Modular Program Verification

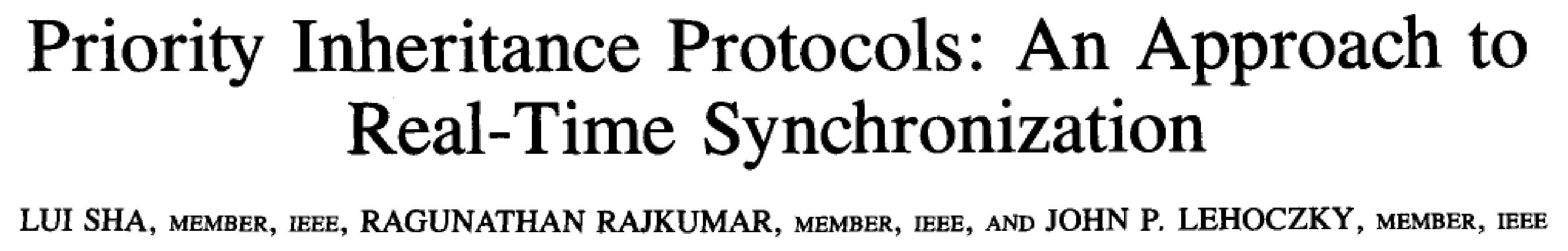
Peter Müller

OpenJDK's java.utils.Collection.sort() is broken:
The good, the bad and the worst case*

Stijn de Gouw[1,2], Jurriaan Rot[3,1], Frank S. de Boer[1,3], Richard Bubel[4], and
Reiner Hähnle[4]

- TimSort is the default sorting algorithm for Collections in Sun's JDK, OpenJDK, and Android SDK
- Certain large arrays (>= 67M) lead to index-out-of-bounds errors
- Bug was detected during a verification attempt
- Previous attempts to fix related errors were ineffective

Testing and code reviews are not sufficient to detect certain bugs

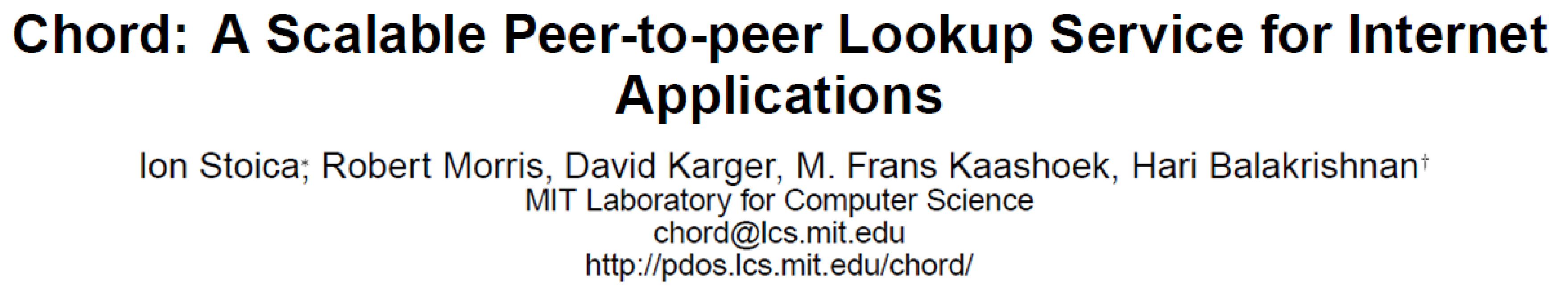


Priority Inheritance Protocols: An Approach to Real-Time Synchronization

LUI SHA, MEMBER, IEEE, RAGUNATHAN RAJKUMAR, MEMBER, IEEE, AND JOHN P. LEHOCZKY, MEMBER, IEEE

- Real-time operating systems use priority inheritance protocol to ensure that low-priority processes do not block high-priority processes
- Several operating systems implement the protocol incorrectly, leading to deadlocks and priority inversion

Code-level verification should complement reasoning on the algorithm/design level



Chord: A Scalable Peer-to-peer Lookup Service for Internet Applications

Ion Stoica[*], Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan[†]
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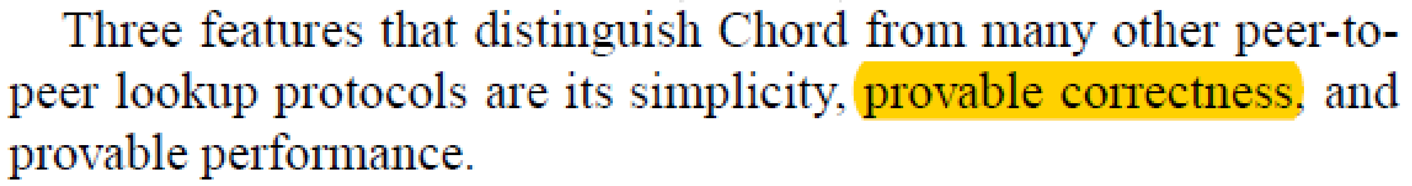
http://pdos.lcs.mit.edu/chord/

- Chord is a distributed hash table developed at MIT



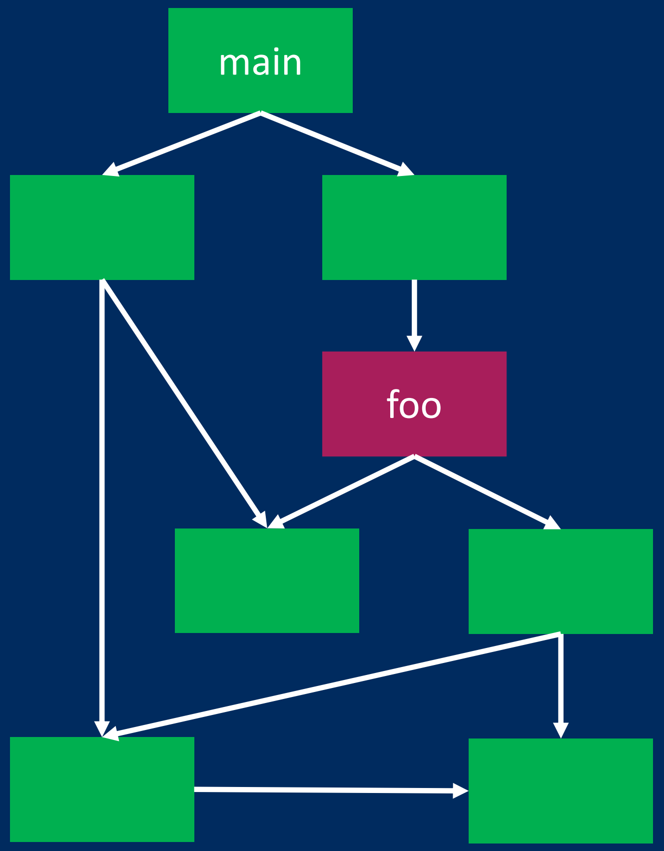
Three features that distinguish Chord from many other peer-to-peer lookup protocols are its simplicity, provable correctness, and provable performance.

- None of the seven properties claimed invariant of the original version is actually an invariant

Reasoning must be supported by tools

Modular Verification

- Verify each method separately
  - Scalability
- Do not use the implementation of callees
  - Software evolution
  - Dynamic method binding
- Do not use the implementation of callers and other methods
  - Correctness guarantees for libraries
  - Software evolution

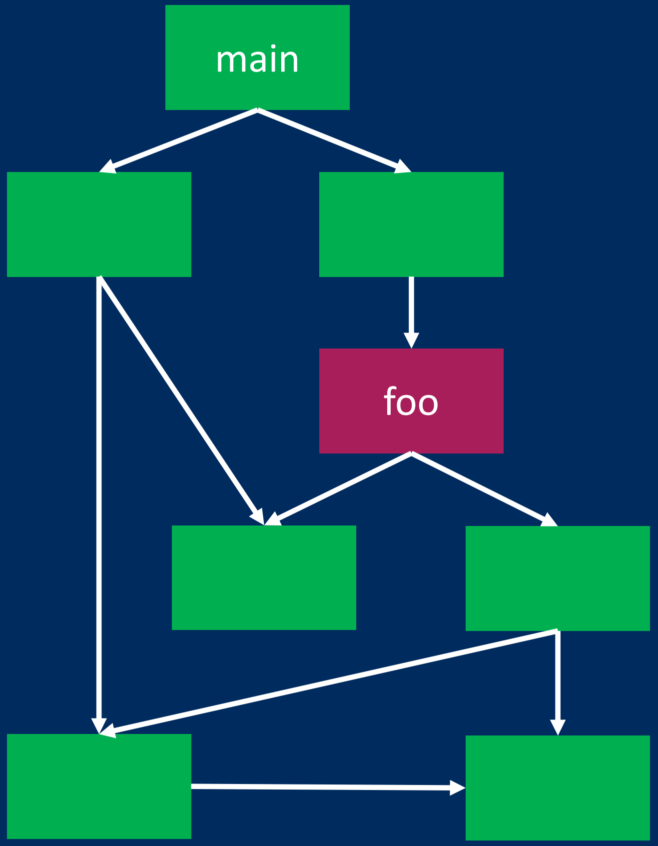


Outline

- Permission-based Verification
- The Viper Intermediate Language
- Building Verifiers
- Encoding of Advanced Verification Techniques

Contracts

- Contracts specify the intended behavior of parts of the program
- For the verification of a method, use the contracts of the rest of the program, not the implementation
- Verify calls in terms of method pre- and postconditions



Example: Contracts

```
class Account {
  var bal: int

  method deposit(amount: int)
    requires 0 < amount
    ensures bal == old(bal) + amount
  { … }

  method withdraw(amount: int)
    requires 0 < amount && amount <= bal
    ensures bal == old(bal) - amount
  { … }
}
```

```
method demo(a: Account)
  requires 0 <= a.bal
{
  a.deposit(200);
  a.withdraw(100);
}
```

Example: Side Effects

```
class Account {
  var bal: int

  method deposit(amount: int)
    requires 0 < amount
    ensures bal == old(bal) + amount
  { … }
}
```

```
method demo(a: Account, l: List)
  ensures l.len == old(l.len)
{
  a.deposit(200)
}
```

Example: Side Effects

```
class Account {
  var bal: int
  var transactions: List

  method deposit(amount: int)
    requires 0 < amount
    ensures bal == old(bal) + amount
  { transactions.add(amount) … }

  method getTransactions() returns (t: List)
  { t := transactions }
}
```

```
method demo(a: Account, l: List)
  ensures l.len == old(l.len)
{
  a.deposit(200)
}
```

```
demo(a, a.getTransactions())
```

The Frame Problem

$$\cancel{\dfrac{\{\,P\,\}\ S\ \{\,Q\,\} \qquad FV(S) \cap FV(R) = \{\,\}}{\{\,P \wedge R\,\}\ S\ \{\,Q \wedge R\,\}}}$$

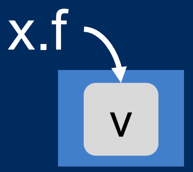
Footprints

$$\frac{\begin{array}{c}\{\,P\,\}\ S\ \{\,Q\,\} \\ \text{footprint}(\,S\,) \cap \text{footprint}(\,R\,) = \{\,\}\end{array}}{\{\,P \wedge R\,\}\ S\ \{\,Q \wedge R\,\}}$$

