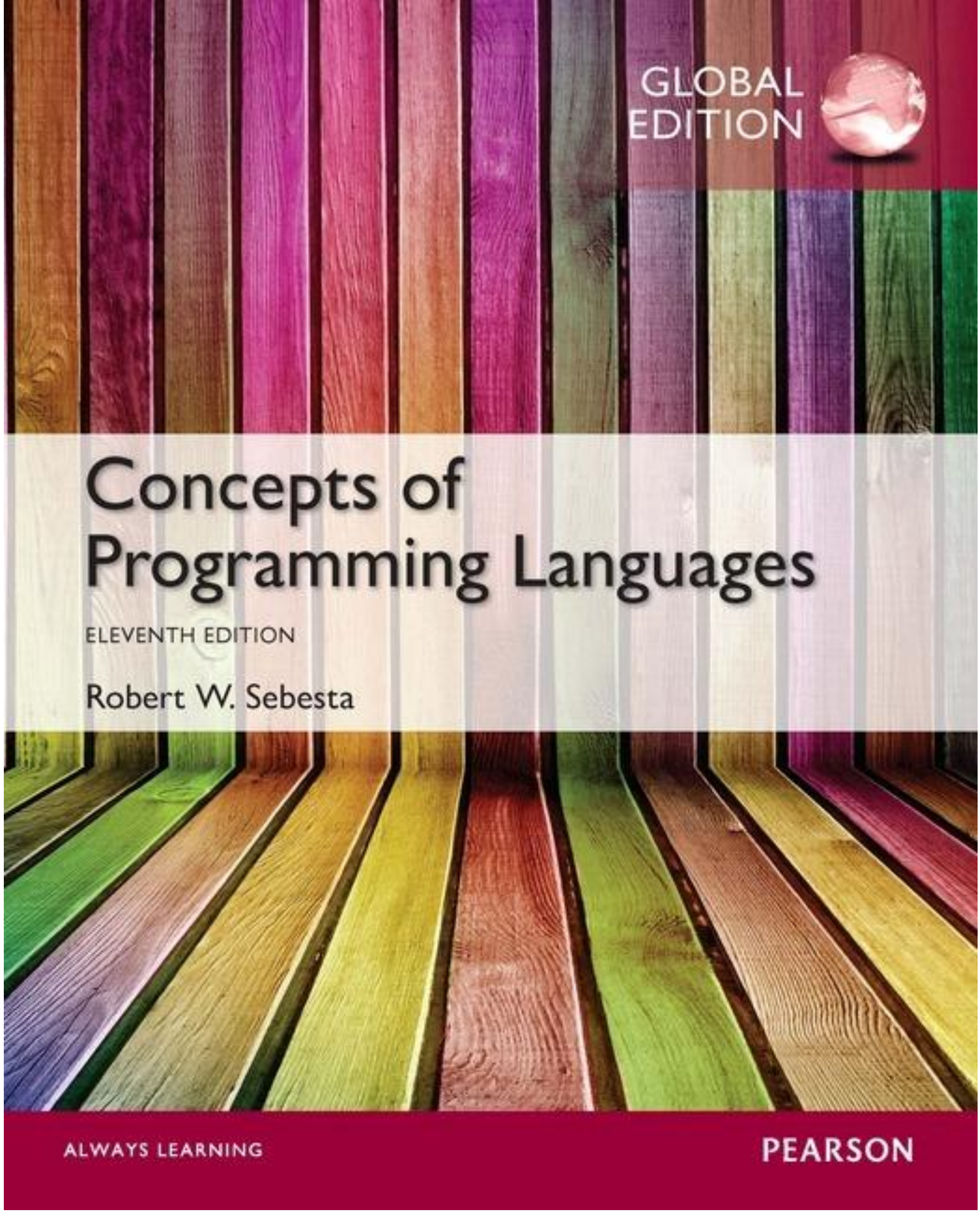
Chapter 10

Implementing Subprograms



Chapter 10 Topics

- The General Semantics of Calls and Returns
- Implementing "Simple" Subprograms
- Implementing Subprograms with Stack-Dynamic Local Variables
- Nested Subprograms
- Blocks
- Implementing Dynamic Scoping

The General Semantics of Calls and Returns

- The subprogram call and return operations of a language are together called its *subprogram linkage*
- General semantics of calls to a subprogram
  – Parameter passing methods
  – Stack-dynamic allocation of local variables
  – Save the execution status of calling program
    • The execution status is everything needed to resume execution of the calling program unit.
  – Transfer of control and arrange for the return
  – If subprogram nesting is supported, access to nonlocal variables must be arranged

