COP4020 Programming Languages

Names, Scopes, and Bindings

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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 $\leftrightarrow$ 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

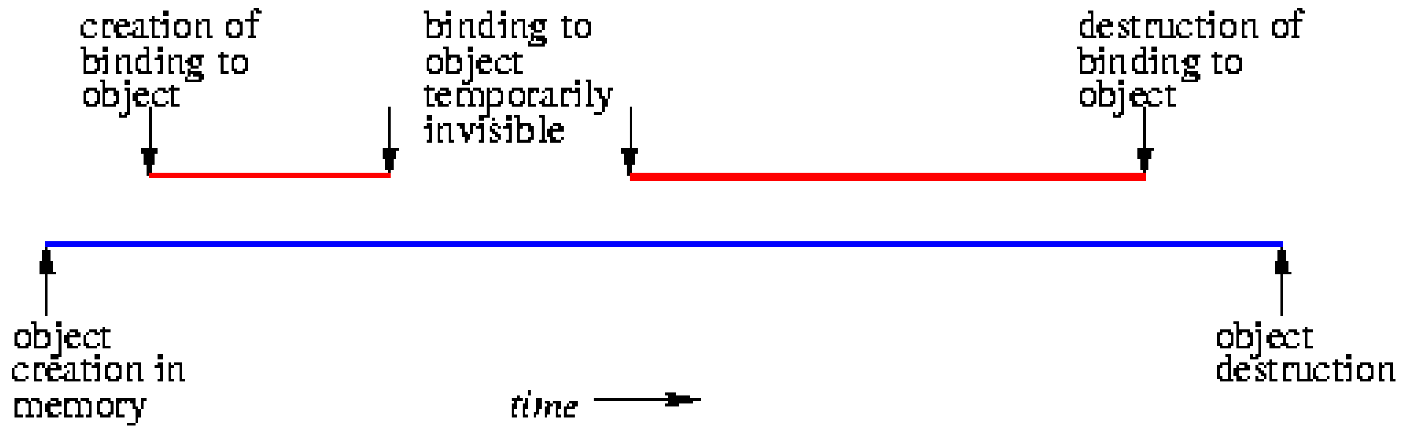
The Effect of Binding Time

- *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)


creation of binding to object
binding to object temporarily invisible
destruction of binding to object
object creation in memory
time
object destruction

- Bindings are temporarily invisible when code is executed where the binding (name $\leftrightarrow$ 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

