

Dynamic Semantics

Eelco Visser

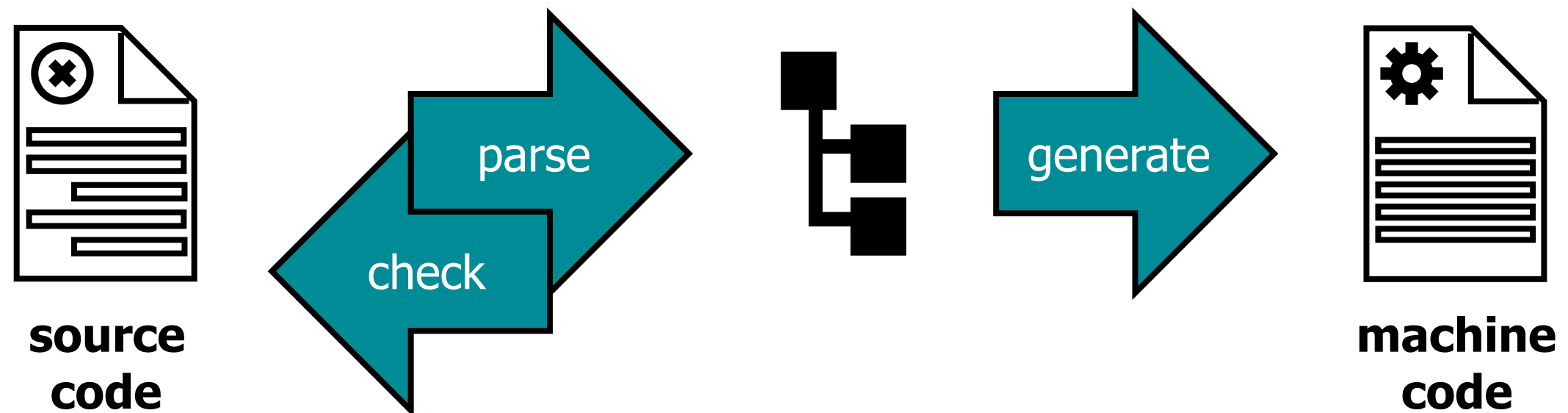
Outline

- The meaning of programs
- Operational semantics
- DynSem: A DSL for dynamic semantics specification
- Interpreter generation
- Scopes describe frames

Semantics

What is the meaning of a program?

$$\text{meaning}(p) = \text{behavior}(p)$$



$\text{meaning}(p)$ = what happens when executing the generated (byte) code to which p is compiled

What is the meaning of a program?

$$\text{meaning}(p) = \text{behavior}(p)$$

What *is* behavior?

How can we *observe* behavior?

Mapping input to output

Changes to state of the system

Which behavior is essential, which accidental?

How can we define the semantics of a program?

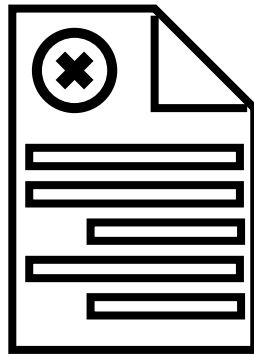
Compiler defines *translational* semantics

$$\text{semanticsL1}(p) = \text{semanticsL2}(\text{translate}(p))$$

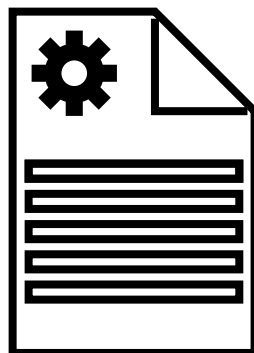
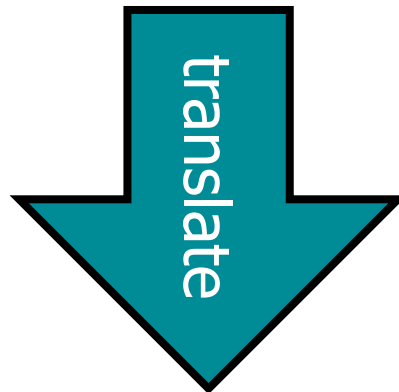
Requires understanding `translate` and `semanticsL2`

How do we know that `translate` is correct?

Is there a more ***direct description*** of `semanticsL1`?

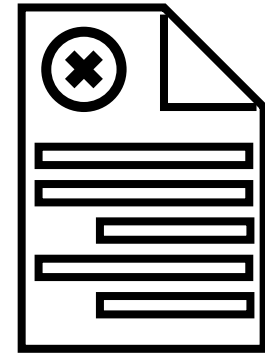
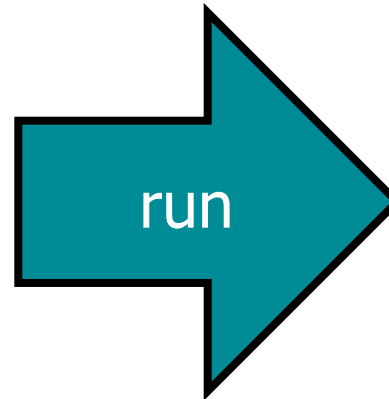


**source
code**

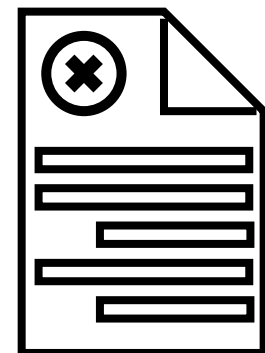
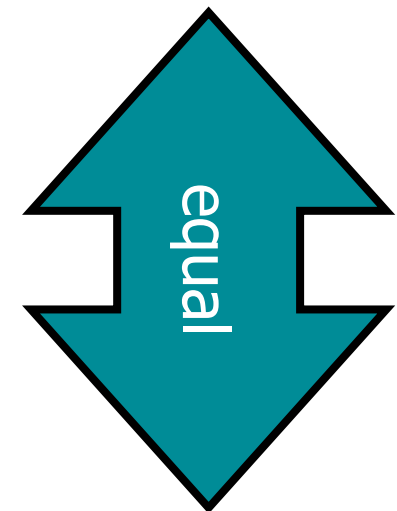


**machine
code**

semanticsL1

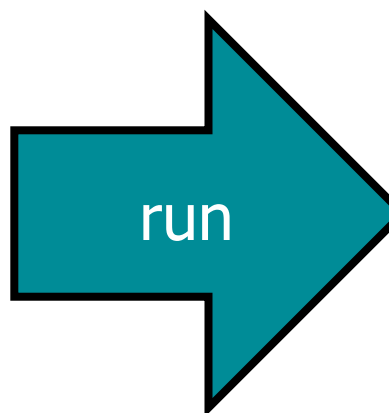


value



value

semanticsL2



Verifying Compiler Correctness

Direct semantics of source language provides a specification

How to check correctness?

Testing: for *many* programs p (and inputs i) ***test*** that

$$\text{run}(p)(i) == \text{run}(\text{translate}(p))(i)$$

Verification: for *all* programs p (and inputs i) ***prove*** that

$$\text{run}(p)(i) == \text{run}(\text{translate}(p))(i)$$

Validating Semantics

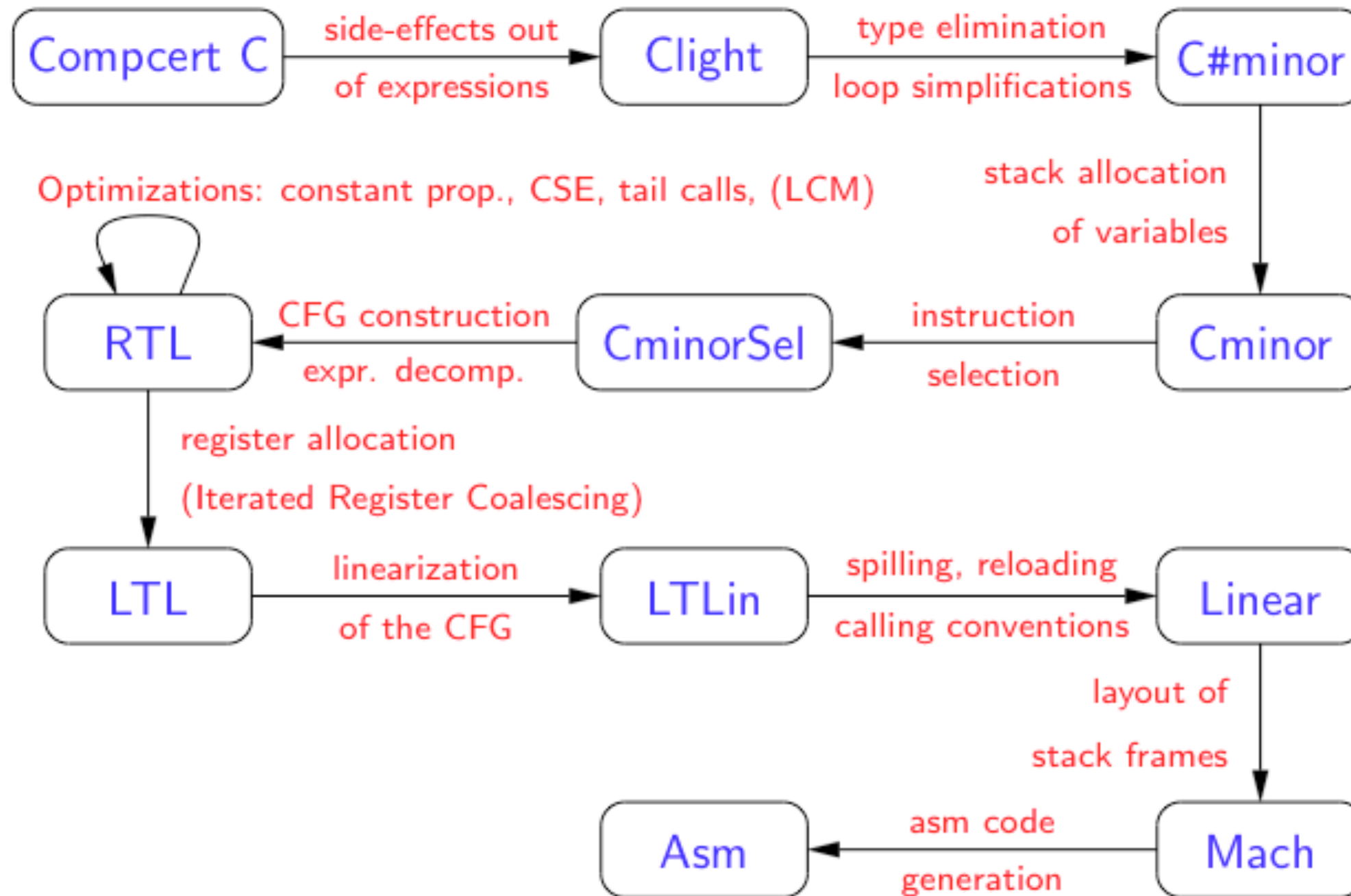
Is this the right semantics?

Testing: for *many* programs p (and inputs i) *test* that

$$\text{run}(p)(i) == v$$

Requires specifying desired $\langle p, i, v \rangle$ combinations
(aka unit testing)

The CompCert C Compiler



Compiler Construction Courses of the Future

Language Specification

syntax definition
name binding
type system
dynamic semantics
translation
transformation

safety properties

Language Implementation

generating implementations
from specifications

parser generation
constraint resolution
partial evaluation

...

Language Testing

test generation

Language Verification

proving correctness

Operational Semantics

Operational Semantics

What is the **result** of execution of a program and **how** is that result achieved?

Structural Operational Semantics: What are the individual steps of an execution?

Natural Semantics: How is overall result of execution obtained?

Defined using a **transition system**

Transition System

rule	$\frac{e_1 \rightarrow e_1' \quad \dots \quad e_n \rightarrow e_n'}{e \rightarrow e'}$	<p>premises</p> <p>conclusion</p>
axiom	$e \rightarrow e'$	
reduction	$p \rightarrow v$	<p>derivation tree to prove v is value of program p</p>

Structural Operational (Small-Step) Semantics

$$e = x \mid i \mid e + e \mid \backslash x.e \mid e \ e \mid \text{ifz}(e) \ e \ \text{else} \ e$$

$$\frac{e_1 \rightarrow e_1'}{e_1 + e_2 \rightarrow e_1' + e_2}$$

$$\frac{e_2 \rightarrow e_2'}{e_1 + e_2 \rightarrow e_1 + e_2'}$$

$$i + j \rightarrow i \pm j$$

$$\frac{e_1 \rightarrow e_1'}{\text{ifz}(e_1) \ e_2 \ \text{else} \ e_3 \rightarrow \text{ifz}(e_1') \ e_2 \ \text{else} \ e_3}$$

$$\text{ifz}(0) \ e_2 \ \text{else} \ e_3 \rightarrow e_2$$

$$\frac{i \neq 0}{\text{ifz}(i) \ e_2 \ \text{else} \ e_3 \rightarrow e_3}$$

$$e \rightarrow e$$

reducing expressions

$$\frac{e_1 \rightarrow e_1'}{e_1 \ e_2 \rightarrow e_1' \ e_2}$$

$$\frac{e_2 \rightarrow e_2'}{v \ e_2 \rightarrow v \ e_2'}$$

$$(\backslash x.e) \ v_1 \rightarrow e[x := v_1]$$

order of evaluation?

Structural Operational (Small-Step) Semantics

$$e = x \mid i \mid e + e \mid \backslash x.e \mid e \ e \mid \text{ifz}(e) \ e \ \text{else} \ e$$

$$\frac{e_1 \rightarrow e_1'}{e_1 + e_2 \rightarrow e_1' + e_2}$$

$$\frac{e_2 \rightarrow e_2'}{v_1 + e_2 \rightarrow v_1 + e_2'}$$

$$i + j \rightarrow i \pm j$$

$$\frac{e_1 \rightarrow e_1'}{\text{ifz}(e_1) \ e_2 \ \text{else} \ e_3 \rightarrow \text{ifz}(e_1') \ e_2 \ \text{else} \ e_3}$$

$$\text{ifz}(0) \ e_2 \ \text{else} \ e_3 \rightarrow e_2$$

$$\frac{i \neq 0}{\text{ifz}(i) \ e_2 \ \text{else} \ e_3 \rightarrow e_3}$$

$$e \rightarrow e$$

reducing expressions

$$\frac{e_1 \rightarrow e_1'}{e_1 \ e_2 \rightarrow e_1' \ e_2}$$

$$\frac{e_2 \rightarrow e_2'}{v \ e_2 \rightarrow v \ e_2'}$$

$$(\backslash x.e) \ v_1 \rightarrow e[x := v_1]$$

order of evaluation?

