges

- Scoping, Simplification, Design
- Formalization of Boogie-specific commands

Without the benefit of existing literature!

Contributions

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Boogie

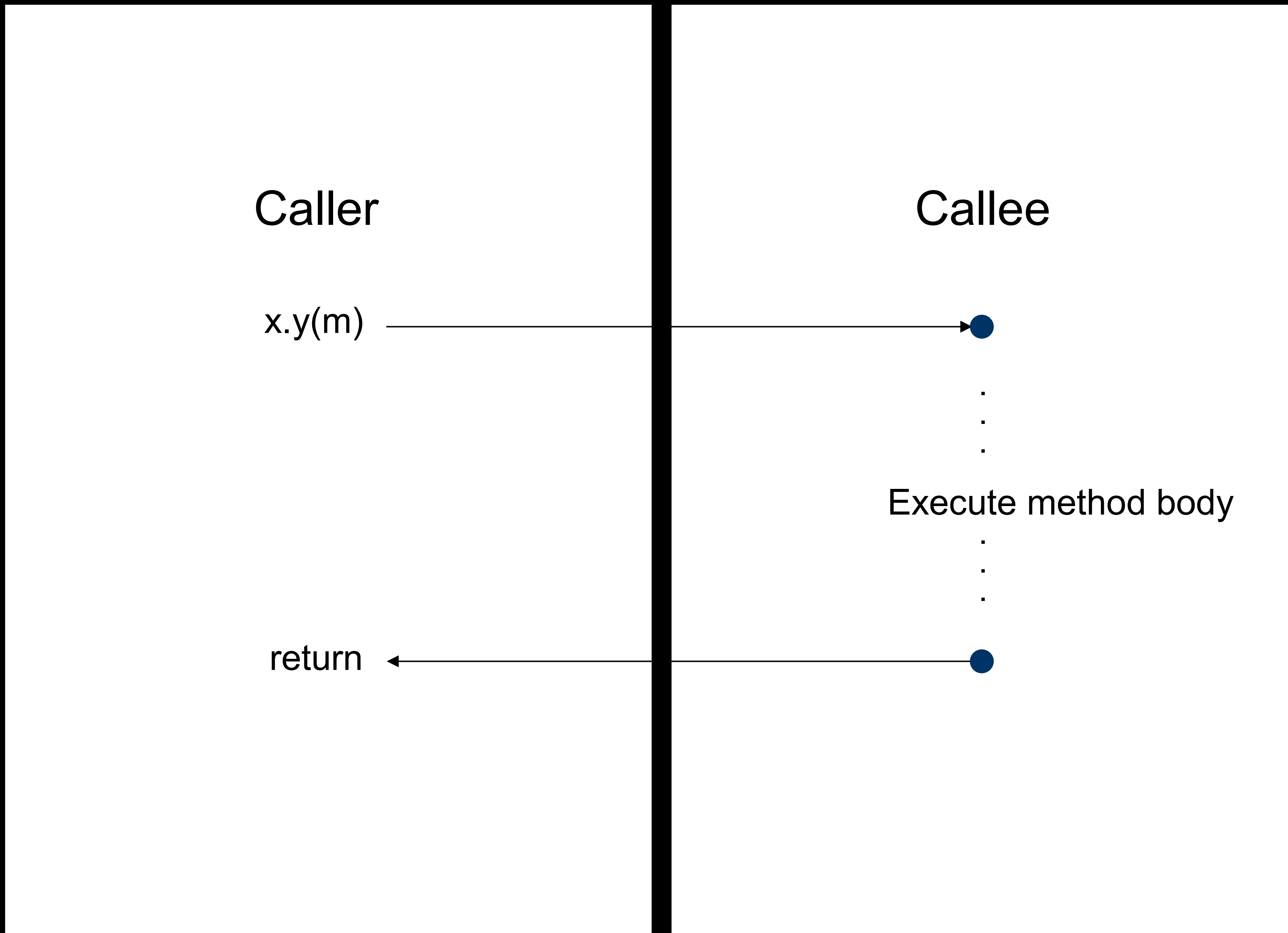
Has special commands and predicates

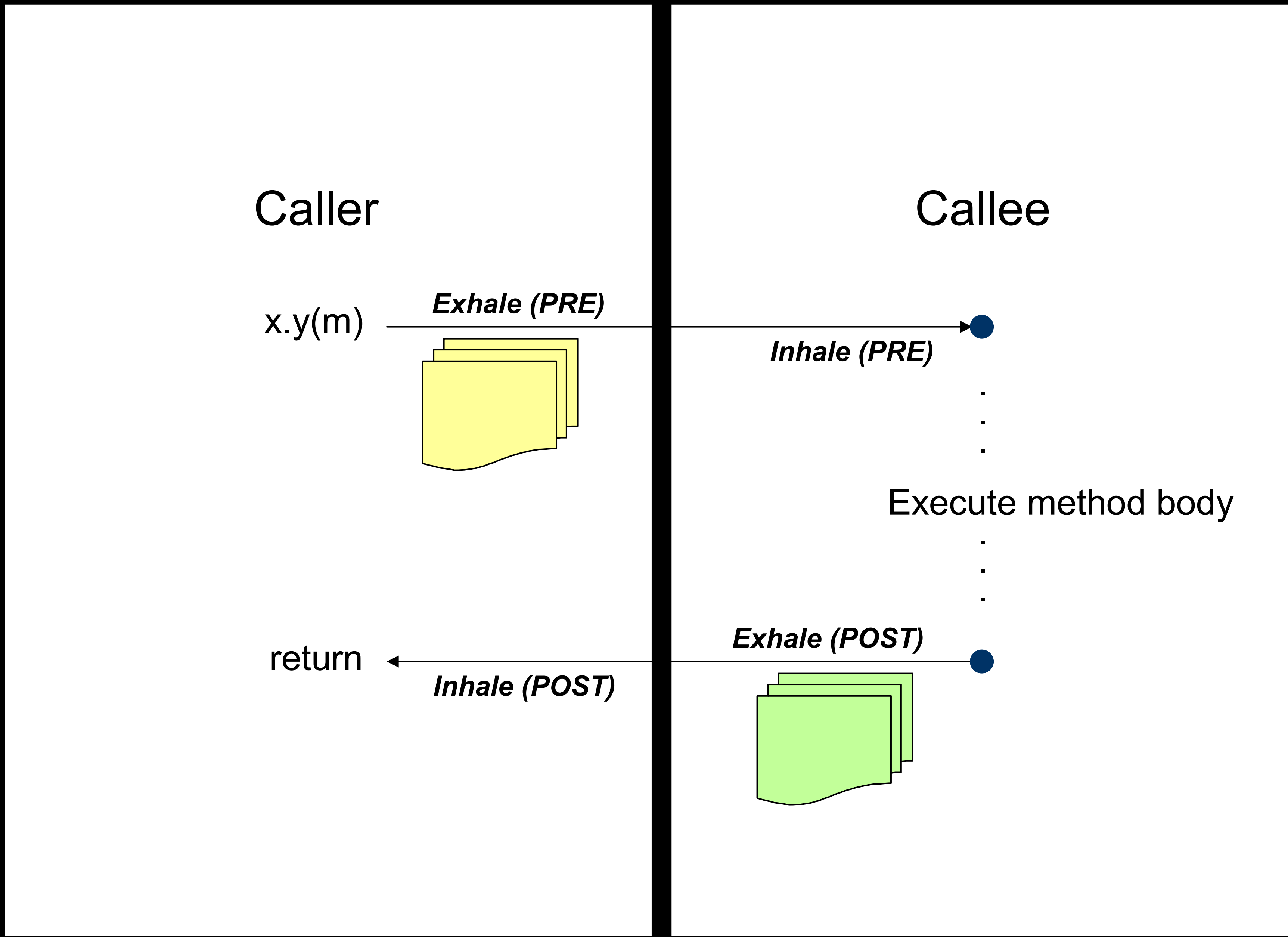
