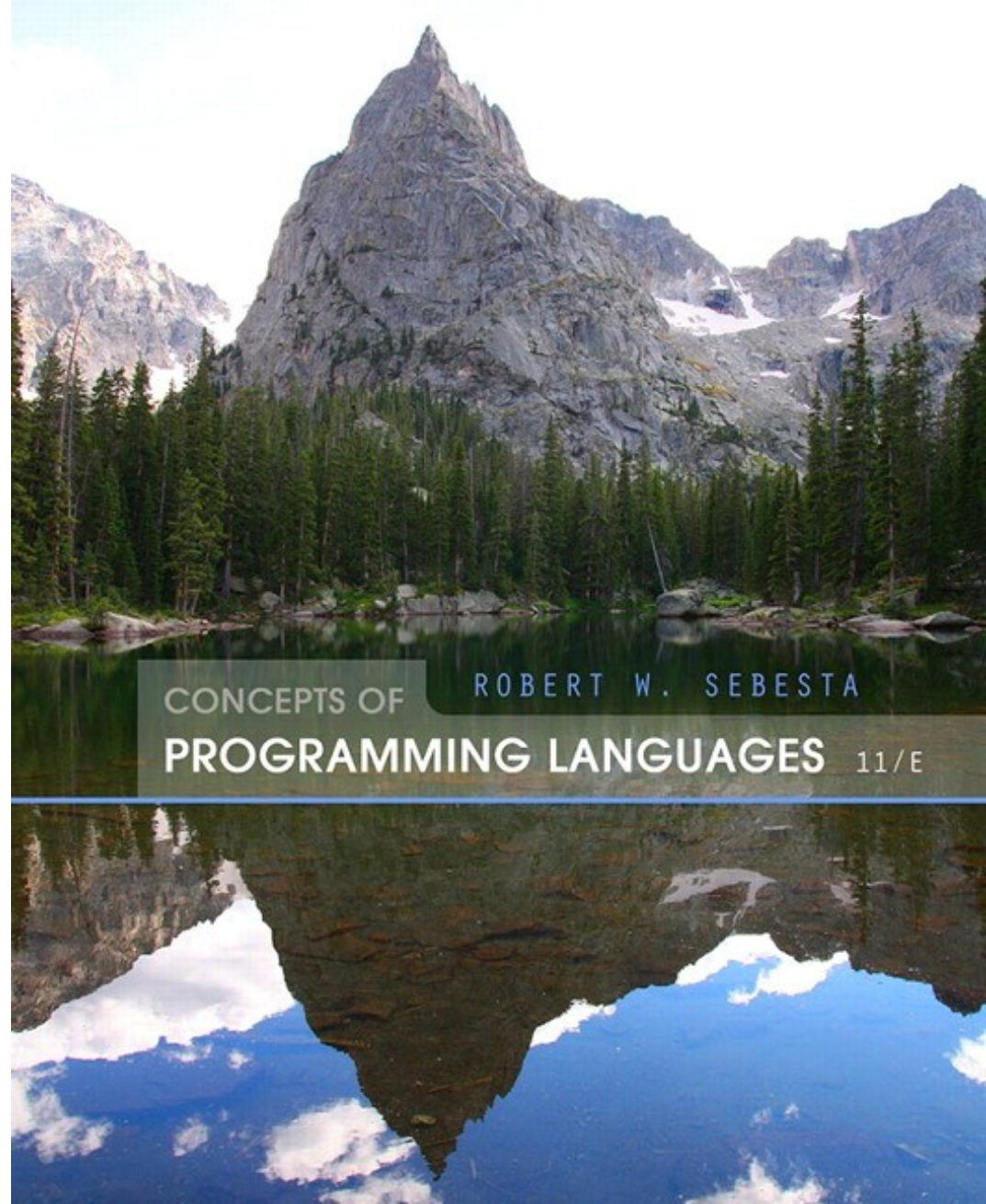


Chapter 10

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
 - 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