Natural (Big-Step) Semantics

$$e = x \mid i \mid e + e \mid \backslash x.e \mid e \ e \mid \text{ifz}(e) \ e \ \text{else} \ e$$

$$E \vdash i \Rightarrow \text{NumV}(i)$$

$$E \vdash e_1 \Rightarrow \text{NumV}(i)$$

$$E \vdash e_2 \Rightarrow \text{NumV}(j)$$

$$E \vdash e_1 + e_2 \Rightarrow \text{NumV}(i + j)$$

$$E \vdash e_1 \Rightarrow \text{NumV}(0)$$

$$E \vdash e_2 \Rightarrow v$$

$$E \vdash \text{if}(e_1) \ e_2 \ \text{else} \ e_3 \Rightarrow v$$

$$E \vdash e_1 \Rightarrow \text{NumV}(i), \ i \neq 0$$

$$E \vdash e_3 \Rightarrow v$$

$$E \vdash \text{if}(e_1) \ e_2 \ \text{else} \ e_3 \Rightarrow v$$

$$E \vdash e \Rightarrow v$$

reducing expressions to values

$$E[x] = v$$

$$E \vdash x \Rightarrow v$$

$$E \vdash \backslash x.e \Rightarrow \text{ClosV}(x, e, E)$$

$$E_1 \vdash e_1 \Rightarrow \text{ClosV}(x, e, E_2)$$

$$E_1 \vdash e_2 \Rightarrow v_1$$

$$\{x \mapsto v_1, E_2\} \vdash e \Rightarrow v_2$$

$$E_1 \vdash e_1 \ e_2 \Rightarrow v_2$$

DynSem: A DSL for Dynamic Semantics Specification

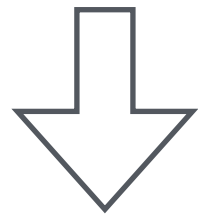
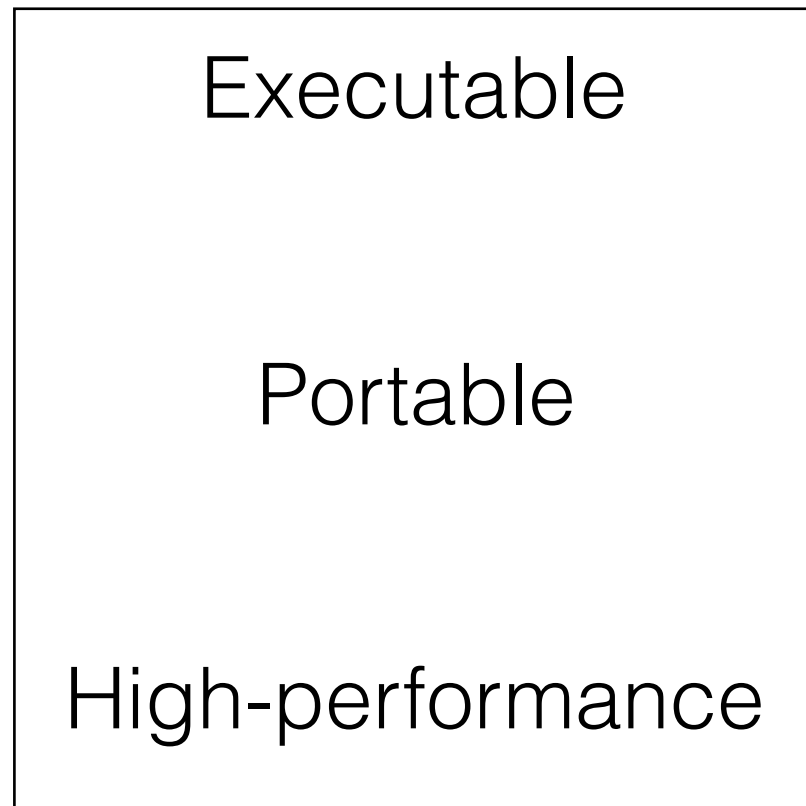
Vlad Vergu, Pierre Neron, Eelco Visser

RTA 2015

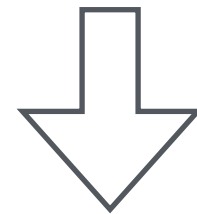
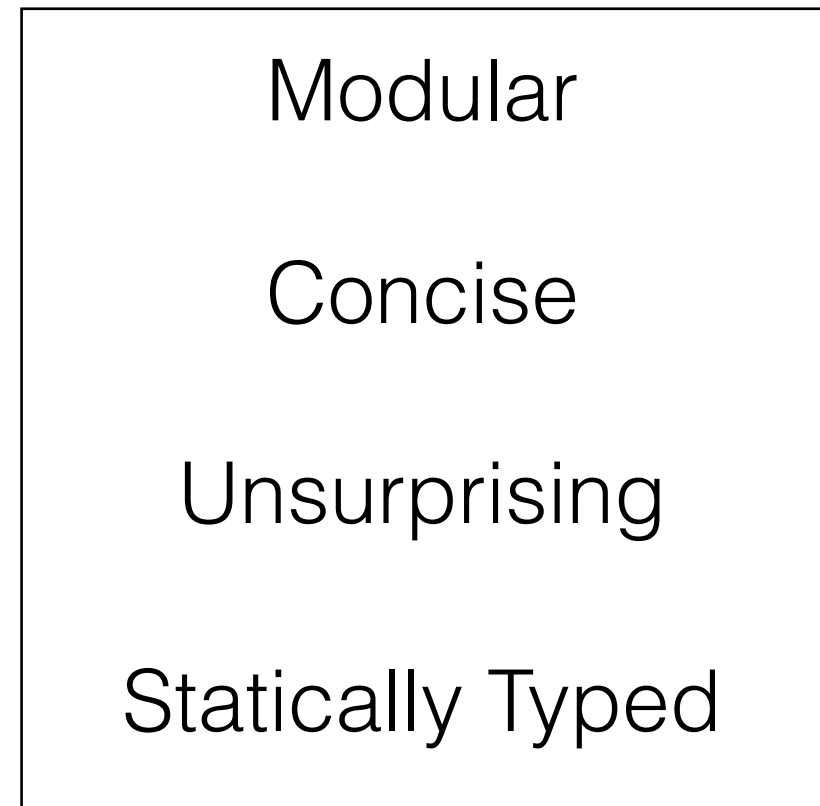
Interpreters for Spoofax Languages

gcdAB.pbox	gcdAB.aterm	gcdAB.evaluated.aterm
<pre>1 let 2 gcd = box(0) 3 in 4 let f = 5 fun (a, b) { 6 if (b == 0) 7 a 8 else 9 unbox(gcd)(b, a % b) 10 end 11 } 12 in 13 setbox(gcd, f); 14 unbox(gcd)(1134903170, 1836) 15 end 16 end 17</pre>	<pre>1 Let(2 [Bind("gcd", Box(Num("0")))] 3 , Let(4 [Bind(5 "f" 6 , Fun(7 ["a", "b"] 8 , If(9 Eq(Var("b"), Num("0")) 10 , Var("a") 11 , App(12 Unbox(Var("gcd")) 13 , [Var("b"), Mod(Var("a"), Var("b"))] 14) 15) 16) 17) 18] 19 , Seq(20 SetBox(Var("gcd"), Var("f")) 21 , App(22 Unbox(Var("gcd")) 23 , [Num("1134903170"), Num("1836")] 24) 25) 26) 27)</pre>	<pre>1 R_default_V(2 NumV(34) 3 , Map(4 "Store" 5 , Bind(923, RefV(925)) 6 , Bind(7 925 8 , ObjV(9 Map(10 "Env" 11 , Bind("outer", 922) 12 , Bind("self", 923) 13 , Bind("super", 924) 14) 15) 16) 17 , Bind(18 926 19 , ClosV(20 Fun(21 ["a", "b"] 22 , If(23 Eq(Var("b"), Num("0")) 24 , Var("a") 25 , App(26 Unbox(Var("gcd")) 27 , [Var("b"), Mod(Var("a"), Var("b"))] 28) 29) 30) 31)</pre>

Design Goals



Big-Step



I-MSOS

M. Churchill, P. D. Mosses, and P. Torrini.
Reusable components of semantic
specifications. In MODULARITY, April 2014.

Example: DynSem Semantics of PAPL-Box

```
let
  fac = box(0)
in
  let f = fun (n) {
    if (n == 0)
      1
    else
      n * (unbox(fac) (n - 1))
    end
  }
  in
    setbox(fac, f);
    unbox(fac)(10)
  end
end
```

Features

- Arithmetic
- Booleans
- Comparisons
- Mutable variables
- Functions
- Boxes

Components

- Syntax in SDF3
- Dynamic Semantics in DynSem

Abstract Syntax from Concrete Syntax

```
module Arithmetic
```

```
imports Expressions
```

```
imports Common
```

```
context-free syntax
```

```
Expr.Num      = INT
```

```
Expr.Plus     = [[Expr] + [Expr]] {left}
```

```
Expr.Minus    = [[Expr] - [Expr]] {left}
```

```
Expr.Times    = [[Expr] * [Expr]] {left}
```

```
Expr.Mod      = [[Expr] % [Expr]] {left}
```

```
context-free priorities
```

```
{left: Expr.Times Expr.Mod }
```

```
> {left: Expr.Minus Expr.Plus }
```

src-gen/ds-signatures/Arithmetic-sig

```
module Arithmetic-sig
```

```
imports Expressions-sig
```

```
imports Common-sig
```

```
signature
```

```
sorts
```

```
Expr
```

```
constructors
```

```
Num : INT -> Expr
```

```
Plus : Expr * Expr -> Expr
```

```
Minus : Expr * Expr -> Expr
```

```
Times : Expr * Expr -> Expr
```

```
Mod : Expr * Expr -> Expr
```

Values, Meta-Variables, and Arrows

```
module values

signature
  sorts V Unit
  constructors
    U : Unit
  variables
    v : V
```

```
module expressions

imports values
imports Expressions-sig

signature
  arrows
    Expr --> V
  variables
    e : Expr
    x : String
```


Term Reduction Rules

```
module arithmetic-explicit
```

```
imports expressions primitives Arithmetic-sig
```

```
signature
```

```
  constructors
```

```
    NumV: Int -> V
```

```
rules
```

```
  Num(__String2INT__(n)) --> NumV(str2int(n)).
```

```
  Plus(e1, e2) --> NumV(plusI(i1, i2))
```

```
  where
```

```
    e1 --> NumV(i1); e2 --> NumV(i2).
```

```
  Minus(e1, e2) --> NumV(minusI(i1, i2))
```

```
  where
```

```
    e1 --> NumV(i1); e2 --> NumV(i2).
```

```
module primitives
```

```
signature
```

```
  native operators
```

```
    str2int : String -> Int
```

```
    plusI   : Int * Int -> Int
```

```
    minusI  : Int * Int -> Int
```

Native Operations

```
public class Natives {
```

```
    public static int plusI_2(int i1, int i2) {  
        return i1 + i2;  
    }
```

```
    public static int str2int_1(String s) {  
        return Integer.parseInt(s);  
    }
```

```
}
```

```
module primitives
```

```
signature
```

```
    native operators
```

```
        str2int : String -> Int
```

```
        plusI   : Int * Int -> Int
```

```
        minusI  : Int * Int -> Int
```

Arrows as Coercions

rules

`Plus(NumV(i1), NumV(i2)) --> NumV(plusI(i1, i2)).`

signature

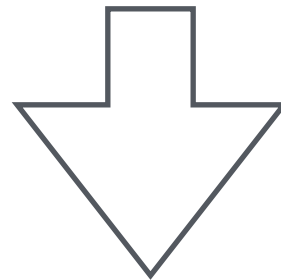
constructors

`Plus : Expr * Expr -> Expr`

`NumV : Int -> V`

arrows

`Expr --> V`



rules

`Plus(e1, e2) --> NumV(plusI(i1, i2))`

where

`e1 --> NumV(i1);`

`e2 --> NumV(i2).`

Modular

```
module arithmetic

imports Arithmetic-sig
imports expressions
imports primitives

signature
  constructors
    NumV: Int -> V

rules

  Num(str) --> NumV(str2int(str)).

  Plus(NumV(i1), NumV(i2)) --> NumV(plusI(i1, i2)).

  Minus(NumV(i1), NumV(i2)) --> NumV(minusI(i1, i2)).

  Times(NumV(i1), NumV(i2)) --> NumV(timesI(i1, i2)).

  Mod(NumV(i1), NumV(i2)) --> NumV(modI(i1, i2)).
```

```
module boolean

imports Booleans-sig expressions

signature
  constructors
    BoolV: Bool -> V

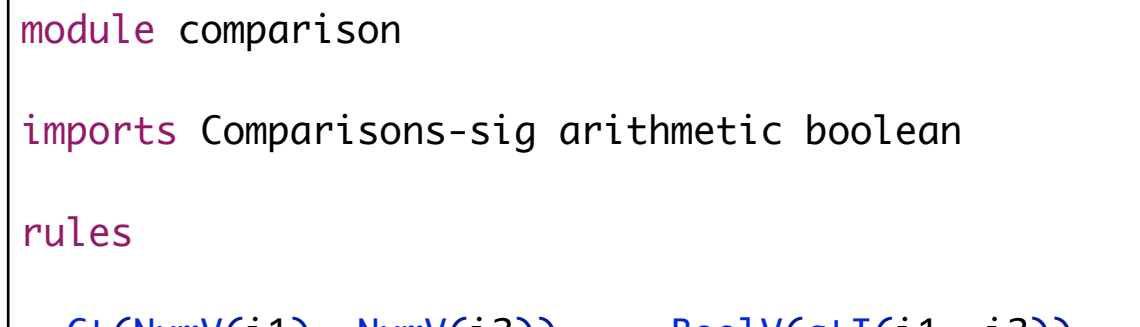
rules

  True() --> BoolV(true).
  False() --> BoolV(false).

  Not(BoolV(false)) --> BoolV(true).
  Not(BoolV(true)) --> BoolV(false).

  Or(BoolV(true), _) --> BoolV(true).
  Or(BoolV(false), e) --> e.

  And(BoolV(false), _) --> BoolV(false).
  And(BoolV(true), e) --> e.
```



```
module comparison

imports Comparisons-sig arithmetic boolean

rules

  Gt(NumV(i1), NumV(i2)) --> BoolV(gtI(i1, i2)).

  Eq(NumV(i1), NumV(i2)) --> BoolV(eqI(i1, i2)).

  Eq(BoolV(b1), BoolV(b2)) --> BoolV(eqB(b1, b2)).
```

Control-Flow

```
module controlflow

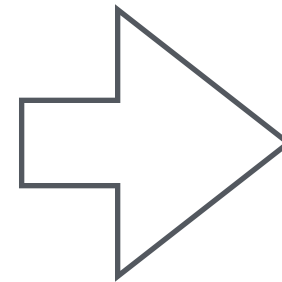
imports ControlFlow-sig
imports expressions
imports boolean

rules

  Seq(v, e2) --> e2.

  If(BoolV(true), e1, _) --> e1.

  If(BoolV(false), _, e2) --> e2.
```



```
module controlflow

imports ControlFlow-sig
imports expressions
imports boolean

rules

  Seq(e1, e2) --> v2
  where
    e1 --> v1;
    e2 --> v2.

  If(e1, e2, e3) --> v
  where
    e1 --> BoolV(true);
    e2 --> v.

  If(e1, e2, e3) --> v
  where
    e1 --> BoolV(false);
    e3 --> v.
```


Immutable Variables: Environment Passing

constructors

```
Let  : ID * Expr * Expr -> Expr  
Var  : ID -> Expr
```

module variables

```
imports Variables-sig environment
```

rules

```
E |- Let(x, v: V, e2) --> v2  
where  
  Env {x |--> v, E} |- e2 --> v2.  
  
E |- Var(x) --> E[x].
```

module environment

```
imports values
```

signature

```
sort aliases
```

```
Env = Map<String, V>
```

```
variables
```

```
E : Env
```

First-Class Functions: Environment in Closure

constructors

Fun : ID * Expr -> Expr

App : Expr * Expr -> Expr

module unary-functions

imports expressions environment

signature

constructors

ClosV : String * Expr * Env -> V

rules

E |- Fun(x, e) --> ClosV(x, e, E).

E |- App(e1, e2) --> v

where

E |- e1 --> ClosV(x, e, E');

E |- e2 --> v2;

Env {x |--> v2, E'} |- e --> v.

module environment

imports values

signature

sort aliases

Env = Map<String, V>

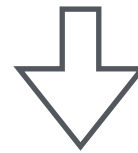
variables

E : Env

Implicit Propagation

rules

$\text{Plus}(\text{NumV}(i1), \text{NumV}(i2)) \rightarrow \text{NumV}(\text{plusI}(i1, i2)).$



rules

$\text{Plus}(e1, e2) \rightarrow \text{NumV}(\text{plusI}(i1, i2))$

where

$e1 \rightarrow \text{NumV}(i1);$

$e2 \rightarrow \text{NumV}(i2).$



rules

$E \vdash \text{Plus}(e1, e2) \rightarrow \text{NumV}(\text{plusI}(i1, i2))$

where

$E \vdash e1 \rightarrow \text{NumV}(i1);$

$E \vdash e2 \rightarrow \text{NumV}(i2).$

Mutable Boxes: Store

```
module box
imports store arithmetic
signature
  constructors
    Box      : Expr -> Expr
    Unbox    : Expr -> Expr
    SetBox   : Expr * Expr -> Expr
```

constructors

```
BoxV: Int -> V
```

rules

```
Box(e) :: S --> BoxV(loc) :: Store {loc |--> v, S'}
```

```
where e :: S --> v :: S';
```

```
fresh => loc.
```

```
Unbox(BoxV(loc)) :: S --> S[loc].
```

```
SetBox(BoxV(loc), v) :: S --> v :: Store {loc |--> v, S}.
```

```
module store
```

```
imports values
```

signature

sort aliases

```
Store = Map<Int, V>
```

variables

```
S : Store
```

Mutable Variables: Environment + Store

constructors

```
Let  : ID * Expr * Expr -> Expr
Var  : ID -> Expr
Set  : String * Expr -> Expr
```

module variables-mutable

imports Variables-sig store

rules

```
E |- Var(x) :: S --> v :: S
where E[x] => loc; S[loc] => v.
```

```
E |- Let(x, v, e2) :: S1 --> v2 :: S3
```

where

```
  fresh => loc;
```

```
  {loc |--> v, S1} => S2;
```

```
  Env {x |--> loc, E} |- e2 :: S2 --> v2 :: S3.
```

```
E |- Set(x, v) :: S --> v :: Store {loc |--> v, S}
```

```
where E[x] => loc.
```

module store

imports values

signature

sort aliases

```
Env = Map<ID, Int>
```

```
Store = Map<Int, V>
```

variables

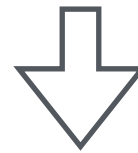
```
E : Env
```

```
S : Store
```

Implicit Store Threading

rules

$\text{Plus}(\text{NumV}(i1), \text{NumV}(i2)) \dashrightarrow \text{NumV}(\text{plusI}(i1, i2)).$



rules

$\text{Plus}(e1, e2) \dashrightarrow \text{NumV}(\text{plusI}(i1, i2))$

where

$e1 \dashrightarrow \text{NumV}(i1);$

$e2 \dashrightarrow \text{NumV}(i2).$



rules

$E \vdash \text{Plus}(e1, e2) :: S1 \dashrightarrow \text{NumV}(\text{plusI}(i1, i2)) :: S3$

where

$E \vdash e1 :: S1 \dashrightarrow \text{NumV}(i1) :: S2;$

$E \vdash e2 :: S2 \dashrightarrow \text{NumV}(i2) :: S3.$

Abstraction: Env/Store Meta Functions

```
module store

imports values

signature
  sort aliases
    Env = Map<String, Int>
    Store = Map<Int, V>
  variables
    E : Env
    S : Store
  arrows
    readVar   : String --> V
    bindVar   : String * V --> Env
    writeVar  : String * V --> V

    allocate  : V --> Int
    write     : Int * V --> V
    read      : Int --> V
```

rules

```
allocate(v) --> loc
where
  fresh => loc;
  write(loc, v) --> _.

write(loc, v) :: S -->
  v :: Store {loc l--> v, S}.

read(loc) :: S --> S[loc] :: S.
```

rules

```
bindVar(x, v) --> {x l--> loc}
where allocate(v) --> loc.

E l- readVar(x) --> read(E[x]).

E l- writeVar(x, v) --> write(E[x], v).
```