Separation Logic

- Heap properties are specified via points-to assertions

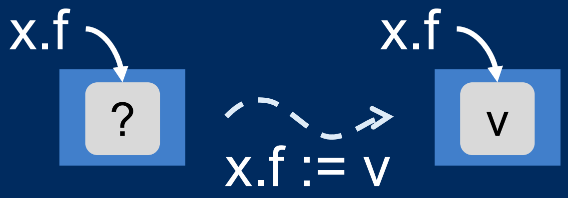
$$x.f \rightarrow v$$



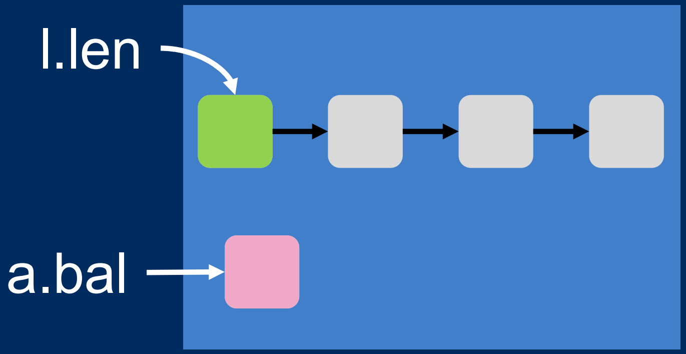
  - Holds in a partial heap that maps the memory location x.f to value v

- Each heap access to x.f requires the current partial heap to contain x.f

$$\{ x.f \rightarrow \_ \} \;\; x.f := v \;\; \{ x.f \rightarrow v \}$$



Footprints in Separation Logic



$$\frac{\{\,P\,\}\ S\ \{\,Q\,\}}{\{\,P \wedge R\,\}\ S\ \{\,Q \wedge R\,\}}$$

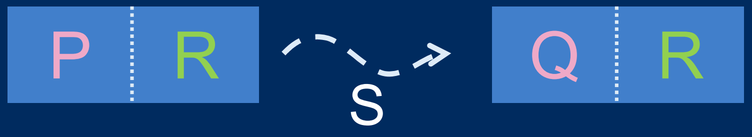
Separation and Framing

- Composition of partial heaps is described using separating conjunction

$$P * R$$

  - Holds in a partial heap if it can be split into two disjoint partial heaps, in which P and Q hold
  - $x.f \rightarrow \_ * x.f \rightarrow \_$ is equivalent to false
  - $x.f \rightarrow \_ * y.f \rightarrow \_$ implies $x \neq y$
- Frame rule

$$\frac{\{\,P\,\}\ S\ \{\,Q\,\}}{\{\,P * R\,\}\ S\ \{\,Q * R\,\}}$$



Example: Framing

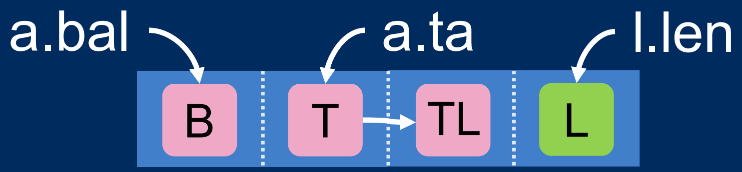
```
class Account {
  var bal: int

  method deposit(amount: int)
    requires this.bal → B ∗ 0 < amount
    ensures this.bal → B + amount
  { … }
}
```

```
method demo(a: Account, l: List)
  requires a.bal → B ∗ l.len → L
  ensures l.len → L
{ a.deposit(200) }
```

Example: Framing

```
class Account {
  var bal: int
  var ta: List

  method deposit(amount: int)
    requires this.bal → B ∗ 0 < amount ∗
             this.ta → T ∗ this.ta.len → TL
    ensures …
  { ta.add(amount) … }
}
```

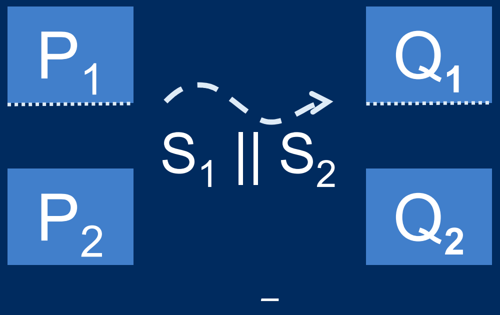
```
method demo(a: Account, l: List)
  requires a.bal → B ∗ l.len → L ∗
           a.ta → T ∗ a.ta.len → TL
  ensures l.len → L
{ a.deposit(200) }
```



Recall $x.f \rightarrow \_ \ast y.f \rightarrow \_$ implies $x \neq y$

demo(a, a.getTransactions())

Parallel Composition



P_1 Q_1

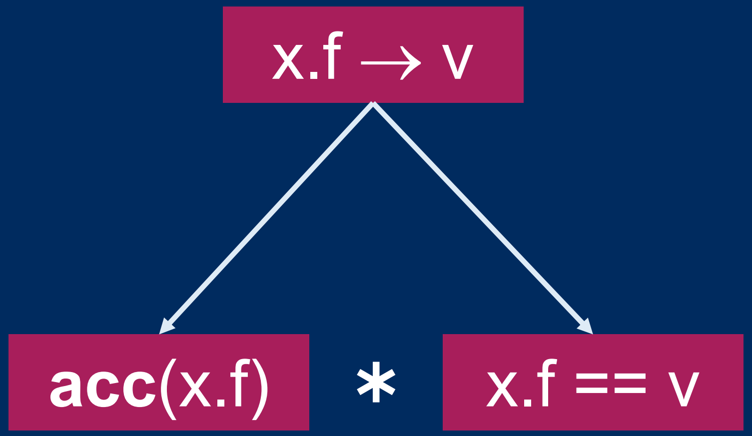
$S_1 \parallel S_2$

P_2 Q_2

Disjointness of footprints ensures data-race freedom

$$\frac{\{\, P_1 \,\}\ S_1\ \{\, Q_1 \,\} \qquad \{\, P_2 \,\}\ S_2\ \{\, Q_2 \,\}}{\{\, P_1 \ast P_2 \,\}\ S_1 \parallel S_2\ \{\, Q_1 \ast Q_2 \,\}}$$

Implicit Dynamic Frames



x.f → v

acc(x.f) ∗ x.f == v

```
method demo(a: Account, l: List)
  requires a.bal → B ∗ l.len → L
  ensures l.len → L
{ a.deposit(200) }
```

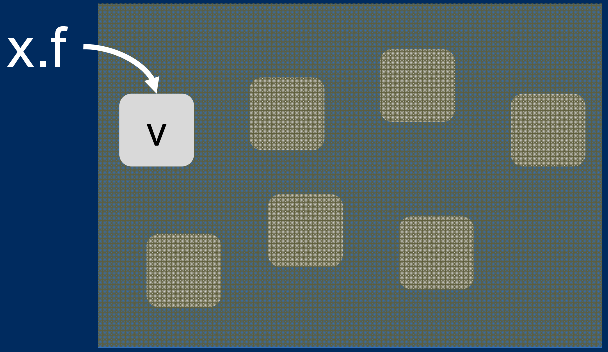
```
method demo(a: Account, l: List)
  requires acc(a.bal) ∗ acc(l.len)
  ensures acc(l.len) ∗ l.len == old(l.len)
{ a.deposit(200) }
```

- Assertions must be self-framing

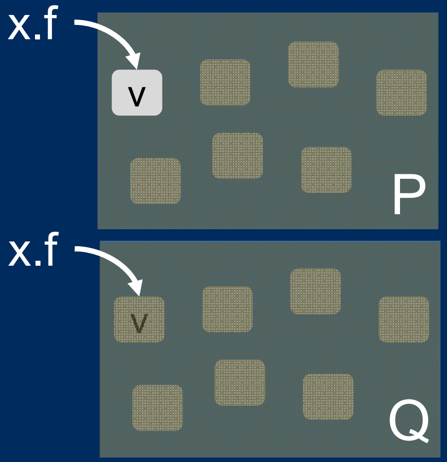
Total-Heap Semantics

- Partial-heap semantics is not suitable

acc(x.f) ∗ x.f == v



- Define semantics relative to a total heap and permission mask
  - x.f == v holds if heap(x,f) yields v
  - **acc**(x.f) holds if permission mask(x,f) yields true
  - P ∗ Q holds if the mask can be split into two compatible masks, in which P and Q hold

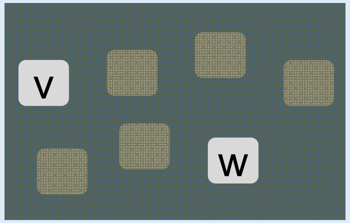


Ownership Transfer

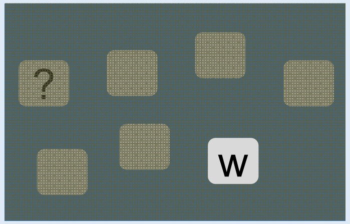
```
class Account {
  var bal: int

  method deposit(amount: int)
    requires acc(this.bal) ∗ …
    ensures acc(this.bal) ∗ …
  { … }
}
```

v’

```
method demo(a: Account, l: List)
  requires acc(a.bal) ∗ acc(l.len)
  ensures acc(l.len) ∗ l.len == old(l.len)
{
```



```
  a.deposit(200)
```



```
}
```

Fractional Permissions

- Permissions can be split and recombined

acc(x.f, 1/2)

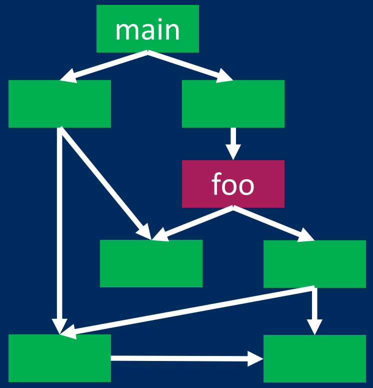
  - Read access requires a non-zero permission
  - Write access requires full permission

- Separating conjunction adds permissions

acc(x.f, 1/2) $\ast$ **acc**(x.f, 1/2) $\equiv$ **acc**(x.f)

Summary

- Modularity is important for scalability, components, and evolution



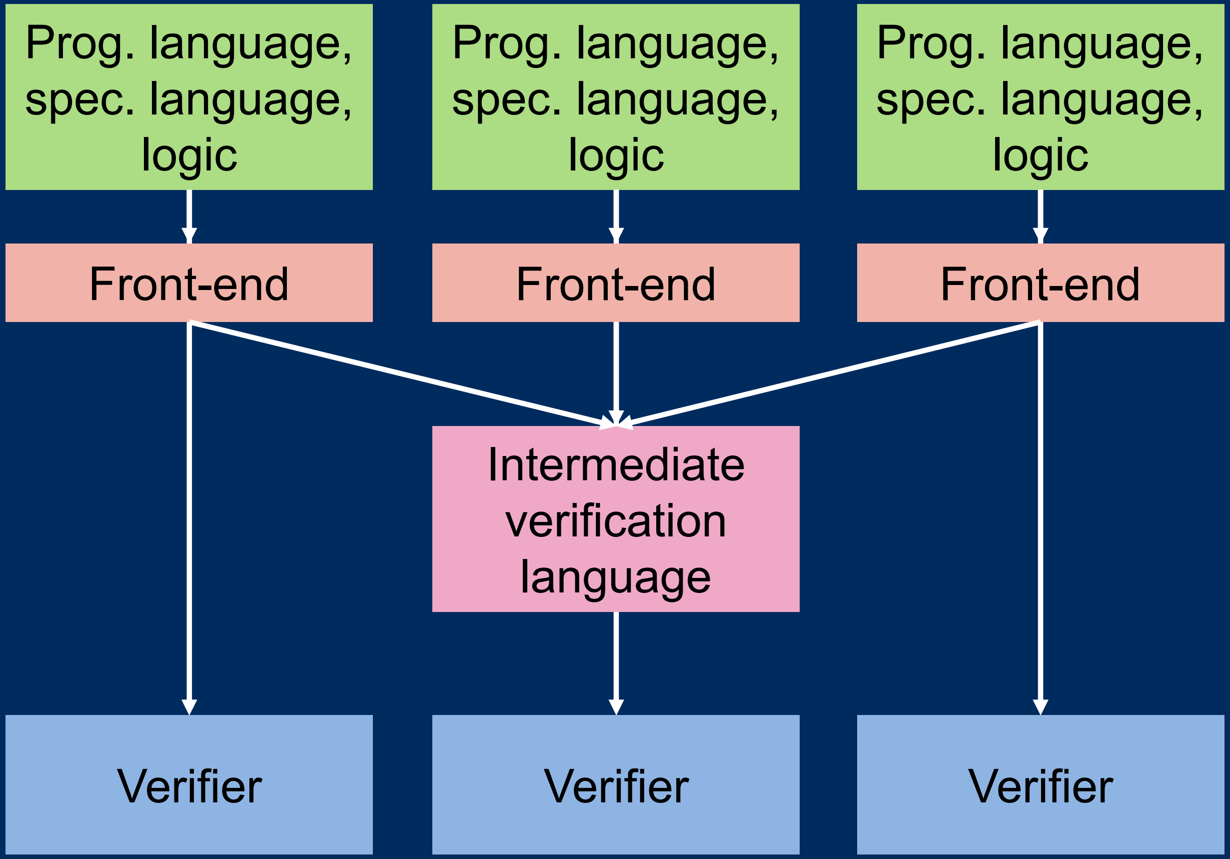
- Contracts enable modular verification
- Permissions
  - provide a solution to the frame problem
  - enable the verification of concurrent programs

