Semantic Analysis

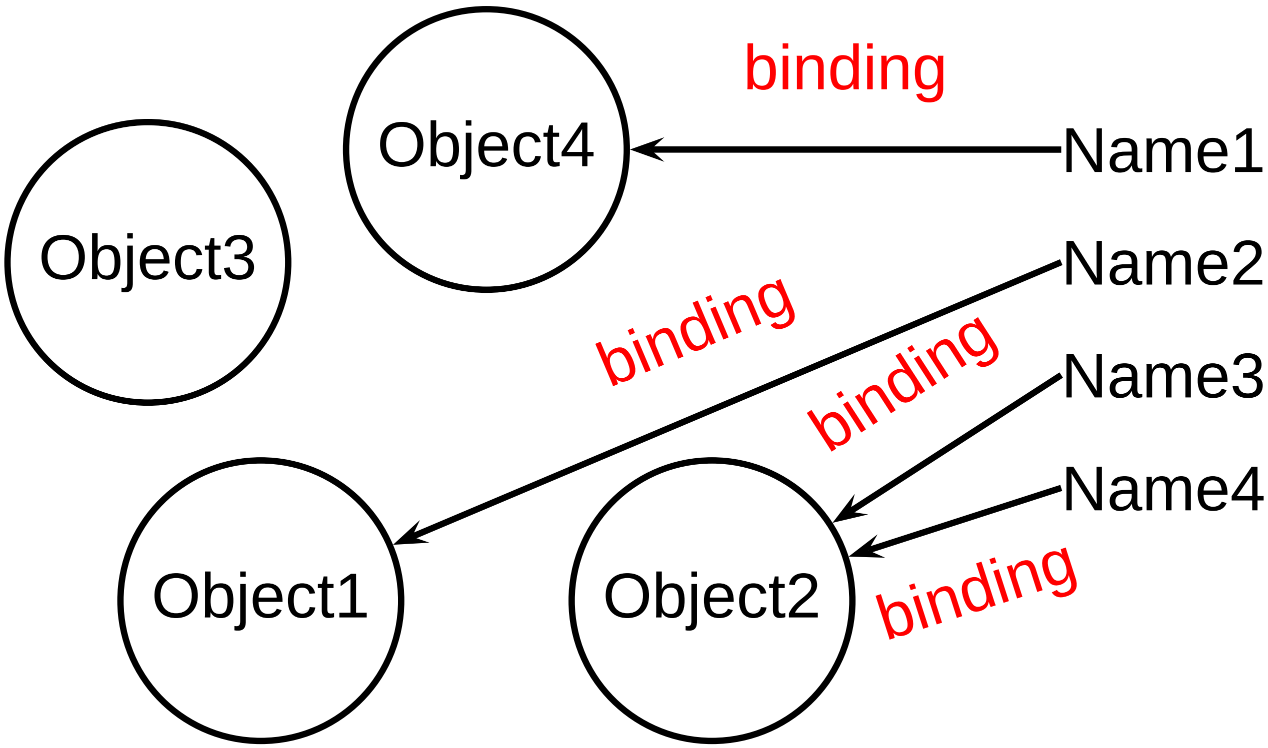
What’s In a Name?

Name: way to refer to something else

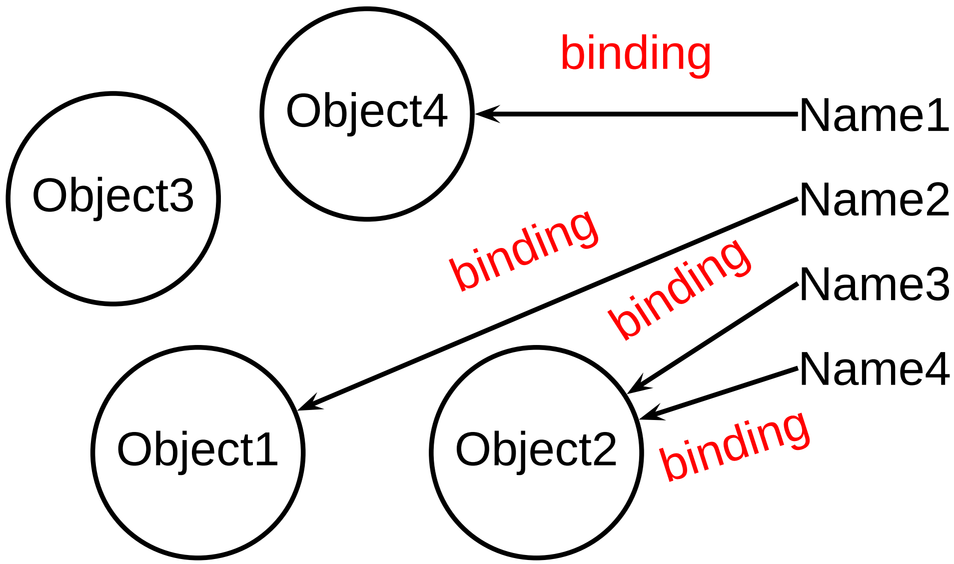
variables, functions, namespaces, objects, types

```
if ( a < 3 ) {
  int bar = baz(a + 2);
  int a = 10;
}
```

Names, Objects, and Bindings



Names, Objects, and Bindings



When are objects created and destroyed?