Boxes with Env/Store Meta Functions

```
module boxes
```

```
signature
```

```
constructors
```

```
Box      : Expr -> Expr
```

```
Unbox    : Expr -> Expr
```

```
SetBox   : Expr * Expr -> Expr
```

```
constructors
```

```
BoxV: V -> V
```

```
rules
```

```
Box(v) --> BoxV(NumV(allocate(v))).
```

```
Unbox(BoxV(NumV(loc))) --> read(loc).
```

```
SetBox(BoxV(NumV(loc)), v) --> write(loc, v).
```

Mutable Variables with Env/Store Meta Functions

constructors

```
Let  : String * Expr * Expr -> Expr
Var  : String -> Expr
Set  : String * Expr -> Expr
```

module variables

imports expressions store

rules

```
Var(x) --> readVar(x).
```

```
E |- Let(x, v1, e) --> v2
```

where

```
  bindVar(x, v1) --> E';
  Env {E', E} |- e --> v2.
```

```
Set(x, v) --> v
```

where

```
  writeVar(x, v) --> _.
```

Functions with Multiple Arguments

```
module functions

imports Functions-sig
imports variables

signature
  constructors
    ClosV      : List(ID) * Expr * Env -> V
    bindArgs   : List(ID) * List(Expr) --> Env

rules

  E |- Fun(xs, e) --> ClosV(xs, e, E).

  App(ClosV(xs, e_body, E_clos), es) --> v'
  where
    bindArgs(xs, es) --> E_params;
    Env {E_params, E_clos} |- e_body --> v'.

  bindArgs([], []) --> {}.

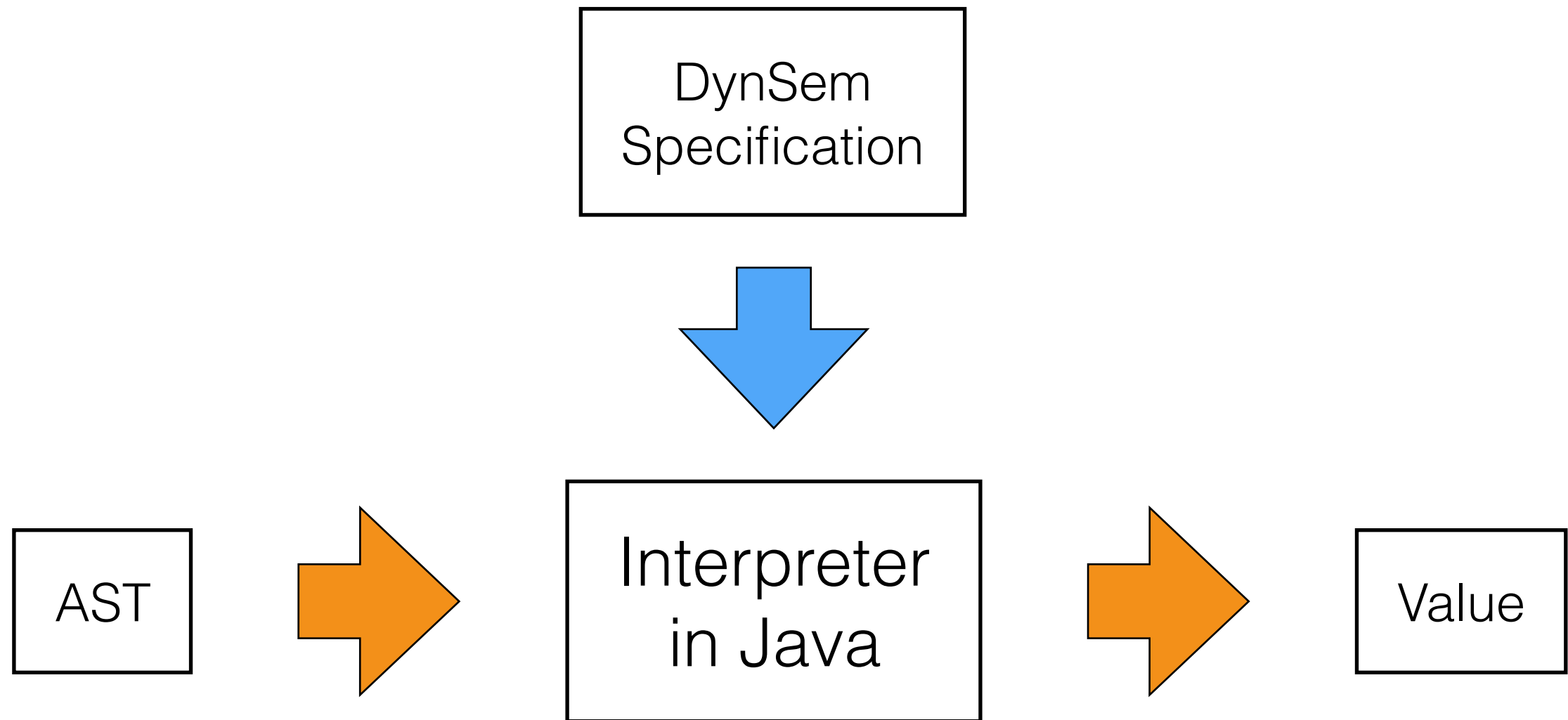
  bindArgs([x | xs], [e | es]) --> {E, E'}
  where
    bindVar(x, e) --> E;
    bindArgs(xs, es) --> E'.
```

Tiger in DynSem

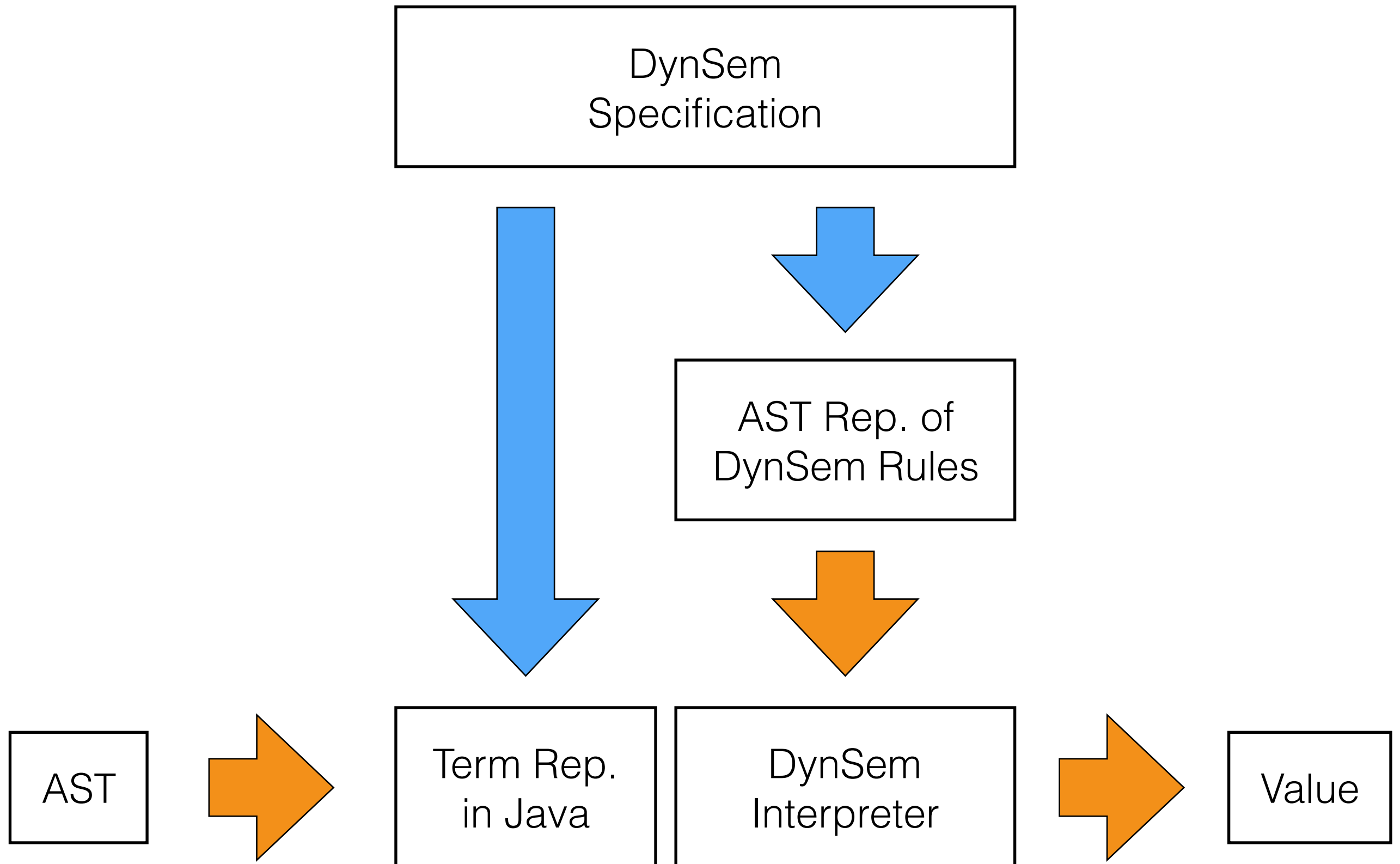
```
store.ds
1
2
3 imports dynamics/values
4
5 signature // lvalue
6 sorts LValue
7 arrows
8   LValue -lval-> Int
9 variables
10  lv : LValue
11
12 signature // environment
13 sorts Id
14 sort aliases
15   // Address = Int
16   Env = Map(Id, Int)
17 variables
18  a : Int
19 components
20  E : Env
21 arrows
22  lookup(Id) --> Int
23  bind(Id, Int) --> Env
24
25 rules
26 E |- lookup(x) --> E[x].
27
28 E |- bind(x, a) --> {x |-> a, E}.
29
30 signature // heap
31 sort aliases
32   Heap = Map(Int, V)
33 components
34  H : Heap
35 arrows
36  read(Int) --> V
37  allocate(V) --> Int
38  write(Int, V) --> V
39
40 rules
41
42 read(a) :: H --> H[a].
43
44 write(a, v) :: H --> v :: H {a |-> v, H}
45
46 allocate(v) --> a
47 where
48   fresh => a;
49   write(a, v) --> .
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Interpreter Generation

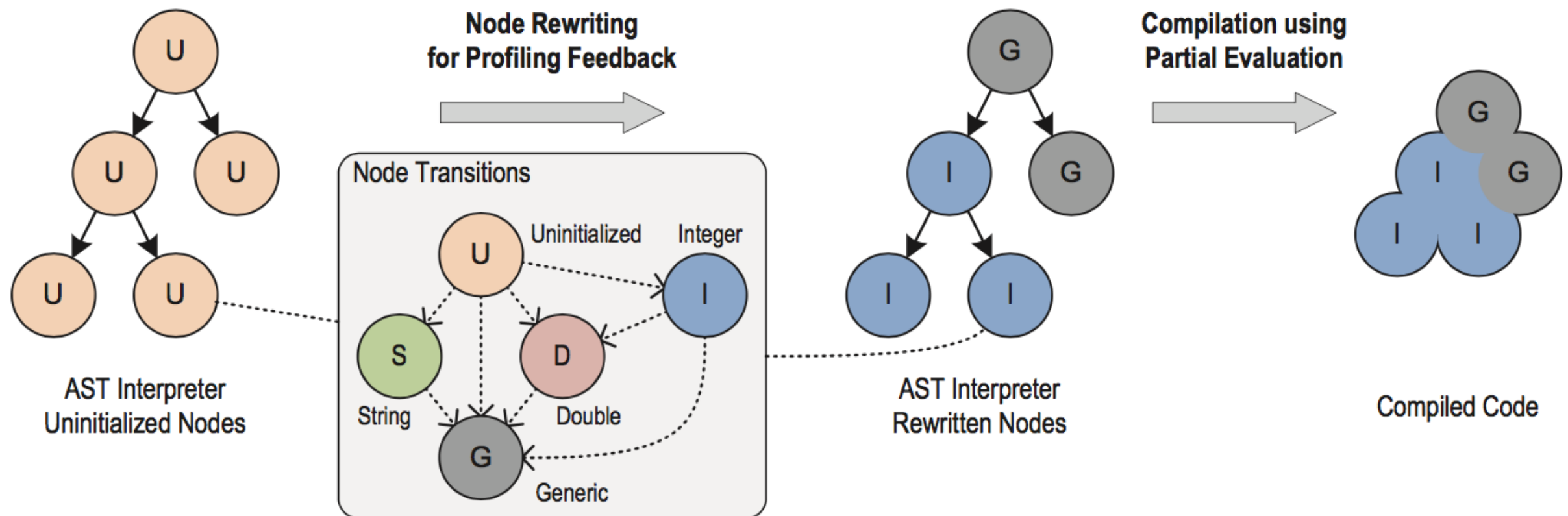
Generating AST Interpreter from Dynamic Semantics



DynSem Meta-Interpreter



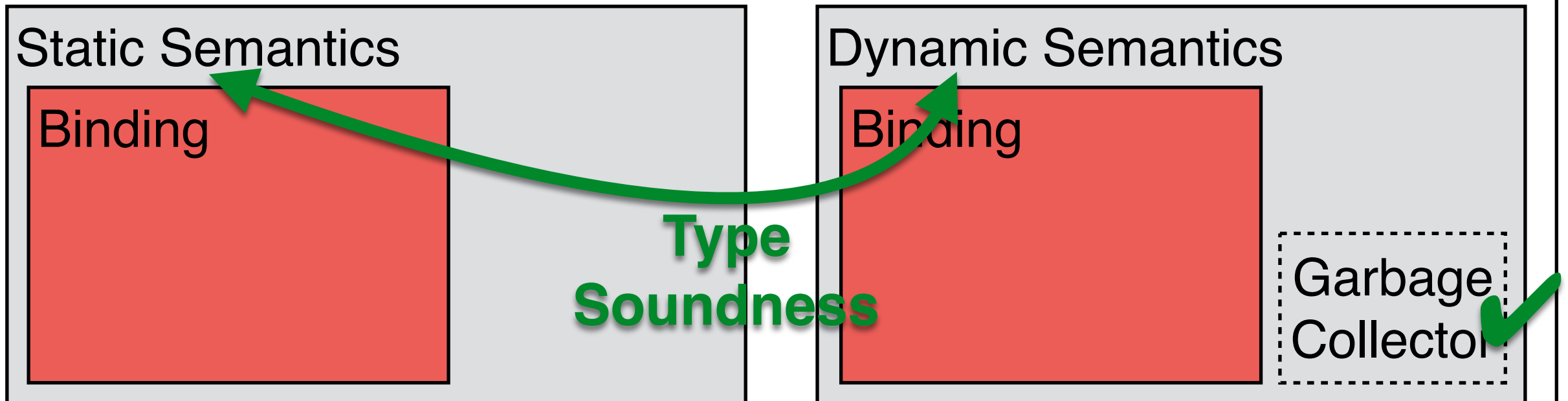
Truffle: Partial Evaluation of AST Interpreters



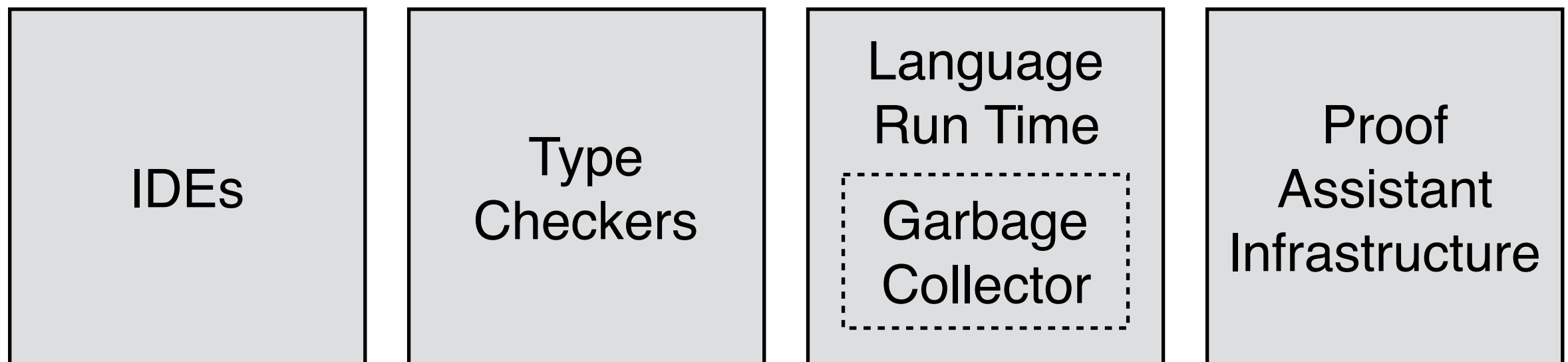
Scopes describe frames: A uniform model for memory layout in dynamic semantics

Casper Bach Poulsen, Pierre Néron, Andrew Tolmach, Eelco Visser
ECOOP 2016

Semantic Specification



Tools



Lexical

