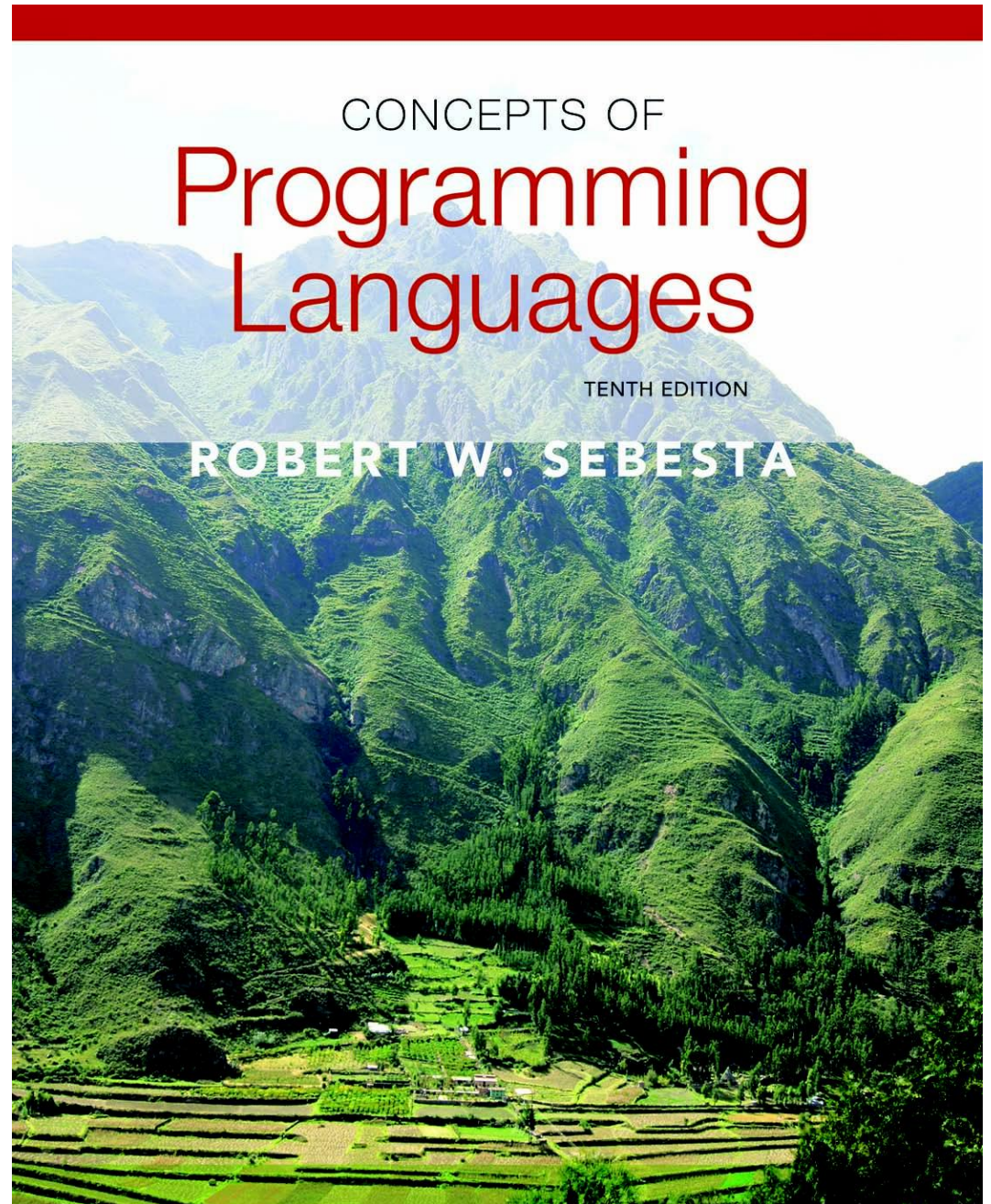


# Chapter 10

## Implementing Subprograms



# Chapter 10 Topics

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- 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

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- 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

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- 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

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- 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)

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- 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