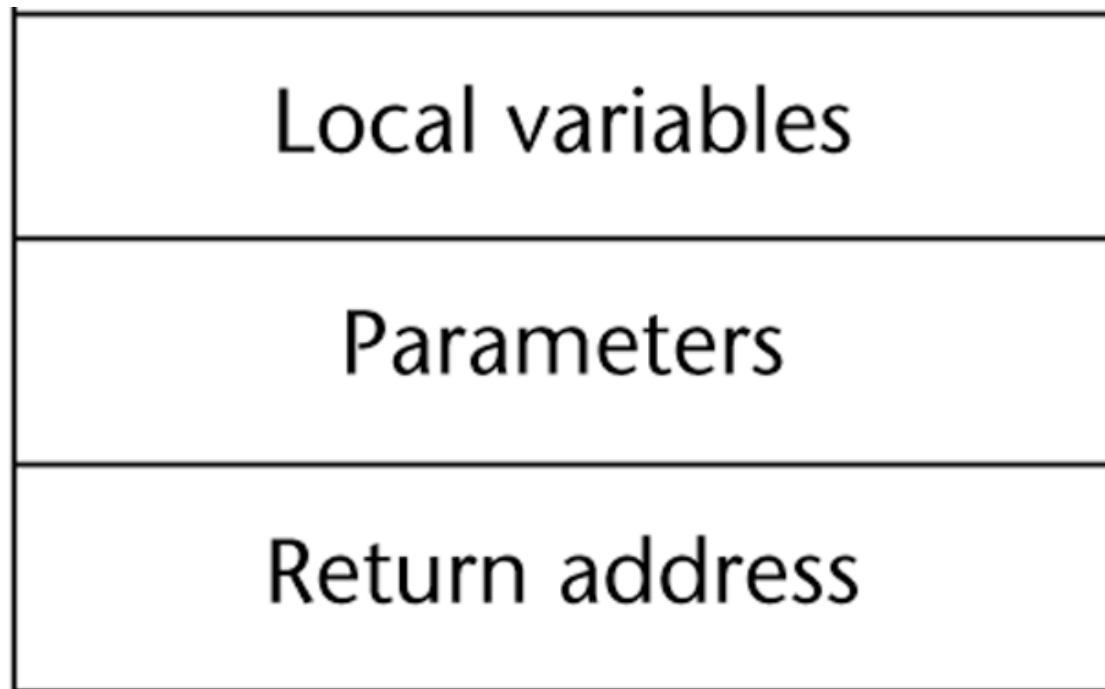
Implementing “Simple” Subprograms (continued)

- 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

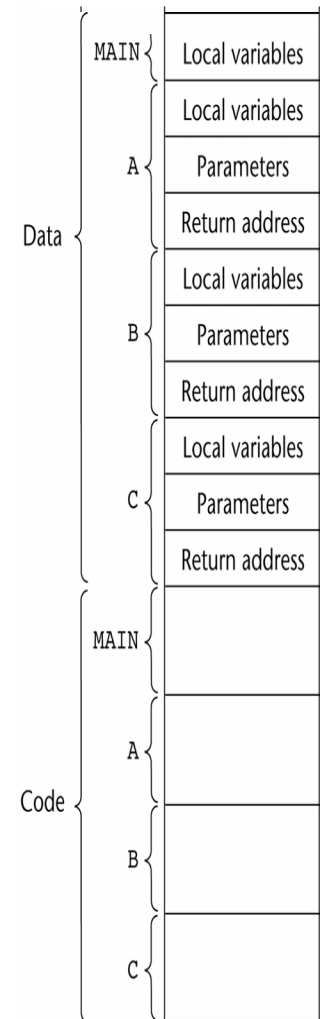
Implementing “Simple” Subprograms (continued)