When are names created and destroyed?

When are bindings created and destroyed?

Object Lifetimes

When are objects created and destroyed?

Object Lifetimes

The objects considered here are regions in memory.

Three principal storage allocation mechanisms:

1. Static

   Objects created when program is compiled, persists throughout run

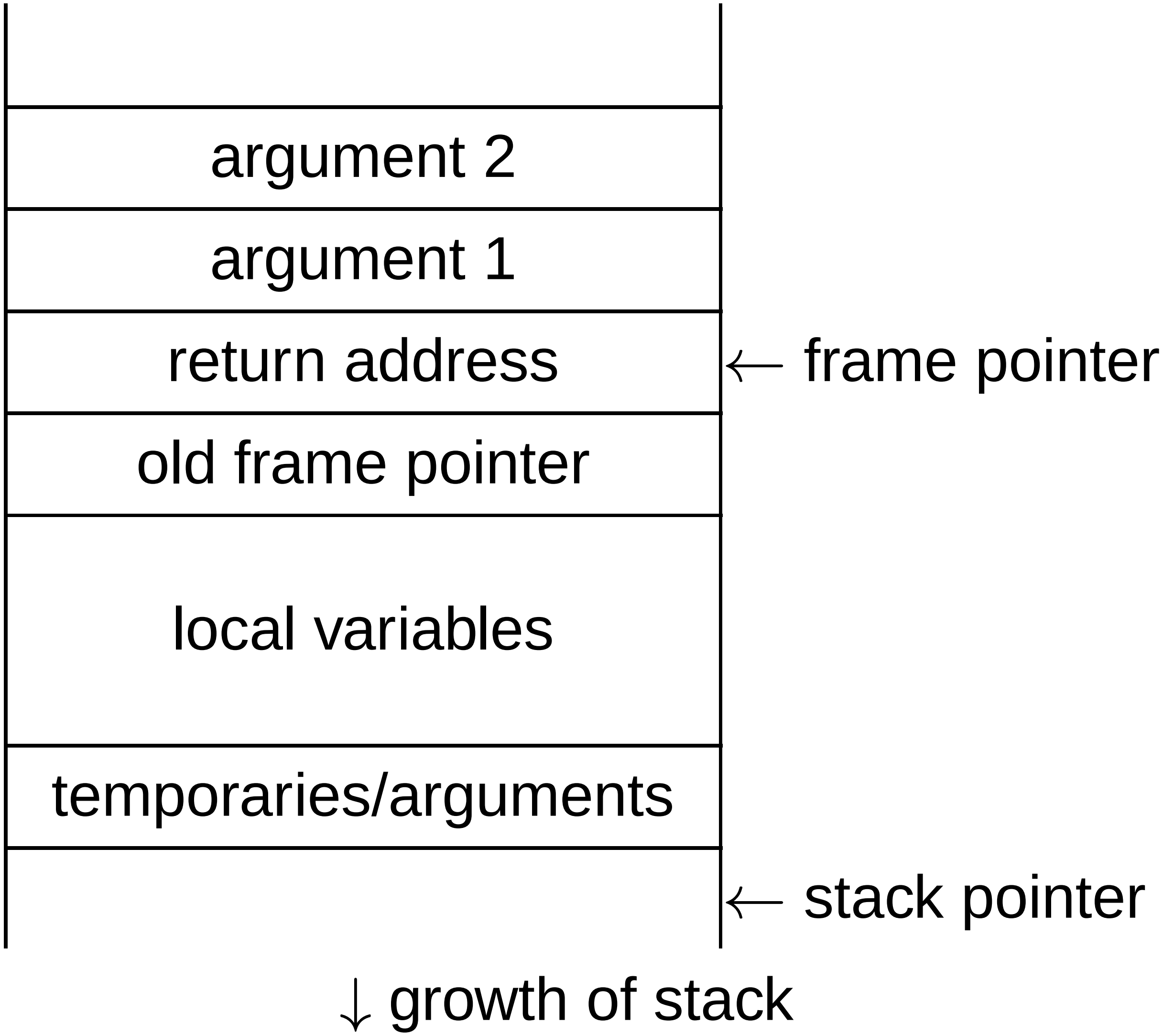
2. Stack

   Objects created/destroyed in last-in, first-out order. Usually associated with function calls.