$$\frac{\{\,P\,\}\ S\ \{\,Q\,\}}{\{\,P * R\,\}\ S\ \{\,Q * R\,\}}$$

$$\frac{\{\,P_1\,\}\ S_1\ \{\,Q_1\,\} \qquad \{\,P_2\,\}\ S_2\ \{\,Q_2\,\}}{\{\,P_1 * P_2\,\}\ S_1 \,||\, S_2\ \{\,Q_1 * Q_2\,\}}$$

Chalice

- Home page: www.pm.inf.ethz.ch/research/chalice.html
- Try online: www.rise4fun.com/Chalice
- Download: chalice.codeplex.com



Prog. language, spec. language, logic

Prog. language, spec. language, logic

Prog. language, spec. language, logic

Front-end

Front-end

Front-end

Intermediate verification language

Verifier

Verifier

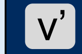
Verifier

Outline

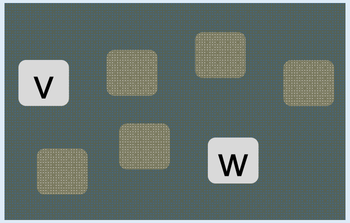
- Permission-based Verification
- The Viper Intermediate Language
- Building Verifiers
- Encoding of Advanced Verification Techniques

Ownership Transfer

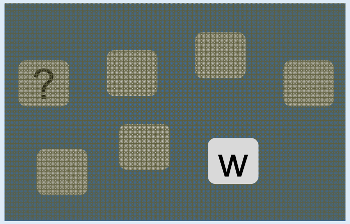
```
class Account {
  var bal: int

  method deposit(amount: int)
    requires acc(this.bal) ∗ …
    ensures acc(this.bal) ∗ …
  { … }
}
```



```
method demo(a: Account, l: List)
  requires acc(a.bal) ∗ acc(l.len)
  ensures acc(l.len) ∗ l.len == old(l.len)
{
```

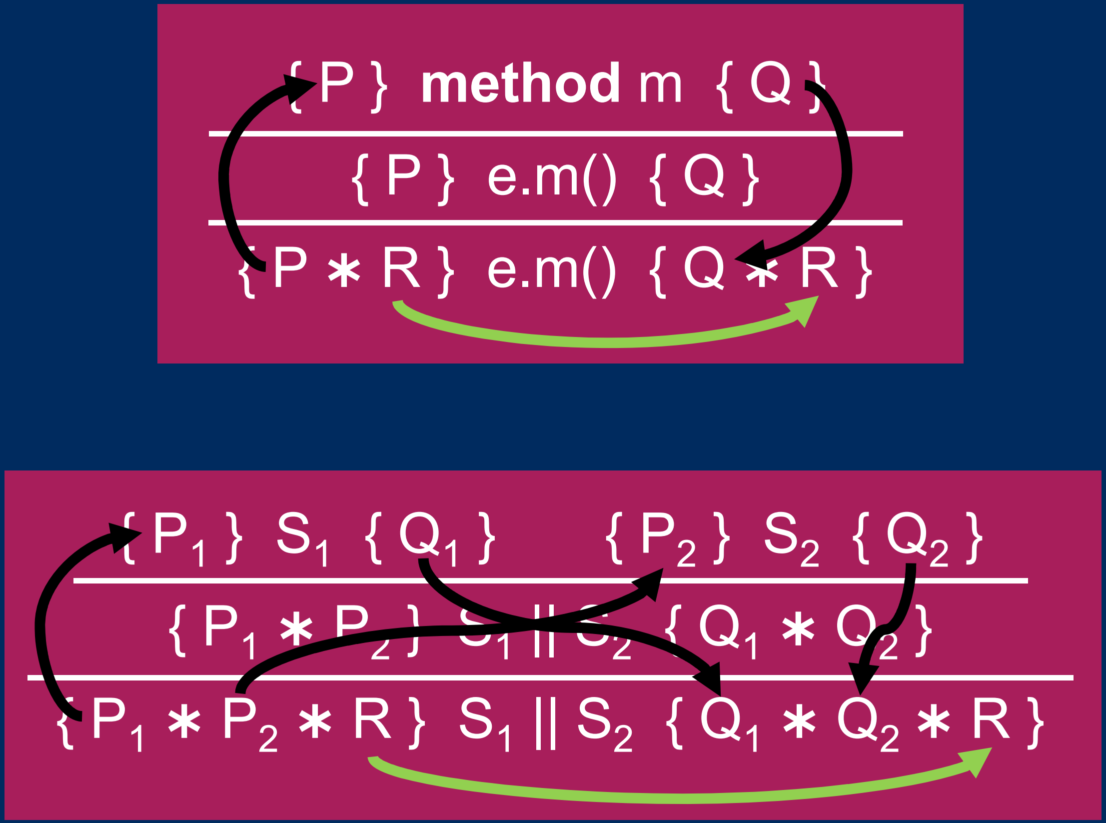


```
  a.deposit(200)
```



```
}
```

Ownership Transfer



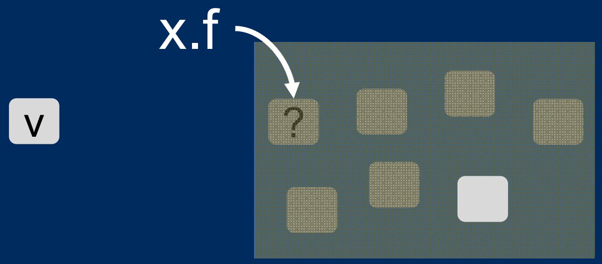
$$\cfrac{\cfrac{\{\,P\,\}\ \ \textbf{method}\ m\ \ \{\,Q\,\}}{\{\,P\,\}\ \ e.m()\ \ \{\,Q\,\}}}{\{\,P \ast R\,\}\ \ e.m()\ \ \{\,Q \ast R\,\}}$$

$$\cfrac{\cfrac{\{\,P_1\,\}\ S_1\ \{\,Q_1\,\} \qquad \{\,P_2\,\}\ S_2\ \{\,Q_2\,\}}{\{\,P_1 \ast P_2\,\}\ S_1 \,\|\, S_2\ \{\,Q_1 \ast Q_2\,\}}}{\{\,P_1 \ast P_2 \ast R\,\}\ S_1 \,\|\, S_2\ \{\,Q_1 \ast Q_2 \ast R\,\}}$$

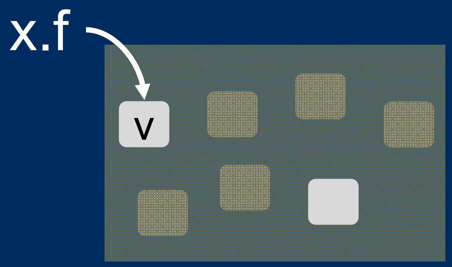
Inhale and Exhale

- **inhale** A means:
  - obtain all permissions required by A
  - assume all logical constraints
- **exhale** A means:
  - assert all logical constraints
  - check and remove all permissions required by A
  - havoc any locations to which all permission is lost
- Analogues of **assume** and **assert**

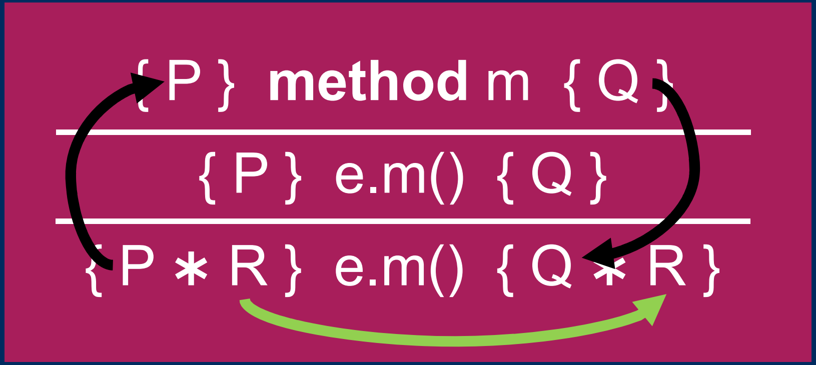
inhale acc(x.f) ∗ x.f == v



exhale acc(x.f) ∗ x.f == v

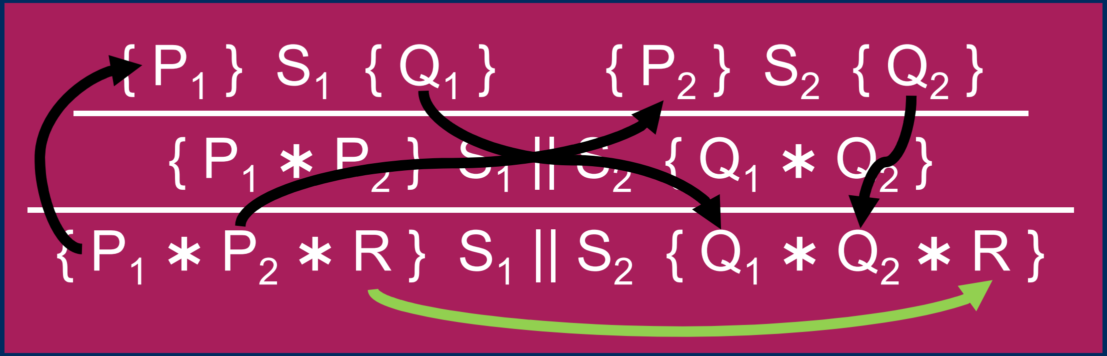


Encoding Ownership Transfer



$$\begin{array}{c} \{P\}\ \textbf{method}\ m\ \{Q\} \\ \hline \{P\}\ e.m()\ \{Q\} \\ \hline \{P * R\}\ e.m()\ \{Q * R\} \end{array}$$

exhale P
inhale Q



$$\begin{array}{c} \{P_1\}\ S_1\ \{Q_1\} \qquad \{P_2\}\ S_2\ \{Q_2\} \\ \hline \{P_1 * P_2\}\ S_1 \,||\, S_2\ \{Q_1 * Q_2\} \\ \hline \{P_1 * P_2 * R\}\ S_1 \,||\, S_2\ \{Q_1 * Q_2 * R\} \end{array}$$

exhale P_1
exhale P_2
inhale Q_1
inhale Q_2

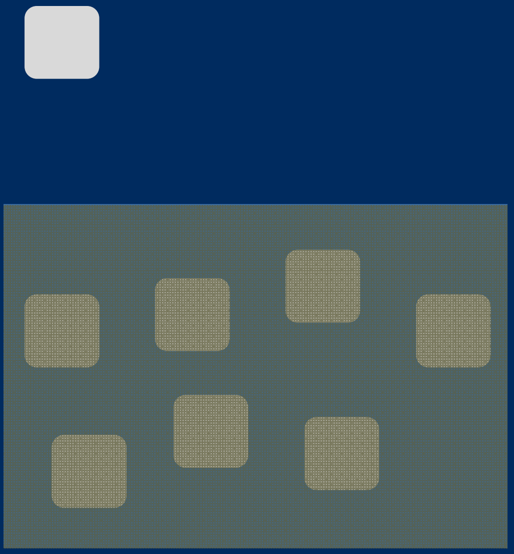
```
method demo(a: Account, l: List)
  requires acc(a.bal) ∗ acc(l.len)
  ensures acc(l.len) ∗ l.len == old(l.len)
{
  a.deposit(200)
}
```

```
method deposit(amount: int)
  requires acc(this.bal)
  ensures acc(this.bal)
```

```
inhale acc(a.bal) ∗ acc(l.len)
exhale acc(a.bal)
inhale acc(a.bal)
exhale acc(l.len) ∗ l.len == old(l.len)
```