```
val x = 31;  
val y = x + 11;
```

Static

Typing Contexts
Type Substitution

Dynamic

Substitution
Environments
De Bruijn Indices
HOAS

Mutable

```
var x = 31;  
x = x + 11;
```

Typing Contexts
Store Typing

Stores/Heaps

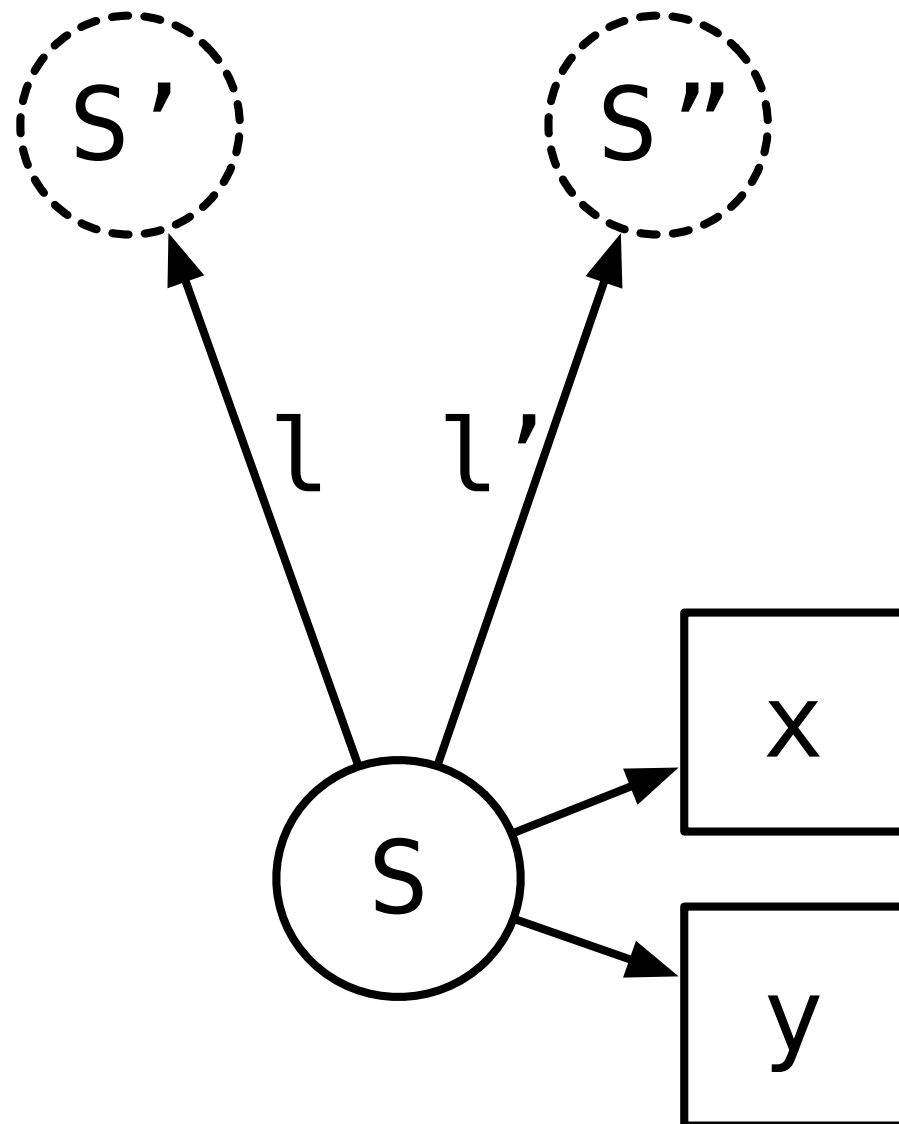
Objects

```
class A {  
    var x = 0;  
    var y = 42;  
}  
var r = new A();
```

Class Tables

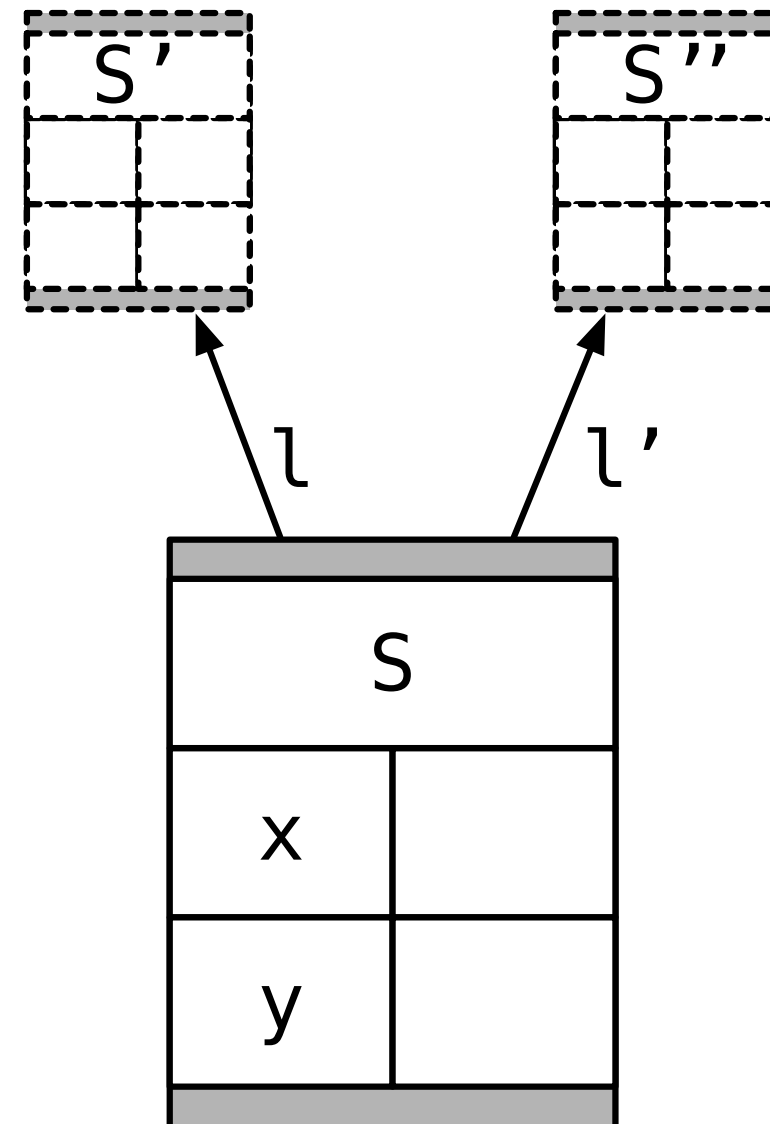
Mutable Objects
Stores/Heaps

Scope



[ESOP'15]

Frame

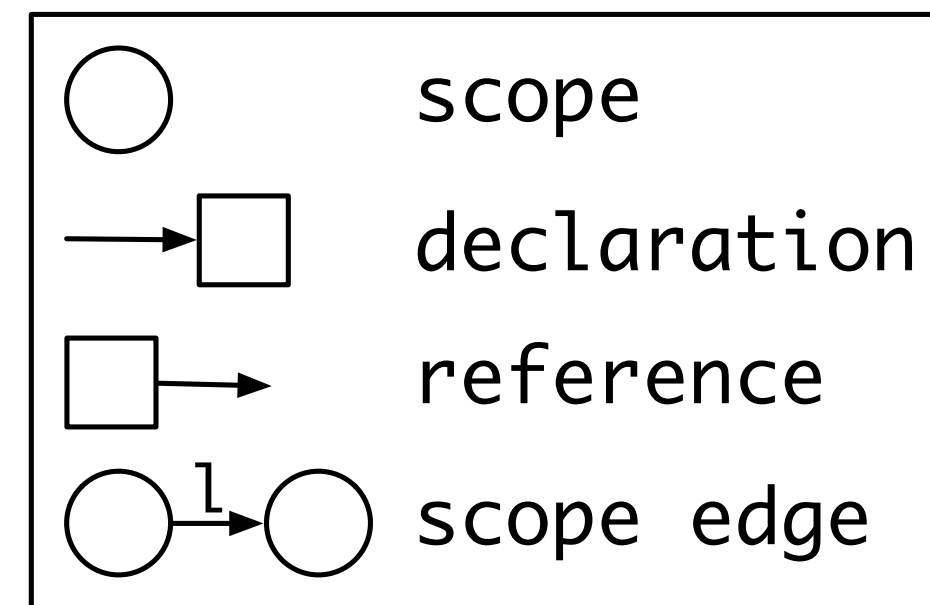
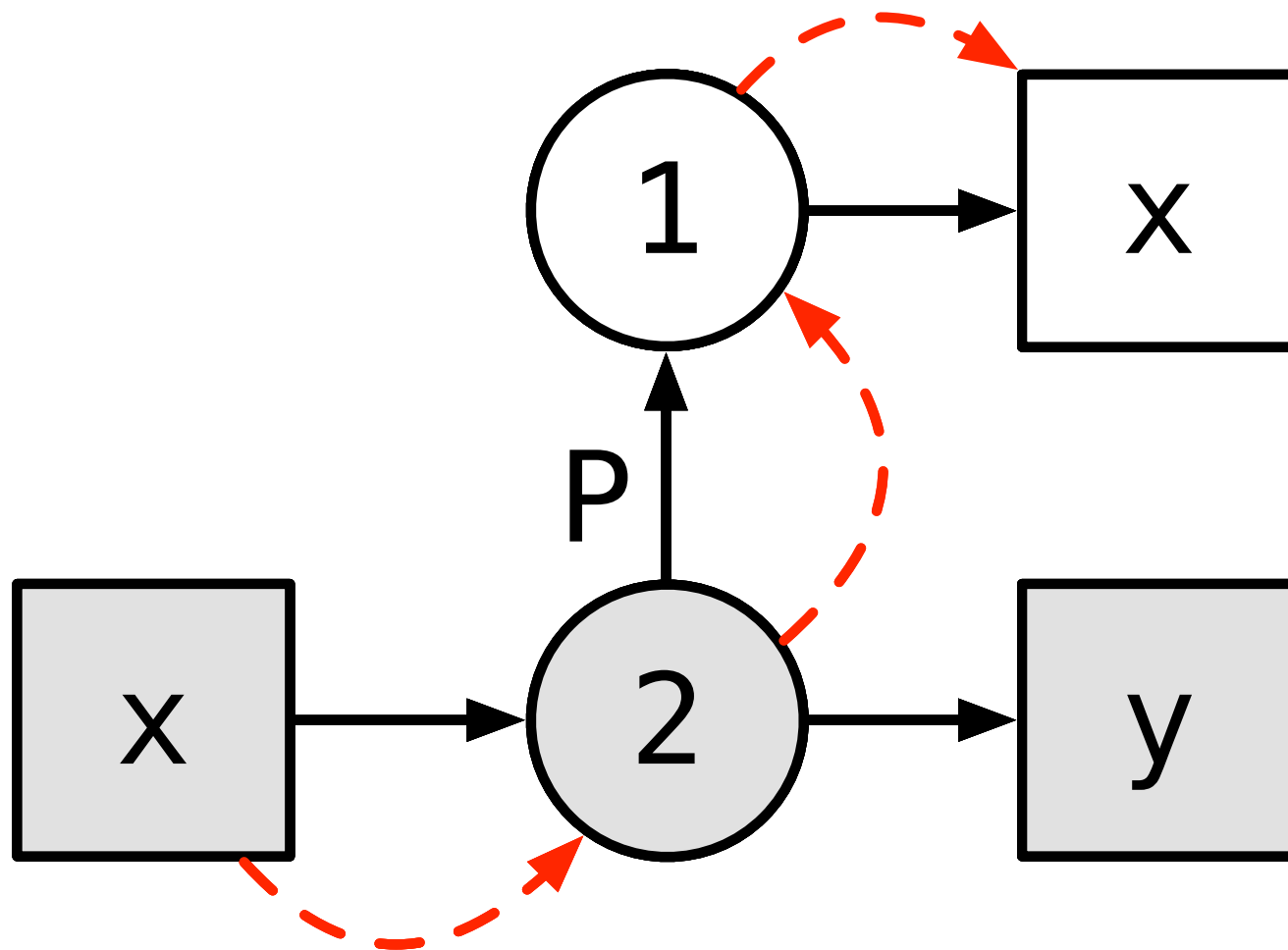


[ECOOP'16]

Lexical Scoping