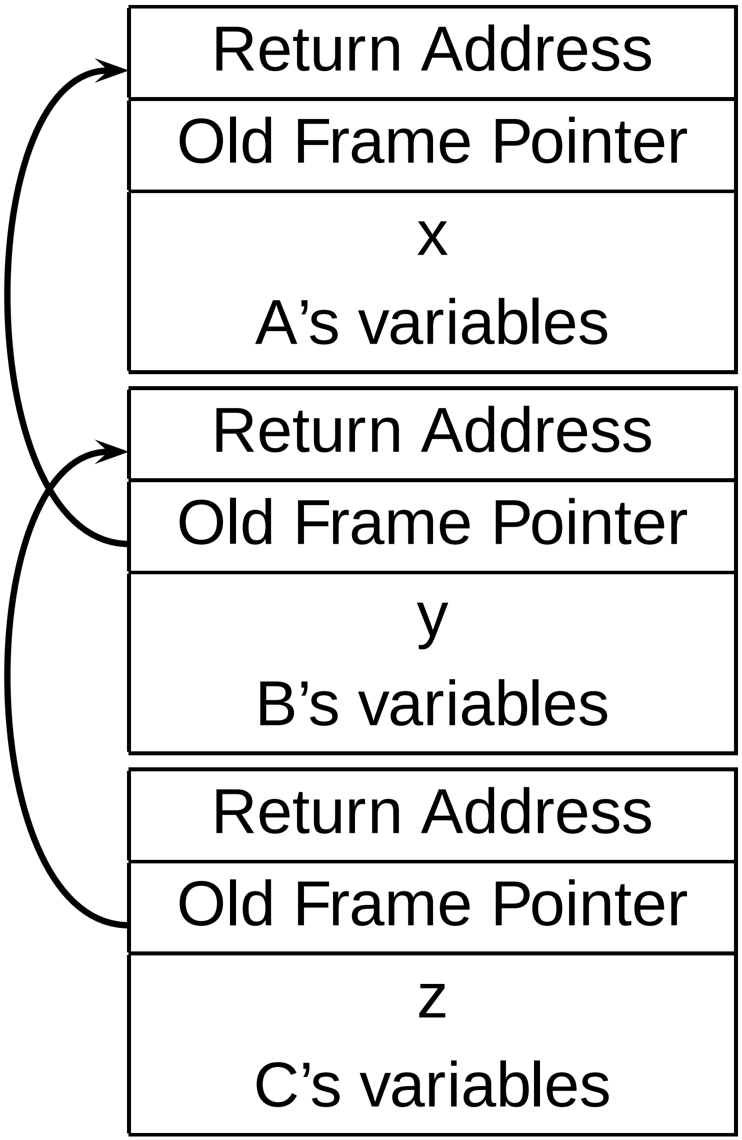
3. Heap

   Objects created/deleted in any order, possibly with automatic garbage collection.

Activation Records



Activation Records




```
int A() {
  int x;
  B();
}

int B() {
  int y;
  C();
}

int C() {
  int z;
}
```

Scope

When are names created, visible, and destroyed?

Scope

The scope of a name is the textual region in the program in which the binding is active.

Static scoping: active names only a function of program text.

Dynamic scoping: active names a function of run-time behavior.

Scope: Why Bother?

Scope is not necessary. Languages such as assembly have exactly one scope: the whole program.

Reason: Information hiding and modularity.

Goal of any language is to make the programmer's job simpler.

One way: keep things isolated.

Make each thing only affect a limited area.

Make it hard to break something far away.

Basic Static Scope

Usually, a name begins life where it is declared and ends at the end of its block.

```
void foo()
{

  int k;




}
```

Hiding a Definition

Nested scopes can hide earlier definitions, giving a hole.

```
void foo()
{
  int x;

   while ( a < 10 ) {
     int x;

  }


}
```