Encoding Monitors

```
class Account {
  var bal: int

  invariant acc(this.bal)

  method deposit(amount: int)
  {
    acquire this
    this.bal := this.bal + amount
    release this
  }
}
```



```
inhale acc(this.bal)
this.bal := this.bal + amount
exhale acc(this.bal)
```

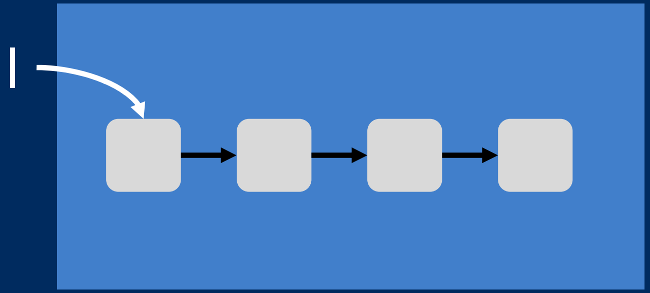
Abstraction

```
method demo(a: Account, l: List)
  requires acc(a.bal) ∗ acc(l.len)
  ensures acc(l.len) ∗ l.len == old(l.len)
{
  a.deposit(200)
}
```

Mentioning field names in contracts:

- Violates information hiding
- Cannot express access to a statically-unknown set of locations

Recursive Predicates



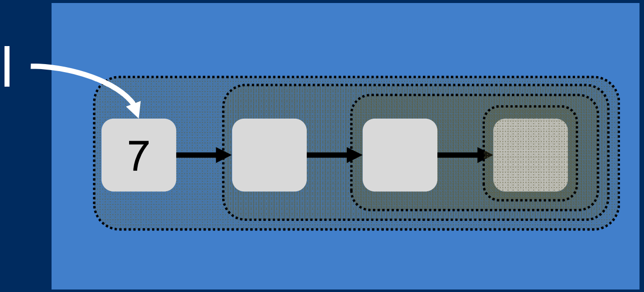
```
predicate list(this: Ref) {
  acc(this.next) ∗ acc(this.data) ∗
  (this.next != null ==> list(this.next))
}
```

- Predicate instances are manipulated similarly to access permissions
  - Ownership is transferred via inhale and exhale
  - But P(x) $*$ P(x) is not equivalent to false

inhale list(a)
exhale list(a)

predicate P(this: **Ref**)
{ **acc**(this.f, 1/3) }

- Folding and unfolding is done manually



unfold list(l)
l.data := 7
fold list(l)

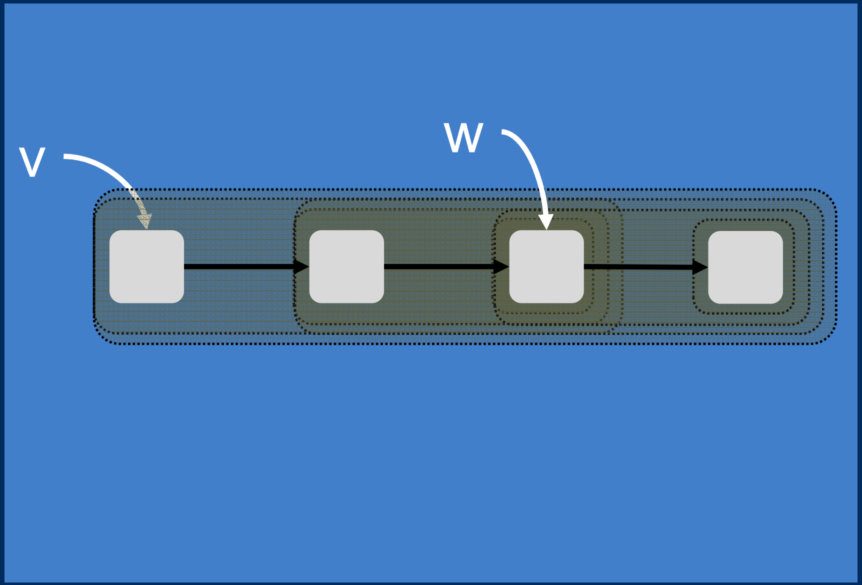
Examples: Recursive Predicates

```
predicate lseg(this: Ref, last: Ref) {
  this != last ==>
       acc(this.next) ∗ acc(this.data) ∗
       lseg(this.next, last)
}
```

```
predicate list(this: Ref) {
  acc(this.next) ∗ acc(this.data) ∗
  (this.next != null ==> list(this.next)) ∗
  0 <= this.data
}
```

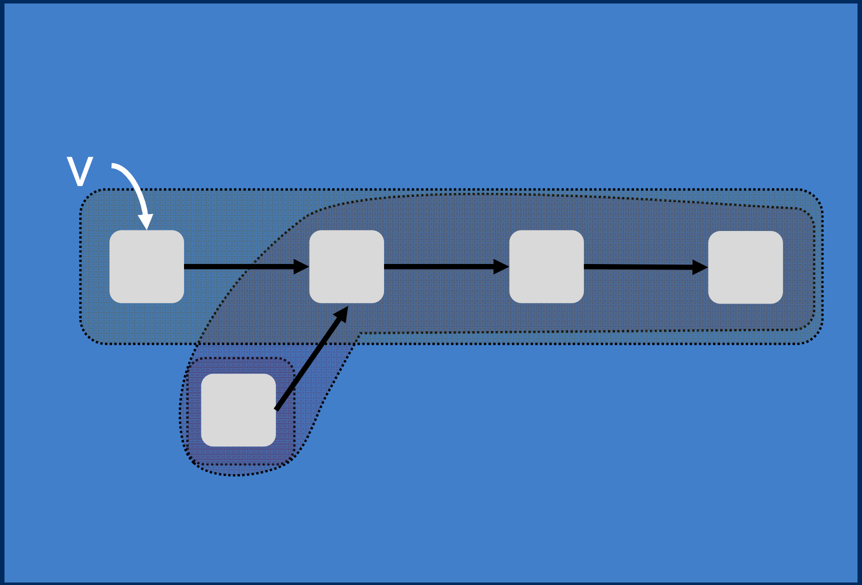
```
predicate list(this: Ref) {
  acc(this.next) ∗ acc(this.data) ∗
  (this.next != null ==> list(this.next) ∗
       this.data <= unfolding list(this.next) in this.next.data)
}
```

Limitations



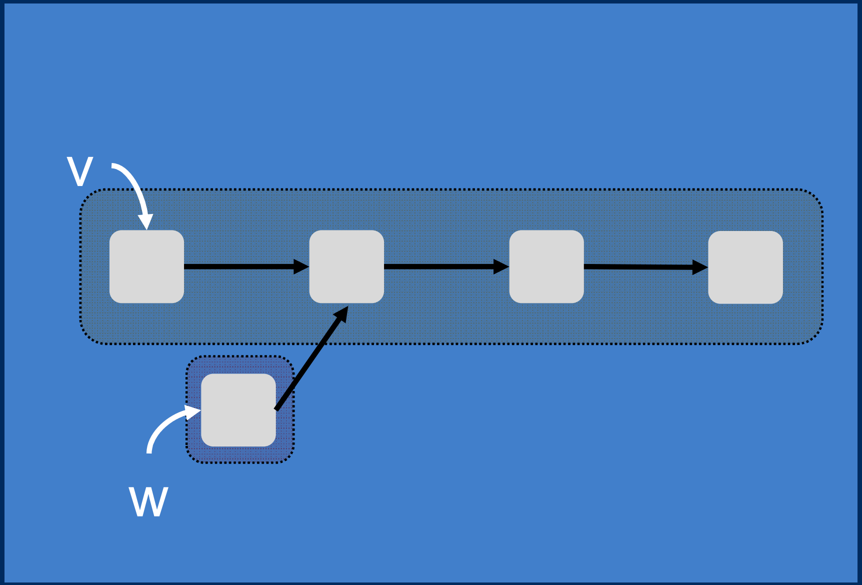
- Extending footprints

Limitations



- Extending footprints
- Sharing

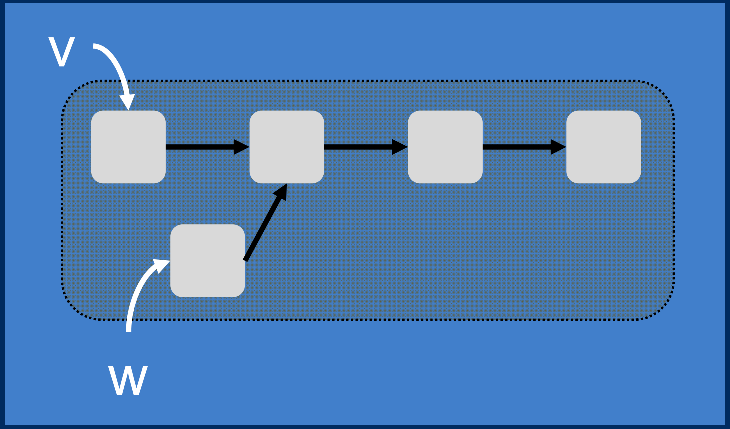
Limitations



- Extending footprints
- Sharing
- Traversal order

Quantified Permissions

```
predicate list( nodes: Set[ Ref ] ) {
  forall n: Ref :: n in nodes ==>
                              acc(n.next) ∗
                              n.next in nodes
}
```



```
list(nodes) ∗
v in nodes ∗ w in nodes
```

Abstraction

```
method demo(a: Account, l: List)
  requires acc(a.bal) ∗ acc(l.len)
  ensures acc(l.len) ∗ l.len == old(l.len)
{
  a.deposit(200)
}
```

Mentioning field names in contracts:

- Violates information hiding
- Cannot express access to a statically-unknown set of locations

Heap-Dependent Functions

- Predicates abstract over permissions

```
predicate list(this: Ref) {
  acc(this.next) ∗ acc(this.data) ∗
  (this.next != null ==> list(this.next))
}
```

- Functions abstract over expressions

```
function length(this: Ref): Int
  requires list(this)
{
  unfolding list(this) in
  this.next == null ? 1 : 1 + length(this.next)
}
```

Abstraction

```
method demo(a: Account, l: List)
  requires account(a) ∗ list(l)
  ensures list(l) ∗ length(l) == old(length(l))
{
  a.deposit(200)
}
```

- Predicates and functions need not have definitions

Function Framing

- Heap-dependent functions are mathematical functions of their arguments and their footprint