- 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



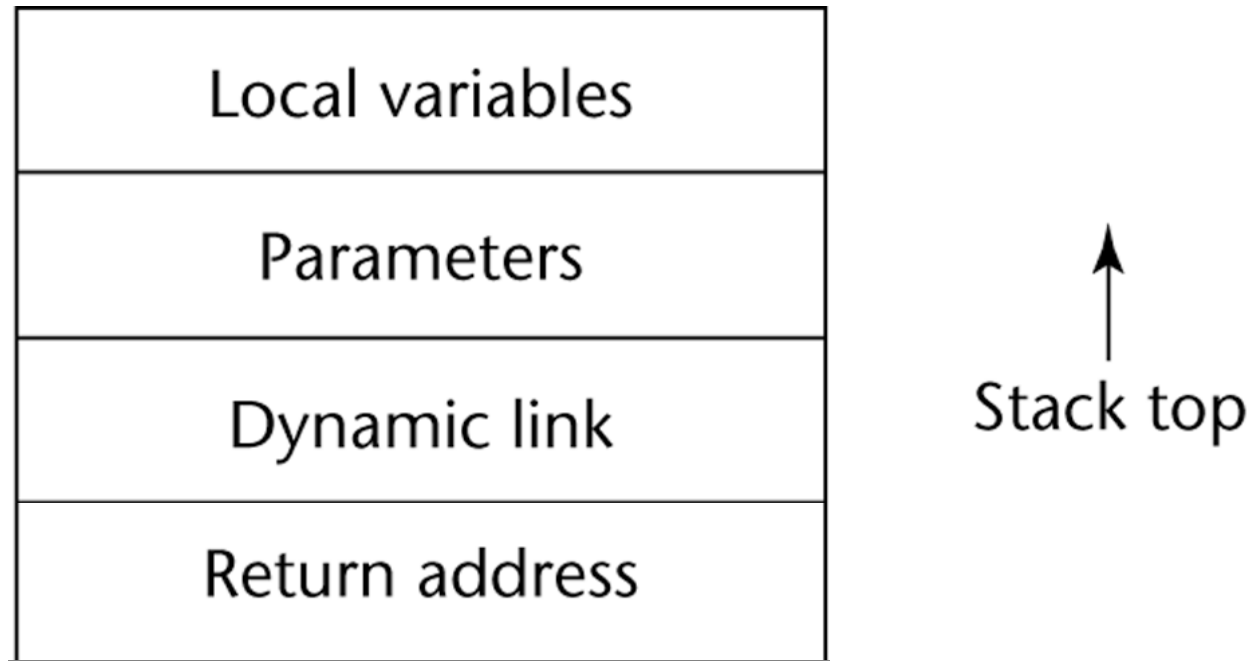
Code and Activation Records of a Program with “Simple” Subprograms



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)

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

An Example: C Function

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

Local	sum
Local	list [4]
Local	list [3]
Local	list [2]
Local	list [1]
Local	list [0]
Parameter	part
Parameter	total
Dynamic link	
Return address	

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

Revised Semantic Call/Return Actions (continued)

