Implementing Subprograms

In Text: Chapter 10

Outline

- General semantics of calls and returns
- Implementing "simple" subroutines
- Call Stack
- Implementing subroutines with stack-dynamic local variables
- Nested programs

General Semantics of Calls and Returns

- The subroutine call and return operations are together called **subroutine linkage**
- The implementation of subroutines must be based on the semantics of the subroutine linkage

Semantics of a subroutine call

- Save the execution status of the current program unit
- Pass the parameters
- Pass the return address to the callee
- Transfer control to the callee

Semantics of a subroutine return

- If there are pass-by-value-result or out-mode parameters, the current values of those parameters are moved to the corresponding actual parameters
- Move the return value to a place accessible to the caller
- The execution status of the caller is restored
- Control is transferred back to the caller

Storage of Information

- The call and return actions require storage for the following:
  - Status information about the caller
  - Parameters
  - Return address
  - Return value for functions
  - Local variables

Implementing "simple" subroutines

- **Simple subroutines** are those that cannot be nested and all local variables are static
- A simple subroutine consists of two parts: code and data
  - Code: constant (instruction space)
  - Data: can change when the subroutine is executed (data space)
  - Both parts have fixed sizes

Activation Record

- The format, or layout, of the data part is called an activation record, because the data is relevant to an activation, or execution, of the subroutine
- The form of an activation record is static
- An activation record instance is a concrete example of an activation record, corresponding to one execution

An activation record for simple subroutine

Local variables
Parameters
Return address

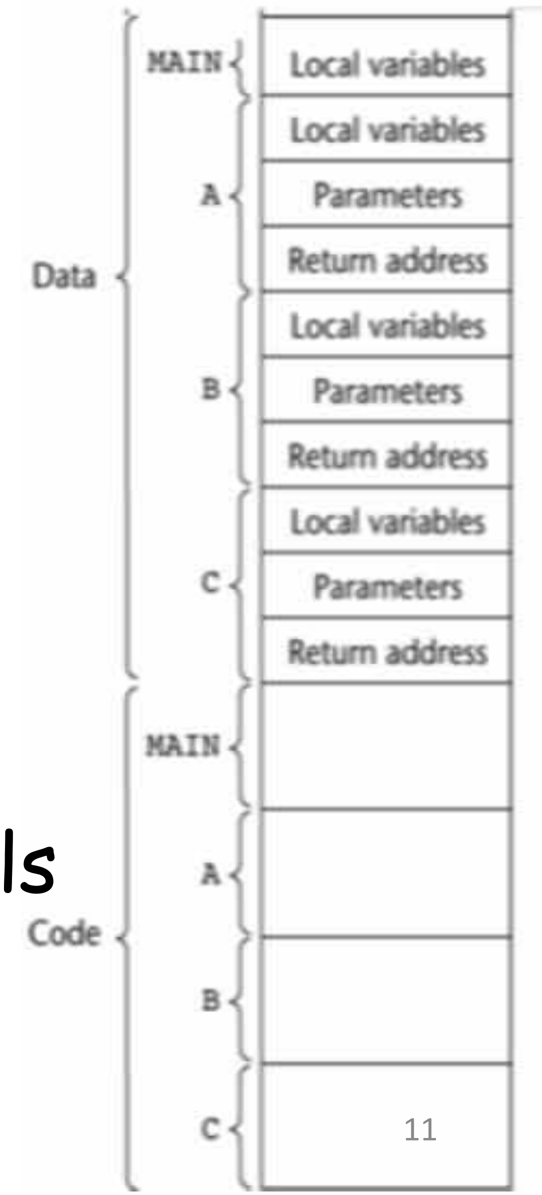
- Since the activation record instance of a "simple" subprogram has fixed size, it can be statically allocated
- Actually, it could be attached to the code part of the subprogram

The code and activation records of a program with simple subroutines

- Four program units—MAIN, *A*, B, and *C*
- MAIN calls *A*, B, and *C*
- Originally, all four programs may be compiled at different times individually
- When each program is compiled, its machine code, along with a list of references to external subprograms are written to a file

How is the code linked?