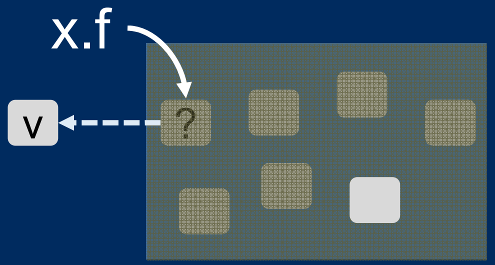
```
function length(this: Ref): Int
  requires list(this)
{
  unfolding list(this) in
  this.next == null ? 1 : 1 + length(this.next)
}
```

Summary

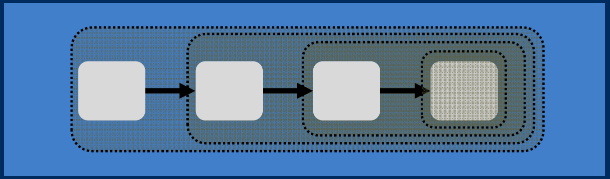
- Intermediate verification languages facilitate the development of program verifiers

- Inhale and exhale primitives express ownership transfer

exhale acc(x.f) ∗ x.f == v



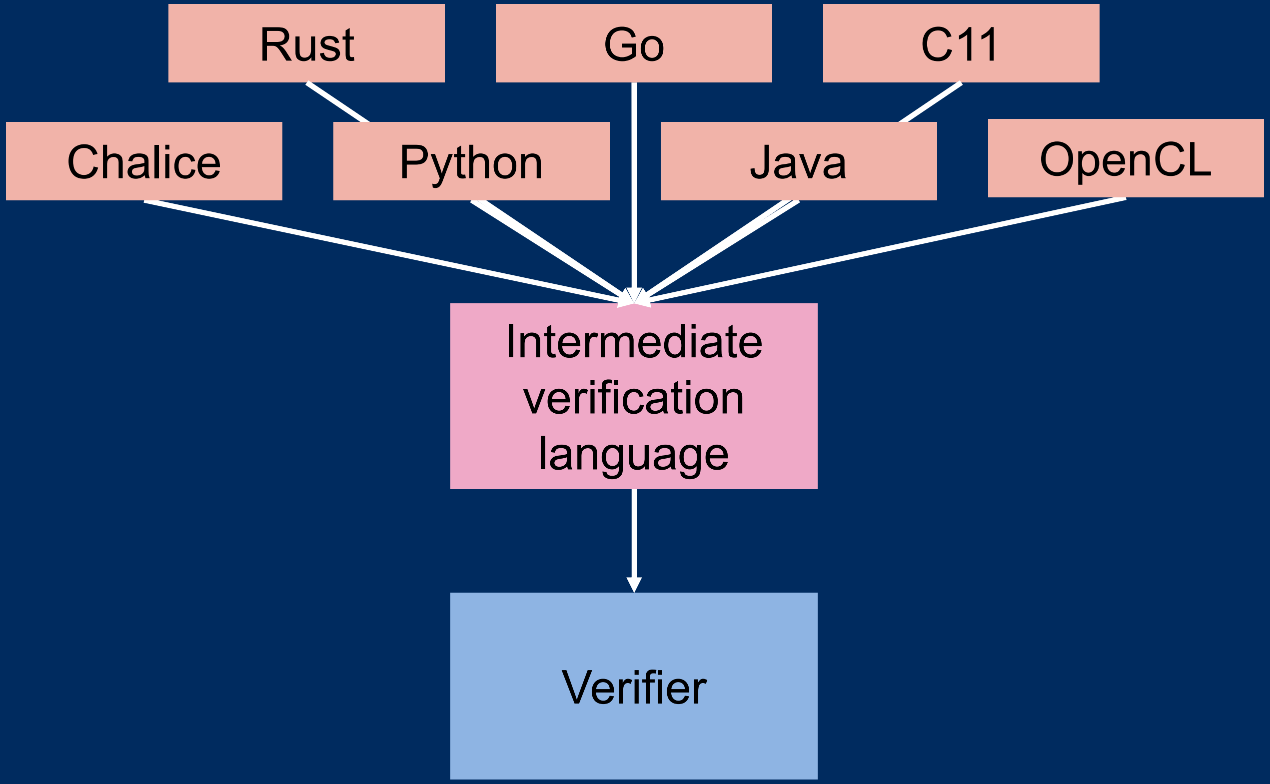
- Predicates and functions abstract over permissions and values



function length(this: **Ref**): **Int**
  requires list(this)

Viper

- Home page: viper.ethz.ch
- Try online: viper.ethz.ch/examples
- Download: bitbucket.org/viperproject
- Download a version for the tutorial on Friday



Rust

Go

C11

Chalice

Python

Java

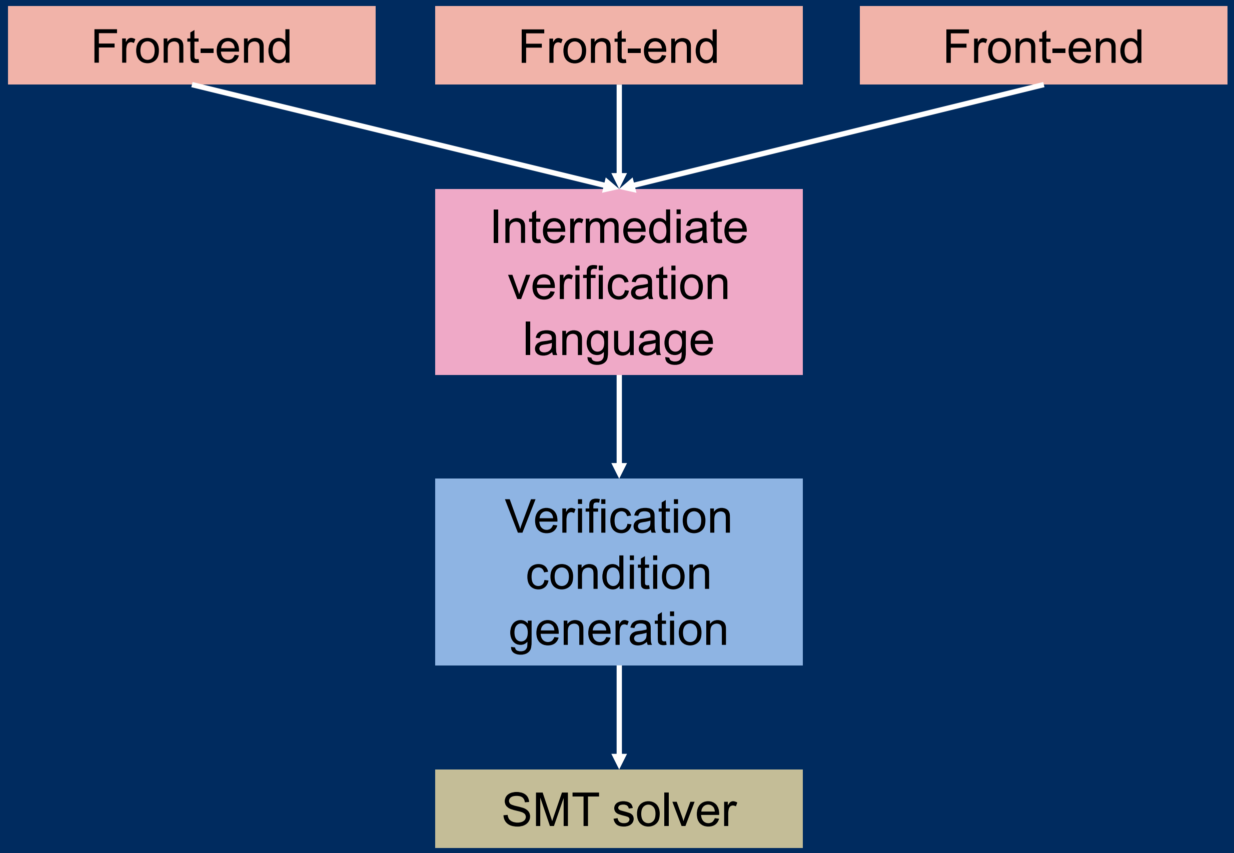
OpenCL

Intermediate verification language

Verifier

Outline

- Permission-based Verification
- The Viper Intermediate Language
- Building Verifiers
- Encoding of Advanced Verification Techniques



Front-end

Front-end

Front-end

Intermediate verification language

Verification condition generation

SMT solver

Verification Condition Generation

- For a given program, verification condition generation computes a logical formula whose validity implies the correctness of the program

- Verification condition reflects semantics of the program and its specification

- We will compute verification conditions in two steps:
  - Encode the Viper program into guarded commands
  - Compute weakest preconditions of guarded-commands programs

Guarded Commands

S ::= x := E
| S_1; S_2
| $S_1 \;\square\; S_2$
| **assert** P
| **assume** P
| **havoc** x

- Assertions P are first-order logic formulas
  - Including quantifiers, uninterpreted functions, arithmetic, etc.

Encoding into Guarded Commands

```
method abs(a: Int) returns (res: Int)
  ensures  0 <= res
{
  if(0 <= a)   { res := a }
  else         { res := -a }
}
```

```
 (
  assume 0 <= a
  res := a
▯
  assume a < 0
  res := -a
)
assert 0 <= res
```

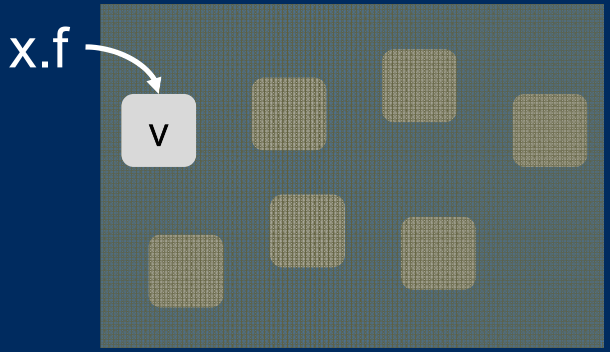
Weakest Preconditions

$$
\begin{aligned}
wp(x := E, Q) &\equiv Q[E/x] \\
wp(S_1; S_2, Q) &\equiv wp(S_1, wp(S_2, Q)) \\
wp(S_1 \, \square \, S_2, Q) &\equiv wp(S_1, Q) \wedge wp(S_2, Q) \\
wp(\textbf{assert } P, Q) &\equiv P \wedge Q \\
wp(\textbf{assume } P, Q) &\equiv P \Rightarrow Q \\
wp(\textbf{havoc } x, Q) &\equiv \forall x \bullet Q
\end{aligned}
$$

To verify statement S, prove that wp(S, true) holds

Heap Model

- Define semantics relative to a total heap and permission mask
  - x.f == v holds if heap(x,f) yields v
  - **acc**(x.f) holds if permission mask(x,f) yields true



- Model heap as total map

Ref × Field<T> → T

- Model permission mask as total map

Ref × Field<T> → Bool

Encoding inhale

$$\begin{aligned}
\langle \textbf{inhale}\ e\rangle &\equiv \textbf{assume}\ \langle e\rangle\\
\langle \textbf{inhale}\ \textbf{acc}(e.f)\rangle &\equiv \textbf{assume}\ \langle e\rangle \neq \text{null}\\
&\ \textbf{assume}\ \neg\text{mask}(\langle e\rangle, f)\\
&\ \text{mask}(\langle e\rangle, f) := \textbf{true}\\
\langle \textbf{inhale}\ a_1 \ast a_2\rangle &\equiv \langle \textbf{inhale}\ a_1\rangle; \langle \textbf{inhale}\ a_2\rangle
\end{aligned}$$