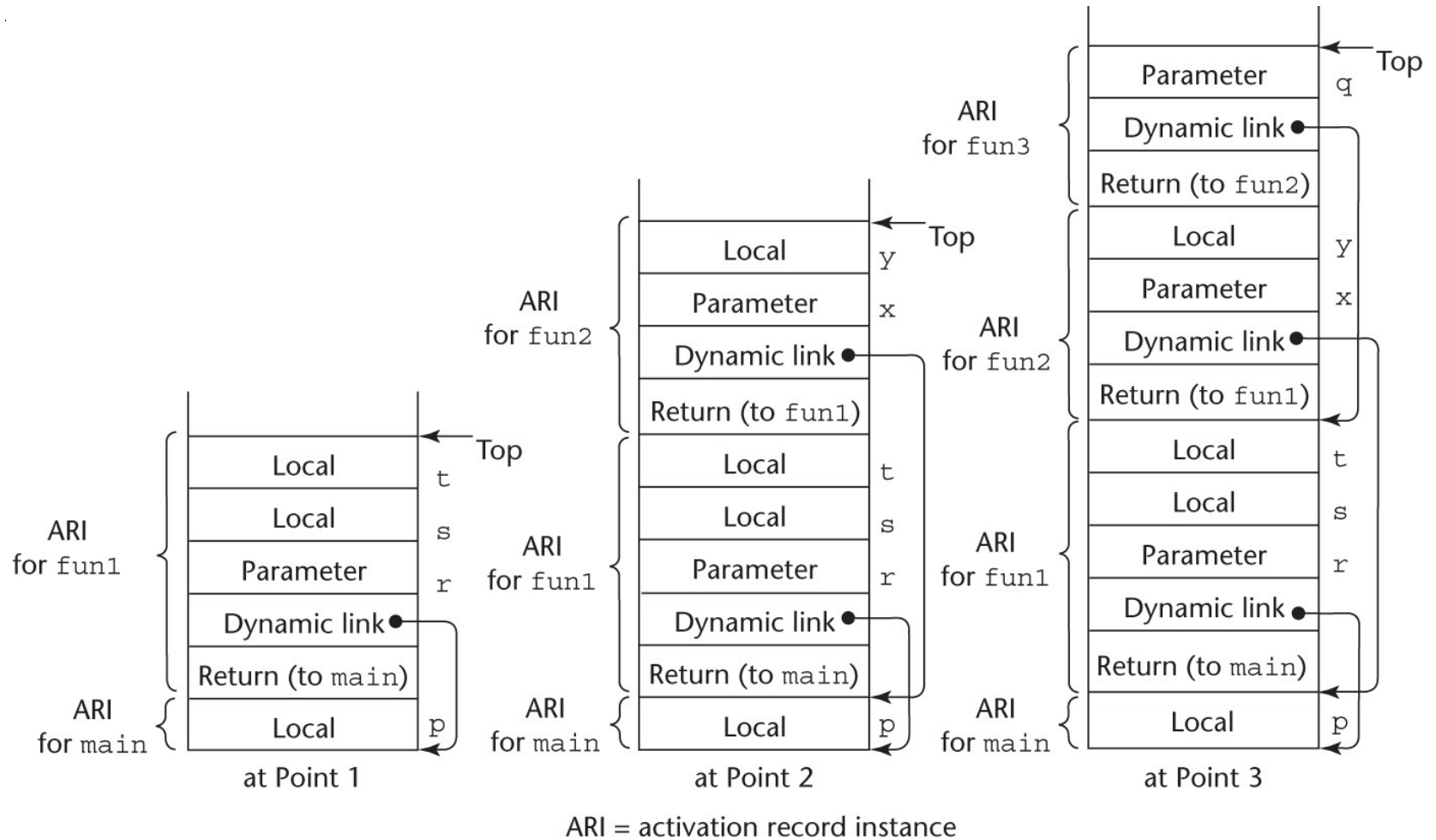
- Epilogue actions of the called:
 - If there are pass-by-value-result or out-mode parameters, the current values of those parameters are moved to the corresponding actual parameters
 - If the subprogram is a function, its value is moved to a place accessible to the caller
 - Restore the stack pointer 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