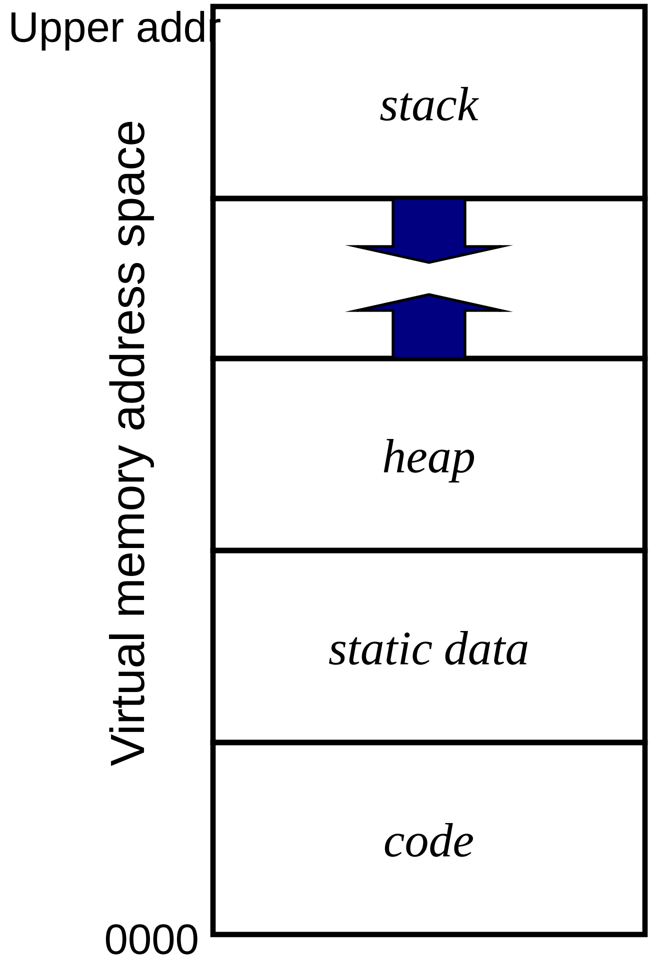
C++ Example

-
  ```
  {
    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

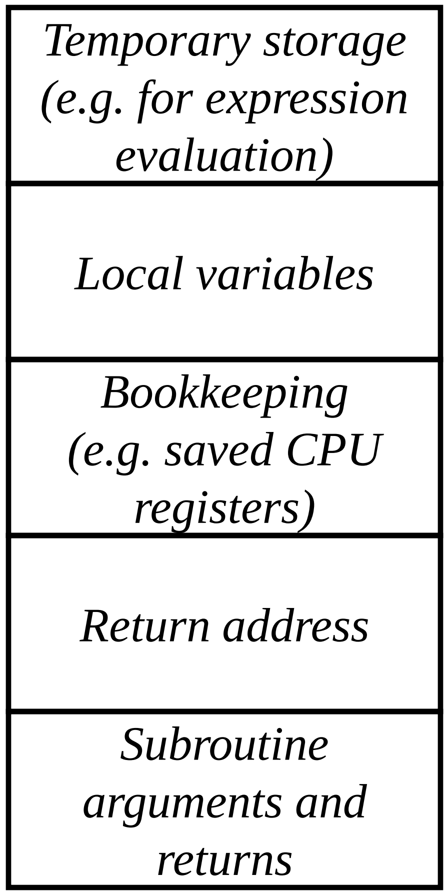


- Program code is at the bottom of the memory region (code section)
  - The code section is protected from run-time modification by the OS
- Static data objects are stored in the static region
- Stack grows downward
- Heap grows upward

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


Temporary storage (e.g. for expression evaluation)
Local variables
Bookkeeping (e.g. saved CPU registers)
Return address
Subroutine arguments and returns

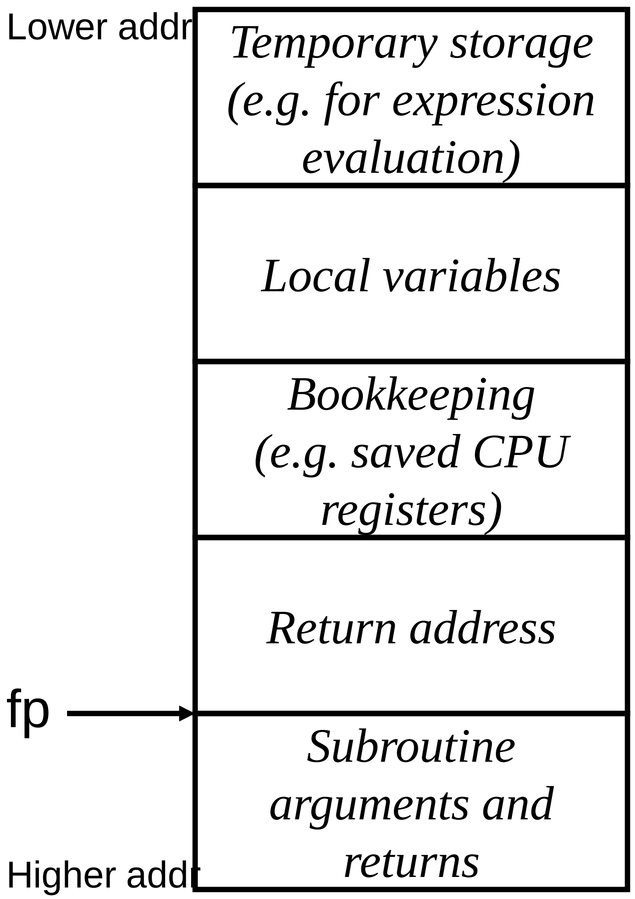
Typical static subroutine frame layout