- *A* linker is called for MAIN to create an executable program
  - Linker is part of the OS
  - Linker is also called *loader*, *linker/loader*, or *link editor*
  - It finds and loads all referenced subroutines, including code and activation records, into memory
  - It sets the target addresses of calls to those subroutines' entry addresses



Assumptions so far…

- All local variables are statically allocated
- No function recursion
- No value returned from any function

Call Stack

- **Call stack** is a stack data structure that stores information about the active subroutines of a program
- Also known as **execution stack**, **control stack**, **runtime-stack**, or **machine stack**
- Large array which typically grows downwards in memory towards lower addresses, shrinks upwards

Call Stack

- Push(r1):
```
stack_pointer--;
M[stack_pointer] = r1;
```
- r1 = Pop();
```
r1 = M[stack_pointer];
stack_pointer++;
```

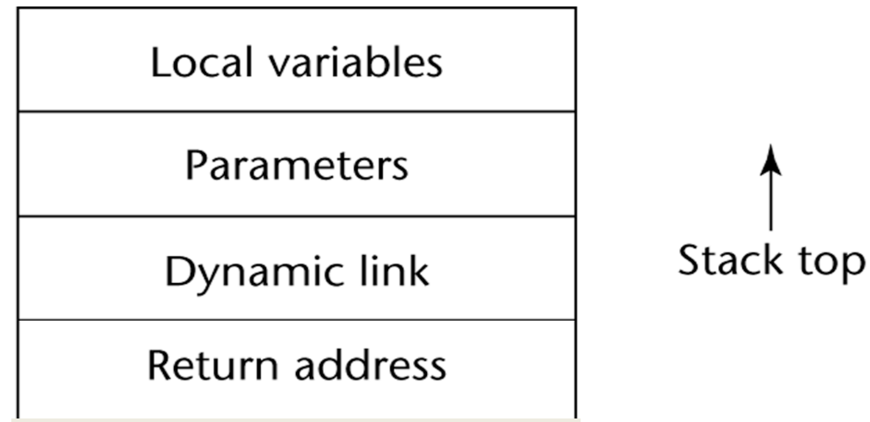
Call Stack

- When a function is invoked, its activation record is created dynamically and pushed onto the stack
- When a function returns, its activation record is popped from the stack
- The activation record on stack is also called **stack frame**
- **Stack pointer(sp):** points to the frame top
- **Frame pointer(fp):** points to the frame base

Implementing subroutines with stack-dynamic local variables

- One important advantage of stack-dynamic local variables is support for recursion
- The implementation requires more complex activation records
  - The compiler must generate code to cause the implicit allocation and deallocation of local variables

More complex activation records

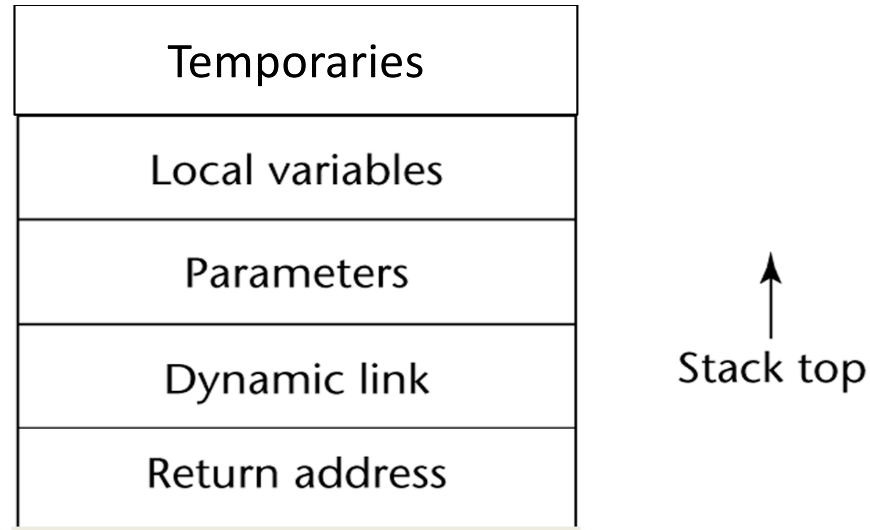


- Since the return address, dynamic link, and parameters are placed in the activation record instance by the caller, these entries must appear first
- Local variables are allocated and possibly initialized in the callee, so they appear last

Dynamic Link (control link) = previous sp

- Used in the destruction of the current activation record instance when the procedure completes its execution
- To restore the sp in previous frame (caller)
- The collection of dynamic links in the stack at a given time is called the **dynamic chain**, or **call chain**, which represents the dynamic history of how execution got to its current position

Why do we need dynamic links?