The General Semantics of Calls and Returns

- General semantics of subprogram returns:
  - In mode and inout mode parameters must have their values returned
  - Deallocation of stack-dynamic locals
  - Restore the execution status
  - Return control to the caller

Implementing “Simple” Subprograms

- Call Semantics:
  - Save the execution status of the caller
  - Pass the parameters
  - Pass the return address to the called
  - Transfer control to the called

Implementing “Simple” Subprograms (continued)

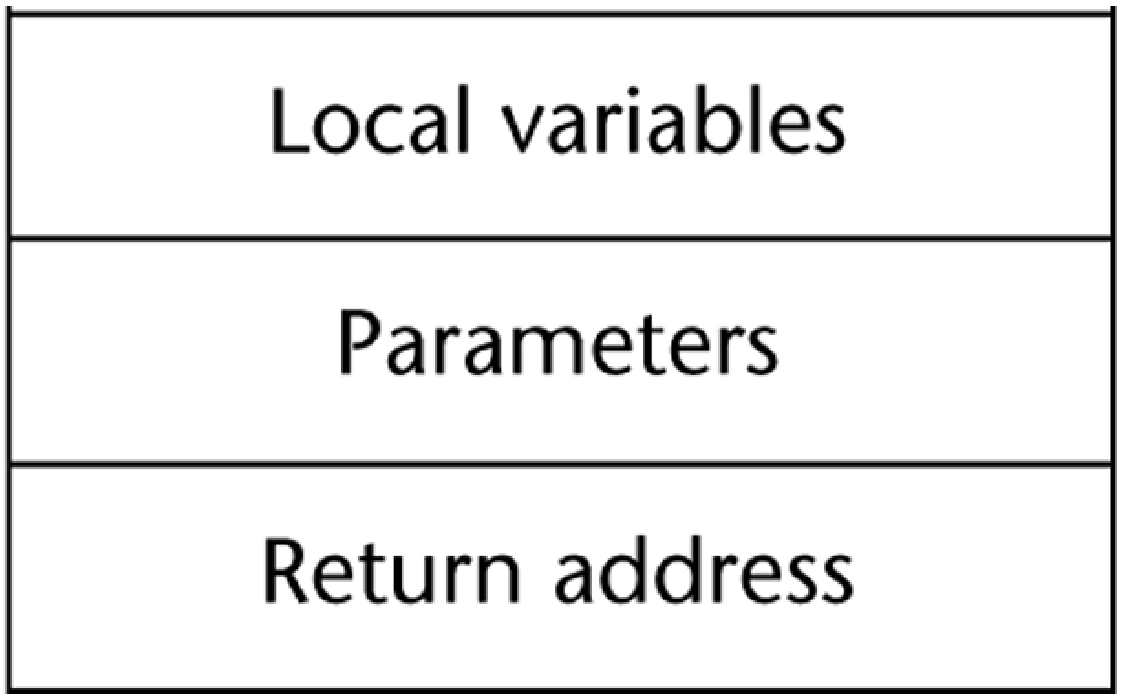
- Return Semantics:
  - If pass-by-value-result or out mode parameters are used, move the current values of those parameters to their corresponding actual parameters
  - If it is a function, move the functional value to a place the caller can get it
  - Restore the execution status of the caller
  - Transfer control back to the caller

- Required storage:
  - Status information, parameters, return address, return value for functions, temporaries

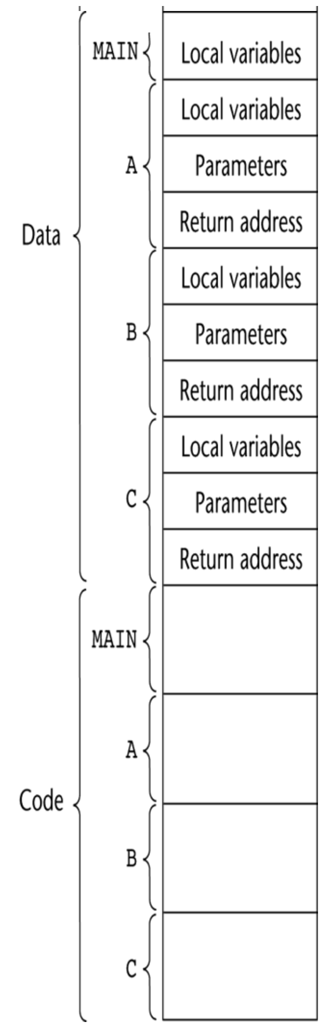
Implementing “Simple” Subprograms (continued)

