COP4020 Programming Languages

Names, Scopes, and Bindings

Robert van Engelen & Chris Lacher

Overview

- Abstractions and names
- Binding time
- Object lifetime
- Object storage management
  - Static allocation
  - Stack allocation
  - Heap allocation
- Scope rules
- Static versus dynamic scoping
- Reference environments
- Overloading and polymorphism

Name = Abstraction

- *Names* enable programmers to refer to variables, constants, operations, and types using identifier names
- Names are *control abstractions* and *data abstractions* for program fragments and data structures
  - Control abstraction:
    - Subroutines (procedures and functions) allow programmers to focus on manageable subset of program text
    - Subroutine interface hides implementation details
  - Data abstraction:
    - Object-oriented classes hide data representation details behind a set of operations
    - Abstraction in the context of high-level programming languages refers to the *degree* or *level* of language features
    - Enhances the level of machine-independence
    - "Power" of constructs

Binding Time

- A *binding* is an association between a *name* and an *entity*
- *Binding time* is the time at which an implementation decision is made to create a name ↔ entity binding:
  - *Language design time*: the design of specific program constructs (syntax), primitive types, and meaning (semantics)
  - *Language implementation time*: fixation of implementation constants such as numeric precision, run-time memory sizes, max identifier name length, number and types of built-in exceptions, etc.
  - *Program writing time*: the programmer's choice of algorithms and data structures
  - *Compile time*: the time of translation of high-level constructs to machine code and choice of memory layout for data objects
  - *Link time*: the time at which multiple object codes (machine code files) and libraries are combined into one executable
  - *Load time*: when the operating system loads the executable in memory
  - *Run time*: when a program executes

Binding Time Examples

- Language design:
  - Syntax (names ↔ grammar)
    - **`if (a>0) b:=a;`** (C syntax style)
    - **`if a>0 then b:=a end if`** (Ada syntax style)
  - Keywords (names ↔ builtins)
    - **`class`** (C++ and Java), **`endif`** or **`end if`** (Fortran, space insignificant)
  - Reserved words (names ↔ special constructs)
    - **`main`** (C), **`writeln`** (Pascal)
  - Meaning of operators (operator ↔ operation)
    - **`+`** (add), `%` (mod), **`**`** (power)
  - Built-in primitive types (type name ↔ type)
    - float, short, int, long, string
- Language implementation
  - Internal representation of types and literals (type ↔ byte encoding)
    - 3.1 (IEEE 754) and "foo bar” (\0 terminated or embedded string length)
  - Storage allocation method for variables (static/stack/heap)

Binding Time Examples (cont'd)

- Compile time
  - The specific type of a variable in a declaration (name↔type)
  - Storage allocation method for a global or local variable (name↔allocation mechanism)
- Linker
  - Linking calls to static library routines (function↔address)
    - **`printf`** (in libc)
  - Merging and linking multiple object codes into one executable
- Loader
  - Loading executable in memory and adjusting absolute addresses
    - Mostly in older systems that do not have virtual memory
- Run time
  - Dynamic linking of libraries (library function↔library code)
    - DLL, dylib
  - Nonstatic allocation of space for variable (variable↔address)
    - Stack and heap

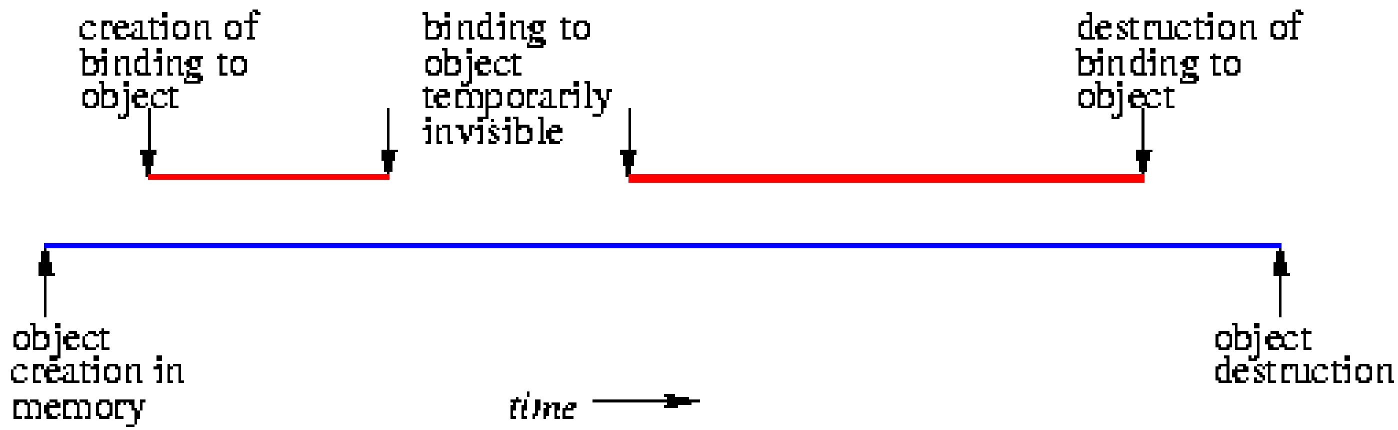
The Effect of Binding Time

- *Early binding times* (before run time) are associated with greater efficiency and clarity of program code
  - Compilers make implementation decisions at compile time (avoiding to generate code that makes the decision at run time)
  - Syntax and static semantics checking is performed only once at compile time and does not impose any run-time overheads
- *Late binding times* (at run time) are associated with greater flexibility (but may leave programmers sometimes guessing what's going on)
  - Interpreters allow programs to be extended at run time
  - Languages such as Smalltalk-80 with polymorphic types allow variable names to refer to objects of multiple types at run time
  - Method binding in object-oriented languages must be late to support *dynamic binding*