- The dynamic link is required in some cases, because there are other allocations from the stack by a subroutine beyond its activation record, such as temporaries
- Even though the activation record size is known, we cannot simply add the size to the stack pointer to remove the activation record
- *Access nonlocal variables in dynamic scoped languages*

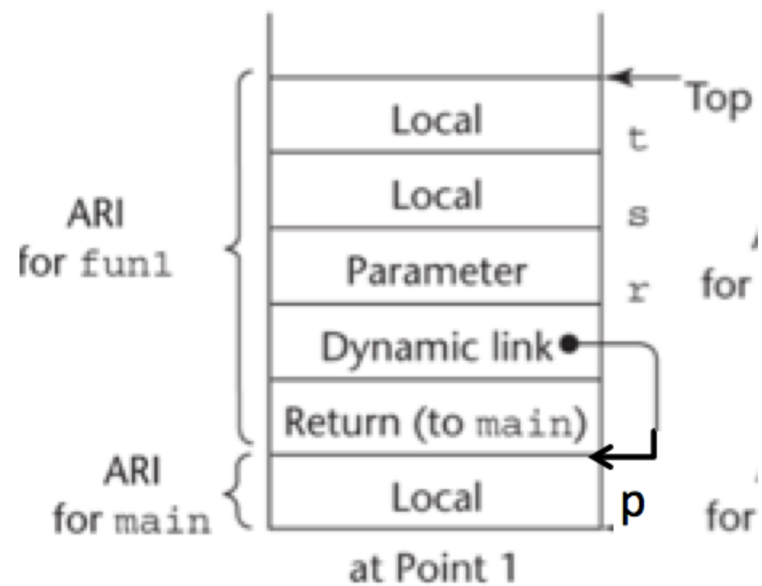
An Example without Recursion

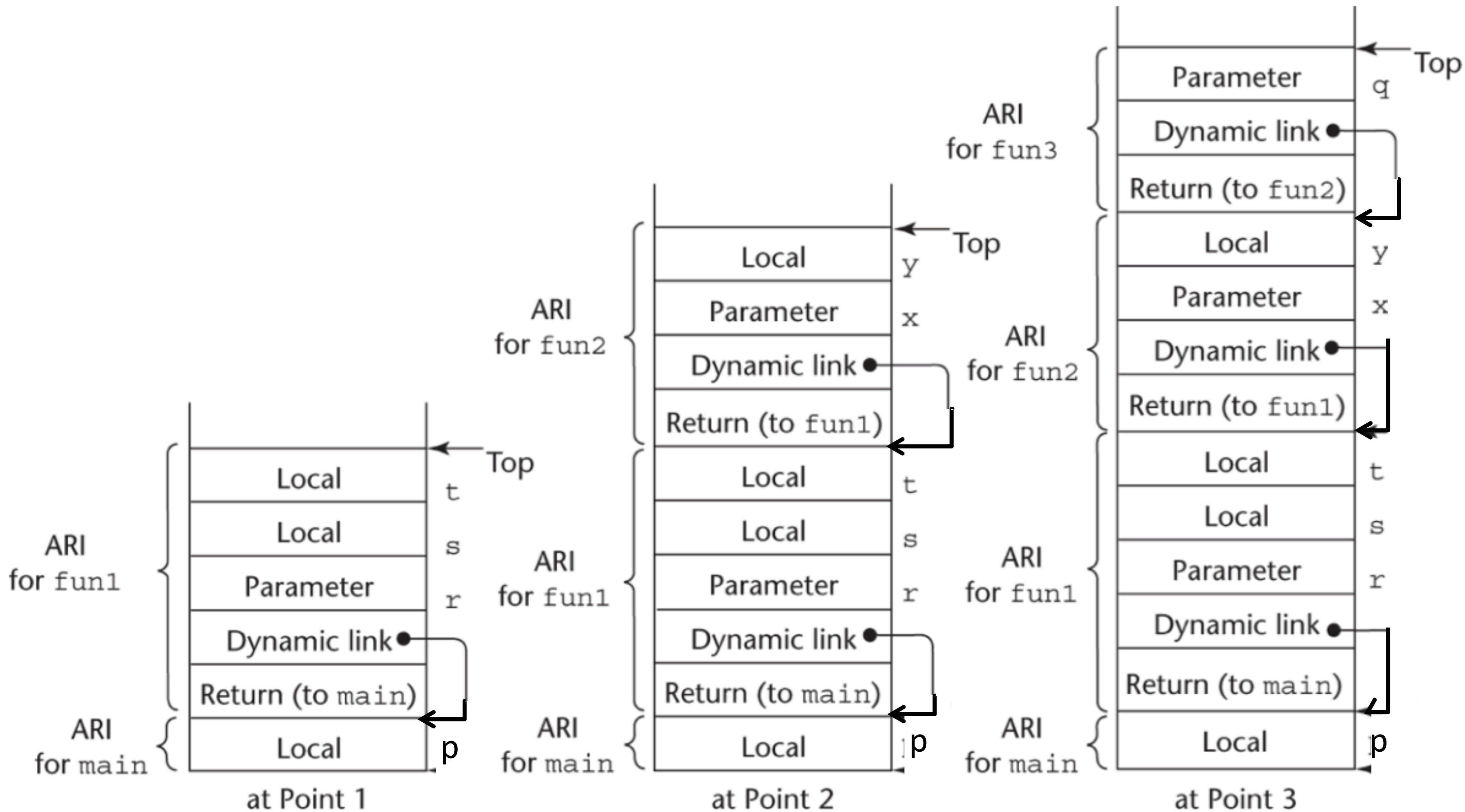
```
void fun1(float r) {
    int s, t;
    … ←---------1
    fun2(s);
}
void fun2(int x) {
    int y;
    …  ←--------2
    fun3(y);
    …
}
void fun3(int q) {
    … ←---------3
}
void main() {
    float p;
    …
    fun1(p);
}
```