- ⟨ _ ⟩ is the encoding function
- a is an assertion
- e is an expression (not containing permissions)

```
inhale acc(x.f) ∗ x.f == v
```

```
assume x ≠ null
assume ¬mask(x,f)
mask(x,f) := true

assume heap(x,f) == v
```

```
inhale acc(x.f) ∗ acc(y.f)
```

```
assume x ≠ null
assume ¬mask(x,f)
mask(x,f) := true

assume y ≠ null
assume ¬mask(y,f)
mask(y,f) := true
```

Encoding exhale

⟨⟨**exhale** e⟩⟩ ≡ **assert** ⟨e⟩

⟨⟨**exhale acc**(e.f)⟩⟩ ≡ **assert** mask(⟨e⟩, f)
mask(⟨e⟩, f) := **false**

⟨⟨**exhale** a_1 ∗ a_2⟩⟩ ≡ ⟨⟨**exhale** a_1⟩⟩; ⟨⟨**exhale** a_2⟩⟩

⟨**exhale** a⟩ ≡ ⟨⟨**exhale** a⟩⟩
h := heap
havoc heap
assume ∀x,f • mask(x,f) ⇒ heap(x,f) == h(x,f)

```
exhale acc(x.f) ∗ x.f == v
```

```
assert mask(x,f)
mask(x,f) := false

assert heap(x,f) == v

// havoc heap(x,f)
```

```
exhale acc(x.f) ∗ acc(y.f)
```

```
assert mask(x,f)
mask(x,f) := false

assert mask(y,f)
mask(y,f) := false

// havoc heap(x,f), heap(y,f)
```

Predicates

- For each predicate, introduce a function that maps a predicate instance to a field name

predicate lseg(this: **Ref**, last: **Ref**)

lsegField: Ref × Ref → Field<**Int**>

- Use this field to index mask

inhale lseg(a, b)

mask(null, lsegField(a, b)) := **true**

Heap-Dependent Functions

- Encode Viper function as mathematical function

```
function balance(this: Ref): Int
  requires acc(this.bal)
```

balance: Ref × Int → **Int**

- Function applications evaluate footprint

```
balance(x)
```

balance(x, heap(x.bal))

Heap-Dependent Functions

- Encode Viper function as mathematical function

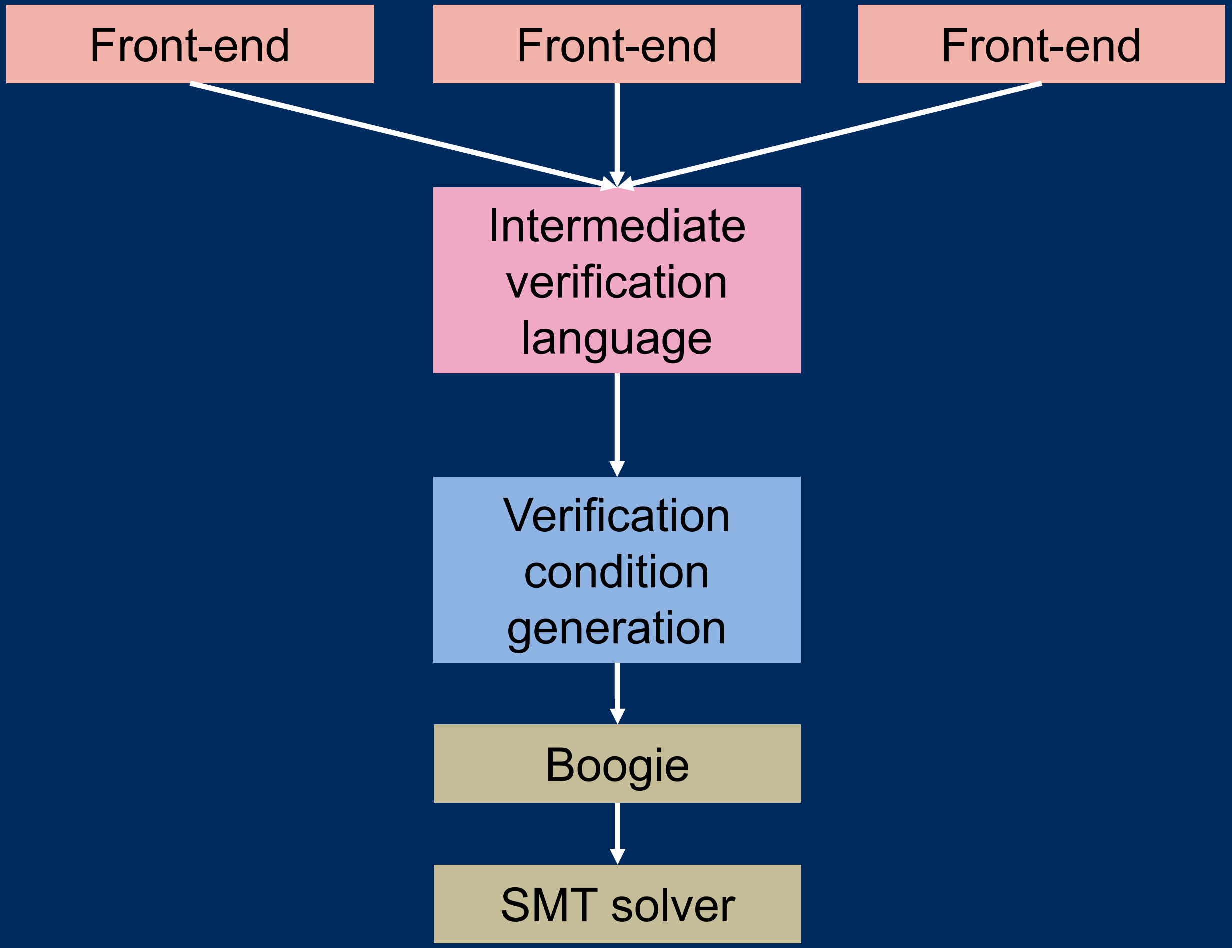
```
function length(this: Ref): Int
  requires list(this)
```

```
balance: Ref × Int→ Int
```

- Give predicate instances a version number
  - Changes each time the predicate’s footprint may change

```
length(x)
```

```
length(x, heap(null, listField(x)))
```



Front-end

Front-end

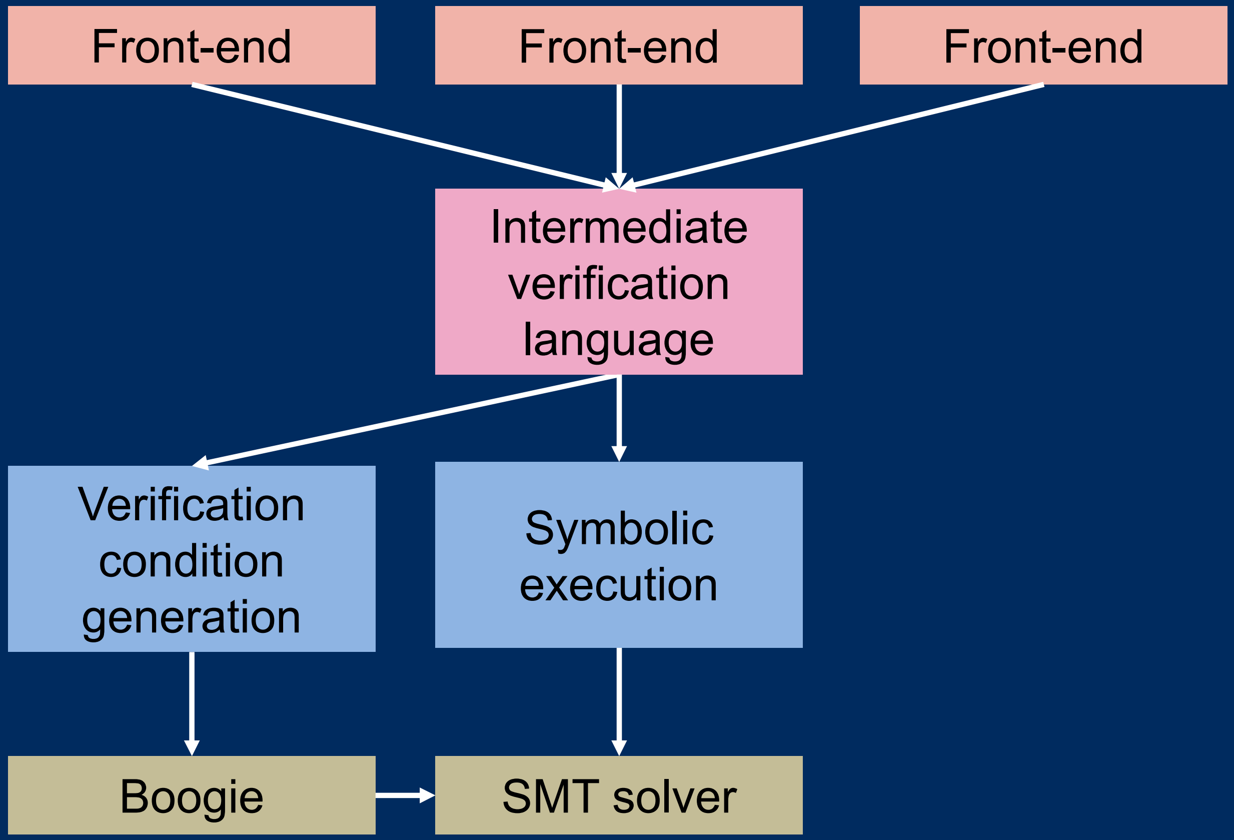
Front-end

Intermediate verification language

Verification condition generation

Boogie

SMT solver



Front-end

Front-end

Front-end

Intermediate verification language

Verification condition generation

Symbolic execution

Boogie

SMT solver

Symbolic Execution

- Symbolic execution simulates the execution of a program statically, using symbolic rather than concrete values
  - Introduce symbolic variables to represent inputs

- A configuration consists of
  - The statement to be executed
  - An environment, mapping program variables to expressions over the symbolic variables
  - A path condition, a logic formula representing information about the symbolic variables

```
method abs(a: Int) returns (res: Int)
  ensures  0 <= res
{
  if(0 <= a)  { res := a }
  else        { res := -a }
}
```

Statement	Environment		Path Condition
	a	res	
if(0 <= a) { res := a } **else** { res := -a } **assert** 0 <= res	A	R	true
res := a; **assert** 0 <= res	A	R	$0 \le A$
assert 0 <= res	A	A	$0 \le A$

check $0 \le A \Rightarrow 0 \le A$ ✓

Statement	Environment		Path Condition
	a	res	
res := -a; **assert** 0 <= res	A	R	$A < 0$
assert 0 <= res	A	-A	$A < 0$

check $A < 0 \Rightarrow 0 \le -A$ ✓

Algorithm

```
$\sigma$ := { (s;stop, $env_0$, true) }
while $\sigma \neq \{ \}$ do
  $\gamma$ := take($\sigma$)
  r := step($\gamma$)
  if r = $\perp$ then return failure
  $\sigma := \sigma \cup r$
end
return success
```

- s is the program to be verified
- stop is an artificial stop-marker
- env_0 maps each program variable to a fresh symbolic variable

Algorithm

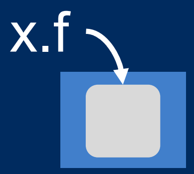
$$\begin{aligned}
&\text{step}(x := e;s,\ env,\ \pi) &&= \{\ (s,\ env[x := \langle e \rangle],\ \pi)\ \}\\
&\text{step}(\textbf{if}(e)\ \{\ s_1\ \}\ \textbf{else}\ \{\ s_2\ \};s,\ env,\ \pi) &&= \{\ (s_1;s,\ env,\ \pi \wedge \langle e \rangle),\ (s_2;s,\ env,\ \pi \wedge \neg\langle e \rangle)\ \}\\
&\text{step}(\textbf{assert}\ e;s,\ env,\ \pi) &&= \text{if check}(\pi \Rightarrow \langle e \rangle)\ \text{then}\ \{\ (s,\ env,\ \pi)\ \}\ \text{else}\ \bot\\
&\text{step}(\text{stop},\ env,\ \pi) &&= \{\ \}
\end{aligned}$$