Static Scoping in Java

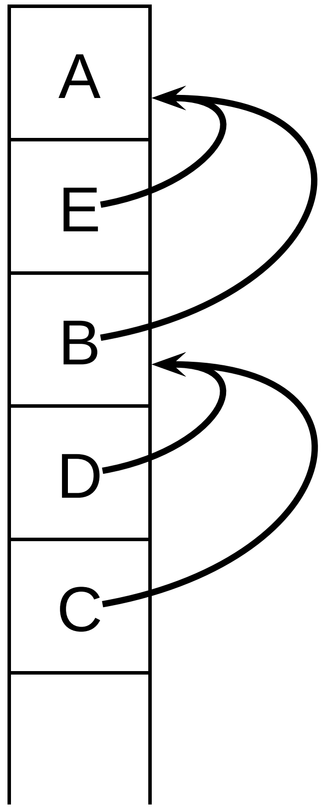
```
public void example() {
  // x, y, z not visible

  int x;
  // x visible

  for ( int y = 1 ; y < 10 ; y++ ) {
    // x, y visible

    int z;
    // x, y, z visible
  }

  // x visible
}
```

Nested Subroutines in Pascal

```
procedure mergesort;
var N : integer;

  procedure split;
  var I : integer;
  begin .. end

  procedure merge;
  var J : integer;
  begin .. end

begin .. end
```

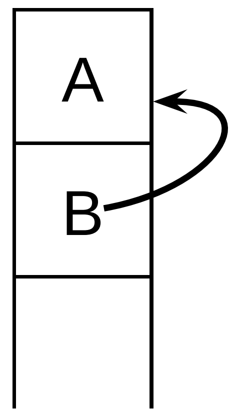
Nested Subroutines in Pascal

```
procedure A;
  procedure B;
    procedure C;
    begin .. end

    procedure D;
    begin C end
  begin D end

  procedure E;
  begin B end
begin E end
```



Example

```
procedure A;
  procedure B;
    procedure C;
    begin if (..) C; end
  begin
    if (..) B;
    C;
    D;
  end
  procedure D;
  begin .. end
begin B; end
```



Example

```
procedure A;
  procedure B;
    procedure C;
    begin if (..) C; end
  begin
    if (..) B;
    C;
    D;
  end
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begin B; end
```
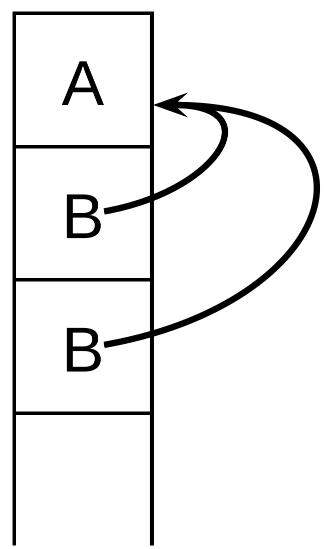
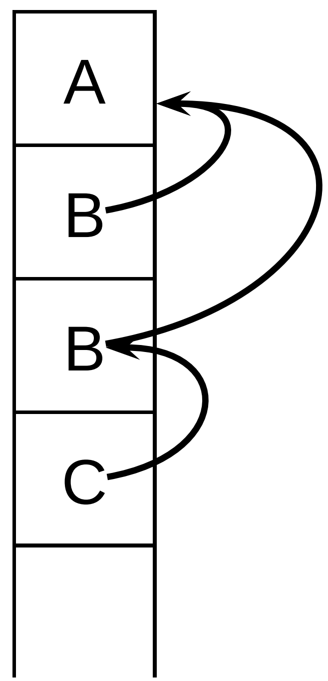



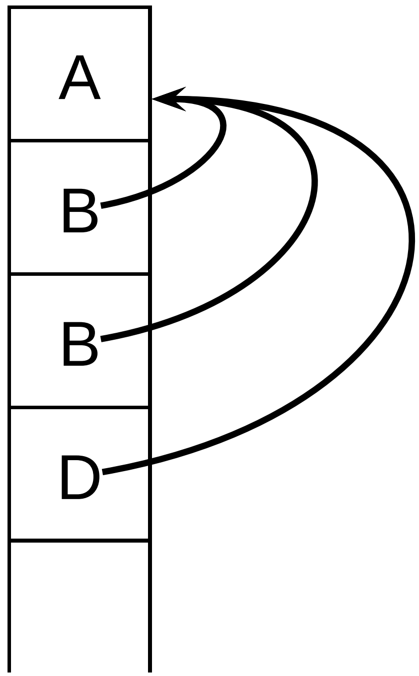
Example

```
procedure A;
  procedure B;
    procedure C;
    begin if (..) C; end
  begin
    if (..) B;
    C;
    D;
  end
  procedure D;
  begin .. end
begin B; end
```