- Two separate parts: the actual code and the non–code part (local variables and data that can change)
- The format, or layout, of the non–code part of an executing subprogram is called an *activation record*
- An *activation record instance* is a concrete example of an activation record (the collection of data for a particular subprogram activation)

An Activation Record for "Simple" Subprograms



Code and Activation Records of a Program with “Simple” Subprograms



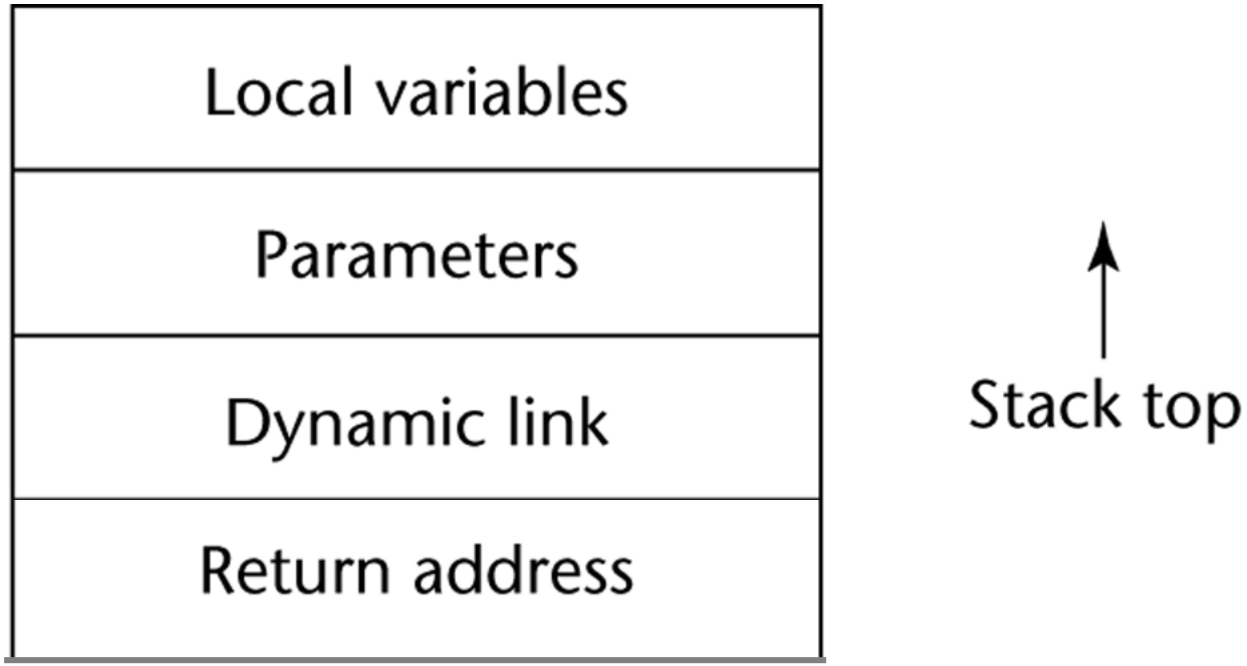
Note: A, B and C are subprograms.

Implementing Subprograms with Stack-Dynamic Local Variables

- More complex activation record
  - The compiler must generate code to cause implicit allocation and deallocation of local variables
  - Recursion must be supported (adds the possibility of multiple simultaneous activations of a subprogram)

(Definition from Chapter 5)
Stack-dynamic variable: Storage bindings are created for variables when their declaration statements are *elaborated*. For example, the variable declarations that appear at the beginning of a Java method are elaborated when the method is called and the variables defined by those declarations are deallocated when the method completes its execution.

Typical Activation Record for a Language with Stack-Dynamic Local Variables



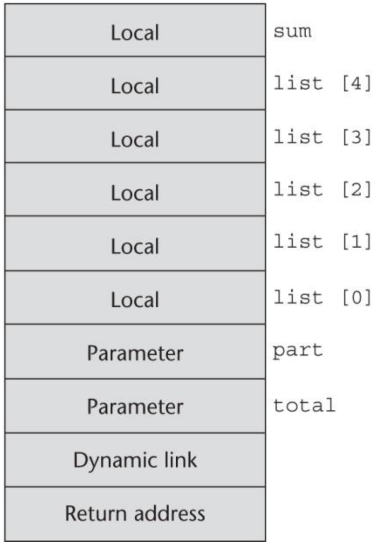
Implementing Subprograms with Stack-Dynamic Local Variables: Activation Record

- The activation record format is static, but its size may be dynamic
- The *dynamic link* points to the top of an instance of the activation record of the caller
- An activation record instance is dynamically created when a subprogram is called
- Activation record instances reside on the run-time stack
- The *Environment Pointer* (EP) must be maintained by the run-time system. It always points at the base of the activation record instance of the currently executing program unit

Note: The **EP**, which is further discussed in Section 10.3, is used to access parameters and local variables during the execution of a subprogram.