< $frame_B$ >

Chalice	to	Boogie
Has notion of star operator	$\Leftrightarrow$	Has special commands and predicates
$< \text{mask}_C , \text{heap}_C , \text{frame}_C >$	$\Leftrightarrow$	$< \text{frame}_B >$

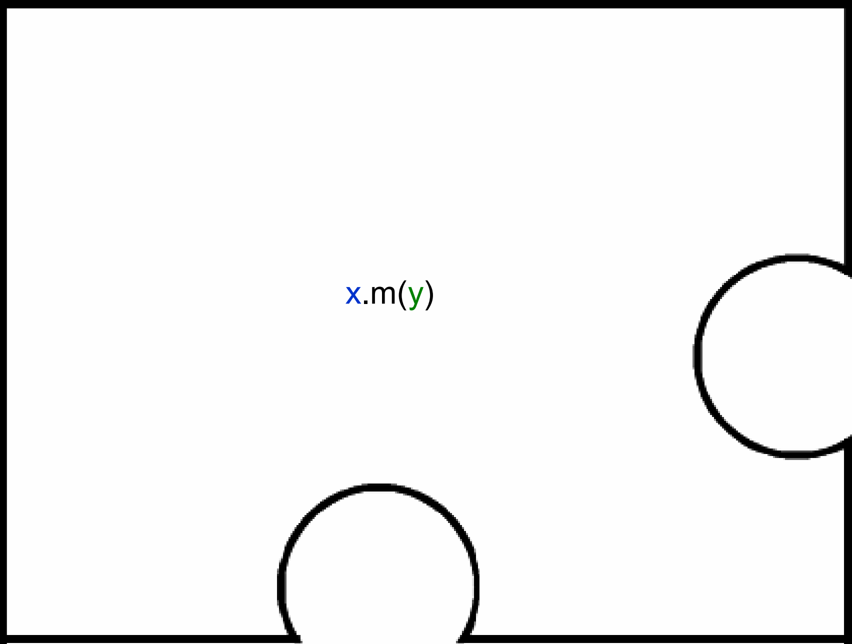
Translation needs to be meaning-preserving

