Principles of Programming Languages

http://www.di.unipi.it/~andrea/Didattica/PLP-14/

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Lesson 19

- Names in programming languages
- Binding times
- Scopes

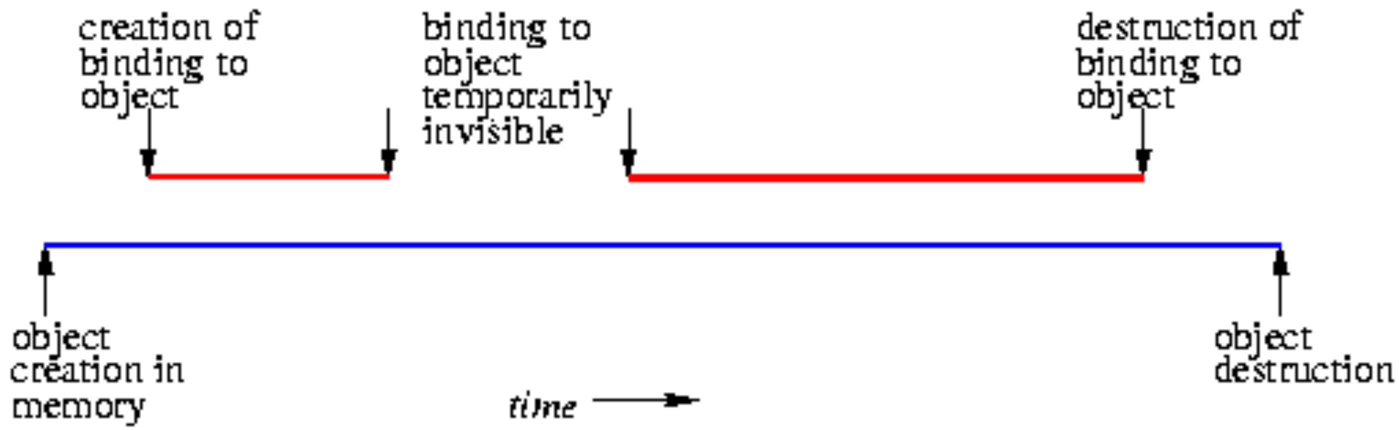
Names, Binding and Scope: Summary

- 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

Binding Time

- A **binding** is an association between a **name** and an **entity**
- An entity that can have an associated name is called **denotable**
- **Binding time** is the time at which a *decision is made* to create a name ↔ entity binding (the actual binding can be created later):
  - **Language design time**
  - **Language implementation time**
  - **Program writing time**
  - **Compile time**
  - **Link time**
  - **Load time**
  - **Run time**

Binding Lifetime versus Object Lifetime (cont’d)