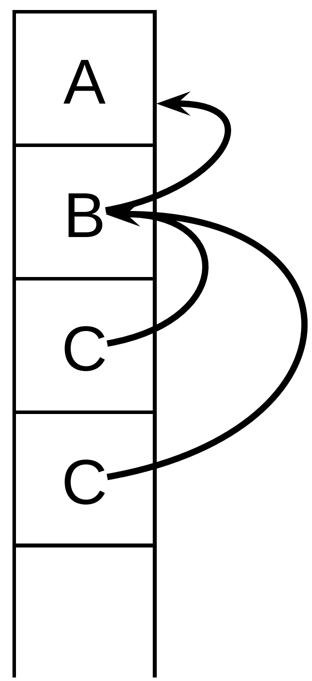
Example

```
procedure A;
  procedure B;
    procedure C;
    begin if (..) C; end
  begin
    if (..) B;
    C;
    D;
  end
  procedure D;
  begin .. end
begin B; end
```



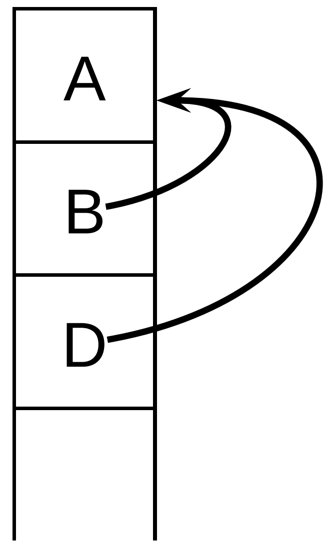
Example

```
procedure A;
  procedure B;
    procedure C;
    begin if (..) C; end
  begin
    if (..) B;
    C;
    D;
  end
  procedure D;
  begin .. end
begin B; end
```



Example

```
procedure A;
  procedure B;
    procedure C;
    begin if (..) C; end
  begin
    if (..) B;
    C;
    D;
  end
  procedure D;
  begin .. end
begin B; end
```



Dynamic Scoping in TeX

```
% \x, \y undefined
{
  % \x, \y undefined
  \def \x 1
  % \x defined, \y undefined

  \ifnum \a < 5
    \def \y 2
  \fi

  % \x defined, \y may be undefined
}
% \x, \y undefined
```

Static vs. Dynamic Scope

```
program example;
var a : integer; (* Outer a *)

  procedure seta;     begin a := 1 end

  procedure locala;
  var a : integer; (* Inner a *)
  begin seta end

begin
  a := 2;
  if (readln() = ’b’) locala
  else seta;
  writeln(a)
end
```

Static vs. Dynamic Scope

Most languages now use static scoping.

Easier to understand, harder to break programs.

Advantage of dynamic scoping: ability to change environment.

A way to surreptitiously pass additional parameters.

Symbol Tables

How does a compiler implement scope rules?

Symbol Tables

Basic mechanism for relating symbols to their definitions in a compiler.

Eventually need to know many things about a symbol:

- Whether it is defined in the current scope. “Undefined symbol”
- Whether its defined type matches its use.
  `1 + "hello"`
- Where its object is stored (statically allocated, on stack).

Symbol Tables

Implemented as a collection of dictionaries in which each symbol is placed.

Two operations: insert adds a binding to a table and lookup locates the binding for a name.

Symbol tables are created and filled, but never destroyed.

Implementing Symbol Tables

Many different ways:

- linked-list
- hash table
- binary tree

Hash tables are faster, but linked lists are good enough for simple compilers.

Symbol Table Lookup

Basic operation is to find the entry for a given symbol.

In many implementations, each symbol table is a scope.

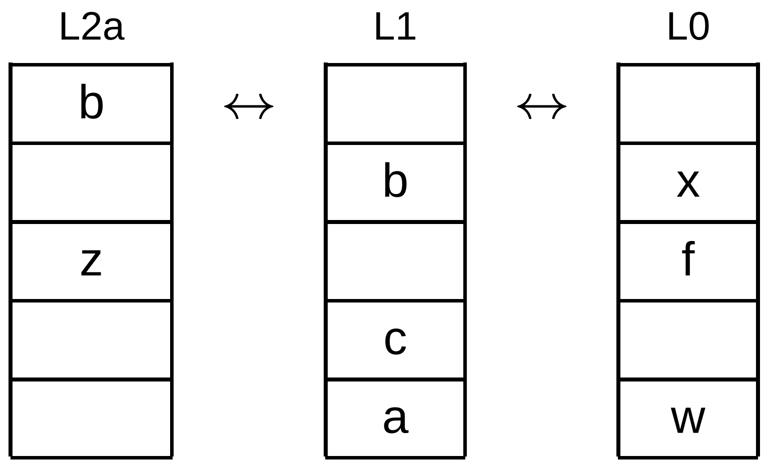
Each symbol table has a pointer to its parent scope.

Lookup: if symbol in current table, return it, otherwise look in parent.