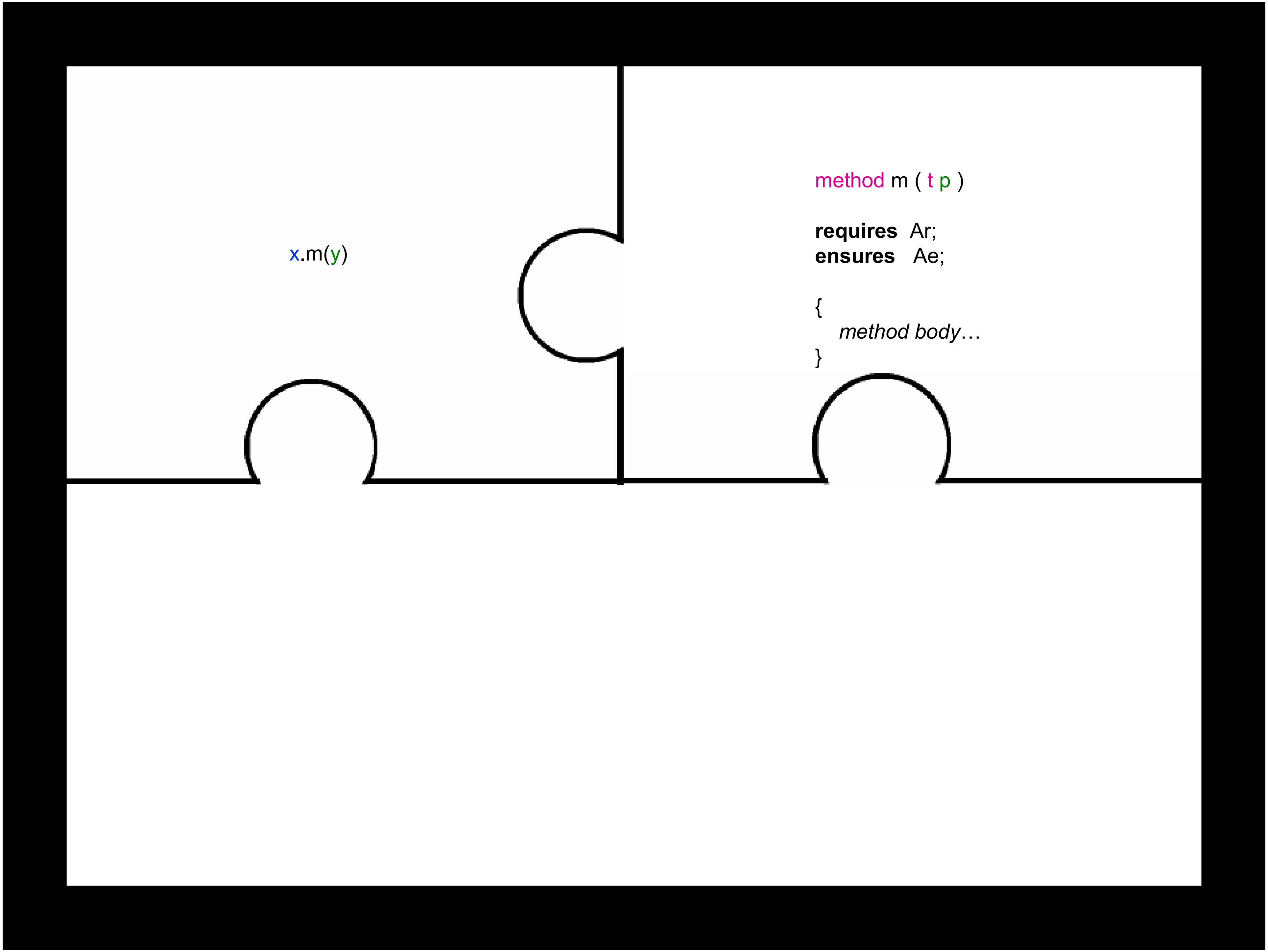
Method Call


Caller
Callee
x.y(m)
Execute method body
return



Caller
Callee
x.y(m)
Exhale (PRE)
Inhale (PRE)
Execute method body
Exhale (POST)
return
Inhale (POST)


x.m(y)


x.m(y)
method m (t p)
requires Ar;
ensures Ae;
{
method body…
}

x.m(y)

```
method m ( t p )

requires  Ar;
ensures   Ae;

{
    method body…
}
```

```
var mask_e : Mask; var heap_i : Heap;
var y1 : Expression;
y1 := y;

mask_e := mask;
exhale( Ar [ this / x ] [ y1 / y ] , mask_e );
mask := mask_e;

havoc heap_i;
assume IsGoodInhaleState( heap_i , heap , mask );
inhale( Ae [ this / x ] [ y1 / y ] , mask , heap_i );
```

```
x.m(y)
```

```
method m ( t p )

requires  Ar;
ensures   Ae;

{
    method body…
}
```

```
var mask_e : Mask; var heap_i : Heap;
var y1 : Expression;
y1 := y;

mask_e := mask;
exhale( Ar [ this / x ] [ y1 / y ] , mask_e );
mask := mask_e;

havoc heap_i;
assume IsGoodInhaleState( heap_i , heap , mask );
inhale( Ae [ this / x ] [ y1 / y ] , mask , heap_i );
```

```
procedure C.m ( this : C , p : t )
{
 var mask_e : Mask;    var heap_i : Heap;

 havoc heap_i;
 assume IsGoodInhaleState ( heap_i , heap , mask );
 inhale ( Ar , mask , heap_i );

 translate ( method body );

 mask_e := mask;
 exhale ( Ae , mask_e );
 mask := mask_e;
}
```

```
exhale( acc( x.f ) , mask ) = assert 0 < mask[ x , C.f ];
                              mask[x , C.f] := mask[ x , C.f ] – 1;
                              assume IsGoodMask ( mask );

exhale( a1 &*& a2 , mask ) = exhale( a1 , mask );
                             exhale( a2 , mask );

exhale( b , mask ) = assert translate ( b );
```

```
inhale( b , mask , heap_i ) = assume translate ( b );

inhale( a1 &*& a2 , mask , heap_i ) = inhale( a1 , mask , heap_i );
                                      inhale( a2 , mask , heap_i );

inhale( acc(x.f) , mask , heap_i ) = heap[ x , C.f ] := heap_i[ x , C.f ];
                                     mask[ x , C.f ] := mask[ x , C.f ] + 1;
                                     assume IsGoodMask ( mask );
```

```
exhale( acc( x.f ) , mask ) = assert 0 < mask[ x , C.f ];
                              mask[x , C.f] := mask[ x , C.f ] – 1;
                              assume IsGoodMask ( mask );

exhale( a1 &*& a2 , mask ) = exhale( a1 , mask );
                              exhale( a2 , mask );

exhale( b , mask ) = assert translate ( b );
```

```
inhale( b , mask , heap_i ) = assume translate ( b );

inhale( a1 &*& a2 , mask , heap_i ) = inhale( a1 , mask , heap_i );
                                      inhale( a2 , mask , heap_i );

inhale( acc(x.f) , mask , heap_i ) = heap[ x , C.f ] := heap_i[ x , C.f ];
                                     mask[ x , C.f ] := mask[ x , C.f ] + 1;
                                     assume IsGoodMask ( mask );
```

Checking self-framedness of assertions in Boogie (1)

Not self-framing:
A = x.f == 3 &*& y.f == 3;

exhale(x.f == 3 &*& y.f == 3, mask) =

assert heap[x , C.f] == 3; //ERROR

assert heap[y , C.f] == 3;

Checking self-framedness of assertions in Boogie (2)

Self-framing:
A = acc(x.f) &*& acc(y.f) &*& x.f == 3 &*& y.f == 3;   ***where x and y not aliases of each other!***

exhale(acc(x.f) &*& acc(y.f) &*& x.f == 3 &*& y.f == 3, mask) =

```
assert 0 < mask[ x , C.f ];
mask[ x , C.f ] := mask[ x , C.f ] – 1;
assume IsGoodMask ( mask );

assert 0 < mask[ y , C.f ];
mask[ y , C.f ] := mask[ y , C.f ] – 1;
assume IsGoodMask ( mask );

assert heap[ x , C.f ] == 3;

assert heap[ y , C.f ] == 3;
```