```
val x = 31;
```

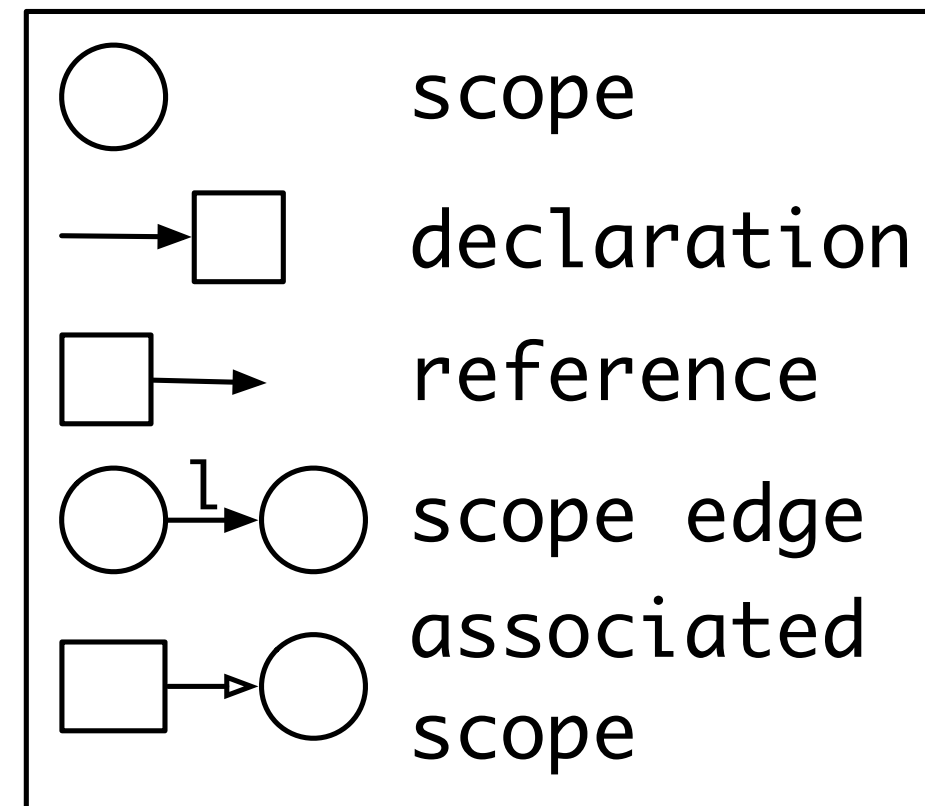
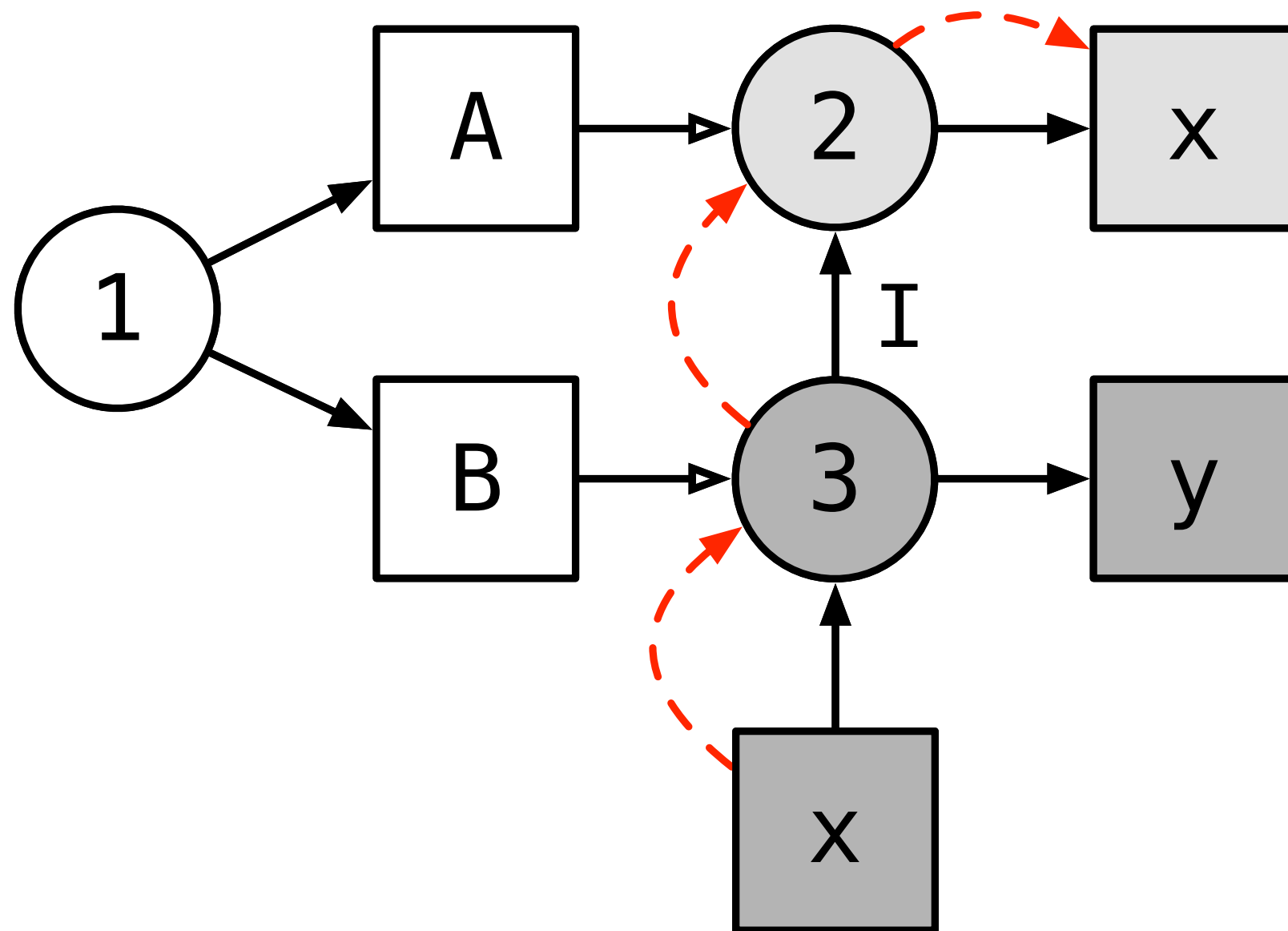
```
val y = x + 11;
```



[ESOP'15; PEPM'16]

Inheritance

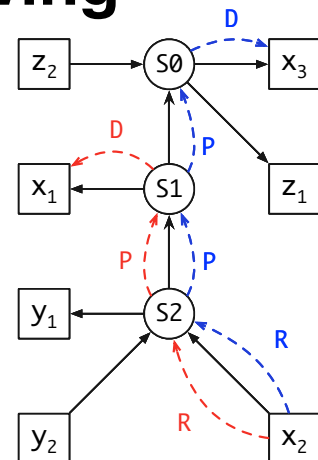
```
class A { var x = 42; }  
class B extends A { var y = x; }
```



More Binding Patterns

Shadowing

```
def x3 = z2 5 7 S0
def z1 =
  fun x1 { S1
    fun y1 { S2
      x2 + y2
    }
  }
```



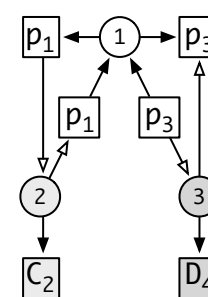
$D < P.p$
 $p < p'$
 $s.p < s.p'$

$R.P.D < R.P.P.D$

Java Packages

```
package p1;
class C2 {}

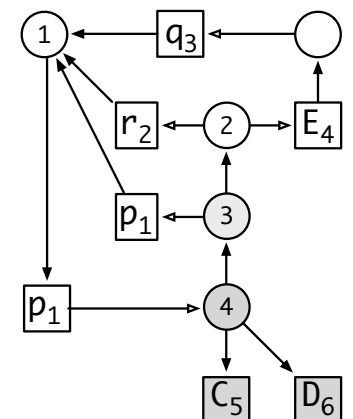
package p3;
class D4 {}
```



Java Import

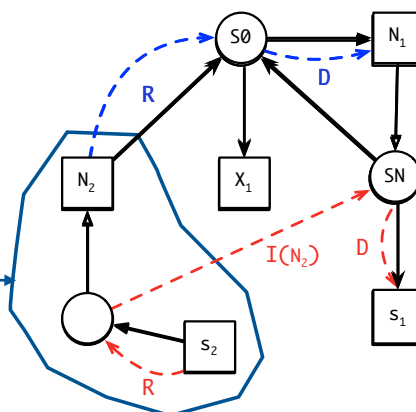
```
package p1;
imports r2.*;
imports q3.E4;

public class C5 {}
class D6 {}
```



Qualified Names

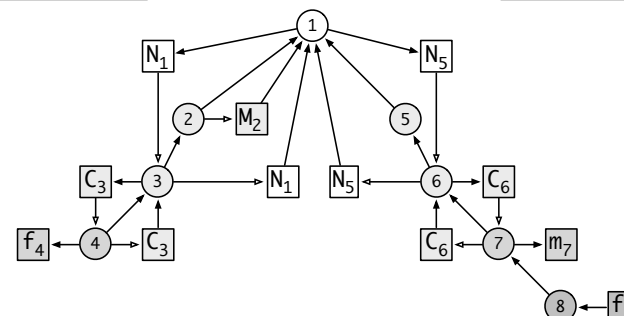
```
module N1 { S0
  def s1 = 5
}
module M1 {
  def x1 = 1 + N2.s2
}
```



C# Namespaces and Partial Classes

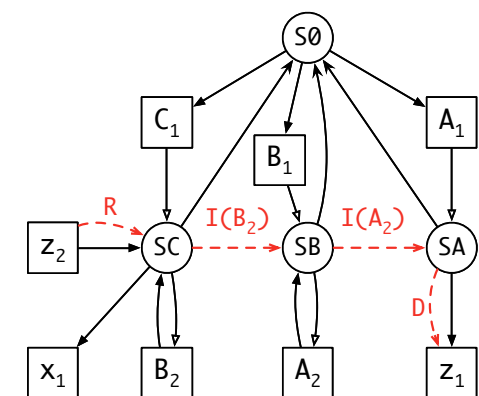
```
namespace N1 {
  using M2;
  partial class C3 {
    int f4;
  }
}
```

```
namespace N5 {
  partial class C6 {
    int m7() {
      return f8;
    }
  }
}
```



Transitive vs. Non-Transitive

```
module A1 {
  def z1 = 5 SA
}
module B1 {
  import A2 SB
}
module C1 {
  import B2 SC
  def x1 = 1 + z2
}
```



With transitive imports, a well formed path is $R.P*.I(*)*.D$
 With non-transitive imports, a well formed path is $R.P*.I(*)?.D$

Lexical

```
val x = 31;  
val y = x + 11;
```

Static

Typing Contexts
Type Substitution

Dynamic

Substitution
Environments
De Bruijn Indices
HOAS

Mutable

```
var x = 31;  
x = x + 11;
```

Typing Contexts
Store Typing

Stores/Heaps

Objects

```
class A {  
    var x = 0;  
    var y = 42;  
}  
var r = new A();
```

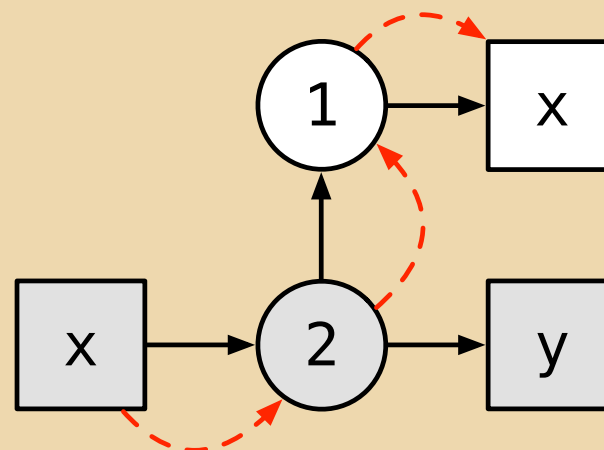
Class Tables

Mutable Objects
Stores/Heaps

Lexical