An Example: C Function

```
void sub(float total, int part)
{
  int list[5];
  float sum;
  …
}
```



Revised Semantic Call/Return Actions

- Caller Actions:
  - Create an activation record instance
  - Save the execution status of the current program unit
  - Compute and pass the parameters
  - Pass the return address to the called
  - Transfer control to the called
- Prologue actions of the called:
  - Save the old EP in the stack as the dynamic link and create the new value
  - Allocate local variables

Note: In general, the linkage actions of the called can occur at two different times, either at the beginning of its execution or at the end. These are sometimes called the ***prologue*** and ***epilogue*** of the subprogram linkage.

Revised Semantic Call/Return Actions (continued)

- Epilogue actions of the called:
  - If there are pass-by-value-result or out-mode parameters, the current values of those parameters are moved to the corresponding actual parameters
  - If the subprogram is a function, its value is moved to a place accessible to the caller
  - Restore the stack pointer by setting it to the value of the current EP-1 and set the EP to the old dynamic link
  - Restore the execution status of the caller
  - Transfer control back to the caller

An Example Without Recursion

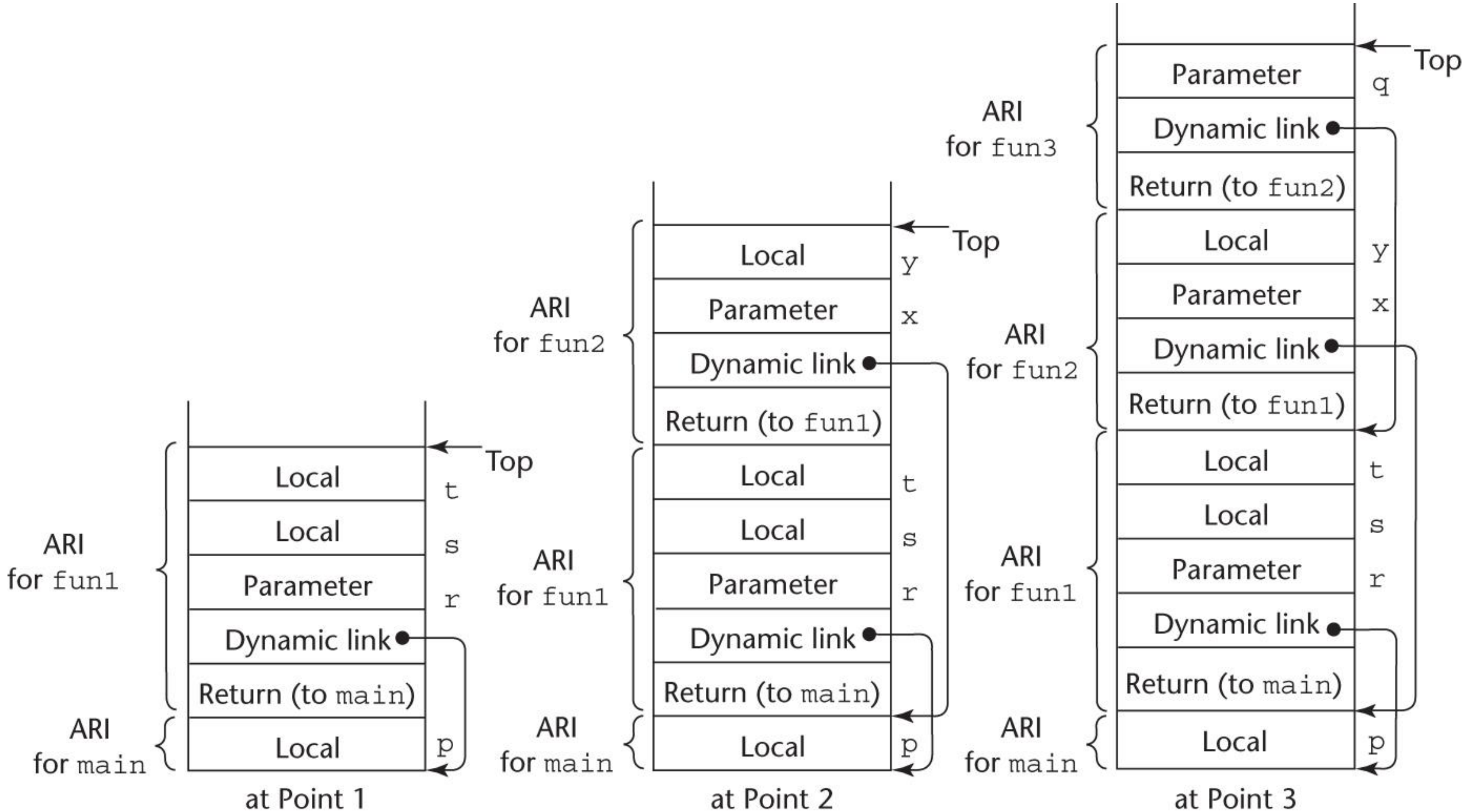
```
void fun1(float r) {
    int s, t;
    ...
    fun2(s);
    ...
}
void fun2(int x) {
    int y;
    ...
    fun3(y);
    ...
}
void fun3(int q) {
    ...
}
void main() {
    float p;
    ...
    fun1(p);
    ...
}
```