Symbol Tables for nested scopes

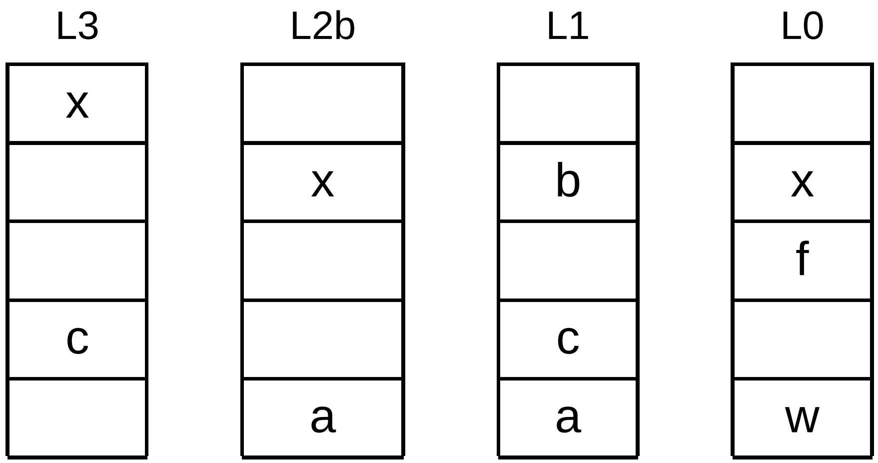
Approach: a stack of symbol tables

```
static int w;        // L0
int x;

void f(int a, int b) {
  int c;             // L1
  { int b, z;        // L2a
    ...
  }
  { int a, x;        // L2b
    ...
    { int c, x;      // L3
      b = a + b + c + w;
    }
  }
}
```



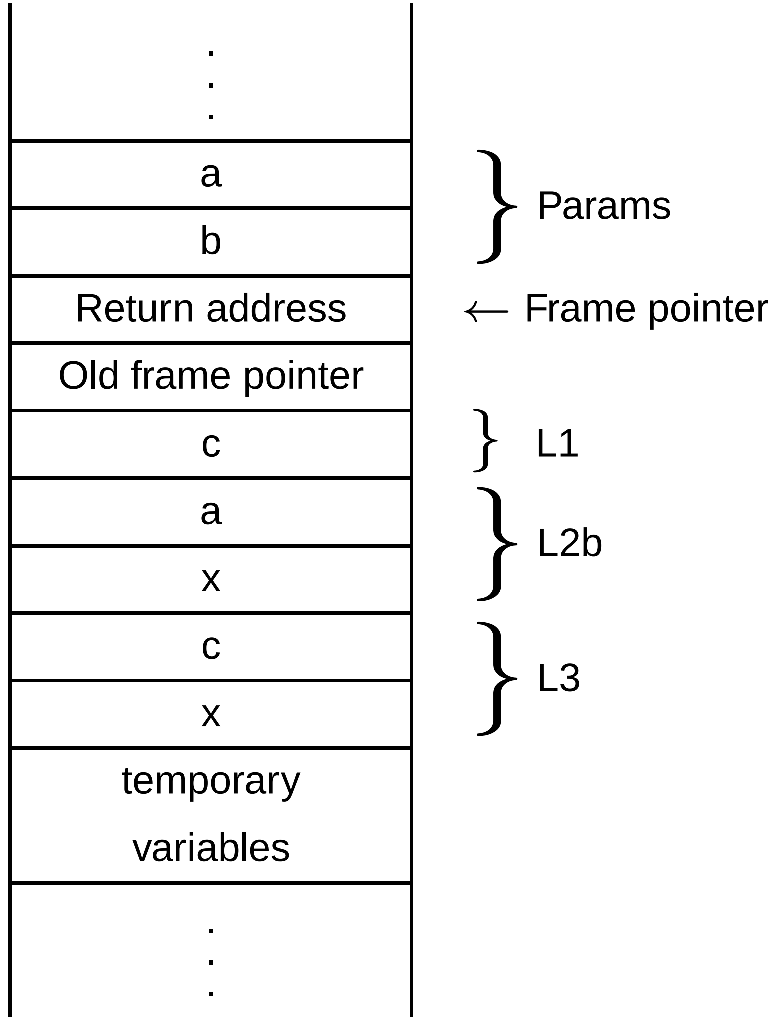
Symbol Tables for nested scopes

```
static int w;       // L0
int x;

void f(int a, int b) {
  int c;            // L1
  { int b, z;       // L2a
    ...
  }
  { int a, x;       // L2b
    ...
    { int c, x;     // L3
      b = a + b + c + w;
    }
  }
}
```