```
val x = 31;  
val y = x + 11;
```

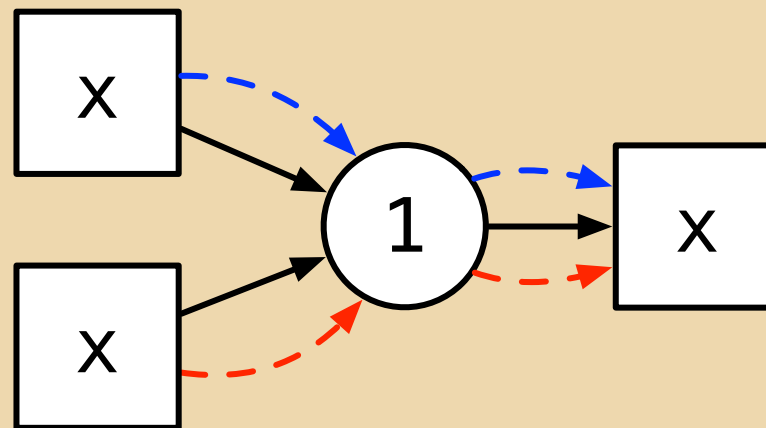
Static



Substitution
Environments
De Bruijn Indices
HOAS

Mutable

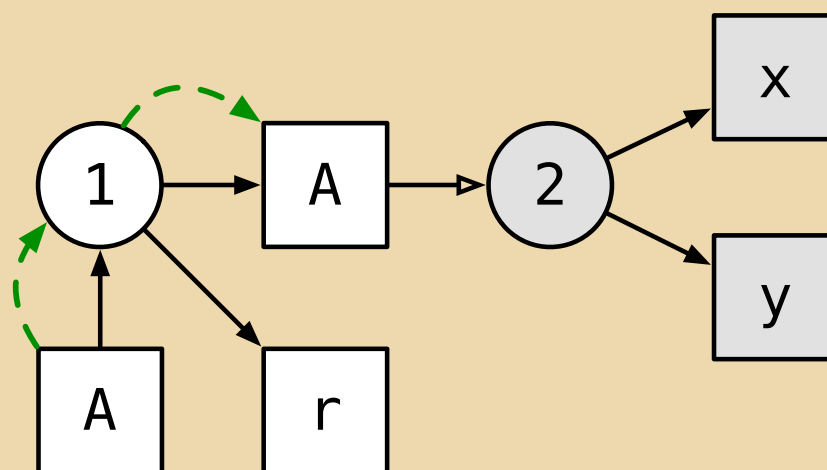
```
var x = 31;  
x = x + 11;
```



Stores/Heaps

Objects

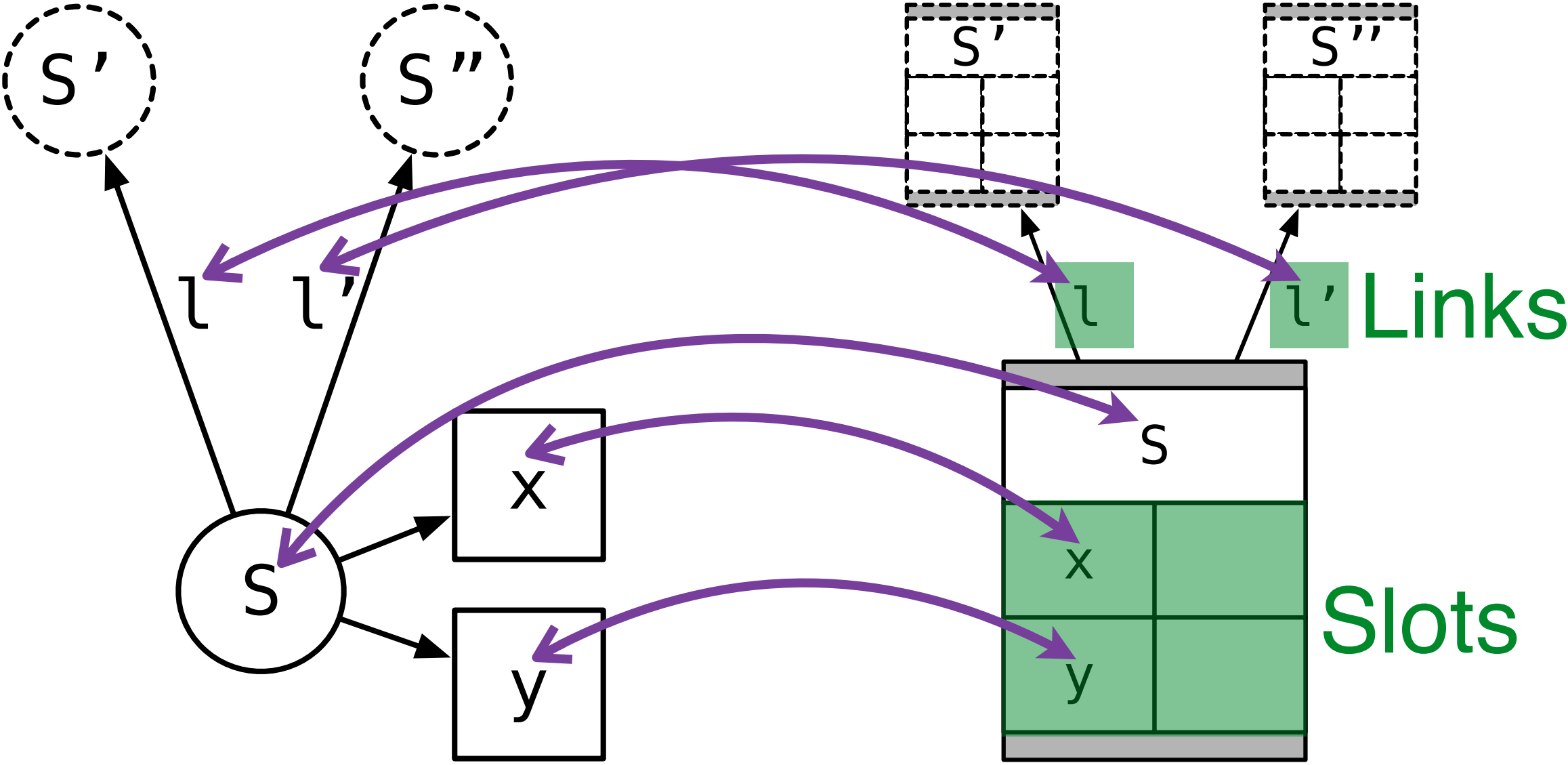
```
class A {  
  var x = 0;  
  var y = 42;  
}  
var r = new A();
```



Mutable Objects
Stores/Heaps

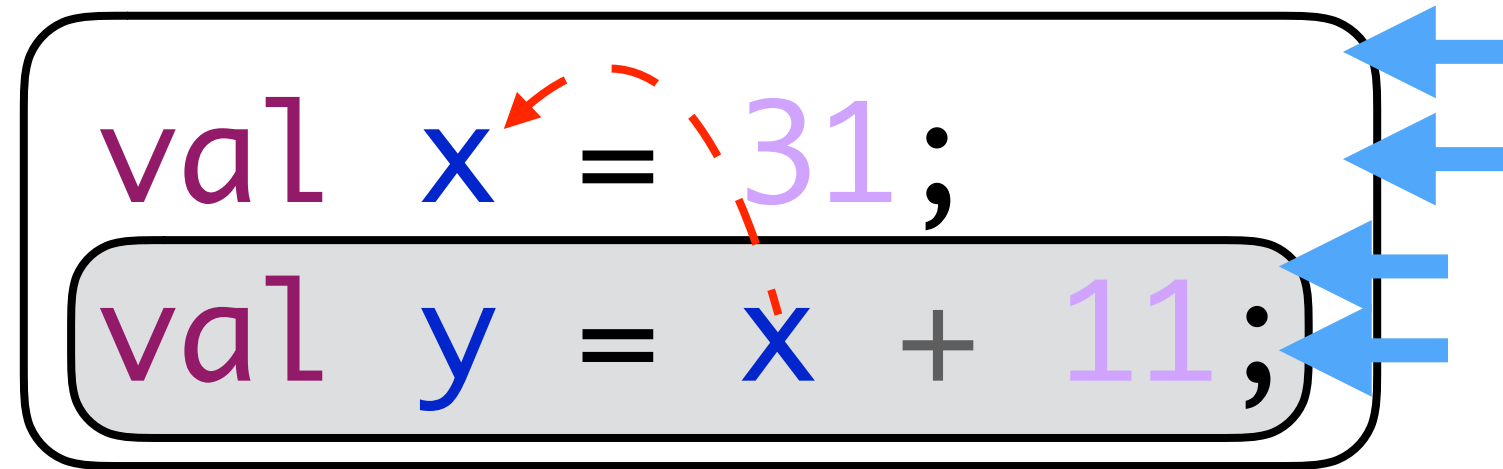
Scope

Frame

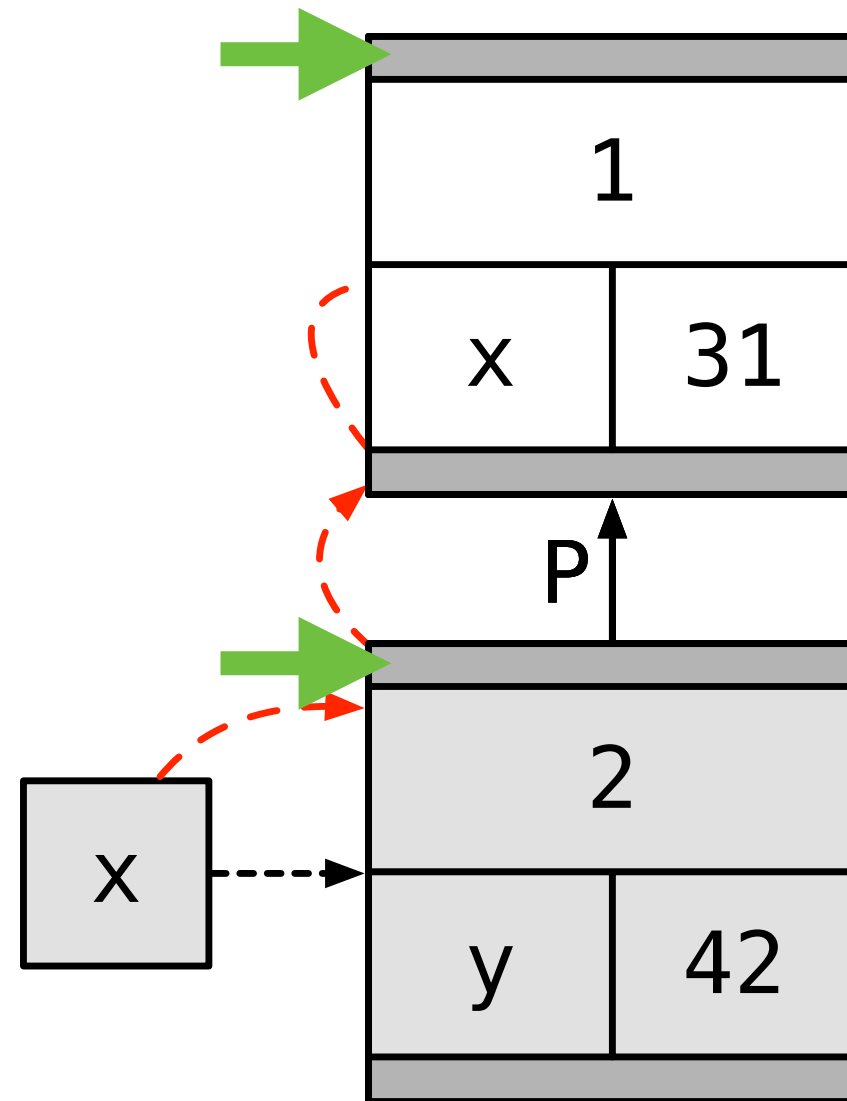
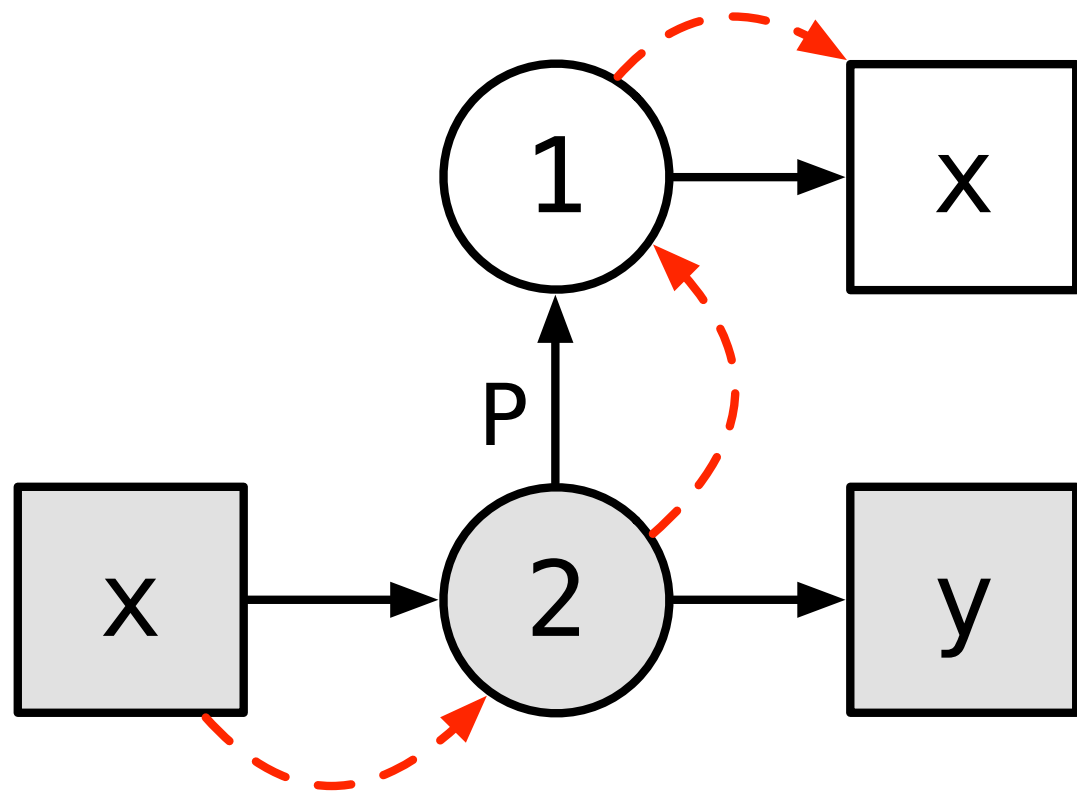


[ECOOP'16]

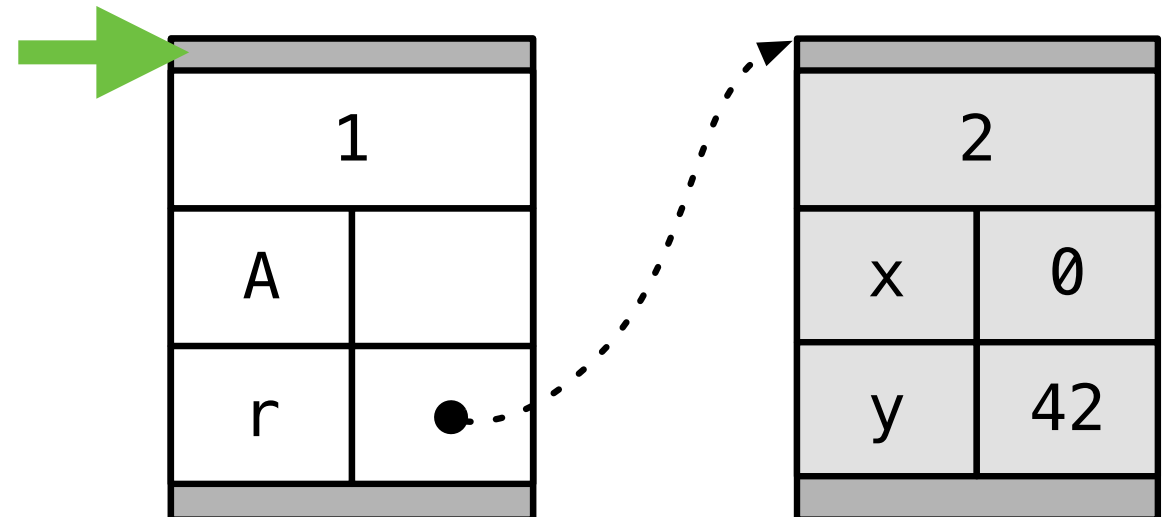
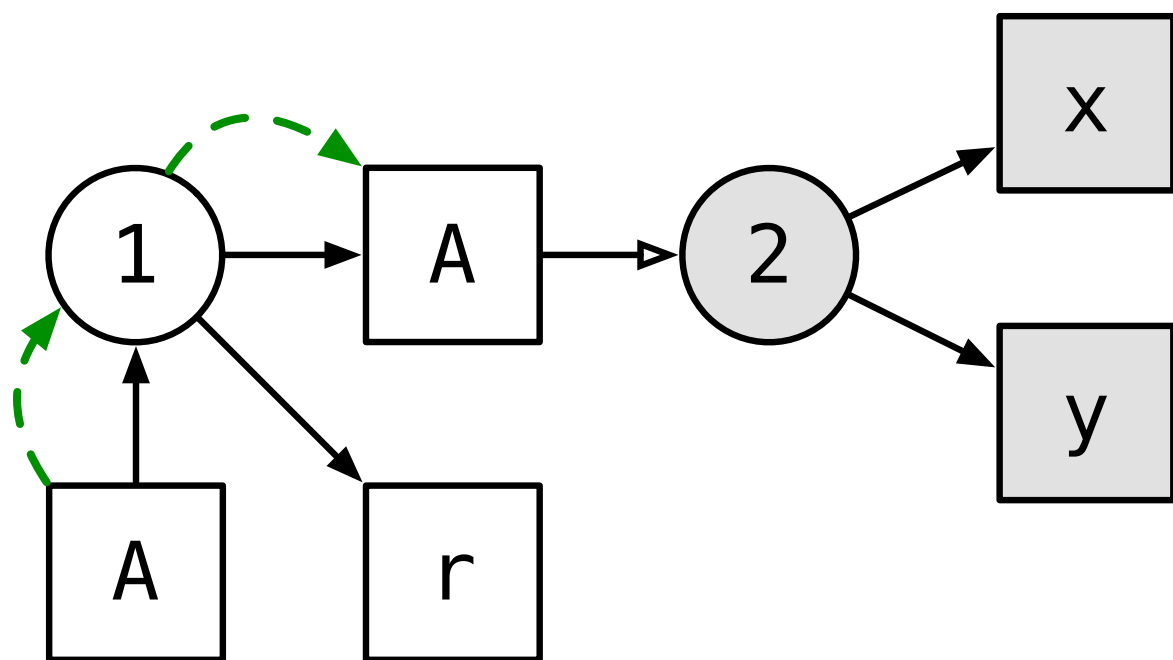
```
val x = 31;  
val y = x + 11;
```



A diagram showing two lines of code in a block. The first line is `val x = 31;` and the second line is `val y = x + 11;`. Both lines are enclosed in a larger rounded rectangle. The second line is enclosed in a smaller rounded rectangle. Blue arrows point from the right towards the code blocks.



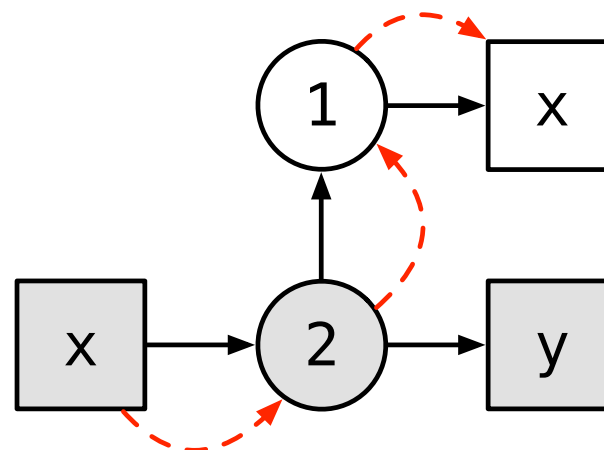

```
class A {  
    var x = 0;  
    var y = 42;  
}  
var r = new A();
```



Lexical

```
val x = 31;  
val y = x + 11;
```

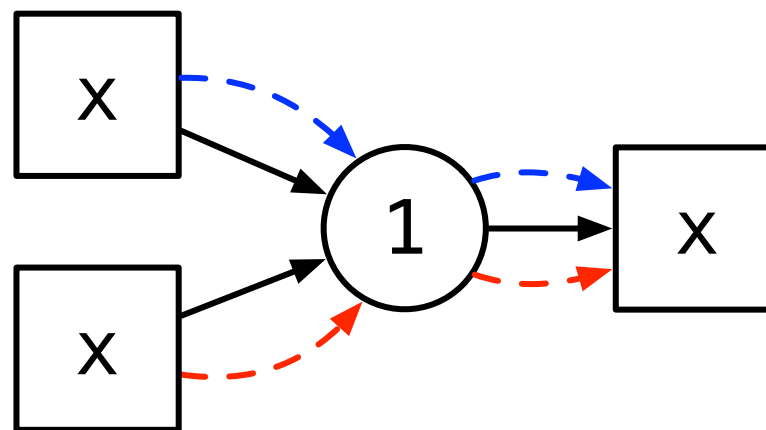
Static



Substitution
Environments
De Bruijn Indices
HOAS

Mutable

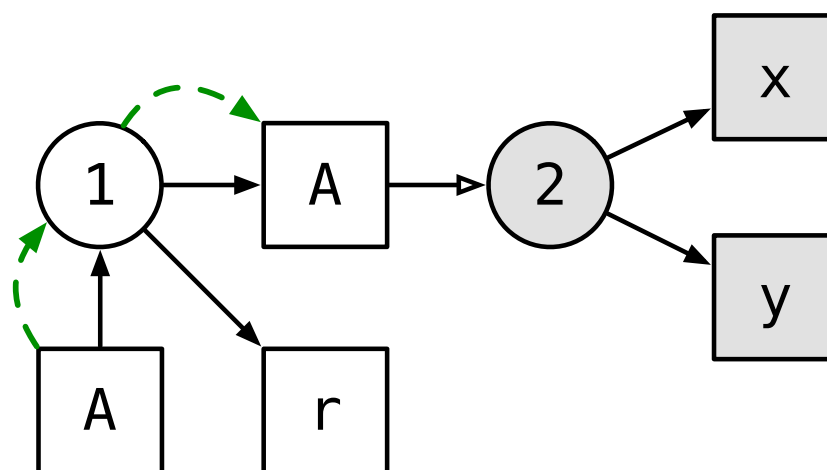
```
var x = 31;  
x = x + 11;
```



Stores/Heaps

Objects

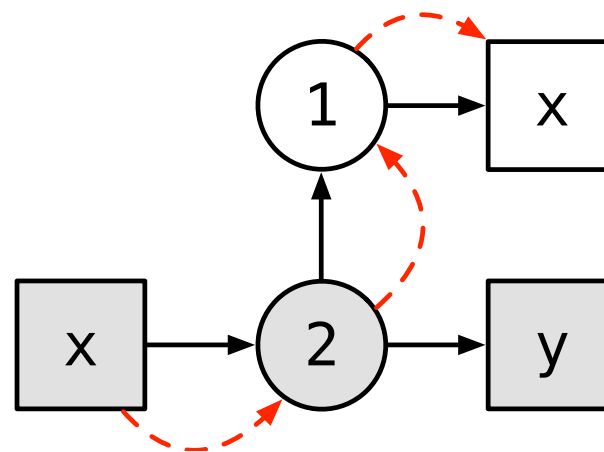
```
class A {  
  var x = 0;  
  var y = 42;  
}  
var r = new A();
```



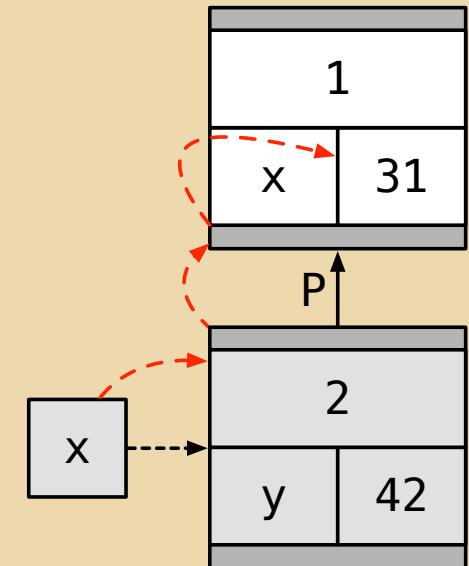
Mutable Objects
Stores/Heaps

Lexical