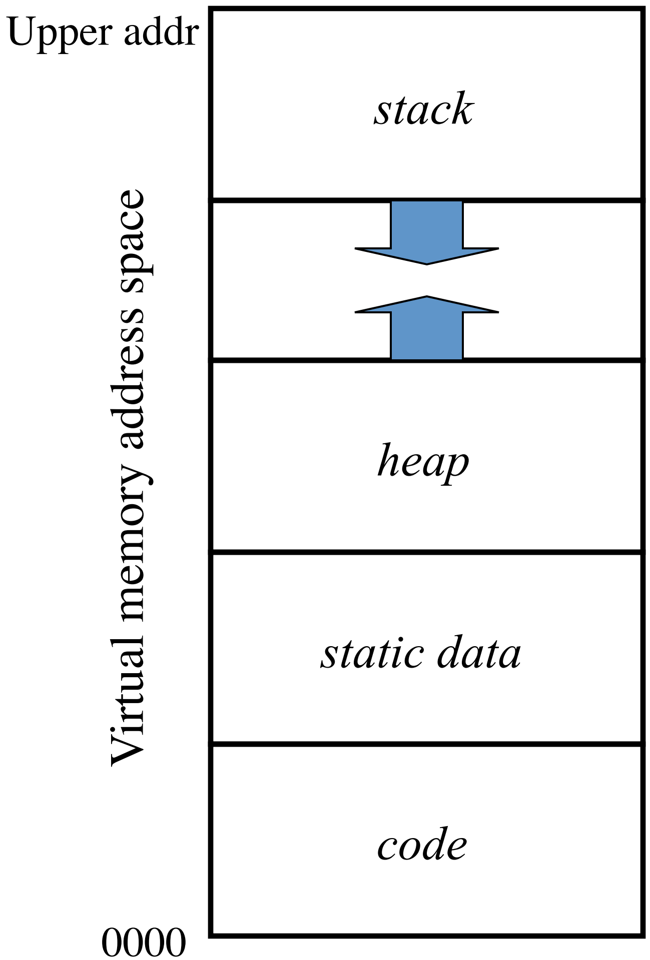


- Bindings are temporarily invisible when code is executed where the binding (name ↔ object) is out of scope
- **Memory leak**: object never destroyed (binding to object may have been destroyed, rendering access impossible)
- **Dangling reference**: object destroyed before binding is destroyed
- **Garbage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

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

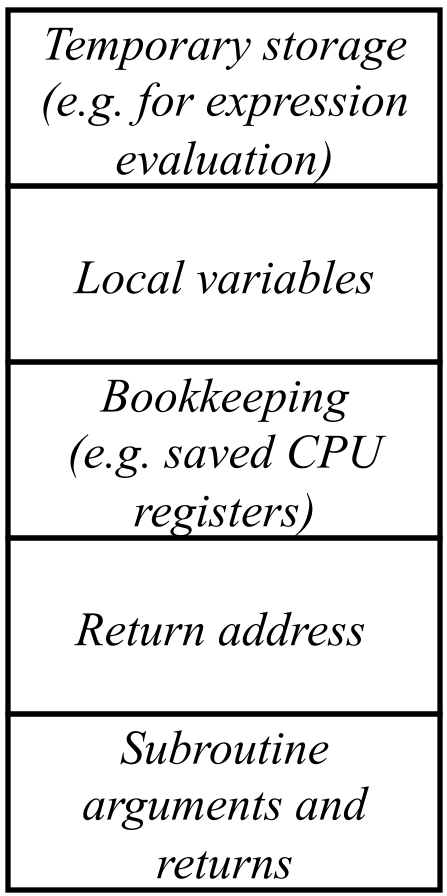


- Program code is at the bottom of the memory region (code section)
  - The code section is protected from run-time modification by the OS
- Static data objects are stored in the static region
- Stack grows downward
- Heap grows upward

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



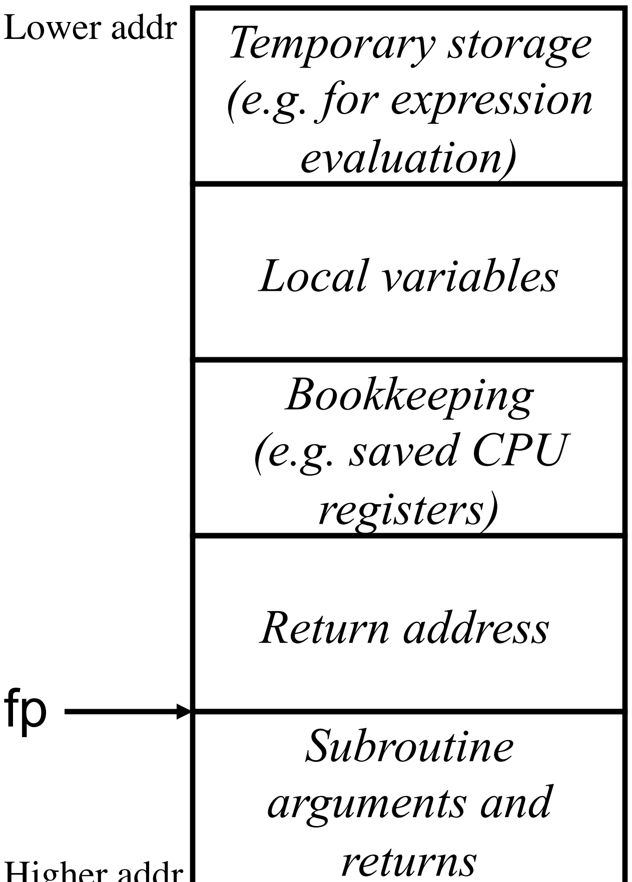
Typical static subroutine frame layout

- 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 an *activation record* (or *subroutine frame*) 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
- Activation record layouts vary between languages, implementations, and machine platforms