- 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

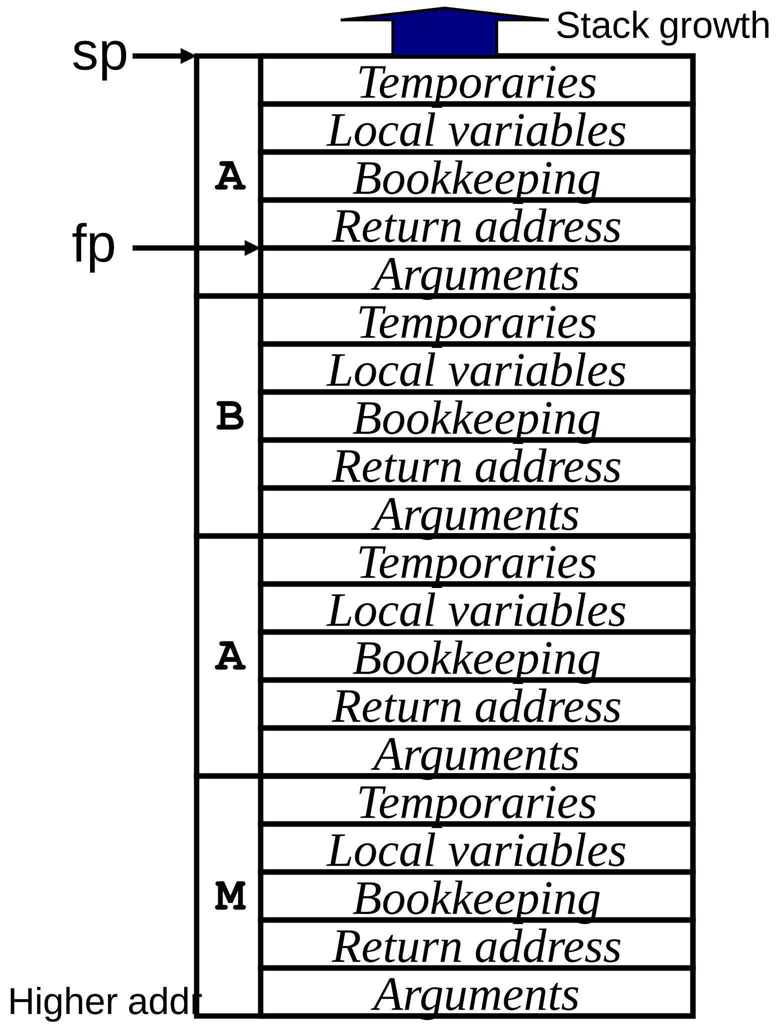
Typical Stack-Allocated Subroutine Frame


Lower addr
Temporary storage (e.g. for expression evaluation)
Local variables
Bookkeeping (e.g. saved CPU registers)
Return address
fp
Subroutine arguments and returns
Higher addr

Typical subroutine frame layout

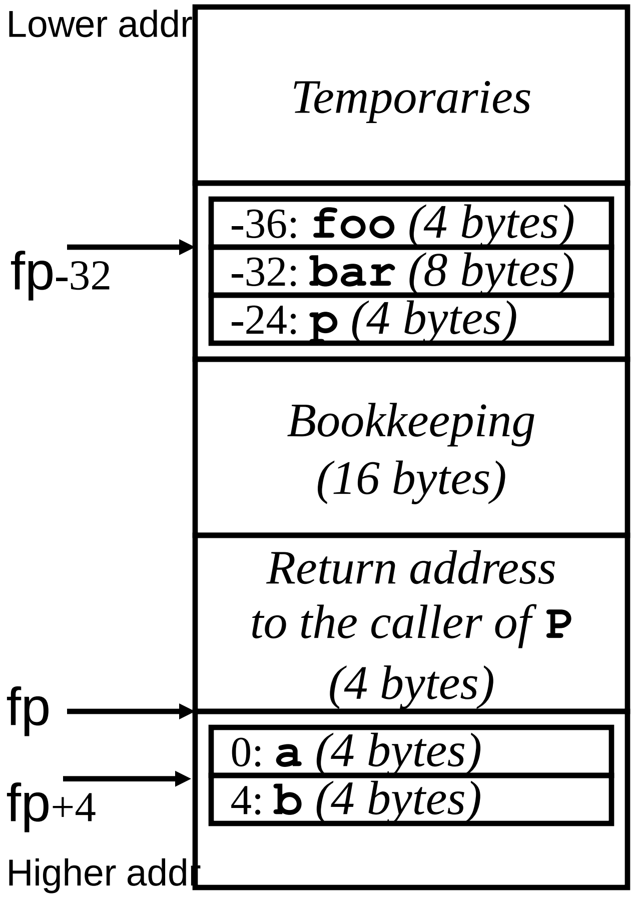
- A *frame pointer* (fp) points to the frame of the currently active subroutine at run time
- Subroutine arguments, local variables, and return values are accessed by constant address offsets from the fp

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