Car program still running ...

```
class Car
{
   var fuel : int;

   void refuel ( amount : int )
   requires acc ( this.fuel );
   ensures acc ( this.fuel ) &*& this.fuel == amount;
   {
      this.fuel := amount;
   }

   void main ( )
   {
      var c1 := new Car;
      var c2 := new Car;

      call c1.refuel ( 3 );

      call c2.refuel ( 5 );
      assert ( c1.fuel == 3 );
   }
}
```

```
call c1.refuel ( 3 );
```

```
//set up variables
var mask_e : Mask;    var heap_i : Heap;
var y : Expression;
y := 3;

mask_e := mask;

//exhale precondition
assert 0 < mask_e [ this , Car.fuel ];
mask_e [ this , Car.fuel ] := mask_e [ this , Car.fuel ] – 1;
assume IsGoodMask ( mask_e );

mask := mask_e;

havoc heap_i;

assume IsGoodInhaleState ( heap_i , heap, mask );

//inhale postcondition
heap [ this , Car.fuel ] := heap_i [ this , Car.fuel ];
mask [ this , Car.fuel ] := mask [ this , Car.fuel ] + 1;
assume IsGoodMask ( mask );
assume heap [ this , Car.fuel ] == y;
```

```
void refuel ( amount : int )
  requires acc ( this.fuel );
  ensures acc ( this.fuel ) &*& this.fuel == amount;
  {
    this.fuel := amount;
  }
```

```
procedure Car.refuel ( this : Car , amount : int )
{
 var mask_e : Mask;    var heap_i : Heap;

 havoc heap_i;
 assume IsGoodInhaleState ( heap_i , heap , mask );

 //inhale precondition
 heap [ this , Car.fuel ] := heap_i [ this , Car.fuel ];
 mask [ this , Car.fuel ] := mask [ this , Car.fuel ] + 1;
 assume IsGoodMask ( mask );

 //translate method body
 CanAccess ( mask , this , Car.fuel );
 heap [ this , Car.fuel ] := amount;

 mask_e := mask;

 //exhale postcondition
 assert 0 < mask_e [ this , Car.fuel ];
 mask_e [ this , Car.fuel ] := mask_e [ this , Car.fuel ] – 1;
 assume IsGoodMask ( mask_e );
 assert heap [ this , Car.fuel ] == amount;
 mask := mask_e;
}
```

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4. Proof of Soundness of Translation