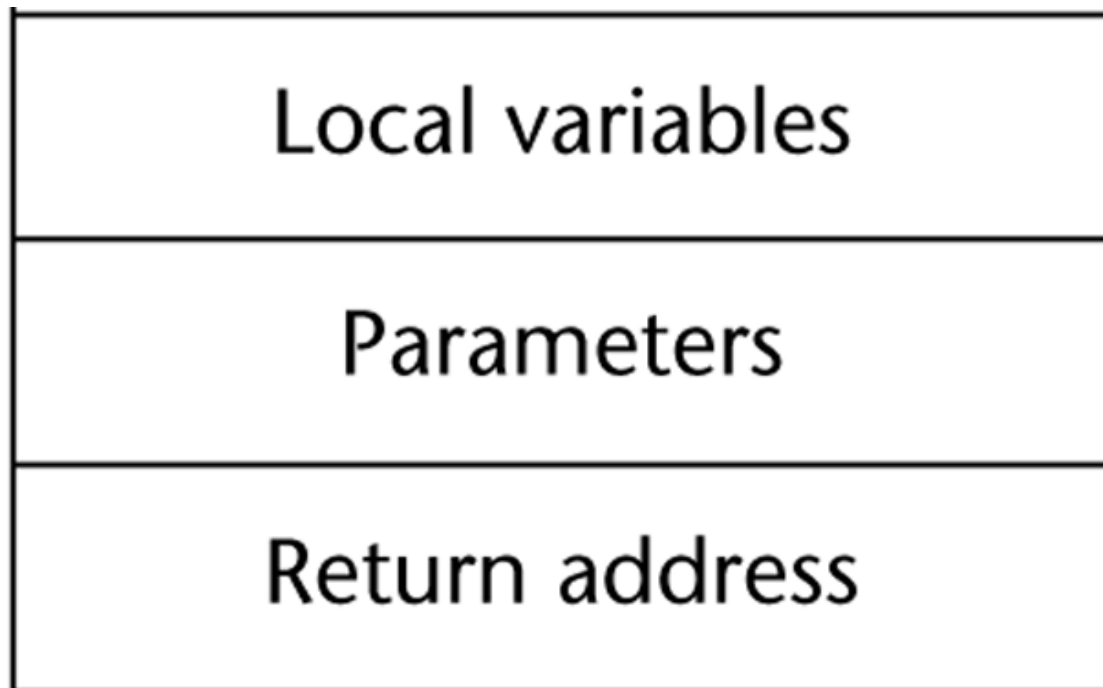
# Implementing “Simple” Subprograms (continued)

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- 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

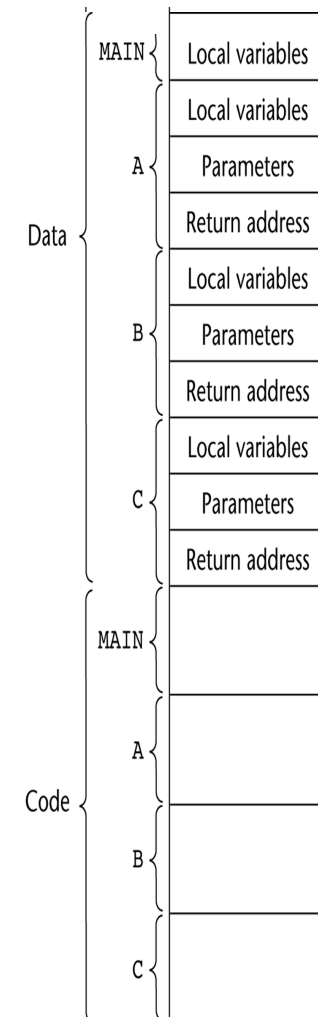
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# Code and Activation Records of a Program with “Simple” Subprograms