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

- 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

Program execution:

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

binding

Program prints “2”

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

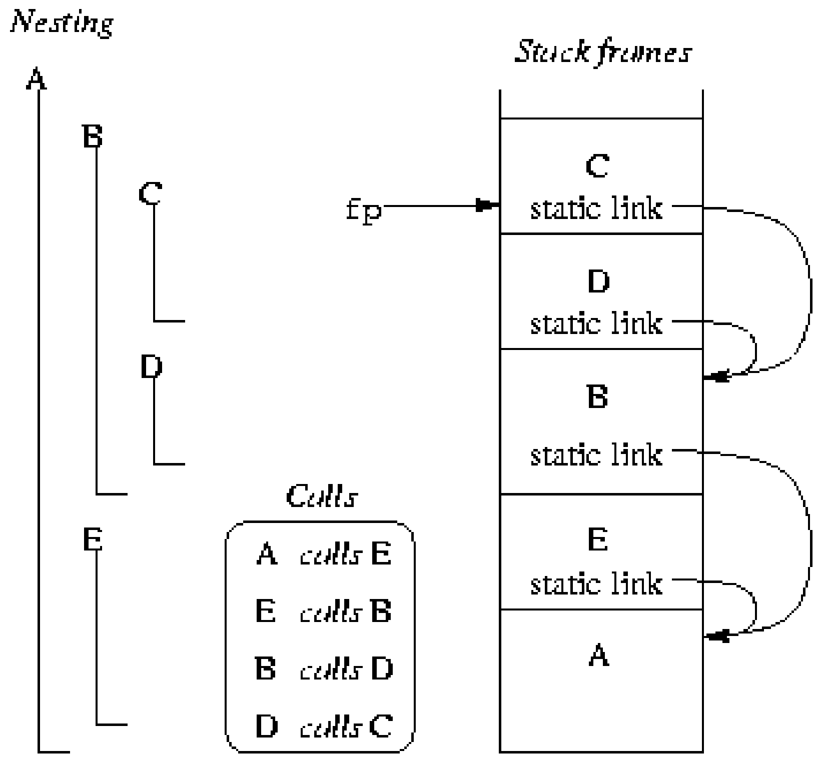
```
procedure P1(A1:T1)
var X:real;
...
  procedure P2(A2:T2);
  ...
    procedure P3(A3:T3);
    ...
    begin
    (* body of P3: P3,A3,P2,A2,X of P1,P1,A1 are visible *)
    end;
  ...
  begin
  (* body of P2: P3,P2,A2,X of P1,P1,A1 are visible *)
  end;
  procedure P4(A4:T4);
  ...
    function F1(A5:T5):T6;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