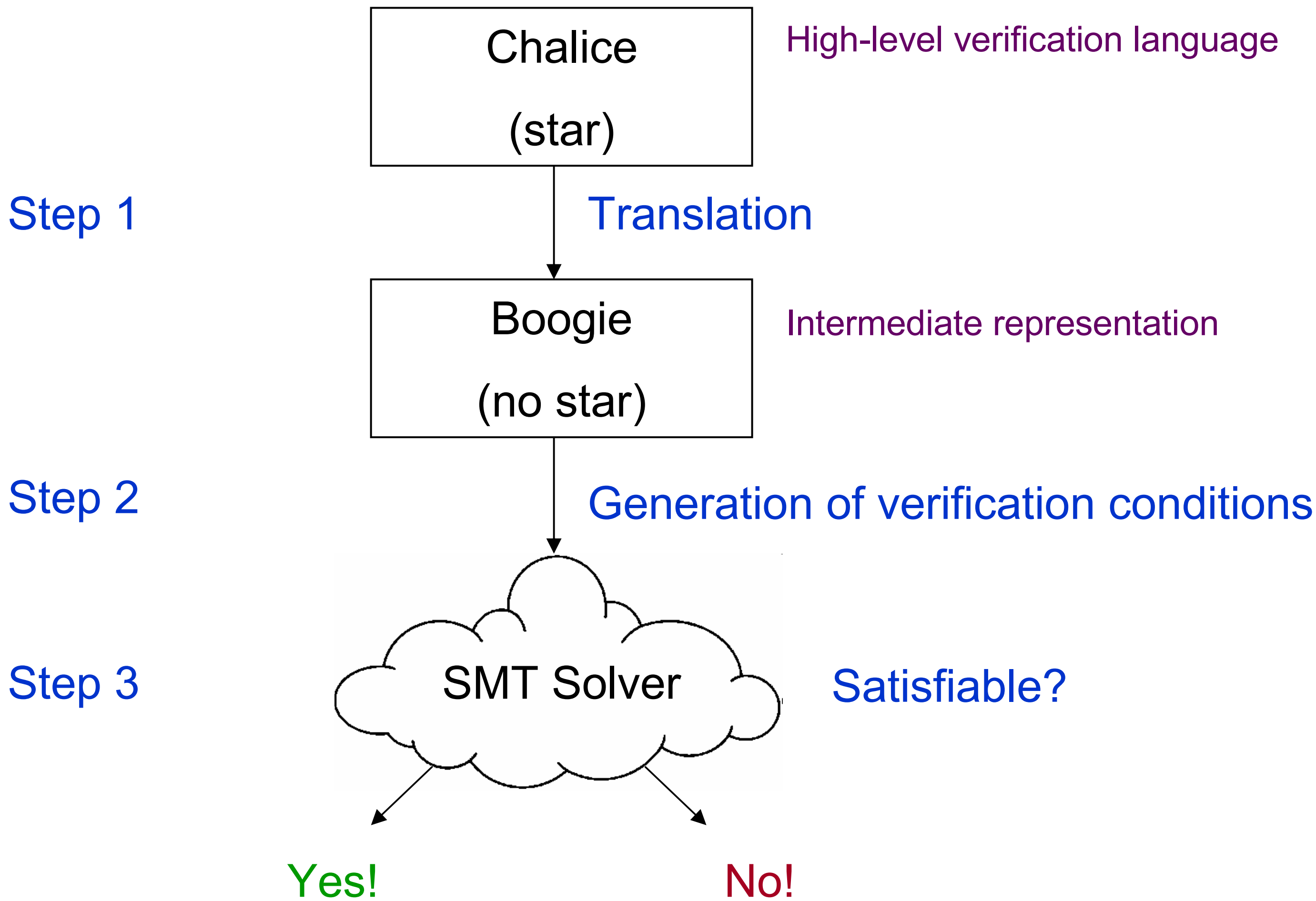
Soundness Argument

The translation of a Chalice program ***P*** is sound

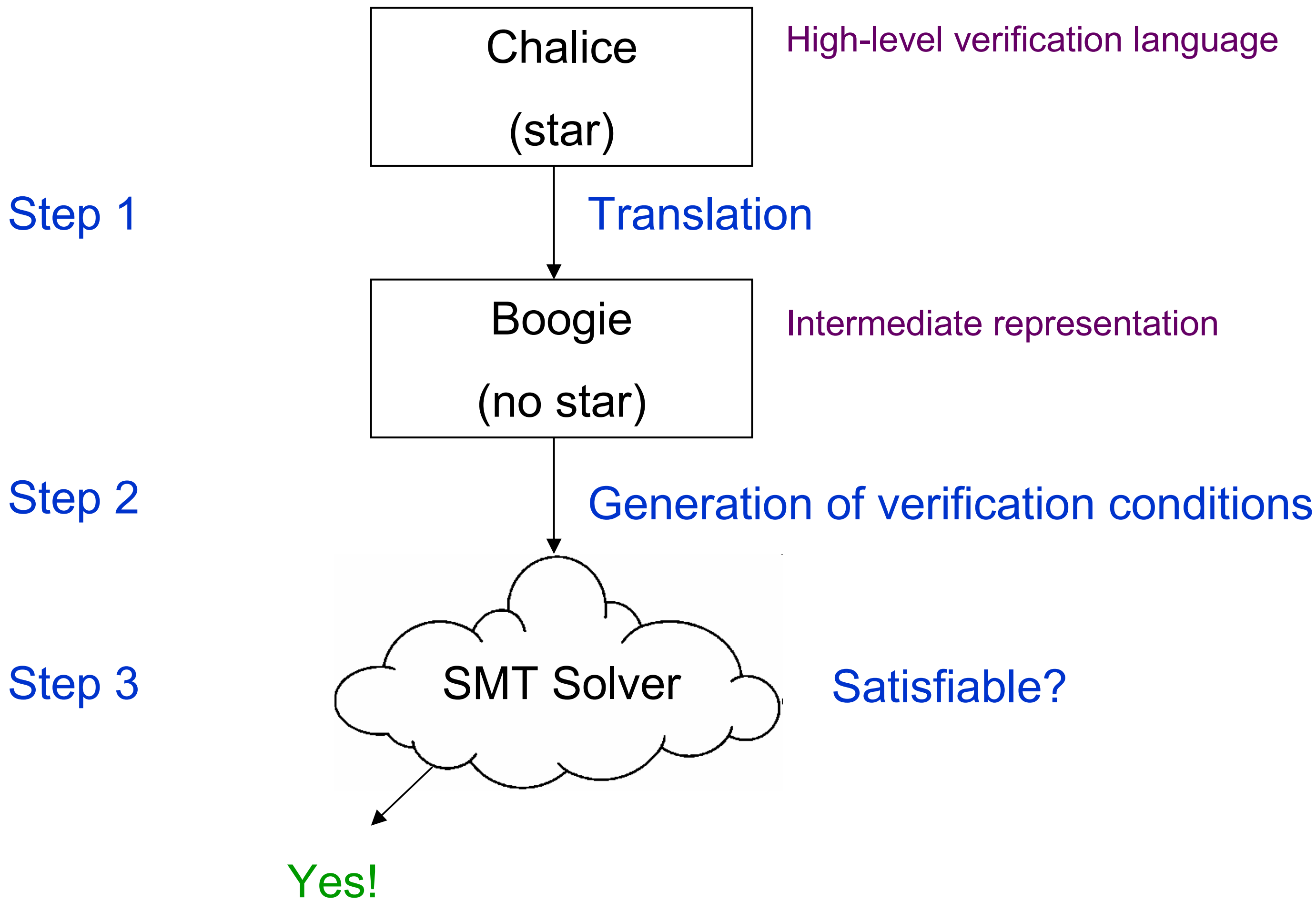
if and only if

given that ***P*** verifies in the Boogie environment, it also verifies in the Chalice environment.

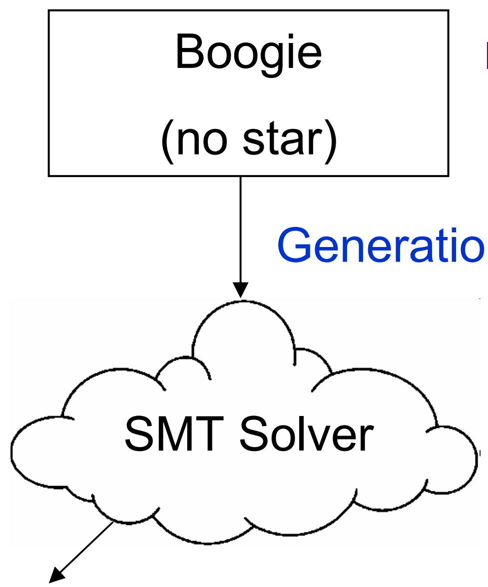
Verification Pipeline Revisited



If program verifies in Chalice environment …



If program verifies in Boogie environment …



Intermediate representation

Step 2

Generation of verification conditions

Step 3

Satisfiable?

Yes!