`main` calls `fun1`

`fun1` calls `fun2`

`fun2` calls `fun3`

An Example Without Recursion



ARI = activation record instance

Dynamic Chain and Local Offset

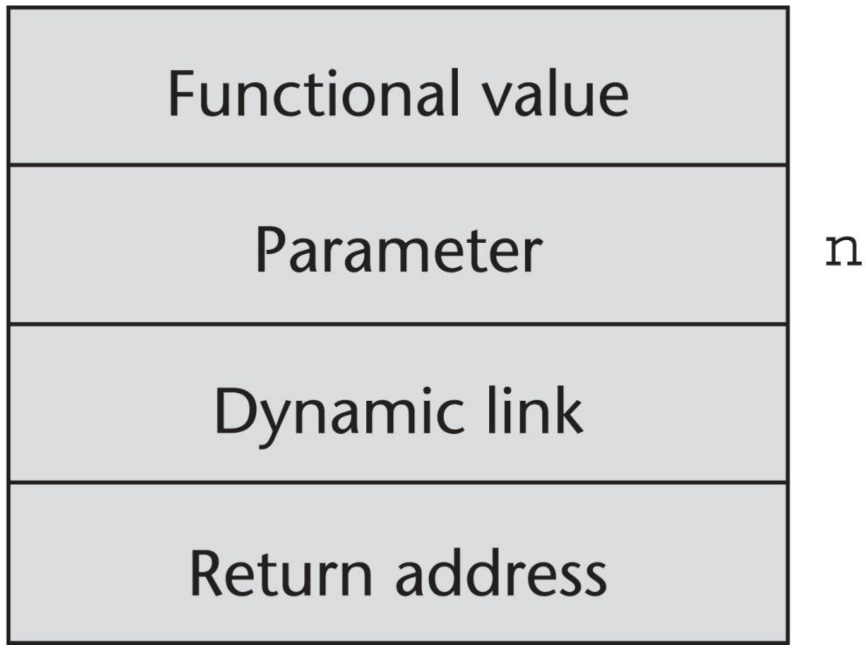
- The collection of dynamic links in the stack at a given time is called the *dynamic chain*, or *call chain*
- Local variables can be accessed by their offset from the beginning of the activation record, whose address is in the EP. This offset is called the *local_offset*
- The local_offset of a local variable can be determined by the compiler at compile time