- Call sequence:

  main -> fun1 -> fun2 -> fun3

- What is the stack content at points labeled as 1, 2, and 3?





ARI = activation record instance

Local Variable Allocation

- Local scalar variables are bound to storage within an activation record instance
- Local variables that are structures are sometimes allocated elsewhere, and only leave their descriptors and a pointer to the storage as part of the activation record

An Example

```
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	

Recursion

- Function recursion means that a function can eventually call itself
- Recursion adds the possibility of multiple simultaneous activations of a subroutine at a *given* time, with at least one call from outside the subroutine, and one or more recursive calls
- Each activation requires its own activation record instance

An Example

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

How does the stack change?

Implementing nested subroutines

- Some static-scoped languages use stack-dynamic local variables and allow subroutines to be nested
  - FORTRAN 95, Ada, Python, and JavaScript
- Challenge
  - How to access nonlocal variables?

Two-step access process

- Find the activation record instance on the stack where the variable was allocated
  - more challenging and more difficult
- Use the **local_offset** of the variable to access it
  - local_offset describes the offset from the beginning/bottom of an activation record

Key Observations

- In a given subroutine, only variables that are declared in static ancestor scopes are visible and can be accessed
- Activation record instances of all static ancestors are always on the stack when variables in them are referenced by a nested subroutine: *A subroutine is callable only when all its static ancestors are active*

Finding Activation Record Instance

- Static chaining
  - A new pointer, **static link (static scope pointer or access link)**, is used to point to the bottom of an activation record instance of the static parent
  - The pointer is used for access to nonlocal variables
  - Typically, the static link appears below parameters in an activation record

Finding Activation Record Instance (cont'd)

- *A* static chain is a chain of static links that connect the activation record instances of all static ancestors for an executing subroutine
- This chain can be used to implement nonlocal variable access

Local variables
Parameters
Dynamic link
Static link
Return address

Finding Activation Record Instance (cont'd)

- With static links, finding the correct activation record instance is simple
  - Search the static chain until a static ancestor is found to contain the variable
- However, the implementation can be even simpler
  - Compiler identifies both nonlocal references, and the length of static chain to follow to reach the correct record

Finding Activation Record Instance (cont'd)

- **static_depth** is an integer associated with a static scope that indicates how deeply it is nested in the outermost scope
- The difference between the static_depth of a nonlocal reference and the static_depth of the variable definition is called **nesting_depth**, or **chain_depth**, of the reference
- Each reference is represented with an ordered integer pair (chain_offset, local_offset)

An Ada Example

```
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;
```

```
Main_2 calls Bigsub
Bigsub calls Sub2
Sub2 calls Sub3
Sub3 calls Sub1
```

What is the static depth for each procedure?
What is the representation of A at points 1, 2, and 3?

Stack Contents

```
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 }
```