Lemma 6.4.4. $\forall C : ClassId, m : MethId :$

If:

1. $Prog_C(C, m) = \texttt{requires}\ \ A; \texttt{ensures}\ \ A'; \{C_C\} \wedge$
2. $(inhale(A, mask, h_i); translate(C_C); exhale(A, mask_e)), \varphi_\varepsilon \not\rightarrow ABORT \wedge$
3. $\Pi, \varphi_C, h_C \models A \wedge$
4. $C_C, \Pi, \varphi_C, h_C \rightsquigarrow \Pi', \varphi'_C, h'_C$

Then $\Pi', \varphi'_C, h'_C \models A'$

Other Machinery

Auxiliary Definitions, Lemmas …

Challenges

- Design of translation function
- Formulating & justifying soundness argument
- Lemmas and proofs

Highlights

1. Formalization of a Chalice subset
   - Approach to self-framing

2. Formalization of a Boogie subset
   - Operational semantics

3. Formalization of a sound translation from Chalice to Boogie
   - Translation function, soundness argument & proofs

Applications

1. Boogie-based verification

2. Pedagogic uses

Applications

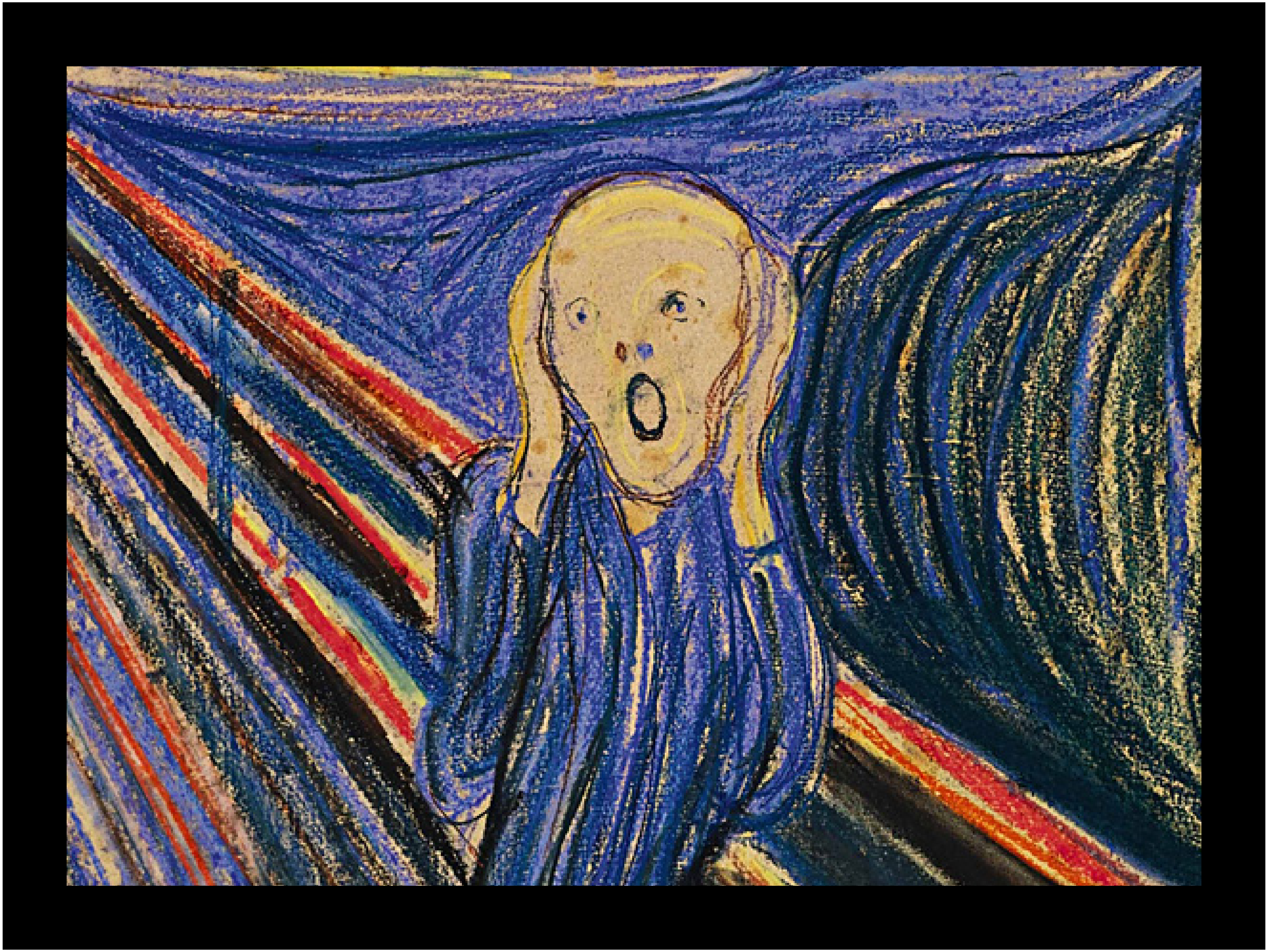
1. Boogie-based verification

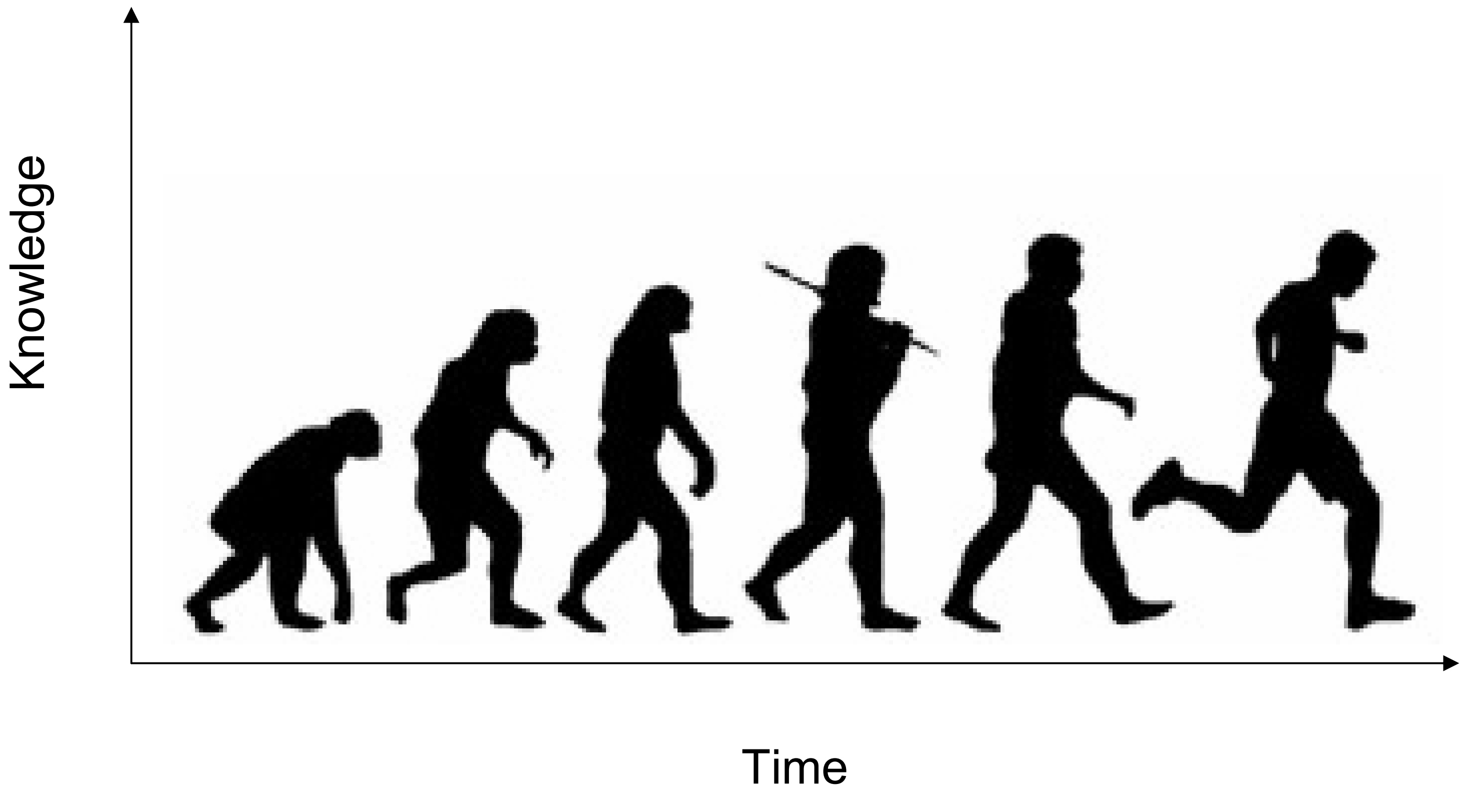
2. Pedagogic uses

http://rise4fun.com/

A Challenging Project

- Lots of background reading
- An open-ended project
- Balancing breadth and depth of investigation
- Experimenting with tools
- Formalizing approaches and arguments
- Making original contributions
- I am not JMC or MEng (but I am passionate about research!)




Knowledge
Time

Future Work

1. **Formalize** translation of while loop, and proof of method call
2. **Extend** language subsets to include concurrency
3. **Consider** translation from VeriFast to Chalice

Q&A

Extra Slides

Usual approach to self-framing

An assertion *A* is ***self-framing***

if and only if

The validity of *A* is preserved in all heaps which agree in the locations mentioned in the permissions. *(Parkinson & Summers, 2011)*

While loop

```
while ( condition )
{

    // check invariant holds upon loop entry (assert …)

    loop body …

    // check invariant holds after arbitrary loop iteration (havoc…)

}
```

Method call

If:

- *x.m(y)*