An Example With Recursion

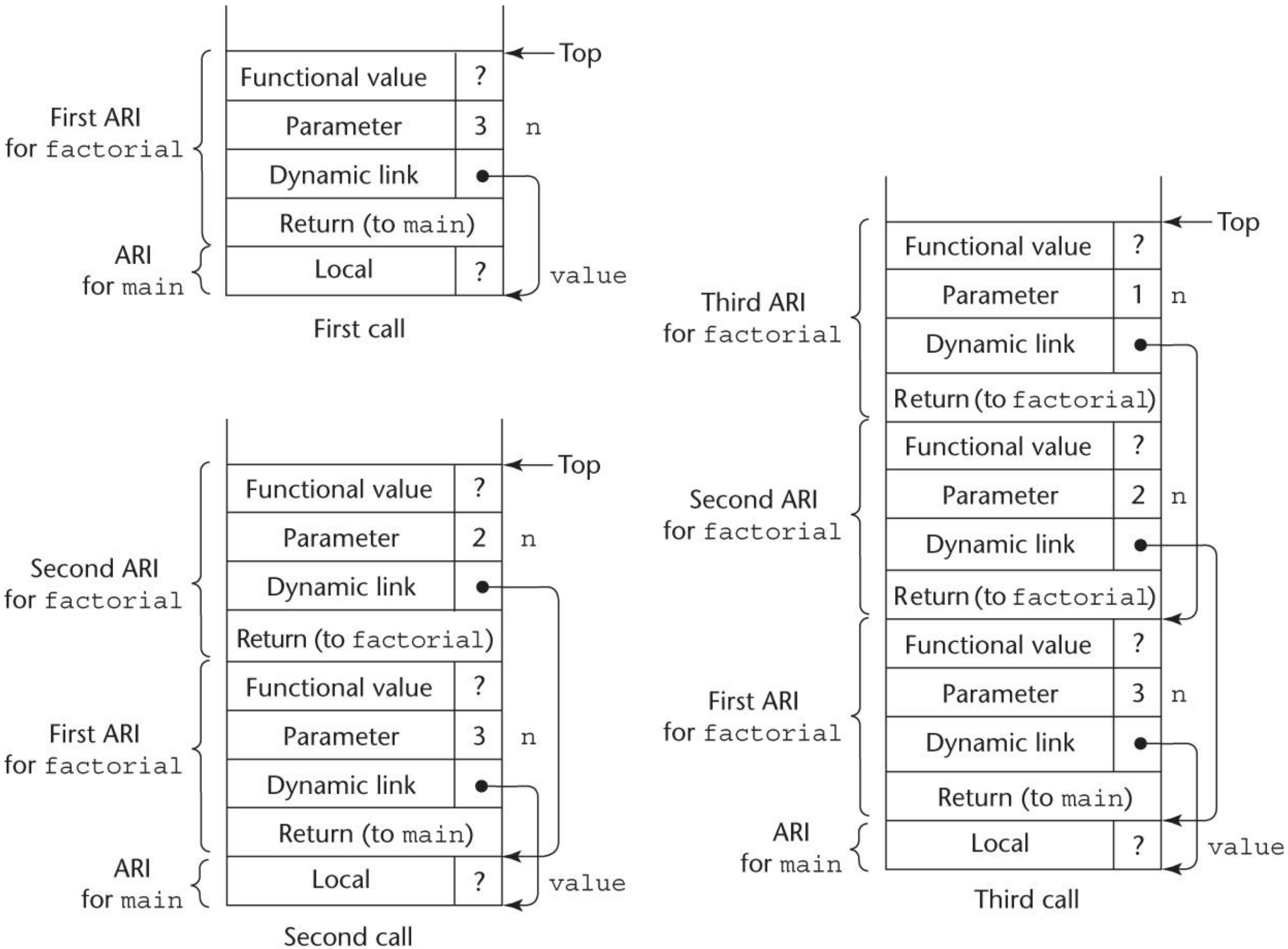
- The activation record used in the previous example supports recursion

```
int factorial (int n) {
    <-----------------------------1
  if (n <= 1) return 1;
  else return (n * factorial(n - 1));
    <-----------------------------2
}
void main() {
  int value;
  value = factorial(3);
    <-----------------------------3
}
```