- $\langle \_ \rangle$ symbolically evaluates an expression to a symbolic expression
- check is a query to the SMT solver

Heap Model

- The symbolic heap models the partial-heap semantics

acc(x.f)



- Model heap as set of heap chunks (E_r and E_v are symbolic expressions)

$E_r.f \rightarrow E_v$

- Extend configurations by a symbolic heap

Executing inhale

$\text{step}(\textbf{inhale}\ e;s,\ env,\ \pi,\ h) \equiv$

$\qquad \{\ (s,\ env,\ \pi \wedge \langle e \rangle,\ h)\ \}$

$\text{step}(\textbf{inhale}\ \textbf{acc}(e.f);s,\ env,\ \pi,\ h) \equiv$

$\qquad \{\ (s,\ env,\ \pi \wedge \langle e \rangle \neq \text{null} \wedge \bigwedge_{E.f \to \_\ \in\ h} E \neq \langle e \rangle,\ h \cup \{\ \langle e \rangle.f \to V\ \})\ \}$

$\text{step}(\textbf{inhale}\ a_1 \ast a_2;s,\ env,\ \pi,\ h) \equiv$

$\qquad \text{step}(\textbf{inhale}\ a_1;\textbf{inhale}\ a_2;s,\ env,\ \pi,\ h)$

Statement	Environment		Path Condition	Heap
	x	v		
inhale acc(x.f) **inhale** x.f == v	X	V	true	{ }
inhale x.f == v	X	V	true	{ X.f→W }
	X	V	W = V	{ X.f→W }

Statement	Environment		Path Condition	Heap
	x	y		
inhale acc(x.f) **inhale acc**(y.f)	X	Y	true	{ }
inhale acc(y.f)	X	Y	true	{ X.f→W }
	X	Y	X ≠ Y	{ X.f→W, Y.f→Z }

Executing exhale

```
inhale acc(x.f) ∗ x.f == v
exhale acc(x.f) ∗ x.f == v
```

Environment		Path Condition	Heap
x	v		
X	V	true	{ }
X	V	true	{ X.f→W }
X	V	W = V	{ X.f→W }
X	V	W = V	{ } ✗

- Solution: evaluate expressions in the heap before the exhale

Executing exhale

step(**exhale** a;s, env, π, h) $\equiv$ step'(**exhale** a;s, env, π, h, h)

step'(**exhale** e;s, env, π, h, h_0) $\equiv$
    if check($\pi \Rightarrow \langle e \rangle_0$) then { (s, env, π, h) } else $\bot$

step'(**exhale acc**(e.f);s, env, π, h, h_0) $\equiv$
    if $\langle e \rangle_0$.f$\rightarrow$_ $\in$ h then { (s, env, π, h \ { $\langle e \rangle_0$.f$\rightarrow$_ }) } else $\bot$

step'(**exhale** $a_1 * a_2$;s, env, π, h, h_0) $\equiv$
    let γ = step'(**exhale** a_1;**exhale** a_2;s, env, π, h, h_0) in
    if $\gamma = \bot$ then $\bot$ else step'(γ, h_0)

Predicates

- Predicate instances are represented by heap chunks of the form

$$p(E_1, \ldots, E_n) \to E_v$$

where E_v is a symbolic expression denoting the instance's footprint

```
predicate list(this: Ref) {
  acc(this.next) ∗ acc(this.data) ∗
  (this.next != null ==> list(this.next))
}
```

$$FP_{list} ::= (Ref, Int, FP_{list}) \mid \varepsilon$$

Heap-Dependent Functions

- Symbolic expressions may contain function applications

```
function balance(this: Ref): Int
  requires acc(this.bal)
```

balance: Ref × **Int**→ **Int**

- Predicate footprints allow framing

```
function length(this: Ref): Int
  requires list(this)
```

length: Ref × $\mathrm{FP}_{\mathrm{list}}$→ **Int**

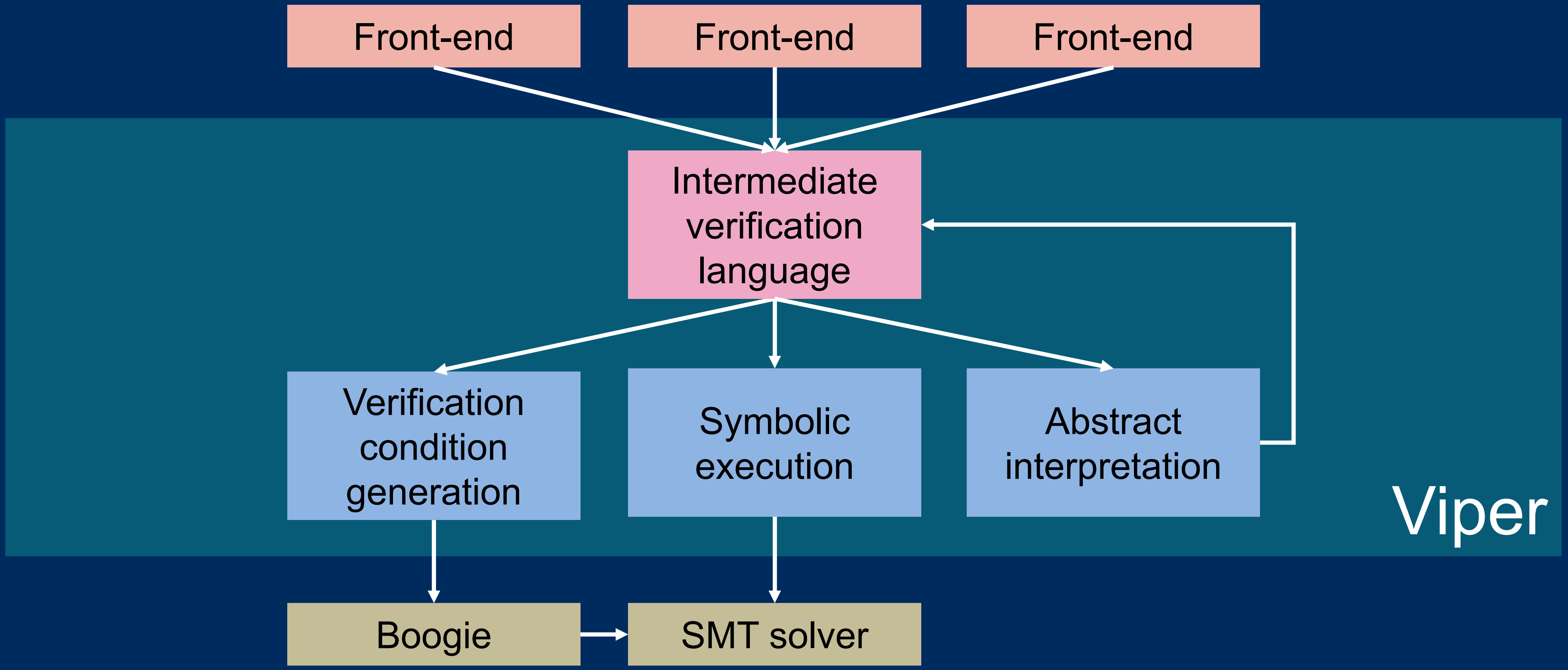
Pros and Cons of Symbolic Execution

Pros

- Small prover queries lead to better, more predictable performance
- Higher control over proof search enables dedicated algorithms

Cons

- Separation of path and heap information can lead to incompleteness
- Internal treatment of heap reasoning requires dedicated algorithms



Front-end

Front-end

Front-end

Intermediate verification language

Verification condition generation

Symbolic execution

Abstract interpretation

Viper

Boogie

SMT solver

Summary

- SMT solvers can be used to automate permission-based verification

- Verification condition generation encodes total-heap semantics
- VCG can be implemented as an encoding into existing languages and tools

- Symbolic execution implements partial-heap semantics
- Performs heap-reasoning internally, and uses SMT solver to reason about value information

Outline

- Permission-based Verification
- The Viper Intermediate Language
- Building Verifiers
- Encoding of Advanced Verification Techniques

Reminder: Encoding Monitors

```
class Account {
  var bal: int

  invariant acc(this.bal)

  method deposit(amount: int)
  {
    acquire this
    this.bal := this.bal + amount
    release this
  }
}
```

```
inhale acc(this.bal)
this.bal := this.bal + amount
exhale acc(this.bal)
```

Non-Blocking Data Structures

- Permissions ensures data race freedom
  - Monitors and other synchronization are used to transfer ownership between threads

- Non-blocking data structures can increase performance by allowing extra concurrency
  - Synchronization is done through atomic operations such as compare-and-swap (CAS)
  - Data races are permitted

```
typedef int SpinLock;

void Lock(SpinLock* sl) {
  while(CAS(sl, 0, 1))
    ;
}

void UnLock(SpinLock* sl) {
  *sl = 0;
}
```

Weak Memory

- Modern hardware often does not provide sequentially consistent shared memory
- Weak memory permits behaviors that are not possible under sequential consistency
- However, data-race free programs have only sequentially consistent behaviors

```
                a = 0;
                b = 0;

a = 1;          ||        b = 1;
print(b);       ||        print(a);
```

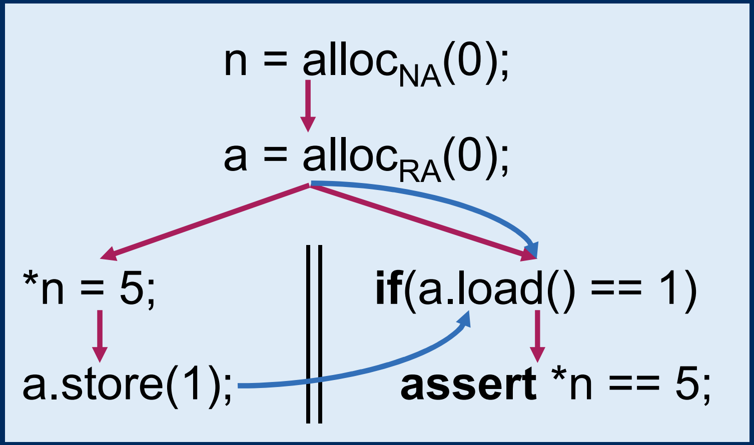
Possible results:
under SC: 10, 01, 11
under WM: also 00

C11

- The C11 memory model provides several kinds of variables

- Non-atomic variables
    - Data races are errors

- Atomic variables with release-write and acquire-read
    - Writes and reads are synchronized



n = alloc_{NA}(0);

a = alloc_{RA}(0);

*n = 5;

a.store(1);

||

if(a.load() == 1)

assert *n == 5;

- Relaxed separation logic (RSL) supports some features of the C11 memory model

Non-Atomic Variables

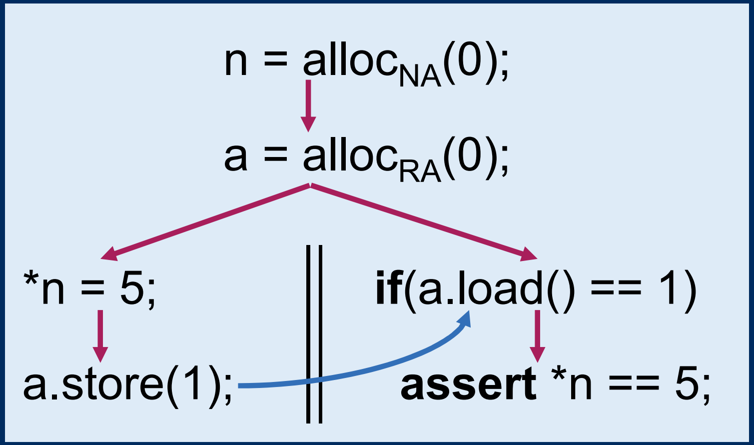
- Permissions prevent data races on non-atomic variables

$$\{\ \text{true}\ \}\ \ x = \text{alloc}_{NA}(v)\ \ \{\ x \rightarrow v\ \}$$

$$\{\ x \rightarrow \_\ \}\ \ {}^*x = v\ \{\ x \rightarrow v\ \}$$

$$\{\ x \rightarrow V\ \}\ \ t = {}^*x\ \{\ x \rightarrow V \ast t = V\ \}$$

Release-Acquire


n = alloc$_{NA}$(0);

a = alloc$_{RA}$(0);

