COS 301

Implementing Subprograms

Semantics of Call and Return

- The call and return operations of a language are together called its subprogram linkage
- Actions involved in implementing call
  - Implement parameter passing method
  - Allocate local storage
  - Bind variables
  - Save execution status of calling program
    - Includes register values, processor flag/status bits, frame pointer
- Actions involved implementing return
  - Deallocate local storage
  - Communicate function return results if any
  - Restore execution environment and program counter

Flat and Nested Execution Scopes

- Subprogram call is further complicated by nested execution scopes
- Called functions need access to non-local variables
  - These can be static variables but more often are stack-dynamic local variables

"Simple" Subroutines

- Simple (like early Fortran):
  - Static locals
  - Not nested
- Call Semantics:
  - Save the execution status of the caller
  - Pass the parameters
  - Pass the return address to the callee
  - Transfer control to the callee

Simple Subroutine Return

- Return Semantics:
  - If pass-by-value-result or out mode parameters are used, copy the current values of those parameters to their corresponding actual parameters
  - If it is a function, copy the return 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, local variables

Distribution of Responsibility

- Generally call semantics are executed by the caller and return semantics by callee
- One possible exception is saving the state of the caller
  - This can be done by either
    - Caller knows what needs to be saved
    - Callee knows what global resources (registers, etc) need to be saved
- Linkage actions of callee are called the "prologue" and the "epilogue"
  - For simple subroutines with static locals and without nested scope there is no need for prologue code

Subroutine Organization

- Subroutines have two separate parts: the code and the non-code part consisting of
  - Data (local and temporary variables)
  - Linkage information (saved frame pointers, return addresses, etc.)
- 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)

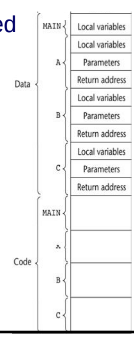
Activation Record for Simple Subs

- Simple subroutines can only have one activation instance per routine (no support for recursion)
  - Activation record is fixed in size and allocated statically
  - Could be actually attached to the code segment
  - Below is a possible layout

Local variables
Parameters
Return address

Linkage

- A program can be composed of multiple parts separately compiled
- The linker is responsible for assembling the overall program layout



Stack-Dynamic Local Variables

- Most languages (whether compiled or interpreted) use stack dynamic local variables
  - Provides support for recursive because each invocation of a subprogram can have a new activation record instance on the stack
- Activation records are more complex
  - The compiler must generate code to cause implicit allocation and deallocation of local variables
  - Activation record instances are created dynamically
  - Usually the caller's frame pointer to its own activation instance has be saved

Frame Pointer / Dynamic Link

- Each subprogram activation needs a pointer to its own activation record
  - Usually called the "frame pointer" from "stack frame" (another name for activation record)
- Some machines may have only one register available for this purpose
  - So the caller's frame pointer has be to saved on the stack
  - But the frame pointer also provides other valuable information
    - For dynamically scoped languages it is a dynamic link to non-local variables
    - For statically scoped languages it can be used to provide stack traceback information

Activation Record

- An activation record is dynamically created when a subprogram is called
  - Activation record instances reside on the run-time stack
  - The activation record format is static, but its size may be dynamic
- The Environment Pointer (EP) or Frame Pointer (FP) must be maintained by the run-time system.
  - It always points at a known location in the activation record instance of the currently executing program unit
  - Conceptually we think of the Frame Pointer as pointing to the base of the activation record but in practice it may point at a known location that is not the base
    - Example: x86 arcchitecture the frame pointer points to the dynamic link and parameters are located at negative offsets

Typical Activation Record Structure

- Diagram from text

Local Variables	↑ Stack Growth
Parameters	
Dynamic Link	
Return Address	

- More common is this order

Local Variables	↑ Stack Growth
Dynamic Link	
Return Address	
Parameters	

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: C Function

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

Local	list[4]	FP+24
Local	list[3]	FP+20
Local	list[2]	FP+16
Local	list[1]	FP+12
Local	list[0]	FP+8
Local	sum	FP+4
Callers FP	<= Frame pointer	FP+0
Return Address		FP-4
parameter	total	FP-8
parameter	part	FP-12

Prologue and Epilogue Code

```
int main() {
  int i, j;
  clock_t start, finish;
_i$ = -4
_j$ = -8
_start$ = -16
_finish$ = -12
$T2208 = -24
$T2209 = -32
$T2210 = -40
$T2211 = -48
. . .
  push ebp
  mov ebp, esp
  sub esp, 64            ; 00000040H
```

Prologue and Epilogue Code

```
char *strcopy1 (char *dst, char *src)      {
      char *cp = dst;
      while( *cp++ = *src++ );
      return( dst );
  }
_dst$ = 8
_src$ = 12
_cp$ = -4
?strcopy1@@YAPADPAD0@Z PROC NEAR
; File strtest.cpp
; Line 79
  push ebp
  mov ebp, esp
  push ecx
; Line 80
  mov eax, DWORD PTR _dst$[ebp]
  mov DWORD PTR _cp$[ebp], eax
```