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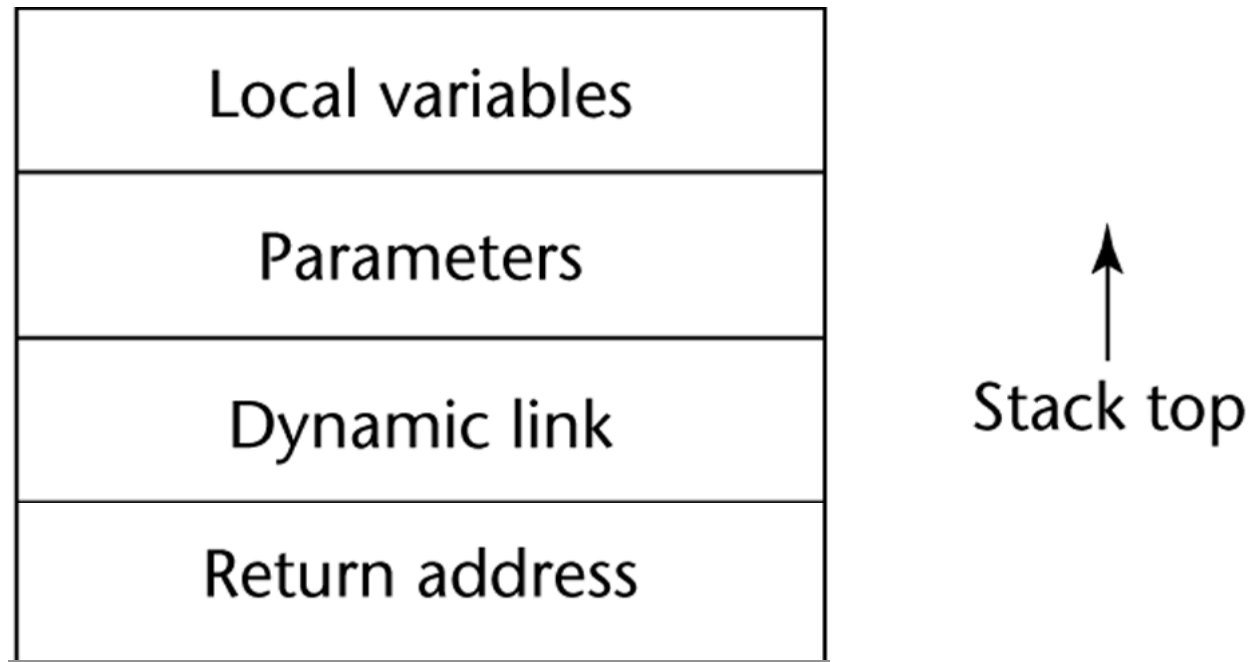
# Implementing Subprograms with Stack-Dynamic Local Variables

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- 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

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# Implementing Subprograms with Stack– Dynamic Local Variables: Activation Record

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- 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

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- 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)

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- 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