```
val x = 31;
val y = x + 11;
```

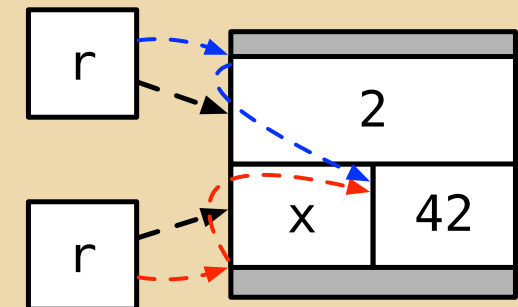
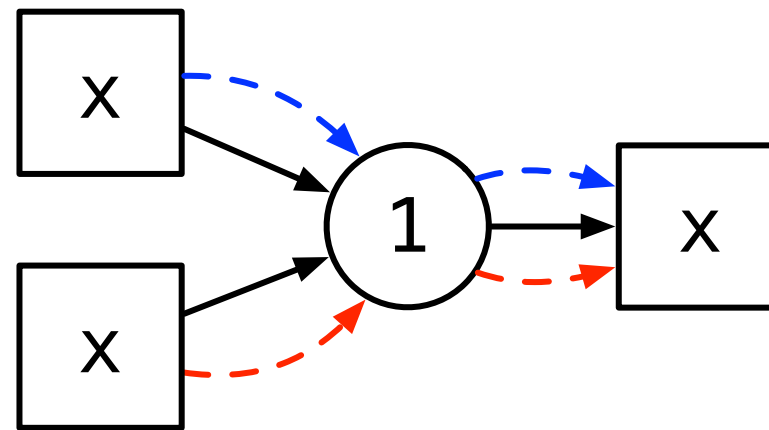


Dynamic



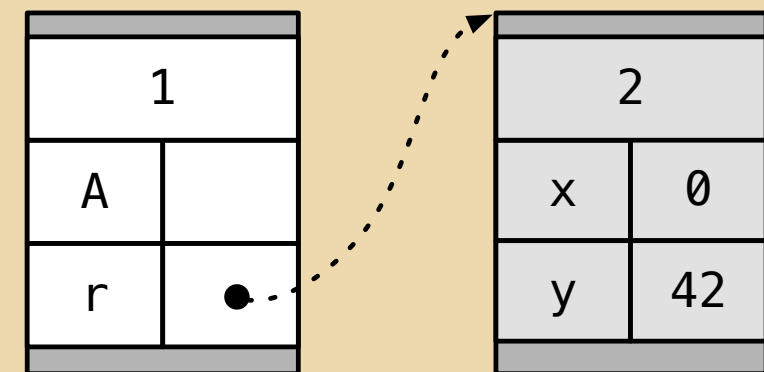
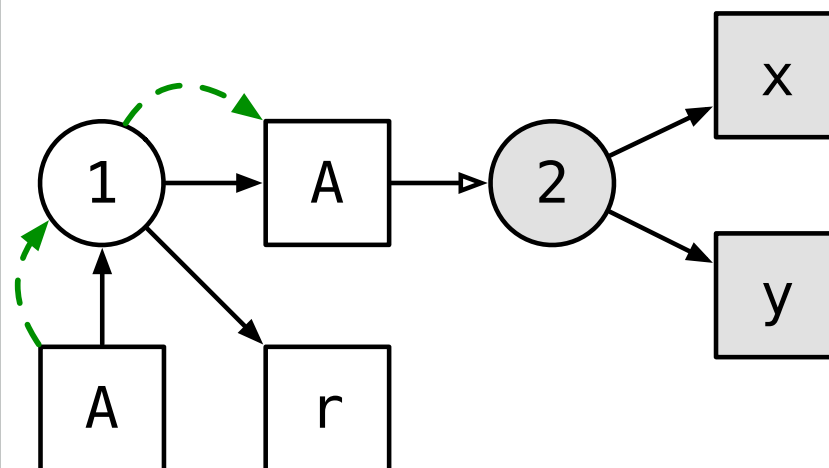
Mutable