Activation Record for `factorial`

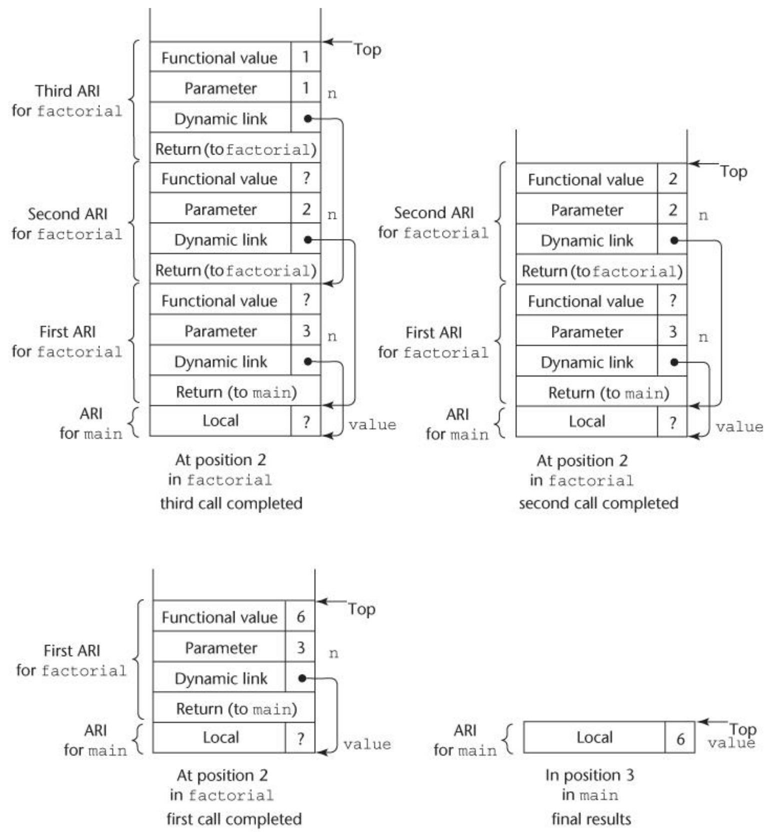


Stacks for calls to `factorial`



ARI = activation record instance

Stacks for returns from `factorial`



ARI = activation record instance

Nested Subprograms

- Some non-C-based static-scoped languages (e.g., Fortran 95+, Ada, Python, JavaScript, Ruby, and Lua) use stack-dynamic local variables and allow subprograms to be nested
- All variables that can be non-locally accessed reside in some activation record instance in the stack
- The process of locating a non-local reference:
  1. Find the correct activation record instance
  2. Determine the correct offset within that activation record instance

Locating a Non-local Reference

- Finding the offset is easy
- Finding the correct activation record instance
  - Static semantic rules guarantee that all non-local variables that can be referenced have been allocated in some activation record instance that is on the stack when the reference is made

Static Scoping

- A *static chain* is a chain of static links that connects certain activation record instances

- The *static link* in an activation record instance for subprogram A points to one of the activation record instances of A's static parent

- The static chain from an activation record instance connects it to all of its static ancestors

- *Static_depth* is an integer associated with a static scope whose value is the depth of nesting of that scope

Static Scoping (continued)

- The *chain_offset* or *nesting_depth* of a nonlocal reference is the difference between the static_depth of the reference and that of the scope when it is declared

- A reference to a variable can be represented by the pair:

  (chain_offset, local_offset),

  where local_offset is the offset in the activation record of the variable being referenced

Example JavaScript Program

```
function main(){
 var x;
 function bigsub() {
  var a, b, c;
  function sub1 {
   var a, d;
   function main(){
 var x;
 function bigsub() {
  var a, b, c;
  function sub1 {
   var a, d;
    a = b + c; <------------------------------1
   ...
  } // end of sub1
  function sub2(x) {
   var b, e;
```

Example JavaScript Program (continued)

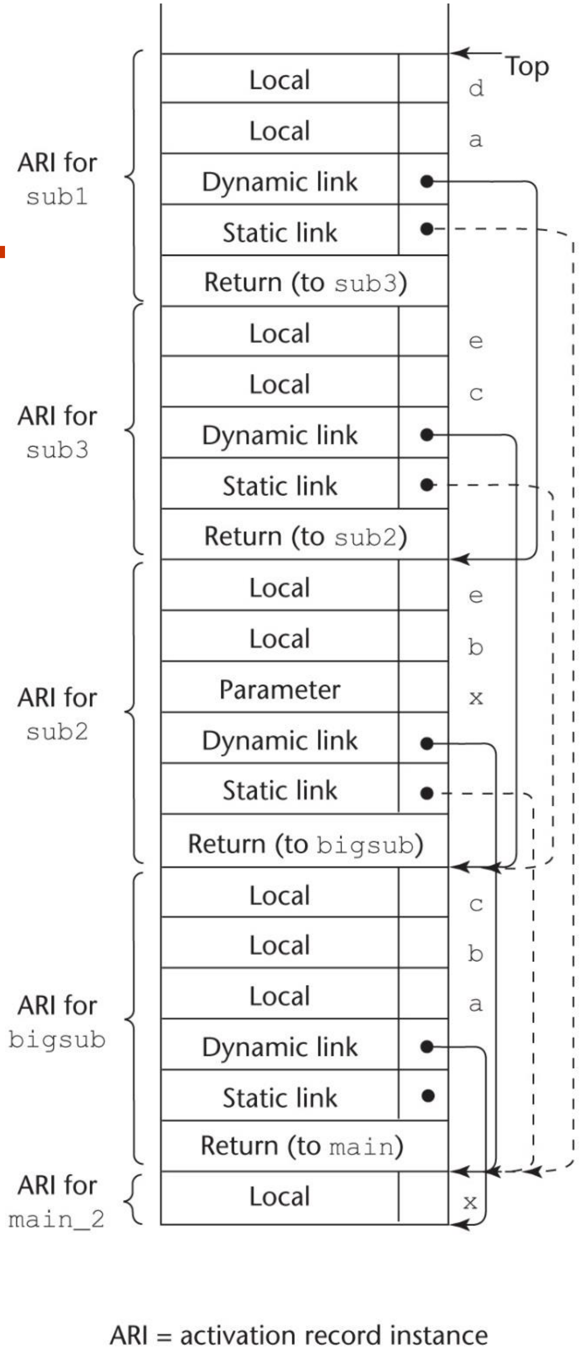
```
    function sub3() {
      var c, e;
     ...
      sub1();
      ...
     e = b + a; ←-------------------------------2
    } // end of sub3 ...
   sub3();
   ...
    a = d + e; ←---------------------------------3
  } // end of sub2
  ...
  sub2(7);
  ...
 } // end of bigsub
 ...
 bigsub();
 ...
} // end of main
```