Binding Lifetime versus Object Lifetime

- Key events in object lifetime:
  - Object creation
  - Creation of bindings
  - The object is manipulated via its binding
  - Deactivation and reactivation of (temporarily invisible) bindings
  - Destruction of bindings
  - Destruction of objects
- *Binding lifetime*: time between creation and destruction of binding to object
  - Example: a pointer variable is set to the address of an object
  - Example: a formal argument is bound to an actual argument
- *Object lifetime*: time between creation and destruction of an object

Binding Lifetime versus Object Lifetime (cont'd)



- Bindings are temporarily invisible when code is executed where the binding (name ↔ object) is out of scope
- *Memory leak*: object never destroyed (binding to object may have been destroyed, rendering access impossible)
- *Dangling reference*: object destroyed before binding is destroyed
- *Garbage collection* prevents these allocation/deallocation problems

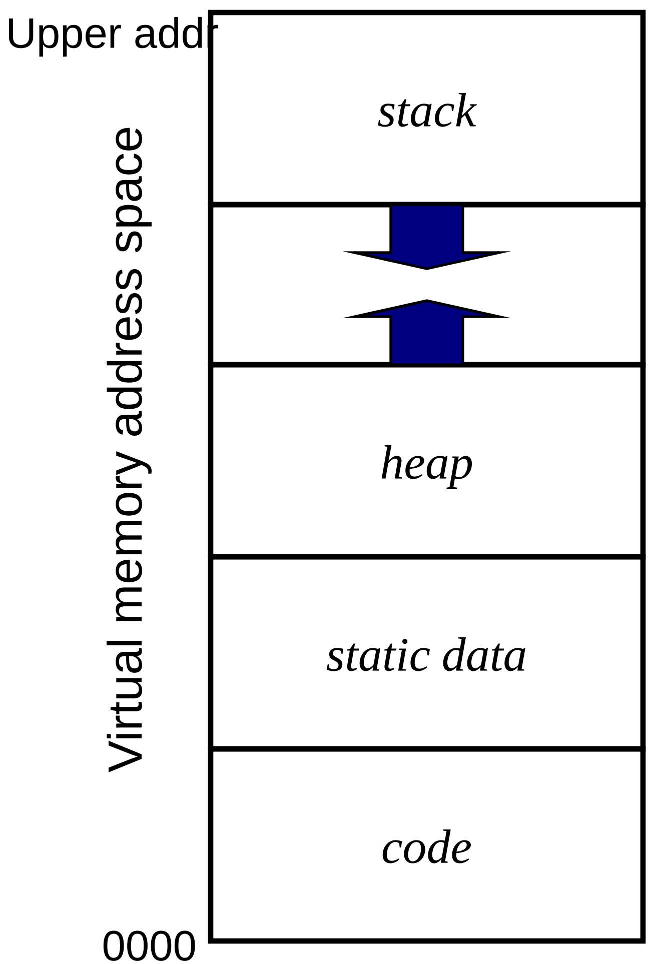
C++ Example

- ```
  {
    SomeClass* myobject = new SomeClass;
    ...
    {
      OtherClass myobject;
      ... // the myobject name is bound to other object
      ...
    }
    ... // myobject binding is visible again
    ...
    myobject->action() // myobject in action():
                       // the name is not in scope
                       // but object is bound to ‘this’
    delete myobject;
    ...
    ... // myobject is a dangling reference
  }
  ```
  ```

Object Storage

- Objects (program data and code) have to be stored in memory during their lifetime
- *Static objects* have an absolute storage address that is retained throughout the execution of the program
  - Global variables and data