```
var x = 31;
x = x + 11;
```



Objects

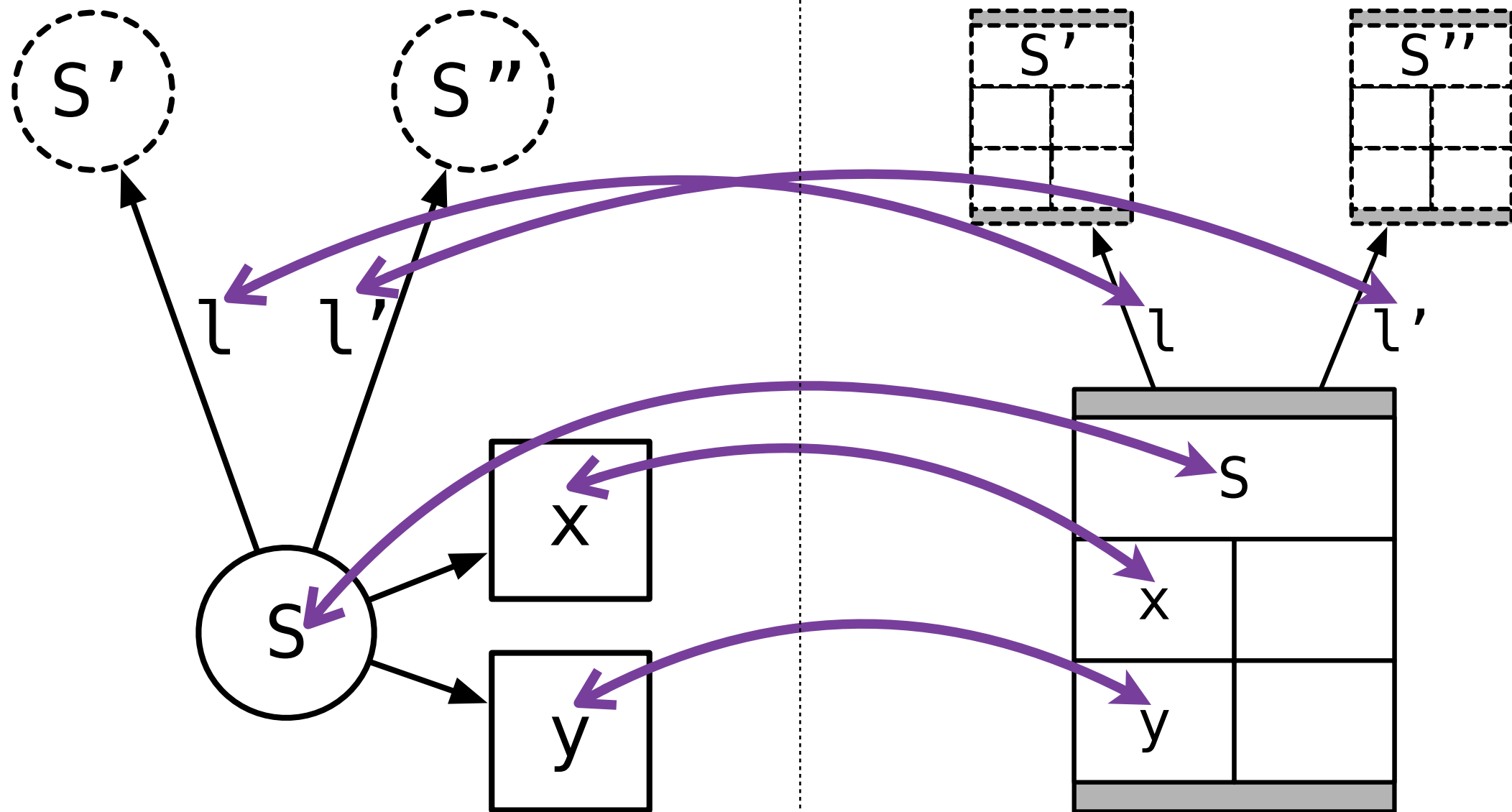
```
class A {
  var x = 0;
  var y = 42;
}
var r = new A();
```



Well-Bound Frame

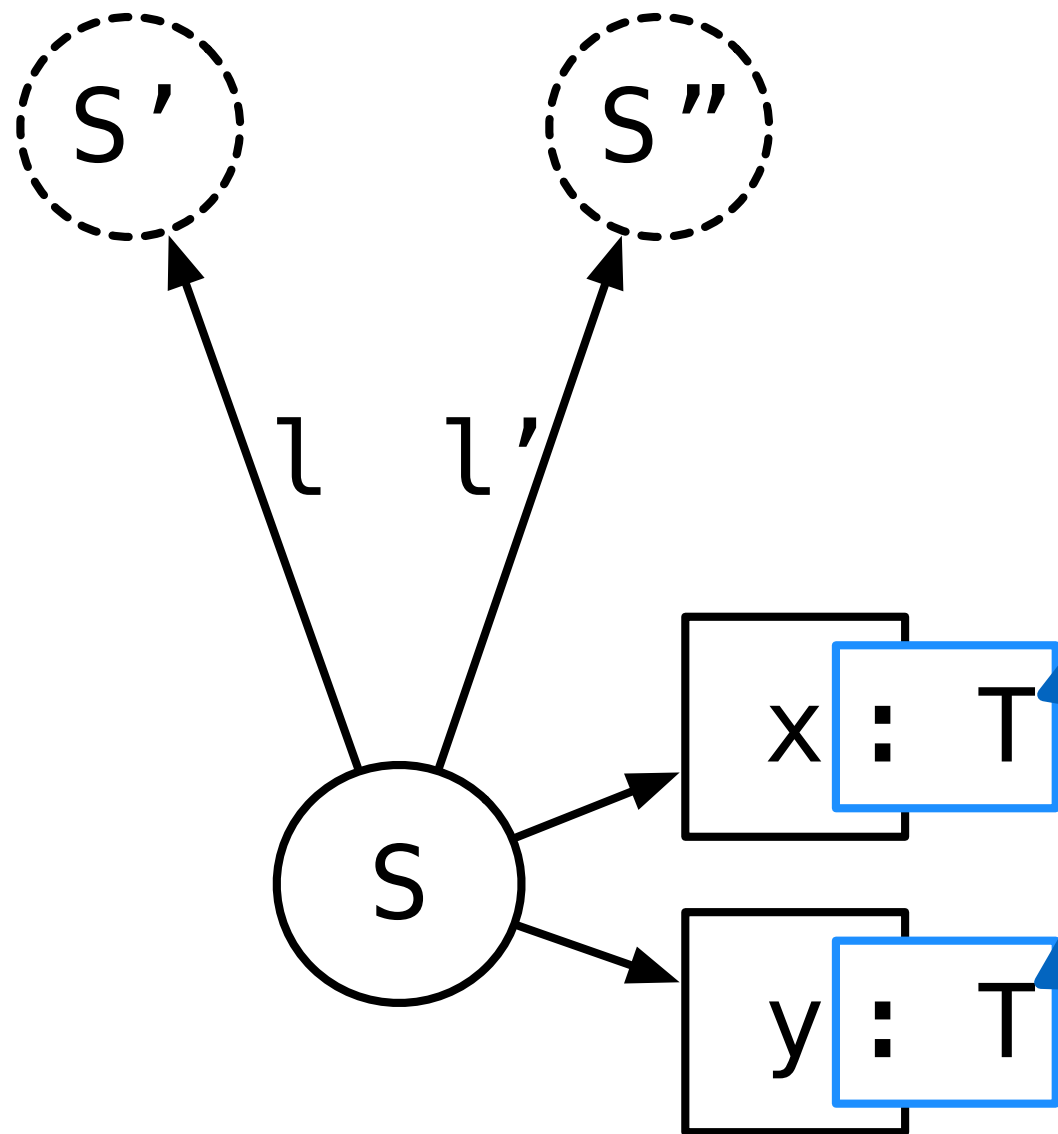
Scope

Frame

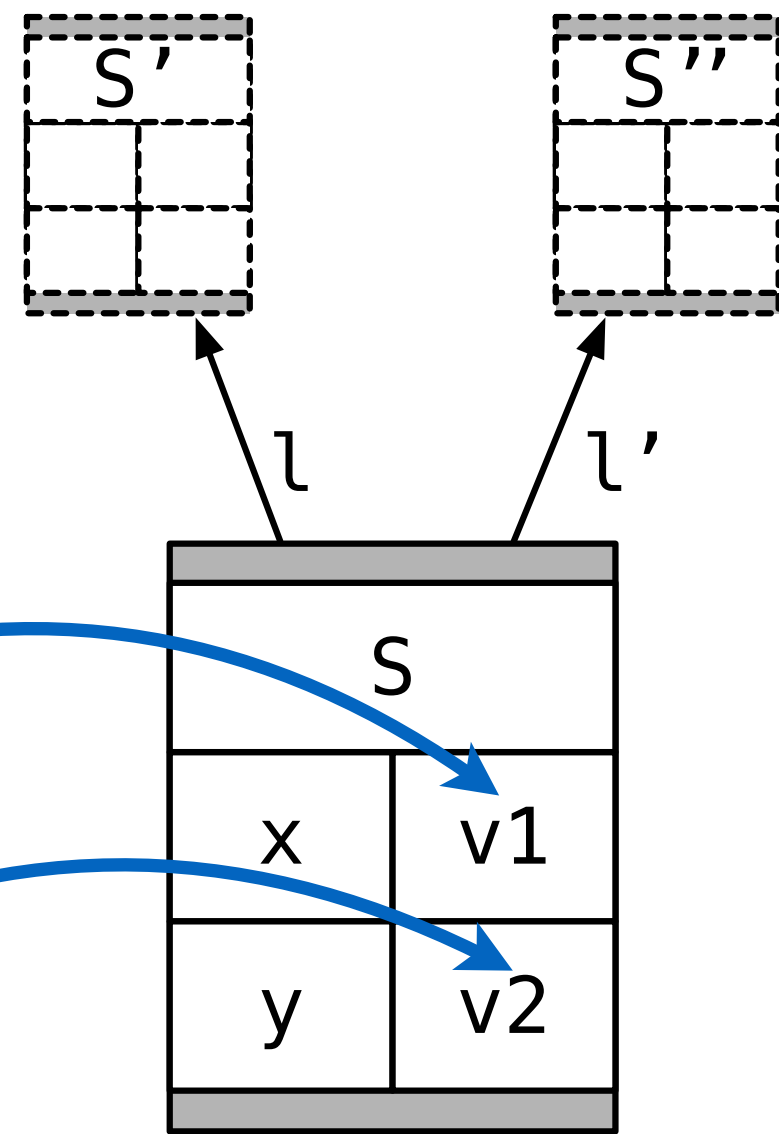


Well-Typed Frame

Scope



Frame

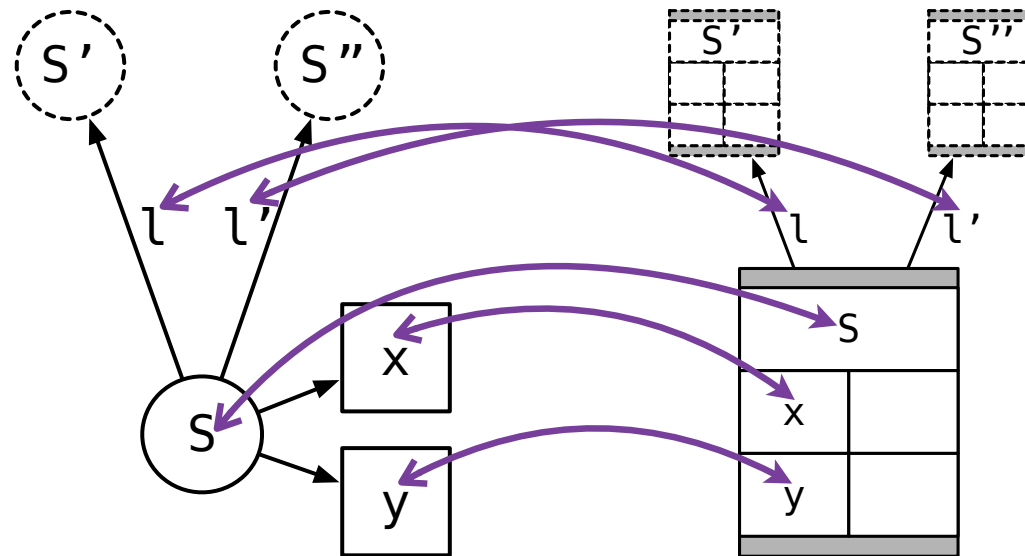


Good Frame Invariant

Well-Bound Frame

Scope

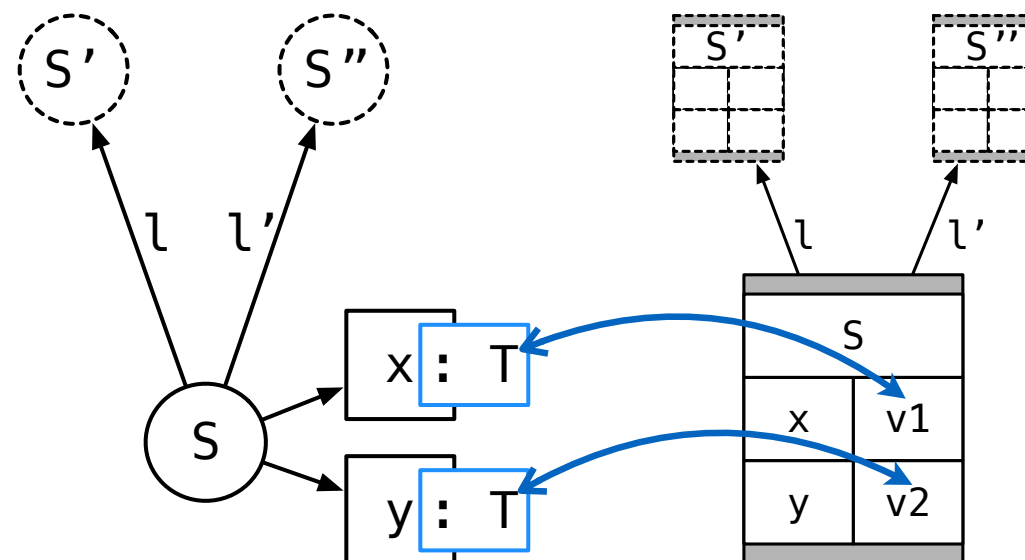
Frame



Well-Typed Frame

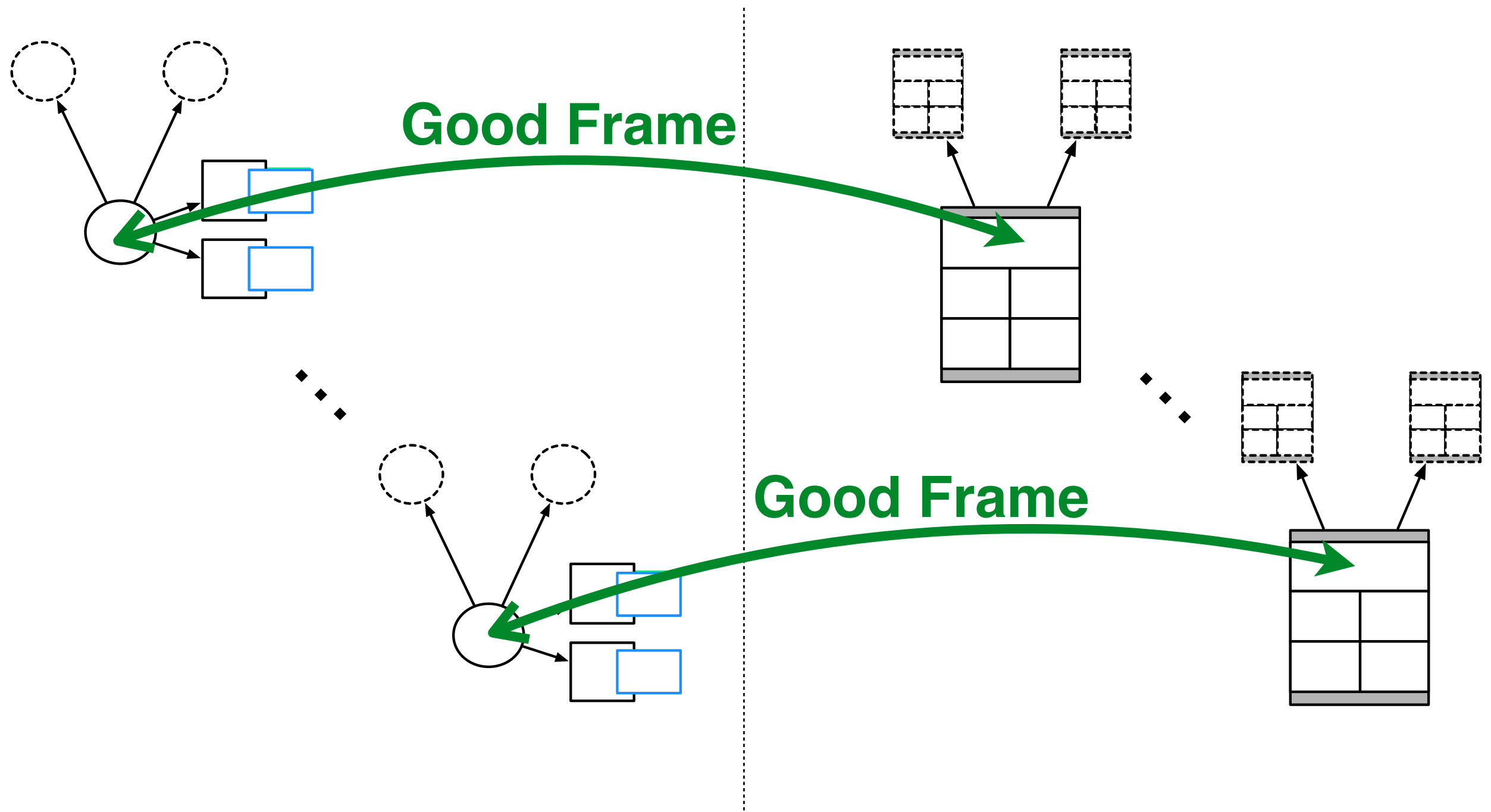
Scope

Frame

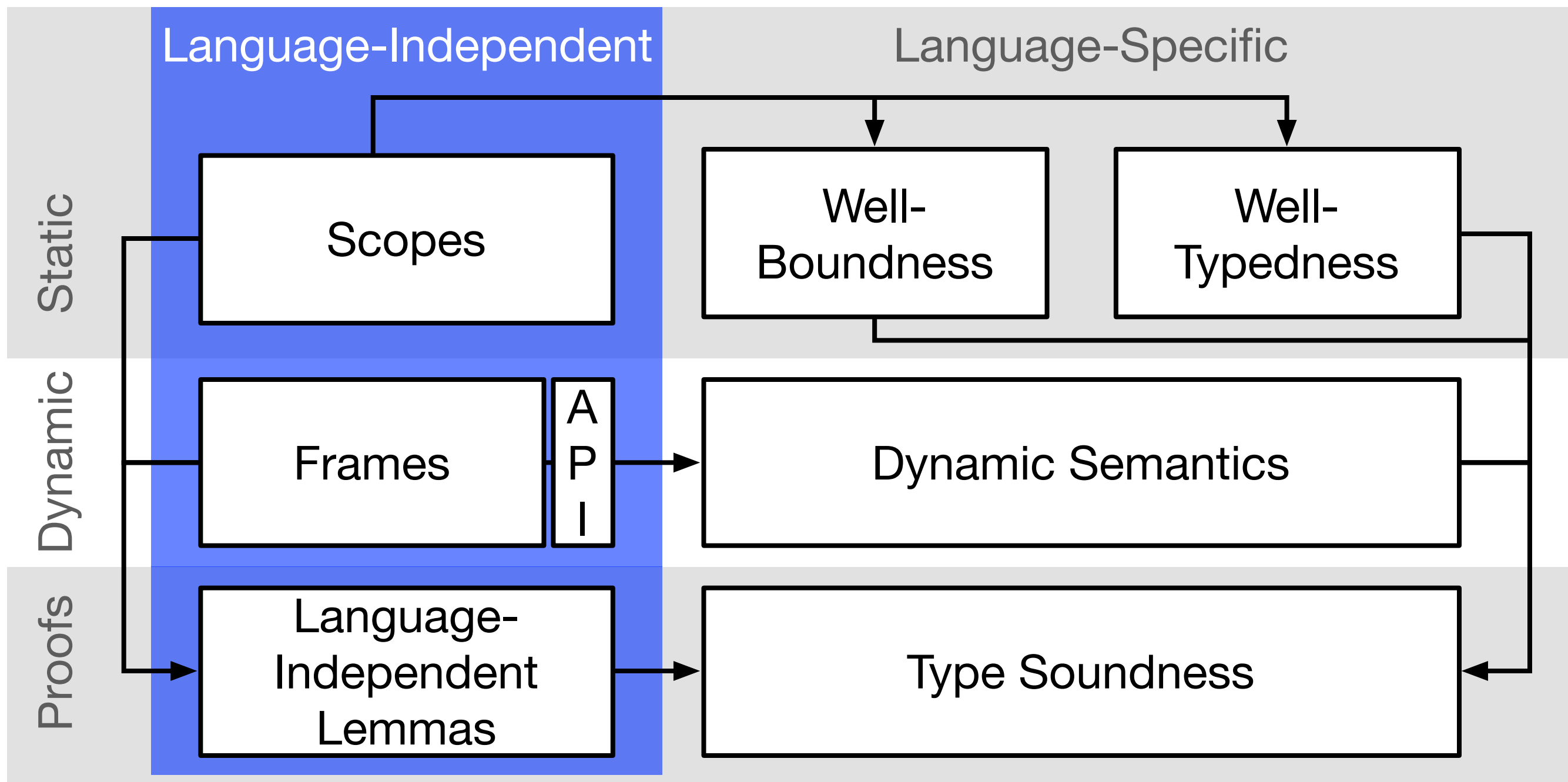


Good Heap Invariant

Every Frame is Well-Bound and Well-Typed

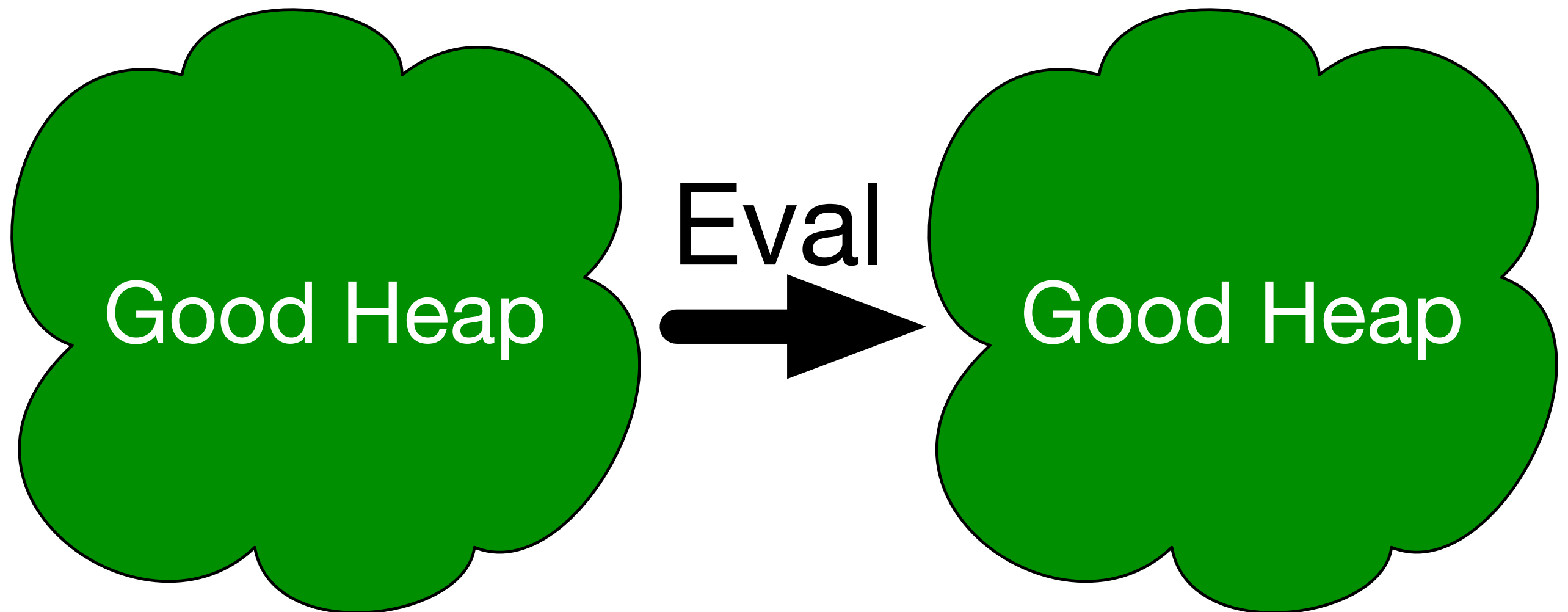


Architecture of a Specification



Type Soundness Principle

Evaluation Preserves
Good Heap Invariant



Summary

Summary

Compilers provide de-facto semantics to programming languages

=> often unclear

Formal specification of source language

is essential to pin down design

Hard requirement for future programming languages

Formal semantics should be live (connected to implementation)

and understandable (through readable meta-DSL)

Research Agenda

Abrupt termination?

Concurrency?

More case studies

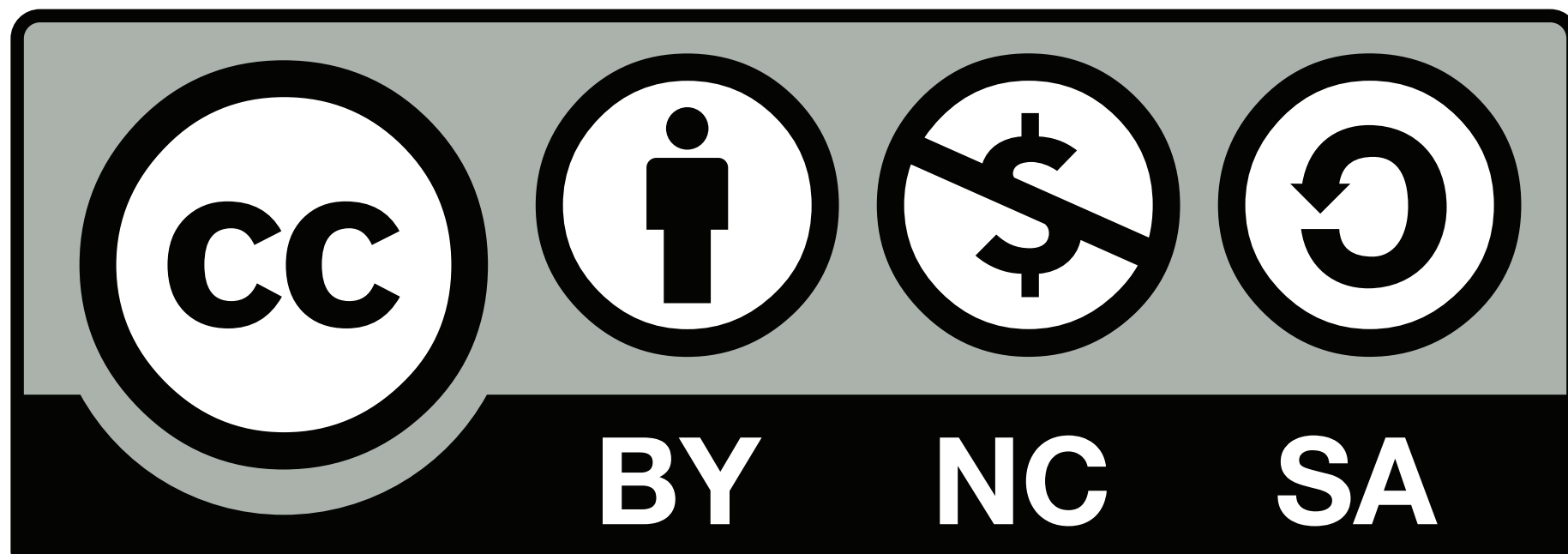
Interpreter Generation

Optimization

Targeting (Graal+Truffle)/PyPy?

Type Soundness Verification

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arrows by Dean Hochman, some rights reserved