Example JavaScript Program (continued)

- Call sequence for `main`

  `main` calls `bigsub`
  `bigsub` calls `sub2`
  `sub2` calls `sub3`
  `sub3` calls `sub1`

Stack Contents at Position 1



Static Chain Maintenance

- At the call,
  - The activation record instance must be built
  - The dynamic link is just the old stack top pointer
  - The static link must point to the most recent ari of the static parent
    - Two methods:
      1. Search the dynamic chain
      2. Treat subprogram calls and definitions like variable references and definitions

Evaluation of Static Chains

- Problems:
  1. A nonlocal areference is slow if the nesting depth is large
  2. Time-critical code is difficult:
     a. Costs of nonlocal references are difficult to determine
     b. Code changes can change the nesting depth, and therefore the cost

Blocks

- Blocks are user-specified local scopes for variables
- An example in C

```
{int temp;
 temp = list [upper];
 list [upper] = list [lower];
 list [lower] = temp
}
```

- The lifetime of `temp` in the above example begins when control enters the block
- An advantage of using a local variable like `temp` is that it cannot interfere with any other variable with the same name

Implementing Blocks

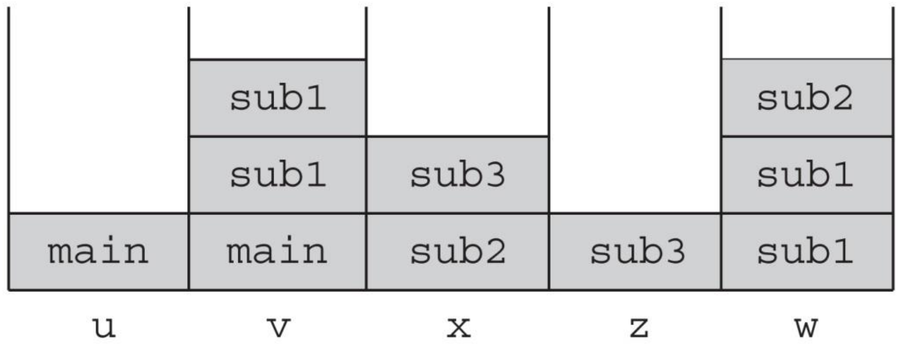
- Two Methods:
  1. Treat blocks as parameter-less subprograms that are always called from the same location
     - Every block has an activation record; an instance is created every time the block is executed
  2. Since the maximum storage required for a block can be statically determined, this amount of space can be allocated after the local variables in the activation record

Implementing Dynamic Scoping

- *Deep Access*: non-local references are found by searching the activation record instances on the dynamic chain
  - Length of the chain cannot be statically determined
  - Every activation record instance must have variable names
- *Shallow Access*: put locals in a central place
  - One stack for each variable name
  - Central table with an entry for each variable name

Using Shallow Access to Implement Dynamic Scoping

```
void sub3() {
  int x, z;
  x = u + v;
  …
}
void sub2() {
  int w, x;
  …
}
void sub1() {
  int v, w;
  …
}
void main() {
  int v, u;
  …
}
```



(The names in the stack cells indicate the program units of the variable declaration.)

Summary

- Subprogram linkage semantics requires many action by the implementation
- Simple subprograms have relatively basic actions
- Stack-dynamic languages are more complex
- Subprograms with stack-dynamic local variables and nested subprograms have two components
  - actual code
  - activation record

Summary (continued)

- Activation record instances contain formal parameters and local variables among other things
- Static chains are the primary method of implementing accesses to non-local variables in static-scoped languages with nested subprograms
- Access to non-local variables in dynamic-scoped languages can be implemented by use of the dynamic chain or thru some central variable table method