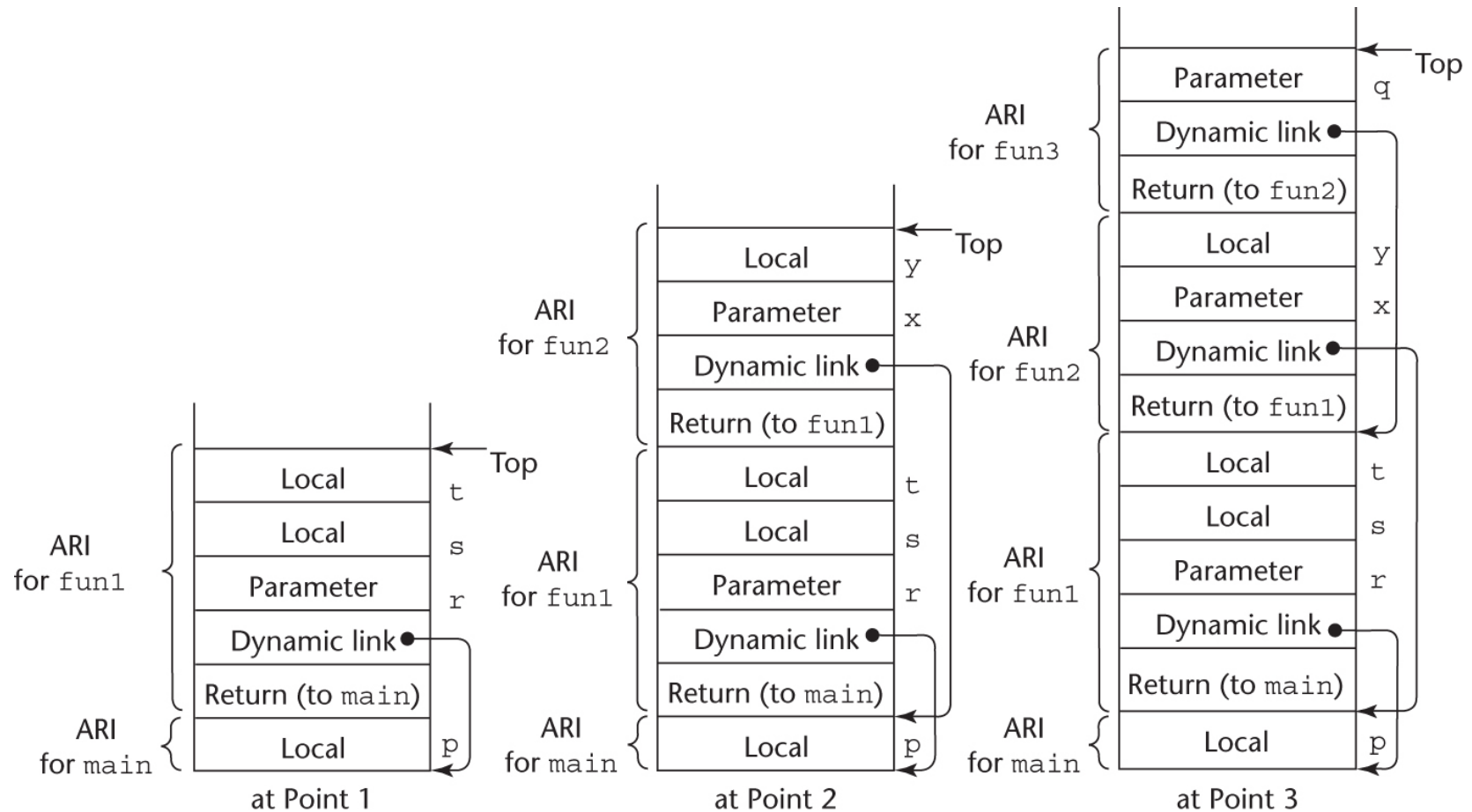
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```
void fun1(float r) {  
    int s, t;  
    ...  
    fun2(s);  
    ...  
}  
void fun2(int x) {  
    int y;  
    ...  
    fun3(y);  
    ...  
}  
void fun3(int q) {  
    ...  
}  
void main() {  
    float p;  
    ...  
    fun1(p);  
 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

main **calls** fun1  
fun1 **calls** fun2  
fun2 **calls** fun3



# An Example Without Recursion



ARI = activation record instance

# Dynamic Chain and Local Offset

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- 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

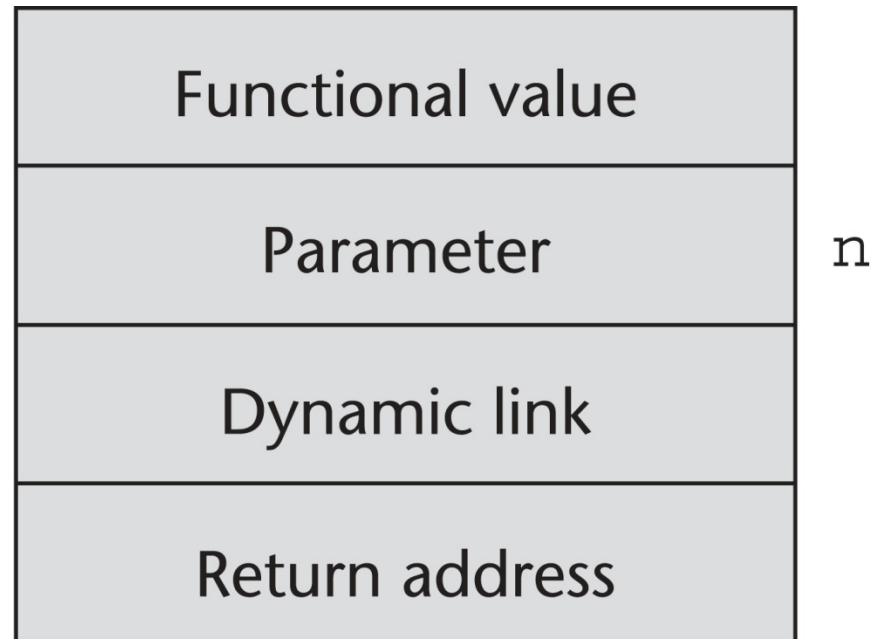
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- The activation record used in the previous example supports recursion