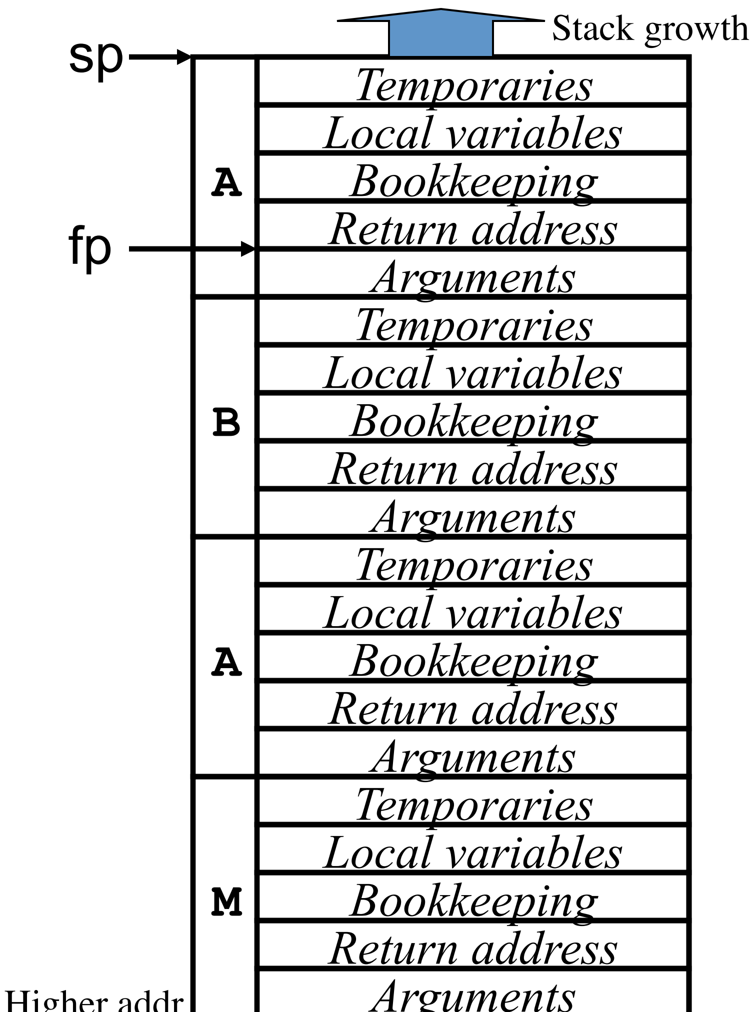
Typical Stack-Allocated Activation Record