  - Subroutine code and class method code
- *Stack objects* are allocated in last-in first-out order, usually in conjunction with subroutine calls and returns
  - Actual arguments passed by value to a subroutine
  - Local variables of a subroutine
- *Heap objects* may be allocated and deallocated at arbitrary times, but require an expensive storage management algorithm
  - Example: Lisp lists
  - Example: Java class instances are always stored on the heap

Typical Program and Data Layout in Memory

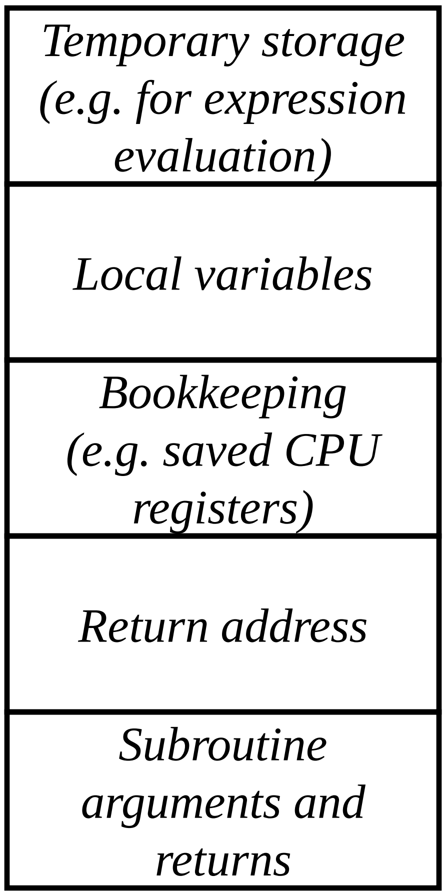


- Program code is at the bottom of the memory region (code section)
  - The code section is protected from run-time modification by the OS
- Static data objects are stored in the static region
- Stack grows downward
- Heap grows upward

Static Allocation

- Program code is statically allocated in most implementations of imperative languages
- Statically allocated variables are history sensitive
  - Global variables keep state during entire program lifetime
  - Static local variables in C functions keep state across function invocations
  - Static data members are “shared” by objects and keep state during program lifetime
- Advantage of statically allocated object is the fast access due to absolute addressing of the object
  - So why not allocate local variables statically?
  - Problem: static allocation of local variables cannot be used for recursive subroutines: each new function instantiation needs fresh locals

Static Allocation in Fortran 77



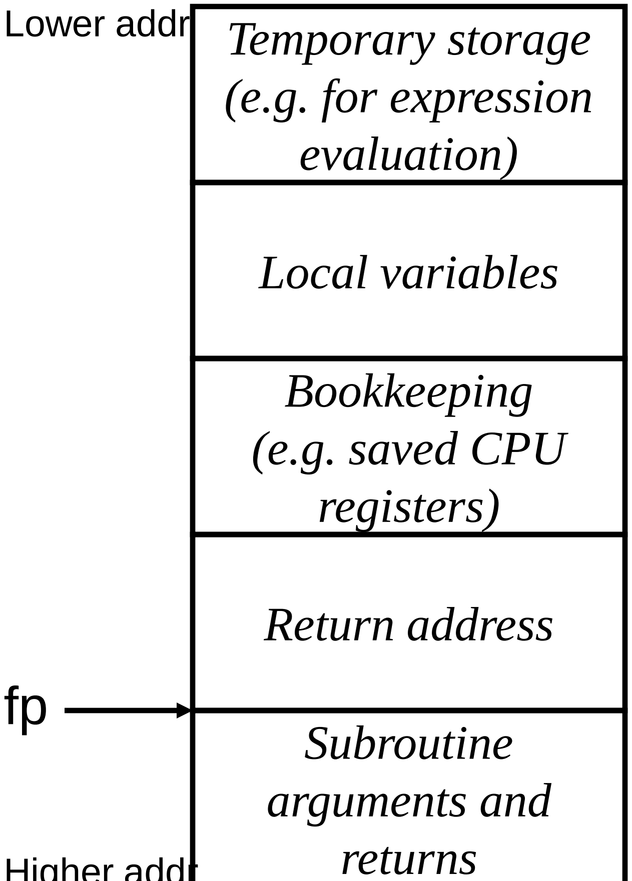
Typical static subroutine frame layout

- Fortran 77 has no recursion
- Global and local variables are statically allocated as decided by the compiler
- Global and local variables are referenced at absolute addresses