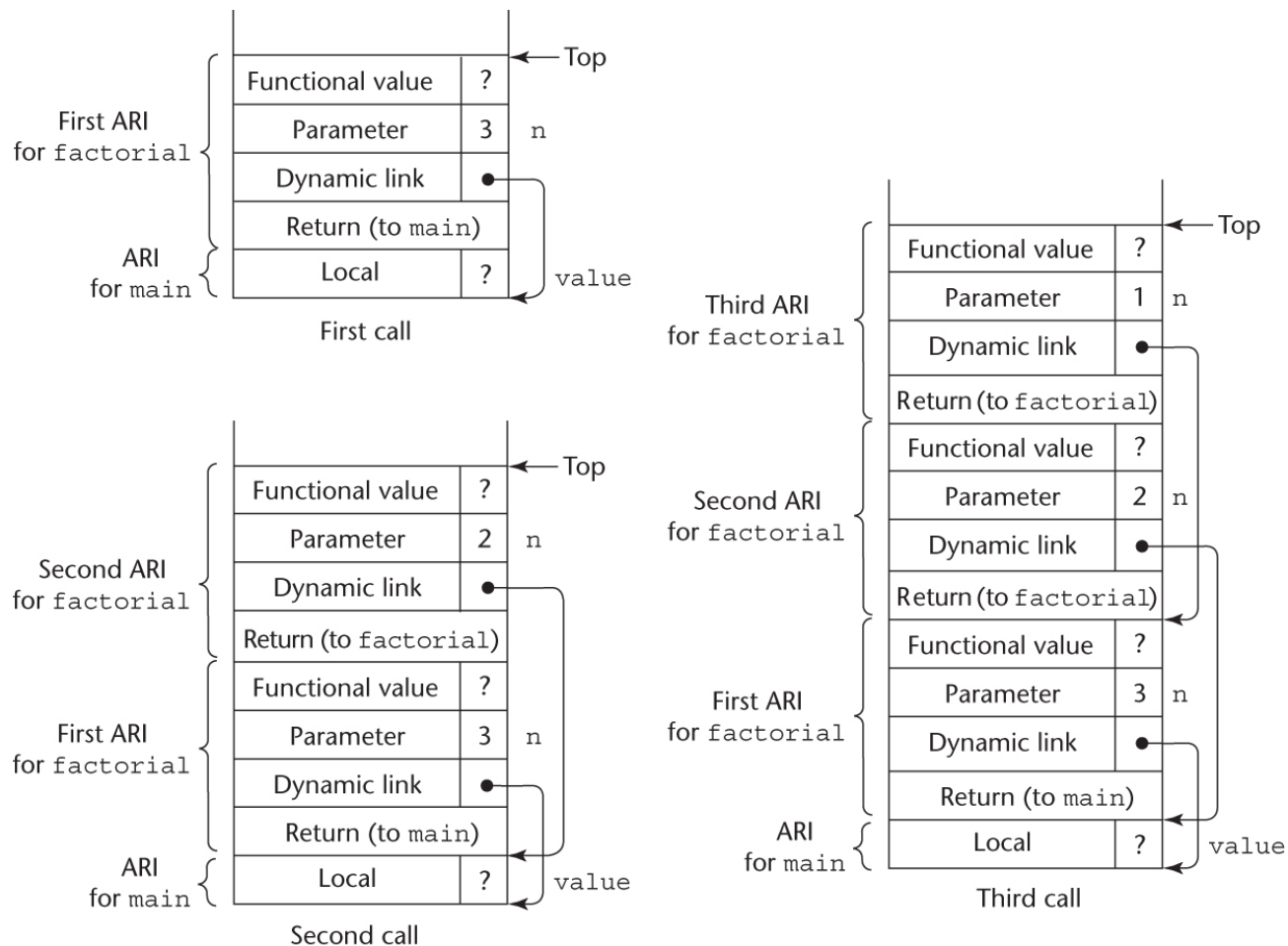
```
int factorial (int n) {  
    <-----1  
    if (n <= 1) return 1;  
    else return (n * factorial(n - 1));  
    <-----2  
}  
void main() {  
    int value;  
    value = factorial(3);  
    <-----3  
}
```