Typical subroutine frame layout

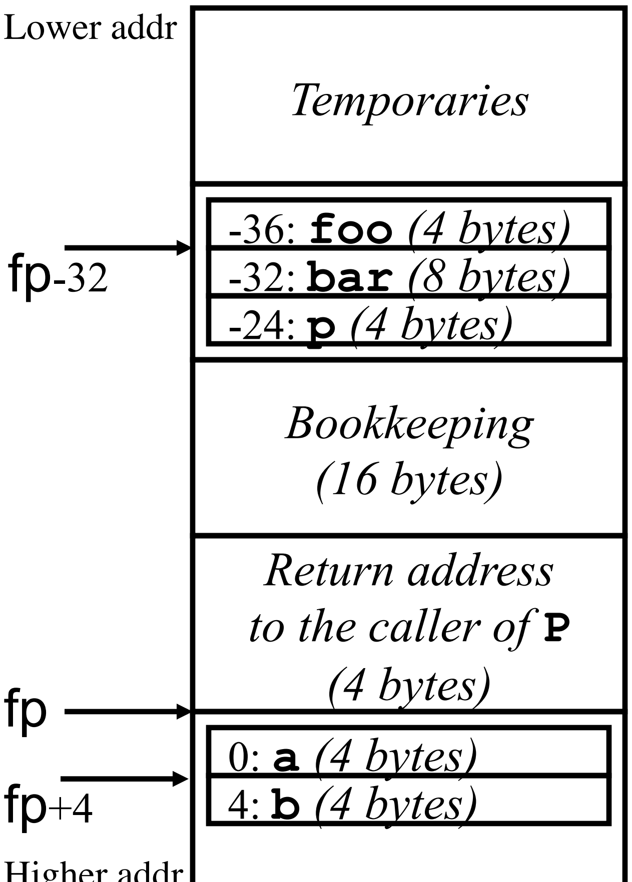
- A *frame pointer* (**fp**) points to the frame of the currently active subroutine at run time
- Subroutine arguments, local variables, and return values are accessed by constant address offsets from the **fp**

Activation Records on the Stack



- Activation records 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 activation record onto when a subroutine is called
- The *frame pointer* (fp) points to the activation record of the currently active subroutine, which is 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 Activation Record



- 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 merged
- **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

Comparison of Storage Allocation

	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

- The **scope of a binding** 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