*n = 5;

a.store(1);

||

if(a.load() == 1)

assert *n == 5;

- Races on atomic variables are permitted
- Release-acquire can be seen as message passing
- Messages may transfer ownership to non-atomic variables

Reminder: Monitor Invariants

- Monitor invariant Q specifies an assertion that holds when monitor is not currently held

- Acquire transfers ownership of Q from monitor to thread

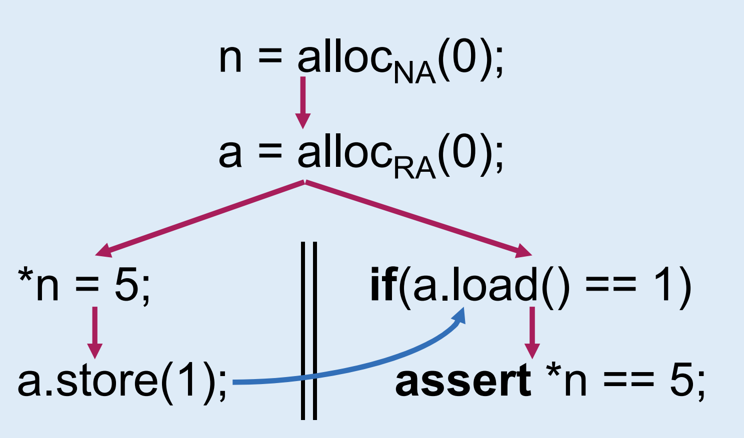
- Release transfers ownership of Q from thread to monitor

```
class Account {
  var bal: int

  invariant acc(this.bal)

  method deposit(amount: int)
  {
    acquire this
    this.bal := this.bal + amount
    release this
  }
}
```

Location Invariants

- Location invariant Q(v) specifies an assertion that holds when the location has value v
- Acquire-read of value v transfers ownership of Q(v) from atomic variable to thread
- Release-write of value v transfers ownership of Q(v) from thread to atomic variable

$$Q(v) \equiv \begin{cases} n \to 5 & \text{if } v = 1 \\ \text{true} & \text{otherwise} \end{cases}$$



n = alloc_{NA}(0);

a = alloc_{RA}(0);

*n = 5; || **if**(a.load() == 1)

a.store(1); || **assert** *n == 5;

Proof Rules

- Choose location invariant when allocating an atomic location

$$\{ Q(v) \} \;\; x = \mathrm{alloc}_{RA}(v) \;\; \{ \mathrm{Rel}_Q(x) \ast \mathrm{Acq}_Q(x) \}$$

- Release-write gives up ownership

$$\{ \mathrm{Rel}_Q(x) \ast Q(v) \} \;\; x.\mathrm{store}(v) \; \{ \mathrm{Rel}_Q(x) \}$$

- Acquire-read gains ownership

$$\{ \mathrm{Acq}_Q(x) \} \;\; t = x.\mathrm{load}() \; \{ Q(t) \ast \mathrm{Acq}_Q(x) \}$$

Proof Outline

$\{ \text{true} \}$

$n = \text{alloc}_{NA}(0);$

$\{ n \rightarrow 0 \}$

$a = \text{alloc}_{RA}(0);$

$\{ n \rightarrow 0 \ast \text{Rel}_Q(a) \ast \text{Acq}_Q(a) \}$

$\{ n \rightarrow 0 \ast \text{Rel}_Q(a) \}$

$*n = 5;$

$\{ n \rightarrow 5 \ast \text{Rel}_Q(a) \}$

$a.\text{store}(1);$

$\{ \text{Rel}_Q(a) \}$

$\{ \text{Acq}_Q(a) \}$

if(a.load() == 1)

$\{ Q(1) \ast \text{Acq}_Q(a) \}$

assert *n == 5;

$$Q(v) \equiv \begin{cases} n \rightarrow 5 & \text{if } v = 1 \\ \text{true} & \text{otherwise} \end{cases}$$

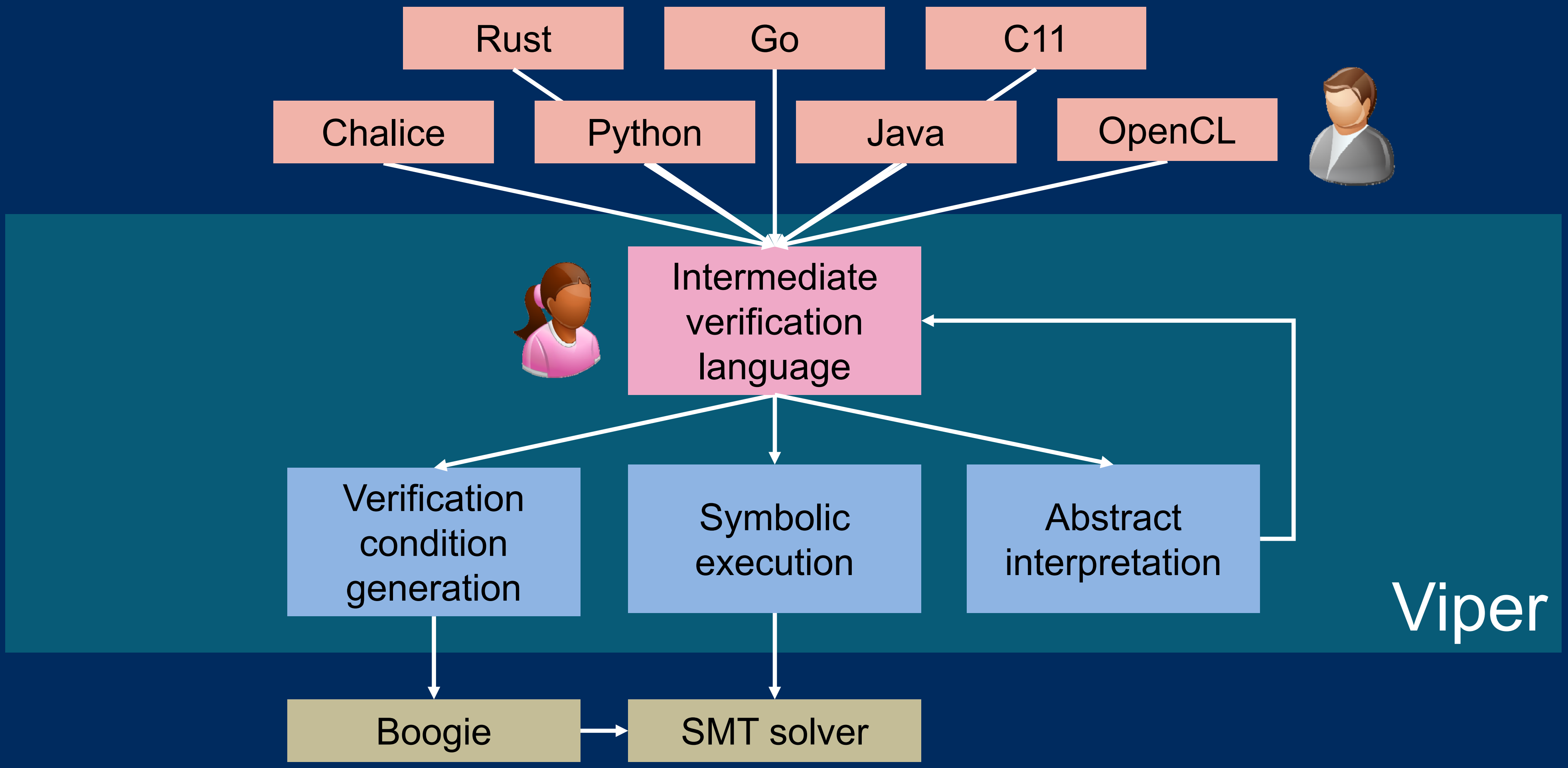
Proof Rules

$$\{\ \mathrm{Acq}_Q(x)\ \}\ \ t = x.\mathrm{load}()\ \{\ Q(t) \ast \mathrm{Acq}_{Q[t\ :=\ \mathrm{true}]}(x)\ \}$$

- Reading the same value more than once would duplicate permissions

$$Q(v) \equiv \begin{cases} n \rightarrow 5 & \text{if } v = 1 \\ \text{true} & \text{otherwise} \end{cases}$$

```
x = a.load();
y = a.load();
if(x == 1 && y == 1)
   assert false;
```



Rust

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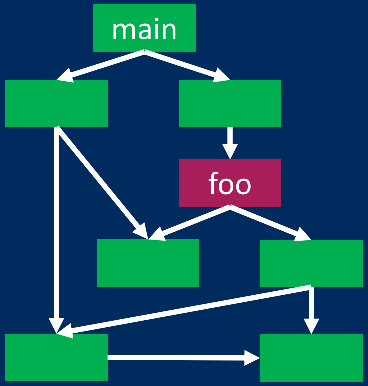


main

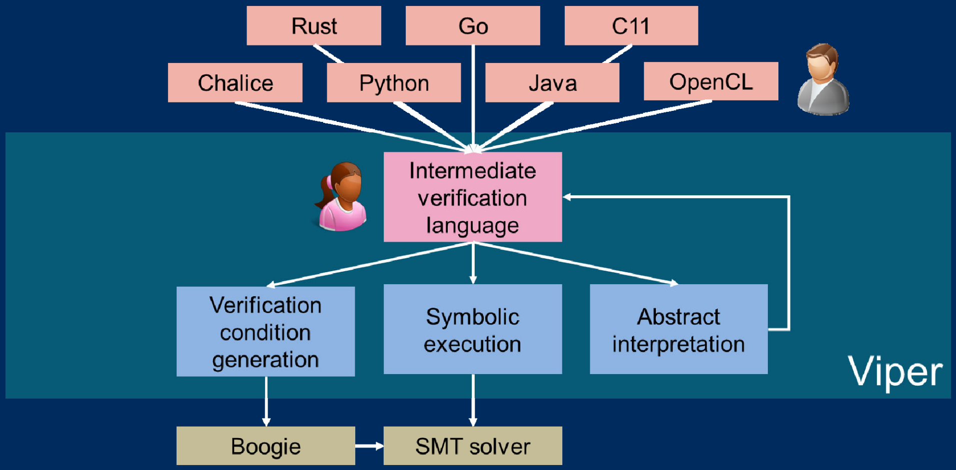
foo

Modularity is important for scalability, components, and evolution

$$\frac{\{\,P\,\}\ S\ \{\,Q\,\}}{\{\,P * R\,\}\ S\ \{\,Q * R\,\}}$$

$$\frac{\{\,P_1\,\}\ S_1\ \{\,Q_1\,\} \qquad \{\,P_2\,\}\ S_2\ \{\,Q_2\,\}}{\{\,P_1 * P_2\,\}\ S_1 \,||\, S_2\ \{\,Q_1 * Q_2\,\}}$$

Permissions enable framing and reasoning about concurrency



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Intermediate languages enable reuse of infrastructure

VIPER

Viper lets you encode a wide variety of reasoning techniques

References: Lecture 1

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References: Lecture 3

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