Dynamic Chain and Local Offset

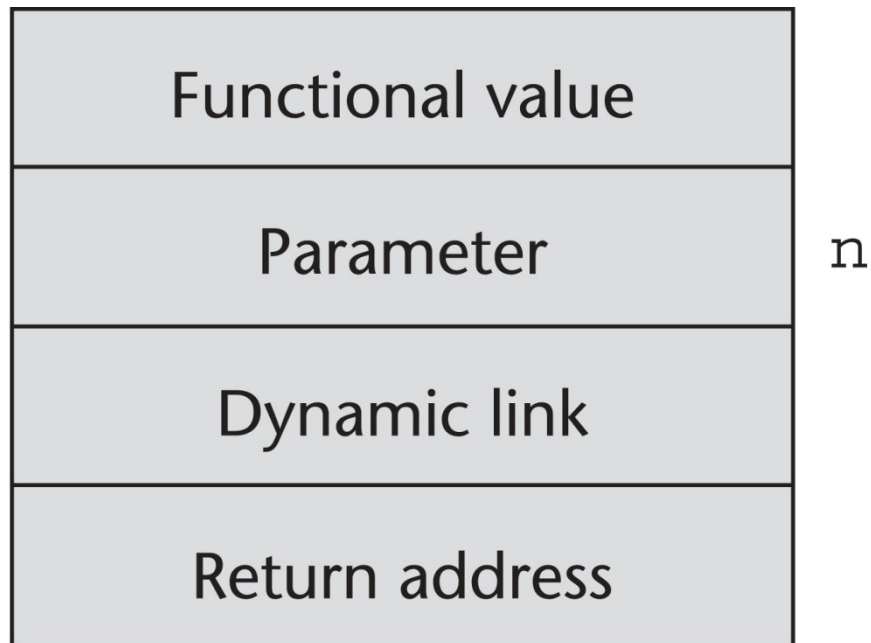
- The collection of dynamic links in the stack at a given time is called the *dynamic chain*, or *call chain*
- Local variables can be accessed by their offset from the beginning of the activation record, whose address is in the EP. This offset is called the *local_offset*
- The *local_offset* of a local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