Activation records for nested scopes

```
static int w;       // L0
int x;

void f(int a, int b) {
  int c;            // L1
  { int b, z;       // L2a
    ...
  }
  { int a, x;       // L2b
    ...
    { int c, x;     // L3
      b = a + b + c + w;
    }
  }
}
```



Symbol table entries

A symbol table entry contains information about:

- Identifer (typically a string)
- Type (integer, double, pointer, array, structure, . . .)
- Attributes (parameter, local variable, temporary variable, static, constant, . . .)
- Memory location (e.g., an offset in the activation record)

Type information in symbol table entries

Symbols can have different types:

- Scalar: integer, float, char, boolean, string, . . .
- Data structures: arrays, struct, pointer, . . .
  - Represented with various attributes (array size, fields of the structure, . . .) and recursive type definitions (e.g., a struct containing an array of struct's containing integers and chars)
- Functions
  - Type of result, number and type of parameters.
- Classes
  - Parent class, list of attributes, list of methods, . . .
- . . .

Static Semantic Checking

Main application of symbol tables.

A taste of things to come:

Enter each declaration into its symbol table.

Check that each symbol used is actually defined in the symbol table.

Check its type. . . (next time)

Static Semantic Analysis

Static Semantic Analysis

Lexical analysis: Make sure tokens are valid

```
if i 3 "This"                /* valid */
#a1123                       /* invalid */
```

Syntactic analysis: Makes sure tokens appear in correct order

```
for i := 1 to 5 do 1 + break /* valid */
if i 3                       /* invalid */
```

Semantic analysis: Makes sure program is consistent

```
let v := 3 in v + 8 end      /* valid */
let v := "f" in v(3) + v end /* invalid */
```

Name vs. Structural Equivalence

```
let
  type a = { x: int, y: int }
  type b = { x: int, y: int }
  var i : a := a { x = 1, y = 2 }
  var j : b := b { x = 0, y = 0 }
in
  i := j
end
```

Not legal because **a** and **b** are considered distinct types.

Name vs. Structural Equivalence

```
let
  type a = { x: int, y: int }
  type b = a
  var i : a := a { x = 1, y = 2 }
  var j : b := b { x = 0, y = 0 }
in
  i := j
end
```

Legal because **`b`** is an alias for type **`a`**.

`{ x: int, y: int }` creates a new type, not the **`type`** keyword.

Things to Check

Make sure variables and functions are defined.

```
let var i := 10
in  i(10,20) /* Error: i is a variable */
end
```

Verify each expression’s types are consistent.

```
let var i := 10
    var j := "Hello"
in  i + j /* Error: i is int, j is string */
end
```

Things to Check

- Used identifiers must be defined
- Function calls must refer to functions
- Identifier references must be to variables
- The types of operands for unary and binary operators must be consistent.
- The first expression in an **`if`** and **`while`** must be a Boolean.
- It must be possible to assign the type on the right side of an assignment to the lvalue on the left.
- . . .

Static Semantic Analysis

Basic paradigm: recursively check AST nodes.

`1 + break`

```
   +
  / \
1   break
```

check(+)

check(1) = int

check(break) = void

FAIL: int $\neq$ void

`1 - 5`

```
  -
 / \
1   5
```

check(**-**)

check(1) = int

check(5) = int

Types match, return int

Ask yourself: at a particular node type, what must be true?

Implementing Static Semantics

Recursive walk over the AST.

Analysis of a node returns its type or signals an error.

Implicit “environment” maintains information about what symbols are currently in scope.

Implementing Static Semantics

```
Symboltable T;

TypeCheck(Function(id,Lpar,Ltype,Lvar,Lblock,Linst))
{
  T.CreateScope();
  T.AddParameters(Lpar);
  T.AddTypes(Ltype);
  CheckCircularTypes();
  T.AddVariables(Lvar);
  T.AddFunctionHeaders(Lblock);
  TypeCheck(Lblock);
  TypeCheck(Linst);
  T.DestroyScope();
}
```

Implementing Static Semantics

```
T.AddType(TypeDecl(id,t))=
   T.add(id,⟨TYPE,TypeId(t)⟩)

T.AddVariable(VarDecl(id,t))=
   T.add(id,⟨LOCALVAR,TypeId(t)⟩)

TypeId(t)=
   if basic_type(t) return t;
   else if defined_type(t) return Index(t);
   else /* structured type */
      for each component c of t do
         t.c.type = TypeId(t.c.type);
      return t;
```

Example

```
Program
  Types t1 Array [1..10] Of Int EndTypes
  Vars x t1 EndVars
  Procedure P(Val y t1)
    Types
      t1 Struct
           a Int
           b Real
         EndStruct
    EndTypes
    Vars
      z t1
    EndVars
    x[3]:=z.a+y[4]
  EndProcedure
  P(x)
EndProgram
```