- Avoids overhead of creation and destruction of local objects for every subroutine call
- Each subroutine in the program has a *subroutine frame* that is statically allocated
- This subroutine frame stores all subroutine-relevant data that is needed to execute

Stack Allocation

- Each instance of a subroutine that is active has a *subroutine frame* (sometimes called *activation record*) on the run-time stack
  - Compiler generates subroutine calling sequence to setup frame, call the routine, and to destroy the frame afterwards
  - Method invocation works the same way, but in addition methods are typically dynamically bound
- Subroutine frame layouts vary between languages, implementations, and machine platforms

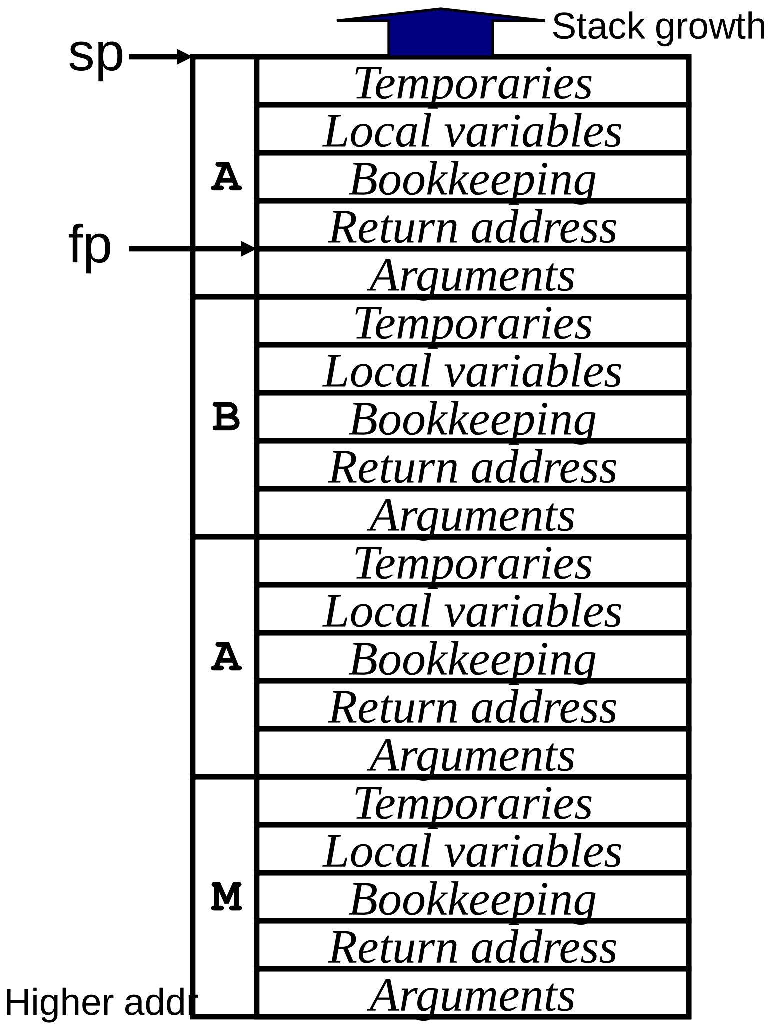
Typical Stack-Allocated Subroutine Frame



Typical subroutine frame layout

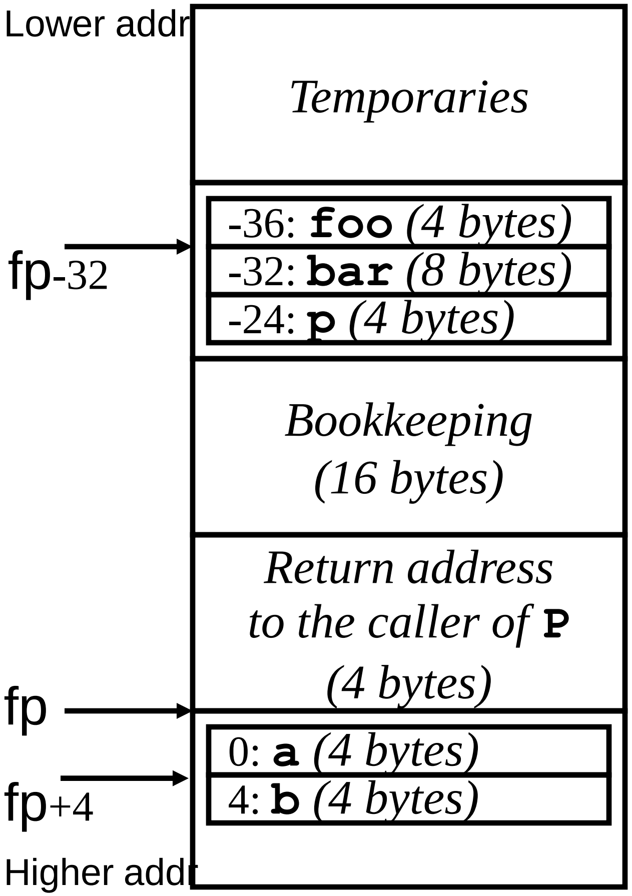
- A *frame pointer* (fp) points to the frame of the currently active subroutine at run time
- Subroutine arguments, local variables, and return values are accessed by constant address offsets from the fp

Subroutine Frames on the Stack



- Subroutine frames are pushed and popped onto/from the runtime stack
- The *stack pointer* (sp) points to the next available free space on the stack to push a new frame onto when a subroutine is called
- The *frame pointer* (fp) points to the frame of the currently active subroutine, which always the topmost frame on the stack
- The fp of the previous active frame is saved in the current frame and restored after the call
- In this example:
  M called **A**
  A called **B**
  B called **A**

Example Subroutine Frame



- The size of the types of local variables and arguments determines the fp offset in a frame
- Example Pascal procedure:

```
procedure P(a:integer,
            var b:real)
(* a is passed by value
   b is passed by reference,
     = pointer to b's value
*)
var
  foo:integer;(* 4 bytes *)
  bar:real;   (* 8 bytes *)
  p:^integer; (* 4 bytes *)
begin
  ...
end
```

Heap Allocation

- Implicit heap allocation:
  - Done automatically
  - Java class instances are placed on the heap
  - Scripting languages and functional languages make extensive use of the heap for storing objects
  - Some procedural languages allow array declarations with run-time dependent array size
  - Resizable character strings
- Explicit heap allocation:
  - Statements and/or functions for allocation and deallocation
  - Malloc/free, new/delete

Heap Allocation Algorithms

- Heap allocation is performed by searching the heap for available free space
- For example, suppose we want to allocate a new object E of 20 bytes, where would it fit?

Object A	Free	Object B	Object C	Free	Object D	Free
30 bytes	8 bytes	10 bytes	24 bytes	24 bytes	8 bytes	20 bytes

- Deletion of objects leaves free blocks in the heap that can be reused
- *Internal heap fragmentation*: if allocated object is smaller than the free block the extra space is wasted
- *External heap fragmentation*: smaller free blocks cannot always be reused resulting in wasted space

Heap Allocation Algorithms (cont'd)

- Maintain a linked list of free heap blocks
- *First-fit*: select the first block in the list that is large enough
- *Best-fit*: search the entire list for the smallest free block that is large enough to hold the object
- If an object is smaller than the block, the extra space can be added to the list of free blocks
- When a block is freed, adjacent free blocks are coalesced
- *Buddy system*: use heap pools of standard sized blocks of size 2^k
  - If no free block is available for object of size between $2^{k-1}+1$ and 2^k then find block of size 2^{k+1} and split it in half, adding the halves to the pool of free 2^k blocks, etc.
- *Fibonacci heap*: use heap pools of standard size blocks according to Fibonacci numbers
  - More complex but leads to slower internal fragmantation

Unlimited Extent

- An object declared in a local scope has *unlimited extent* if its lifetime continues indefinitely
- A local stack-allocated variable has a lifetime limited to the lifetime of the subroutine
  - In C/C++ functions should never return pointers to local variables
- Unlimited extent requires static or heap allocation
  - Issues with static: limited, no mechanism to allocate more variables
  - Issues with heap: should probably deallocate when no longer referenced (no longer bound)
- Garbage collection
  - Remove object when no longer bound (by any references)

Garbage Collection

- Explicit manual deallocation errors are among the most expensive and hard to detect problems in real-world applications
  - If an object is deallocated too soon, a reference to the object becomes a dangling reference
  - If an object is never deallocated, the program leaks memory
- Automatic garbage collection removes all objects from the heap that are not accessible, i.e. are not referenced
  - Used in Lisp, Scheme, Prolog, Ada, Java, Haskell
  - Disadvantage is GC overhead, but GC algorithm efficiency has been improved
  - Not always suitable for real-time processing

Storage Allocation Compared

	Static	*Stack*	*Heap*
Ada	N/A	local variables and subroutine arguments of fixed size	*implicit*: local variables of variable size; *explicit*: new (destruction with garbage collection or explicit with **`unchecked deallocation`**)
C	global variables; static local variables	local variables and subroutine arguments	*explicit* with **`malloc`** and **`free`**
C++	Same as C, and static class members	Same as C	*explicit* with **`new`** and **`delete`**
Java	N/A	only local variables of primitive types	*implicit*: all class instances (destruction with garbage collection)
Fortran77	global variables (in common blocks), local variables, and subroutine arguments (implementation dependent); **`SAVE`** forces static allocation	local variables and subroutine arguments (implementation dependent	N/A
Pascal	global variables (compiler dependent)	global variables (compiler dependent), local variables, and subroutine arguments	Explicit: **`new`** and **`dispose`**

Scope

- *Scope* is the textual region of a program in which a name-to-object binding is active
- *Statically scoped language*: the scope of bindings is determined at compile time
  - Used by almost all but a few programming languages
  - More intuitive to user compared to dynamic scoping
- *Dynamically scoped language*: the scope of bindings is determined at run time
  - Used in Lisp (early versions), APL, Snobol, and Perl (selectively)

Effect of Static Scoping

Program execution:

```
a:integer
main()
  a:=2
  second()
    a:integer
    first()
      a:=1
  write_integer(a)
```

binding

Program prints "1"

- The following pseudo-code program demonstrates the effect of scoping on variable bindings:
- ```
  a:integer
  procedure first
    a:=1
  procedure second
    a:integer
    first()
  procedure main
    a:=2
    second()
    write_integer(a)
  ```
  ```

Effect of Dynamic Scoping

Program execution:

```
a:integer
main()
  a:=2
  second()
    a:integer
    first()
      a:=1
  write_integer(a)
```

binding

Program prints “2”

- The following pseudo-code program demonstrates the effect of scoping on variable bindings:
- ```
  a:integer
  procedure first
    a:=1
  procedure second
    a:integer
    first()
  procedure main
    a:=2
    second()
    write_integer(a)
  ```

Binding depends on execution
  ```

Static Scoping

- The bindings between names and objects can be determined by examination of the program text
- *Scope rules* of a program language define the scope of variables and subroutines, which is the region of program text in which a name-to-object binding is usable
  - Early Basic: all variables are global and visible everywhere
  - Fortran 77: the scope of a local variable is limited to a subroutine; the scope of a global variable is the whole program text unless it is hidden by a local variable declaration with the same variable name
  - Algol 60, Pascal, and Ada: these languages allow nested subroutines definitions and adopt the *closest nested scope rule* with slight variations in implementation

Closest Nested Scope Rule

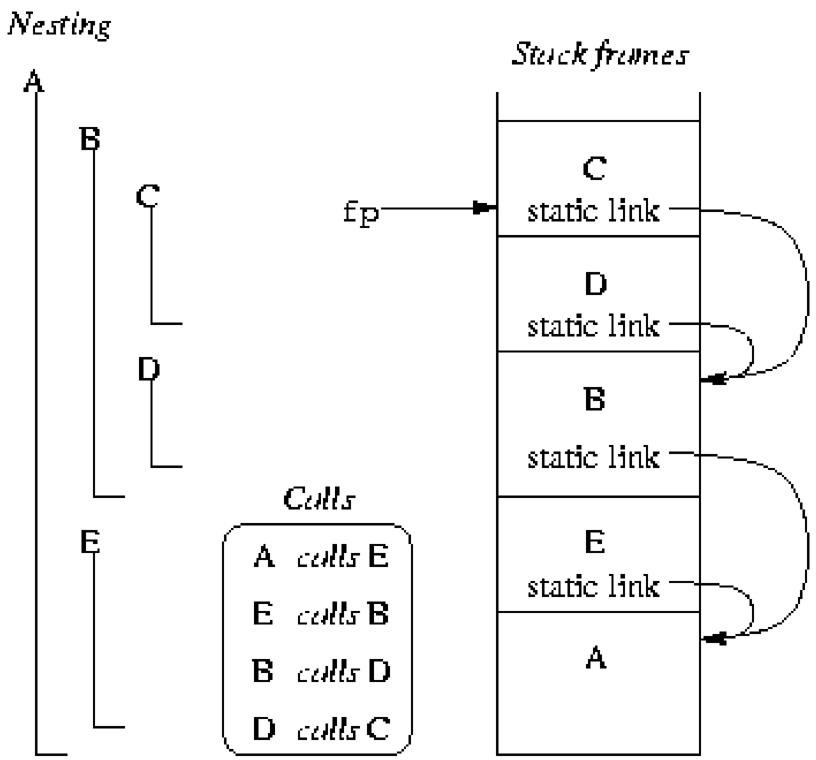
```
procedure P1(A1:T1)
var X:real;
...
  procedure P2(A2:T2);
  ...
    procedure P3(A3:T3);
    ...
    begin
    (* body of P3: P3,A3,P2,A2,X of P1,P1,A1 are visible *)
    end;
  ...
  begin
  (* body of P2: P3,P2,A2,X of P1,P1,A1 are visible *)
  end;
  procedure P4(A4:T4);
  ...
    function F1(A5:T5):T6;
    var X:integer;
    ...
    begin
    (* body of F1: X of F1,F1,A5,P4,A4,P2,P1,A1 are visible *)
    end;
  ...
  begin
  (* body of P4: F1,P4,A4,P2,X of P1,P1,A1 are visible *)
  end;
...
begin
(* body of P1: X of P1,P1,A1,P2,P4 are visible *)
end
```

- To find the object referenced by a given name:
  - Look for a declaration in the current innermost scope
  - If there is none, look for a declaration in the immediately surrounding scope, etc.

Static Scope Implementation with Static Links

- Scope rules are designed so that we can only refer to variables that are alive: the variable must have been stored in the frame of a subroutine
- If a variable is not in the local scope, we are sure there is a frame for the surrounding scope somewhere below on the stack:
  - The current subroutine can only be called when it was visible
  - The current subroutine is visible only when the surrounding scope is active
- Each frame on the stack contains a static link pointing to the frame of the *static parent*

Example Static Links

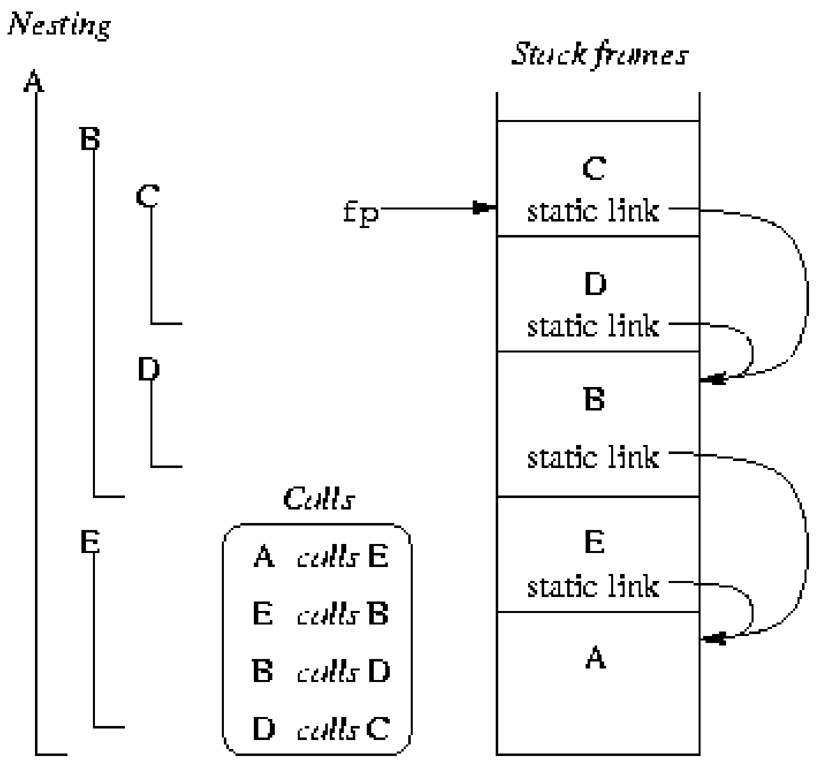


- Subroutines C and D are declared nested in B
  - B is static parent of C and D
- B and E are nested in A
  - A is static parent of B and E
- The fp points to the frame at the top of the stack to access locals
- The static link in the frame points to the frame of the static parent

Static Chains

- How do we access non-local objects?
- The static links form a static chain, which is a linked list of static parent frames
- When a subroutine at nesting level *j* has a reference to an object declared in a static parent at the surrounding scope nested at level *k*, then *j*-*k* static links forms a static chain that is traversed to get to the frame containing the object
- The compiler generates code to make these traversals over frames to reach non-local objects

Example Static Chains



- Subroutine A is at nesting level 1 and C at nesting level 3
- When C accesses an object of A, 2 static links are traversed to get to A's frame that contains that object

Out of Scope

- Non-local objects can be *hidden* by local name-to-object bindings and the scope is said to have a hole in which the non-local binding is temporarily inactive but not destroyed
- Some languages, notably Ada and C++ use qualifiers or scope resolution operators to access non-local objects that are hidden
  - P1.X in Ada to access variable X of P1 and ::X to access global variable X in C++

Out of Scope Example