- translation of *x.m(y)* gives a Boogie encoding C_B
- C_B verifies in Boogie
- Chalice and Boogie starting configurations are congruent
- and given preconditions of operational semantics for *x.m(y)*…

Then:

(esp. using Lemmas for Inhale / Exhale …)

Show that there exists a terminal Boogie configuration φ_B s. t.

- C_B execution in Boogie leads to φ_B
- Terminal configurations in Chalice and Boogie match

Lemma 6.4.1. *Given* $C : Command_C, \forall \Pi : Mask_C, \varphi_C : Store_C, h_C : Heap_C, \varphi_B : Store_B,$

If:

1. $translate(C), \varphi_B \not\rightsquigarrow ABORT$
2. $\Pi, \varphi_C, h_C \cong \varphi_B$
3. $C, \Pi, \varphi_C, h_C \rightsquigarrow \Pi', \varphi'_C, h'_C$

Then there exists a $\varphi'_B : Store_B$ *such that:*

4. $translate(C), \varphi_B \rightsquigarrow \varphi'_B$
5. $\Pi', \varphi'_C, h'_C \cong \varphi'_B$

Lemma 6.4.2. *Given $A : Assertion_C, mask : Mask_B, h_B : Heap$ (where A is self-framing, $mask$ is the current mask, and h_B is the current heap),*

If:

1. $\texttt{inhale}(A, mask, h_B) = C_i$ *where* $C_i : Command_B$
2. $C_i, \varphi_B \rightsquigarrow \varphi'_B$ *where* $\varphi'_B : Store_B$ *such that* $\varphi'_B \neq ABORT$
3. $\Pi', \varphi'_c, h'_c \cong \varphi'_B$, *where* $\Pi' : Mask_C, \varphi'_C : Store_C, h'_c : Heap_C$

Then:

4. $\Pi', \varphi'_c, h'_c \models A$
5. *There exists a* $mask' : Mask_B$ *such that* $\varphi'_B \equiv \varphi_B[mask \mapsto mask']$, *and* $mask \leq_\Pi mask'$.

Lemma 6.4.3. *Given* $A : Assertion_C, mask : Mask_B$, *(where* A *is self-framing, and* $mask$ *is the current mask)*

If:

1. $\texttt{exhale}(A, mask) = C_e$ *where* $C_e : Command_B$
2. $C_e, \varphi_B \rightsquigarrow \varphi'_B$ *where* $\varphi'_B : Store_B$ *such that* $\varphi'_B \neq ABORT$
3. $\Pi, \varphi_c, h_c \cong \varphi_B$

Then:

4. $\Pi, \varphi_c, h_c \models A$, *where* $\Pi : Mask_C, \varphi_C : Store_C, h_c : Heap_C$
5. *There exists a* $mask' : Mask_B$ *such that* $\varphi'_B \equiv \varphi_B[mask \mapsto mask']$, *and* $mask' \leq_\Pi mask$.