# Activation Record for `factorial`

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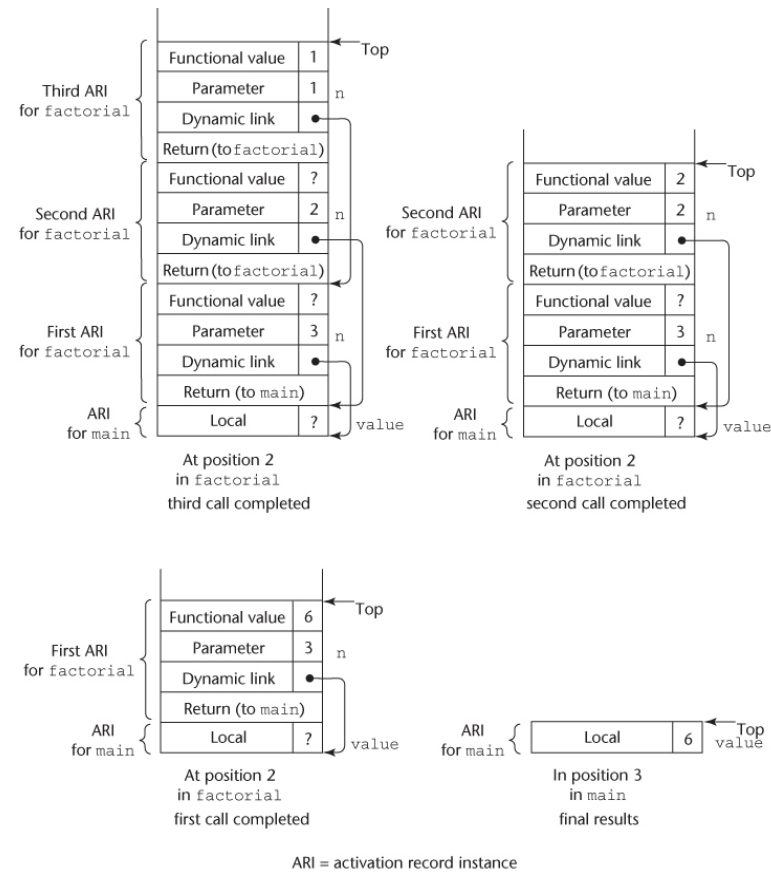


# Stacks for calls to `factorial`



ARI = activation record instance

# Stacks for returns from `factorial`



# Nested Subprograms

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- 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

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- 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)

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- 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 Ada Program

---

```
procedure Main_2 is
  X : Integer;
  procedure Bigsub is
    A, B, C : Integer;
    procedure Sub1 is
      A, D : Integer;
      begin -- of Sub1
        A := B + C; <-----1
      end; -- of Sub1
    procedure Sub2(X : Integer) is
      B, E : Integer;
      procedure Sub3 is
        C, E : Integer;
        begin -- of Sub3
          Sub1;
          E := B + A; <-----2
        end; -- of Sub3
      begin -- of Sub2
        Sub3;
        A := D + E; <-----3
      end; -- of Sub2 }
    begin -- of Bigsub
      Sub2(7);
    end; -- of Bigsub
  begin
    Bigsub;
  end; of Main_2 }
```

# Example Ada Program (continued)

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- Call sequence for `Main_2`