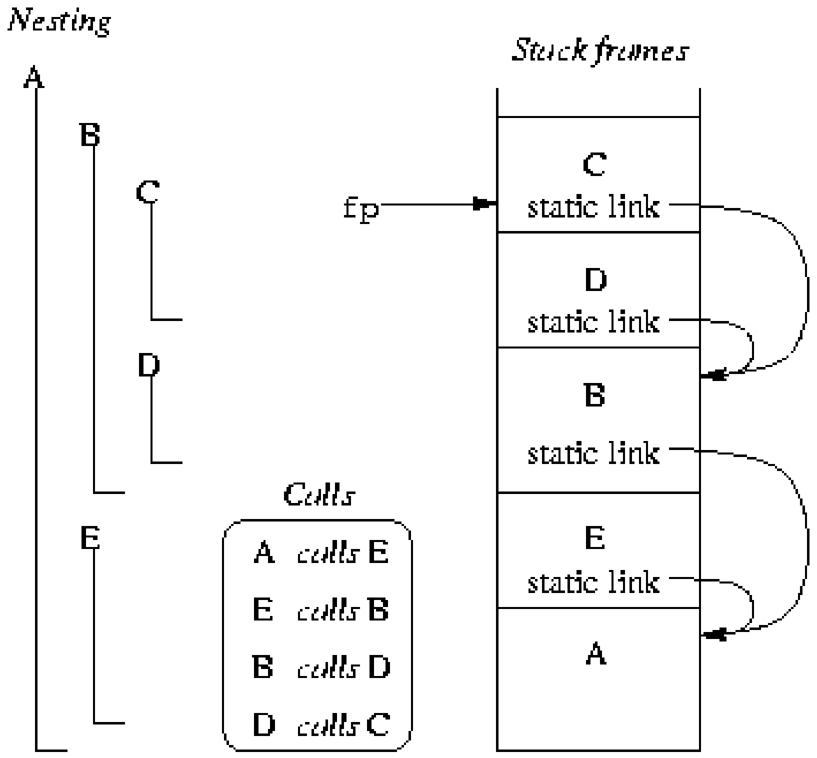


- Subroutines C and D are declared nested in B
  - B is static parent of C and D
- B and E are nested in A
  - A is static parent of B and E
- The fp points to the frame at the top of the stack to access locals
- The static link in the frame points to the frame of the static parent

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

Program prints persons older than 35

Effect of Shallow 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        binding
      older(p)
         return p.age>thres
      if  return value is true
         write(p)
```

Program prints persons older than 20

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

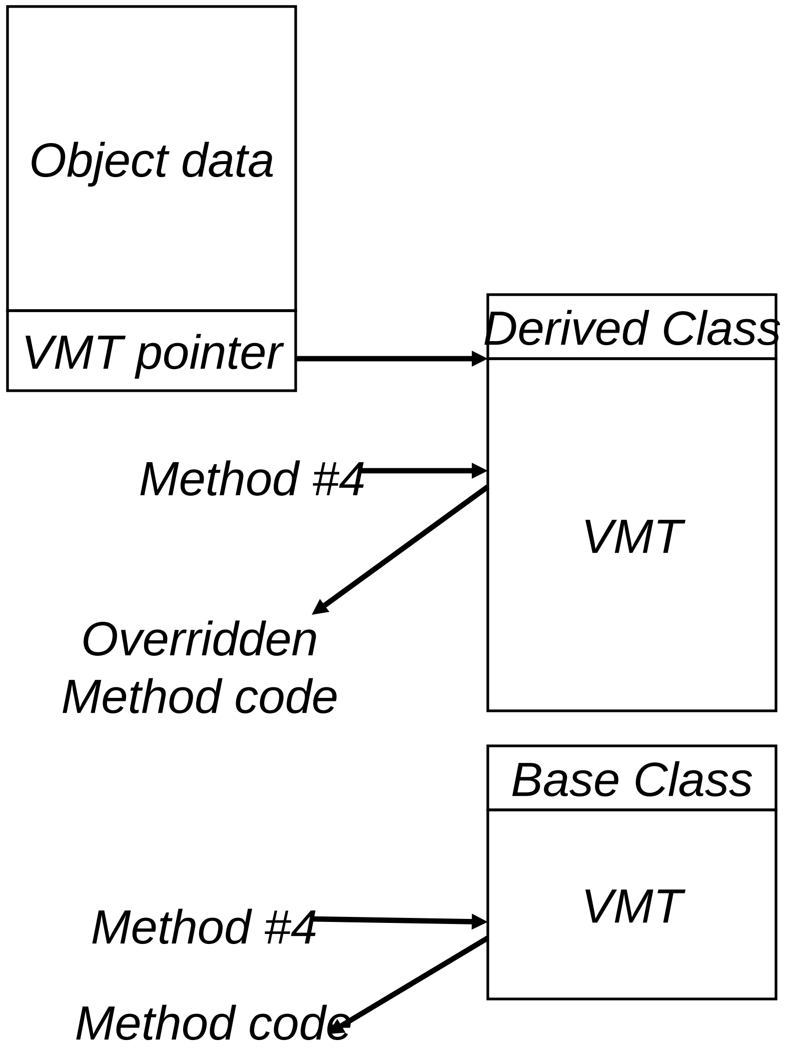
Overloaded Bindings Example

- 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