Implementing Static Semantics

Type(e$_1$[e$_2$])	=	**Type(t)** , if **Type(e$_1$)** is **array(i,j,t)** and **Type(e$_2$)=INT**.
	=	**ERROR**, otherwise.
Type(&e)	=	**pointer(Type(e))**, if **Addressable(e)**.
	=	**ERROR** , otherwise.
Type(eˆ)	=	**Type(t)** , if **Type(e)** is **pointer(t)**.
	=	**ERROR** , otherwise.
Type(id)	=	**Type(Table[id].type)**
Type(t)	=	**t**, if **t** is a basic type.

Implementing Static Semantics

$$
\begin{array}{lcl}
\texttt{Addressable(op e)} & = & \texttt{False} \\
\texttt{Addressable(e}_1\texttt{ op e}_2\texttt{)} & = & \texttt{False} \\
\texttt{Addressable(\&e)} & = & \texttt{False} \\
\texttt{Addressable(e\^{})} & = & \texttt{True} \\
\texttt{Addressable(e}_1\texttt{[e}_2\texttt{])} & = & \texttt{Addressable(e}_1\texttt{)} \\
\texttt{Addressable(e.id)} & = & \texttt{Addressable(e)} \\
\texttt{Addressable(id(L\_real\_params))} & = & \texttt{False} \\
\texttt{Addressable(id)} & = & \texttt{True}
\end{array}
$$

Note: We assume that any **`id`** is addressable, even in the case it is a function name, since it can be passed as a reference parameter to another function.

Implementing Static Semantics

TypeCheck(e_1**:=**e_2**)** = **OK**, if (**Type(**e_1**)=Type(**e_2**)** or
(**Type(**e_1**)=REAL and Type(**e_2**)=INT)**
or (**Type(**e_1**)** is **pointer(t)** and e_2**=NULL**))
and **Addressable(**e_1**)**
= **ERROR**, otherwise.

TypeCheck(while e do l) = **OK** , if **Type(e)=BOOL** and
TypeCheck(l)=OK
= **ERROR**, otherwise.

Exercise

Define the function **TypeCheck** for the following instructions:

$$\texttt{TypeCheck(if e then l}_1\texttt{ else l}_2\texttt{)} = ?$$

$$\texttt{TypeCheck(id(List\_Real\_Params)))} = ?$$

Exercises

We look at a simple language with an exception mechanism:

$$
\begin{array}{lcl}
S & \rightarrow & \textbf{throw}\ \mathtt{\textbf{id}} \\
S & \rightarrow & S\ \textbf{catch}\ \mathtt{\textbf{id}} \Rightarrow S \\
S & \rightarrow & S\ \textbf{or}\ S \\
S & \rightarrow & \textit{other}
\end{array}
$$

A *throw* statement throws a named exception. This is caught by the nearest enclosing catch statement (i.e., where the throw statement is in the left sub-statement of the catch statement) using the same name, whereby the statement after the arrow in the catch statement is executed. An *or* statement is a non-deterministic choice between the two statements, so either one can be executed. *other* is a statement that does not throw any exceptions. We want the type checker to ensure that all possible exceptions are caught and that no catch statement is superfluous, i.e., that the exception it catches can, in fact, be thrown by its left sub-statement. Write type-check functions that implement these checks. Hint: Let the type of a statement be the set of possible exceptions it can throw.

Let us consider the following fragment of C code:

```
struct {
  int a;
  char b;
} c;
(int *) d[10];
struct {
  struct {
    int *e;
    char f[10];
  } *g;
  (char *) h[10];
} e, *f;
```

```
1: (*((*f).g)).f[*(d[4])] = c.b;
2: e.h[11] = &(c.b);
3: *(e.g + int) = *((*f).g);
4: d[12] = &(c.a+1);
5: c.a = e.2[h];
6: (*f)..h[1];
```

- Give an AST for the type of variable **`f`**. Use the label **`struct`** to represent the root node of a struct's AST and the label **`array[`n`]`** to represent the root node of an array of n elements.
- Give an AST representing the assignment in line 1 and infer the type associated to each node of the AST. Is it a correct assignment?
- Indicate which errors are found in the code and when they are detected (lexical, syntax, semantic, runtime).
  - **`&`** can only be used for an addressable memory location.
  - The LHS and RHS types of an assignment are not compatible.
  - A character does not belong to the alphabet of the language.
  - An array index is out of bounds.
  - An array index must be integer.
  - Only integer values can be added to pointers.