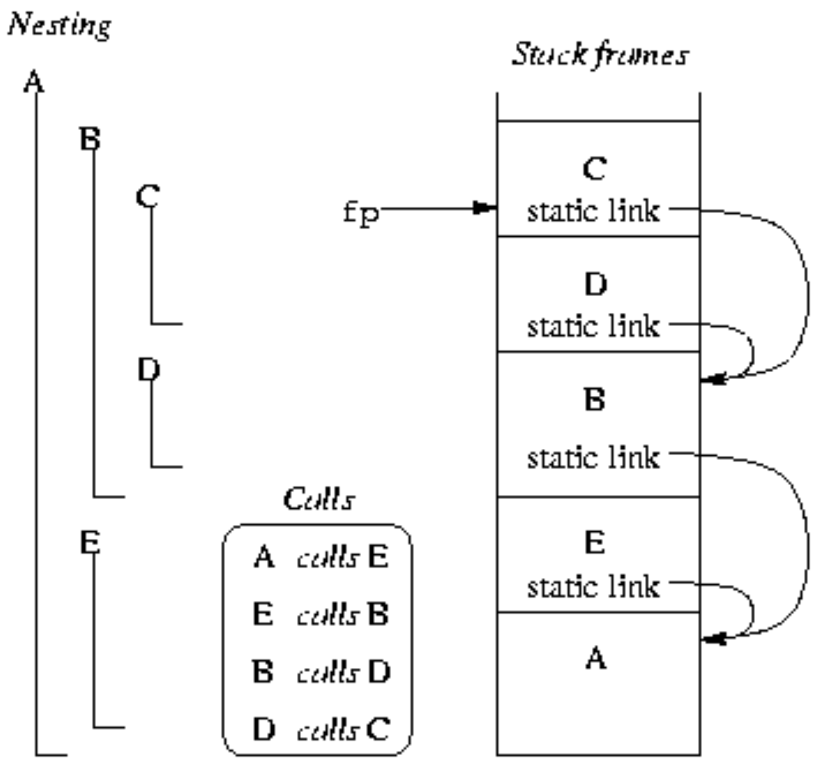
```
procedure P1(A1:T1)
var X:real;
...
  procedure P2(A2:T2);
  ...
    procedure P3(A3:T3);
    ...
    begin
    (* body of P3: P3,A3,P2,A2,X of P1,P1,A1 are visible *)
    end;
  ...
  begin
  (* body of P2: P3,P2,A2,X of P1,P1,A1 are visible *)
  end;
  procedure P4(A4:T4);
  ...
    function F1(A5:T5):T6;
    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 activation record of a subroutine
- If a variable is not in the local scope, we are sure there is an activation record 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

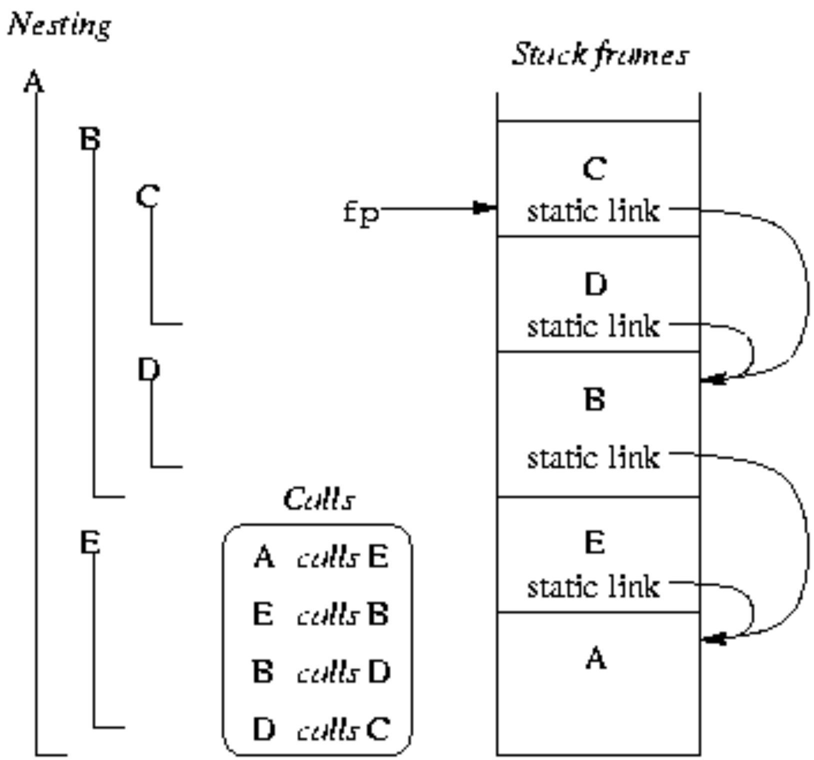


- Subroutines C and D are declared nested in B
  - B is static parent of C and D
- B and E are nested in A
  - A is static parent of B and E
- The fp points to the frame at the top of the stack to access locals
- The static link in the frame points to the frame of the static parent

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

A Typical Calling Sequence

- The caller
  - Saves any registers whose values will be needed after the call
  - Computes values of arguments and moves them into the stack or registers
  - Computes the static link and passes it as an extra, hidden argument
  - Uses a special subroutine call instruction to jump to the subroutine, simulta- neously passing the return address on the stack or in a register
- In its prologue, the callee
  - allocates a frame by subtracting an appropriate constant from the **sp**
  - saves the old **fp** into the stack, and assigns it an appropriate new value
  - saves any registers that may be overwritten by the current routine (including the static link and return address, if they were passed in registers)

A Typical Calling Sequence (cont'd)

- After the subroutine has completed, the epilogue
  - Moves the return value (if any) into a register or a reserved location in the stack
  - Restores registers if needed
  - Restores the **fp** and the **sp**
  - Jumps back to the return address
- Finally, the caller
  - Moves the return value to wherever it is needed
  - Restores registers if needed

Displays

- Access to an object in a scope *k* levels out requires that the static chain be dereferenced *k* times.
- An object *k* levels out will require *k* + 1 memory accesses to be loaded in a register.
- This number can be reduced to a constant by use of a **display**, a vector where the *k*-th element contains the pointer to the activation record at nesting level *k* that is currently active.
- Faster access to non-local objects, but bookeeping cost larger than that of static chain

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, like Ada, C++ and Java, use qualifiers or scope resolution operators to access non-local objects that are hidden
  - P1.X in Ada to access variable X of P1
  - ::X to access global variable X in C++
  - this.x or super.x in Java

Out of Scope Example

- 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

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

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