```
procedure P1;
var X:real;
  procedure P2;
  var X:integer
  begin
    ... (* X of P1 is hidden *)
  end;
begin
  ...
end
```

- P2 is nested in P1
- P1 has a local variable X
- P2 has a local variable X that hides X in P1
- When P2 is called, no extra code is executed to inactivate the binding of X to P1

Dynamic Scope

- Scope rule: the "current" binding for a given name is the one encountered most recently *during execution*
- Typically adopted in (early) functional languages that are interpreted
- Perl v5 allows you to choose scope method for each variable separately
- With dynamic scope:
  - Name-to-object bindings *cannot* be determined by a compiler in general
  - Easy for interpreter to look up name-to-object binding in a stack of declarations
- Generally considered to be "a bad programming language feature"
  - Hard to keep track of active bindings when reading a program text
  - Most languages are now compiled, or a compiler/interpreter mix
- Sometimes useful:
  - Unix environment variables have dynamic scope

Dynamic Scoping Problems

- In this example, function **`scaled_score`** probably does not do what the programmer intended: with dynamic scoping, **`max_score`** in **`scaled_score`** is bound to **`foo`**'s local variable **`max_score`** after **`foo`** calls **`scaled_score`**, which was the most recent binding during execution:

```
max_score:integer
function scaled_score(raw_score:integer):real
  return raw_score/max_score*100
  ...
procedure foo
  max_score:real := 0
  ...
  foreach student in class
    student.percent := scaled_score(student.points)
    if student.percent > max_score
      max_score := student.percent
```

Dynamic Scope Implementation with Bindings Stacks

- Each time a subroutine is called, its local variables are pushed on a stack with their name-to-object binding
- When a reference to a variable is made, the stack is searched top-down for the variable's name-to-object binding
- After the subroutine returns, the bindings of the local variables are popped
- Different implementations of a binding stack are used in programming languages with dynamic scope, each with advantages and disadvantages

Referencing Environments

- If a subroutine is passed as an argument to another subroutine, when are the static/dynamic scoping rules applied?
  - When the reference to the subroutine is first created (i.e. when it is passed as an argument)
  - Or when the argument subroutine is finally called
- That is, what is the *referencing environment* of a subroutine passed as an argument?
  - Eventually the subroutine passed as an argument is called and may access non-local variables which by definition are in the referencing environment of usable bindings
- The choice is fundamental in languages with dynamic scope
- The choice is limited in languages with static scope

Effect of Deep Binding in Dynamically-Scoped Languages

- The following program demonstrates the difference between deep and shallow binding:

```
function older(p:person):boolean
  return p.age>thres
procedure show(p:person,c:function)
  thres:integer
  thres := 20
  if c(p)
    write(p)
procedure main(p)
  thres:integer
  thres := 35
  show(p,older)
```

Program execution:

```
main(p)
  thres:integer
  thres := 35
  show(p,older)
    thres:integer
    thres := 20
    older(p)
      return p.age>thres
    if return value is true
      write(p)
```

binding

Program prints persons older than 35

Effect of Shallow Binding in Dynamically-Scoped Languages

Program execution:

```
main(p)
  thres:integer
  thres := 35
  show(p,older)
    thres:integer
    thres := 20          binding
    older(p)
      return p.age>thres
    if  return value is true
      write(p)
```

Program prints persons older than 20

- The following program demonstrates the difference between deep and shallow binding:

```
function older(p:person):boolean
  return p.age>thres
procedure show(p:person,c:function)
  thres:integer
  thres := 20
  if c(p)
    write(p)
procedure main(p)
  thres:integer
  thres := 35
  show(p,older)
```

Implementing Deep Bindings with Subroutine Closures

- The referencing environment is bundled with the subroutine as a *closure* and passed as an argument
- A subroutine closure contains
  - A pointer to the subroutine code
  - The current set of name-to-object bindings
- Depending on the implementation, the whole current set of bindings may have to be copied or the head of a list is copied if linked lists are used to implement a stack of bindings

Statement Blocks

C

```
{ int t = a;
  a = b;
  b = t;
}
```

Ada

```
declare t:integer
begin
  t := a;
  a := b;
  b := t;
end;
```

C++
Java
C#

```
{ int a,b;
  ...
  int t;
  t=a;
  a=b;
  b=t;
  ...
}
```

- In Algol, C, and Ada local variables are declared in a block or compound statement
- In C++, Java, and C# declarations may appear anywhere statements can be used and the scope extends to the end of the block
- Local variables declared in nested blocks in a single function are all stored in the subroutine frame for that function (most programming languages, e.g. C/C++, Ada, Java)

Modules and Module Scope

- Modules are the most important feature of a programming language that supports the construction of large applications
  - Teams of programmers can work on separate modules in a project
  - No language support for modules in C and Pascal
  - Modula-2 modules, Ada packages, C++ namespaces
  - Java packages
- Scoping: modules encapsulate variables, data types, and subroutines in a package
  - Objects inside are visible to each other
  - Objects inside are not visible outside unless exported
  - Objects outside are not visible inside unless imported
- A module interface specifies exported variables, data types, and subroutines
- The module implementation is compiled separately and implementation details are hidden from the user of the module

First, Second, and Third-Class Subroutines

- *First-class object*: an object entity that can be passed as a parameter, returned from a subroutine, and assigned to a variable
  - Primitive types such as integers in most programming languages
- *Second-class object*: an object that can be passed as a parameter, but not returned from a subroutine or assigned to a variable
  - Fixed-size arrays in C/C++
- *Third-class object*: an object that cannot be passed as a parameter, cannot be returned from a subroutine, and cannot be assigned to a variable
  - Labels of goto-statements and subroutines in Ada 83

- Functions in Lisp, ML, and Haskell are unrestricted first-class objects
- With certain restrictions, subroutines are first-class objects in Modula-2 and 3, Ada 95, (C and C++ use function pointers)

First-Class Subroutine Implementation Requirements