Definition 6.3.1. *combine* $: Mask_C \times Store_C \times Heap_C \rightarrow Store_B$ *such that, for* $\Pi : Mask_C, \varphi_C : Store_C, h_C : Heap_C$ *we:*

1. *Create a fresh Boogie variable* $mask_B : Mask_B$ *and populate it with the access permissions found in* Π*, such that* $\forall v : \{0, 1\}, r : ObjectReference, f : FieldId.(\Pi[r, f] = v \Rightarrow mask[(r, C.f) \mapsto v])$ *where* f *is a field of class* C*.*

2. *Create a fresh Boogie variable* $h_B : Heap_B$ *and populate it with the values found in* h_C*, such that* $\forall r : ObjectReference, f : FieldId.(h_B[(r, C.f) \mapsto [\![r.f]\!]_{\varphi, h_C}])$ *where* f *is a field of class* C*.*

3. *Now take an empty store* $\varphi_\varepsilon : Store_B$*, such that* $\varphi_\varepsilon = \{mask \mapsto \emptyset, heap \mapsto \emptyset\}$*.*

4. *Construct a* $\varphi_B : Store_B$*, such that* $\varphi_B = \varphi_\varepsilon[mask \mapsto mask_B, h \mapsto h_B] \cup \varphi_C$

Definition 6.3.2. $\cong : Mask_C \times Store_C \times Heap_C \times Store_B$ *such that, for* $\Pi : Mask_C, \varphi_C : Store_C, h_C : Heap_C, \varphi_B : Store_B$*, we have*

$$\Pi, \varphi_C, h_C \cong \varphi_B \iff combine(\Pi, \varphi_C, h_C) = \varphi_B$$

$$Program : ClassId \rightharpoonup FieldId \times (MethId \times MethDef)$$

$$B \in Boolean ::= \texttt{true} \mid \texttt{false} \mid \neg B \mid E == E$$

$$E \in Expression ::= n \mid x \mid x.f \mid E + E \mid x.m_{pure}(E)$$

$$\begin{aligned} C \in Command ::= {} & x := y.f \mid x.f := y \mid \texttt{if } B \texttt{ then } C \texttt{ else } C \mid \\ & \texttt{while } B \texttt{ do } C \mid C;C \mid \texttt{skip} \mid x := y.m(E) \mid \\ & x := \texttt{new } C \mid \texttt{assert } A \end{aligned}$$

$$A \in Assertion ::= B \mid \texttt{acc}(x.f) \mid A * A$$

$$ClassID, FieldID ::= (a - zA - Z)+$$

$$Term ::= Boolean | Expression | Command | Assertion$$

Figure 3.1: **Our Subset of the full Chalice Syntax**

$$[\![\cdot]\!] : (Assertion \cup Expression) \times Mask \times Store \times Heap \rightharpoonup \mathbb{Z}$$

$$\rightsquigarrow : Command \times Mask \times Store \times Heap \rightharpoonup Mask \times Store \times Heap$$

$$\Pi \in Mask : ObjectReference \times (ClassId \times (FieldId \rightharpoonup \{0, 1\}))$$

$$\varphi \in Store : Variable \rightharpoonup \mathbb{Z}$$

$$h \in Heap : ObjectReference \rightharpoonup (ClassId \times (FieldId \rightharpoonup \mathbb{Z}))$$

$$ObjectReference ::= \mathbb{Z}^+$$

$$Variable, ClassID, FieldID ::= (a - zA - Z)+$$

Figure 3.2: **Runtime Configuration for Our Chalice Subset**

$$
\begin{aligned}
B \in \mathit{Boolean} ::= {} & \texttt{true} \mid \texttt{false} \mid \neg B \mid E == E \mid \\
& \texttt{CanAccess(}\mathit{mask}\texttt{,}\, r\texttt{,}\, f\texttt{)} \mid \\
& \texttt{IsGoodInhaleState(}h\texttt{,}\, h\texttt{,}\, \mathit{mask}\texttt{)} \mid \\
& \texttt{IsGoodMask(}\mathit{mask}\texttt{)}
\end{aligned}
$$

$$
E \in \mathit{Expression} ::= n \mid x \mid h[r, C.f] \mid \mathit{mask}[r, C.f] \mid E + E
$$

$$
\begin{aligned}
C \in \mathit{Command} ::= {} & \mathit{var}\ x\ :\ t \mid x := E \mid h[r, C.f] := E \mid \mathit{mask}[r, C.f] := E \mid \\
& \texttt{havoc(}x\texttt{)} \mid \texttt{if}\ B\ \texttt{then}\ C\ \texttt{else}\ C \mid C; C \mid \\
& \texttt{assume}\ B \mid \texttt{assert}\ B
\end{aligned}
$$

$$
\mathit{Term} ::= \mathit{Boolean} | \mathit{Expression} | \mathit{Command}
$$

Figure 4.1: **Our Subset of the full Boogie Syntax**

$$[\![\cdot]\!] : (Boolean \cup Expression) \times Store \rightharpoonup \mathbb{Z}$$

$$\rightsquigarrow : Command \times Store \rightharpoonup Store$$

$$\varphi \in Store : Variable \rightharpoonup Value$$

$$mask \in Mask : ObjectReference \times (ClassId \times (FieldId \rightharpoonup \{0, 1\}))$$

$$h \in Heap : ObjectReference \times (ClassId \times (FieldId \rightharpoonup Value))$$

$$Variable, ClassId, FieldId ::= (a - zA - Z)+$$

$$ObjectReference ::= \mathbb{Z}^+$$

$$Value ::= \mathbb{Z}|Heap|Mask$$

Figure 4.2: **Runtime Configuration for Our Boogie Subset**