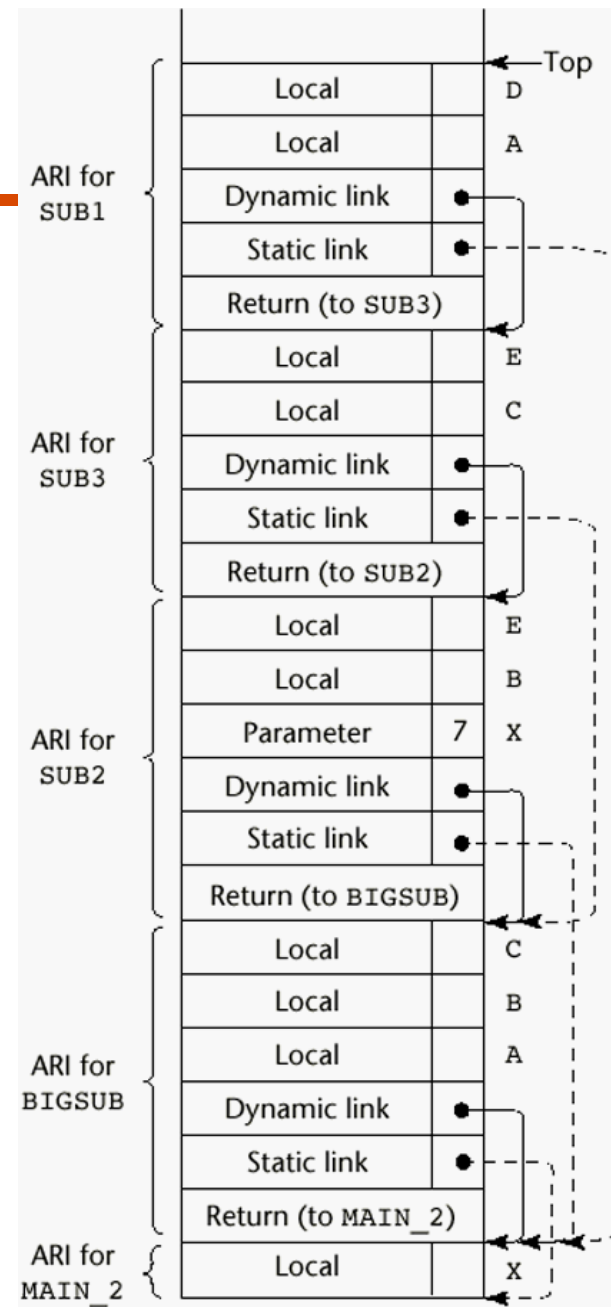
`Main_2` **calls** `Bigsub`

`Bigsub` **calls** `Sub2`

`Sub2` **calls** `Sub3`

`Sub3` **calls** `Sub1`

# Stack Contents at Position 1



# Static Chain Maintenance

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- 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

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- 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

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- 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

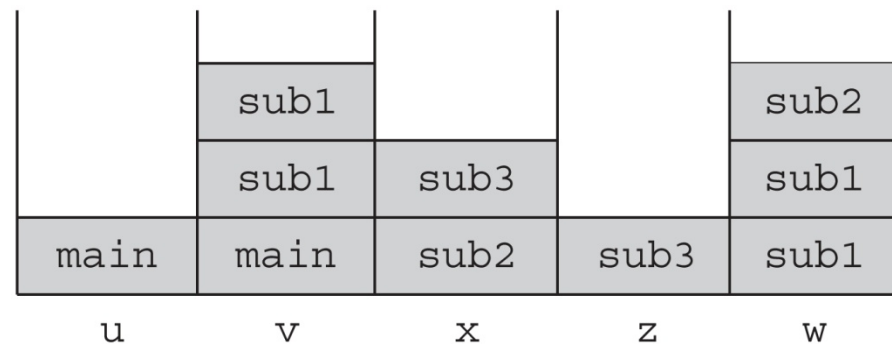
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- *Deep Access*: non-local references are found by searching the activation record instances on the dynamic chain
  - Length of the chain cannot be statically determined
  - Every activation record instance must have variable names
- *Shallow Access*: 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

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- 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)

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- 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