```
function new_int_printer(port:integer):procedure
  procedure print_int(val:int)
  begin
    write(port, val)
  end
begin
  return print_int
end

procedure main
begin
  myprint:procedure
  myprint := new_int_printer(80)
  myprint(7)
end
```

- Problem: subroutine returned as object may lose part of its reference environment in its closure!
- Procedure **`print_int`** uses argument **`port`** of **`new_int_printer`**, which is in the referencing environment of **`print_int`**
- After the call to **`new_int_printer`**, argument **`port`** should be kept alive somehow (it is normally removed from the run-time stack and it will become a dangling reference)

First-Class Subroutine Implementations

- In functional languages, local objects have *unlimited extent*: their lifetime continue indefinitely
  - Local objects are allocated on the heap
  - *Garbage collection* will eventually remove unused objects
- In imperative languages, local objects have *limited extent* with stack allocation
- To avoid the problem of dangling references, alternative mechanisms are used:
  - C, C++, and Java: no nested subroutine scopes
  - Modula-2: only outermost routines are first-class
  - Ada 95 "containment rule": can return an inner subroutine under certain conditions

Overloaded Bindings

- A name that can refer to more than one object is said to be *overloaded*
  - Example: + (addition) is used for integer and and floating-point addition in most programming languages
- Semantic rules of a programming language require that the context of an overloaded name should contain sufficient clues to deduce the intended binding
- Semantic analyzer of compiler uses type checking to resolve bindings
- Ada and C++ function overloading enables programmer to define alternative implementations depending on argument types
- Ada, C++, and Fortran 90 allow built-in operators to be overloaded with user-defined functions, which enhances expressiveness but may mislead programmers that are unfamiliar with the code

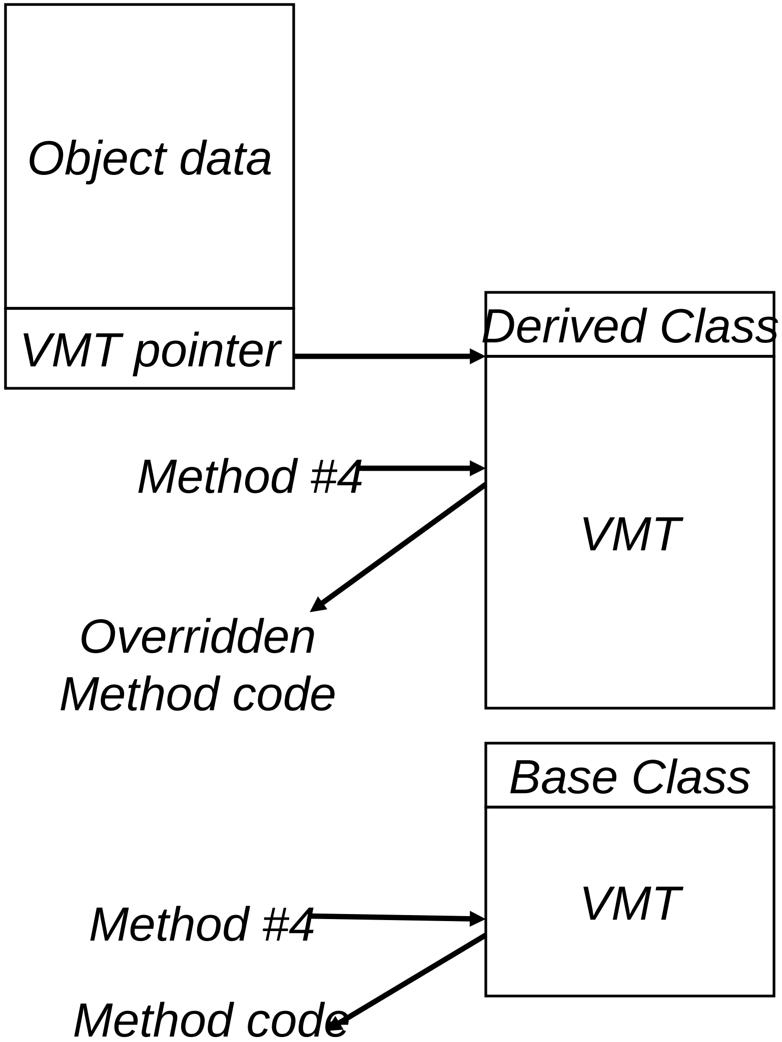
Overloaded Bindings Example

- Example in C++:

```
struct complex {...};
enum base {dec, bin, oct, hex};

void print_num(int n) { ... }
void print_num(int n, base b) { ... }
void print_num(struct complex c) { ... }
```

Dynamic Bindings



- Polymorphic functions and operators based on overloading are statically bound by the compiler based on type information
- Polymorphism with *dynamic bindings* is supported by class inheritance (C++ virtual methods)
- Each class has a *virtual method table* (VMT) with pointers to methods, where each method is indexed into the table
- Method invocation proceeds by getting the class VMT from the object and indexing it to select the method to invoke