An Example With Recursion

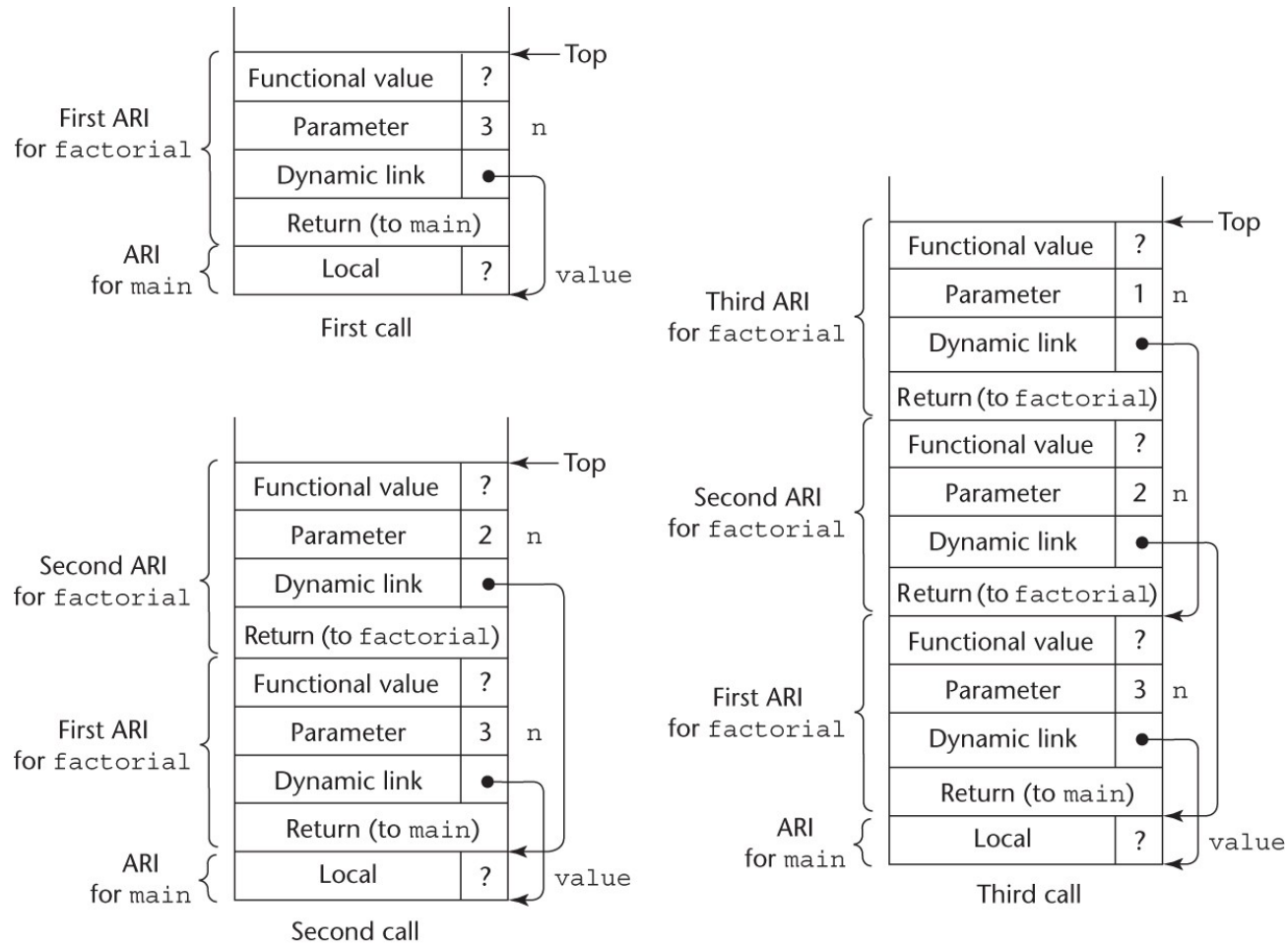
- The activation record used in the previous example supports recursion

```
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**

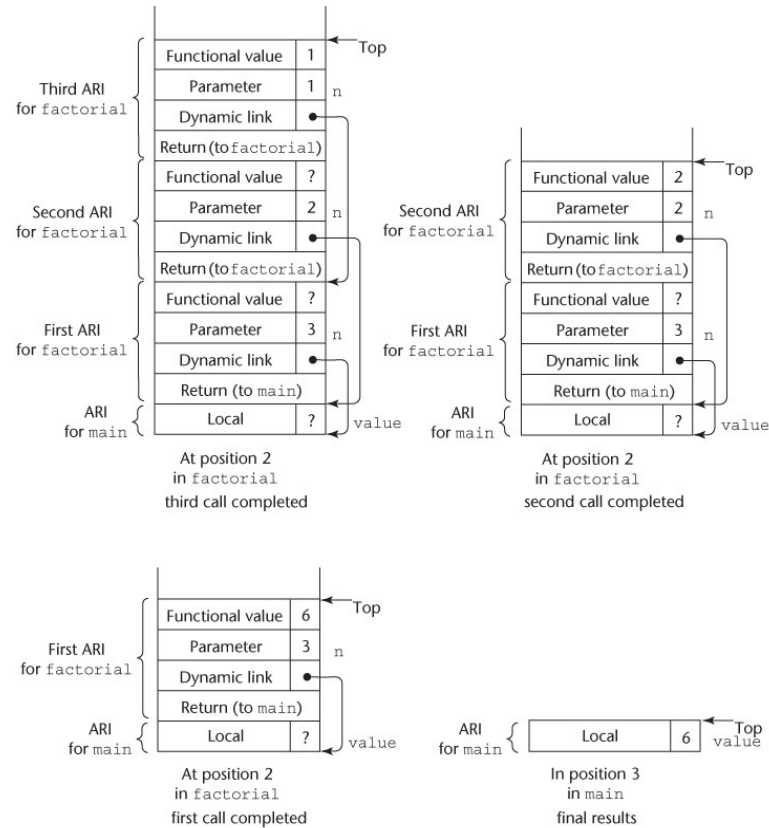


Stacks for calls to factorial



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)

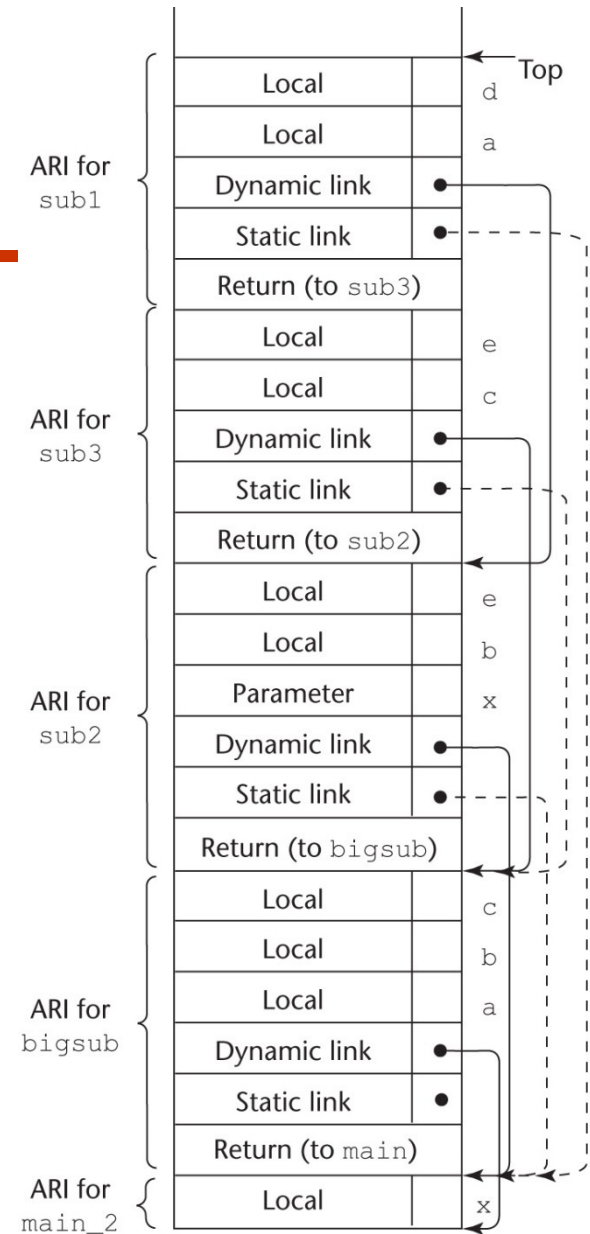
```
function sub3() {  
    var c, e;  
    ...  
    sub1();  
    ...  
    e = b + a; ←-----2  
} // end of sub3 ...  
sub3();  
...  
a = d + e; ←-----3  
} // end of sub2  
...  
sub2(7);  
...  
} // end of bigsub  
...  
bigsub();  
...  
} // end of main
```

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



ARI = activation record instance

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

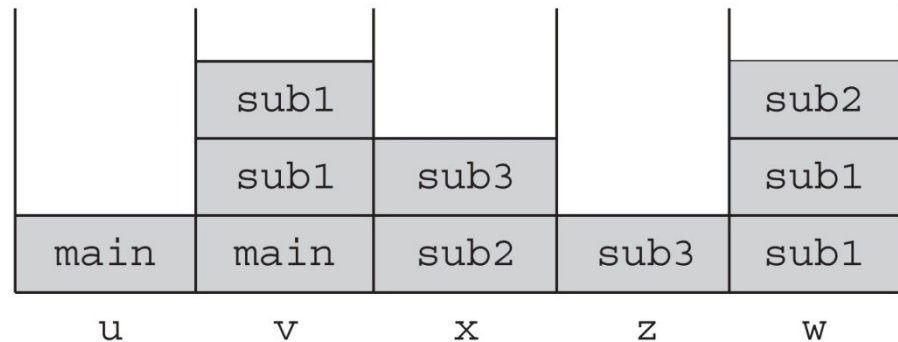
- Two Methods:
 1. Treat blocks as parameter-less subprograms that are always called from the same location
 - Every block has an activation record; an instance is created every time the block is executed
 2. Since the maximum storage required for a block can be statically determined, this amount of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