Prologue and Epilogue Code

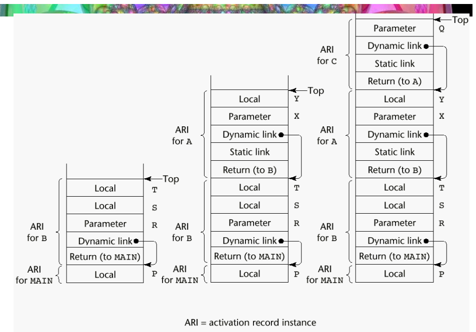
```
   return( dst );
}

  mov eax, DWORD PTR _dst$[ebp]
; Line 84
  mov esp, ebp
  pop ebp
  ret
```

An Example Without Recursion

```
void A(int x) {
   int y;
   ...
   C(y);
   ...
}
void B(float r) {
   int s, t;
   ...
   A(s);
   ...
}
void C(int q) {
   ...
}
void main() {
   float p;
   ...
   B(p);
   ...
}
```

main calls B
B calls A
A calls C

An Example Without Recursion

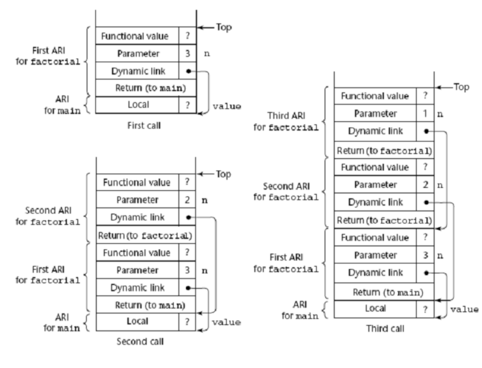


An Example With Recursion

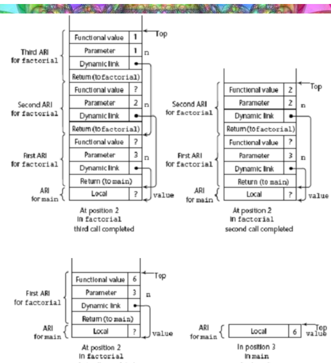
- The activation record used in the previous example supports recursion, e.g.

```
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`

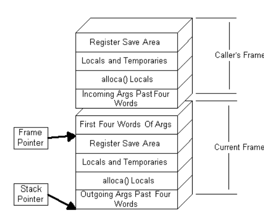


Unwinding Recursion

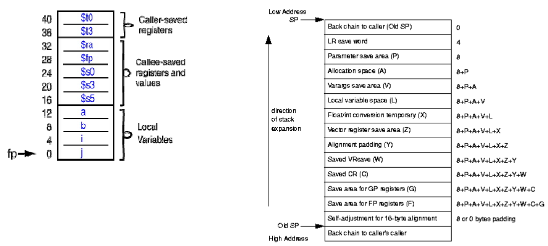


Real-world stack frames

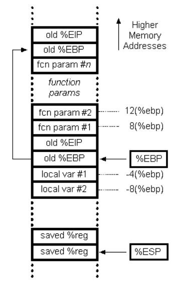
- Can be substantially more complex and vary with architecture
- Ex: ARM Processor



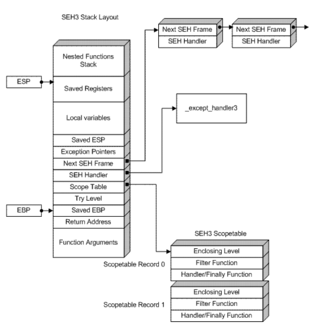
MIPS and Power PC



Win32 cdecl



Win32 C++ With Exception Handlers



Nested Subprograms

- Static scoped languages such 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
  - By definition a nested routine can only be called when its ancestors are active
  - Therefore all non-local references are either to stack dynamic local variables of an ancestor or are global references
- To locate 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 is a bit more tricky
- Two major techniques:
  1. Static chain: add a static link to the activation record that points to the static link of the direct ancestor
  2. Display: maintain static links in a separate stack
- We will discuss static chains only

Static Scoping

- A static chain is a chain of static links that connects activation records
  - The static link in an activation record 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

- 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 where 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
- Chain offset is thus the number of static links that we follow to find the referencing environment

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 }
```

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

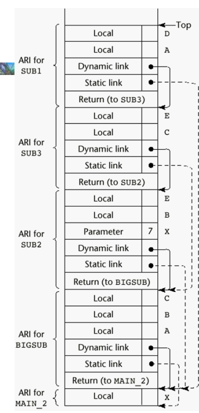
Static Depth

- Static depth for each procedure

```
procedure Main_2 is         --0
  procedure Bigsub is       --1
    procedure Sub1 is       --2
    procedure Sub2 is       --2
      procedure Sub3 is     --3
```

- Sub3 has **E(s3) := B(s2) + A(bigsub);**
  - So Sub3 reference to B has chain offset 1 and the reference to B has chain offset 2
  -

Stack Contents at 1



Static Chain Maintenance

- When a call is made, the activation record instance must be built
  - The dynamic link is the old frame pointer
  - The static link will point to the most recent activation record of the static parent
  - Two methods to construct the static link:

    1. Search the dynamic chain
    2. Treat subprogram calls and definitions like variable references and definitions

Issues with Static Chains

- Problems:
  1. A nonlocal reference 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

Displays

- An alternative to static chains that solves the problems with that approach
- Static links are stored in a single array called a display
- The contents of the display at any given time is a list of addresses of the accessible activation record instances

Blocks

- Blocks are user-specified local scopes for variables
- Example in C:

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

- The lifetime of **`temp`** begins when control enters the block
- An advantage of using a local variable like **`temp`** is that assignments cannot alter any other variable with the same name

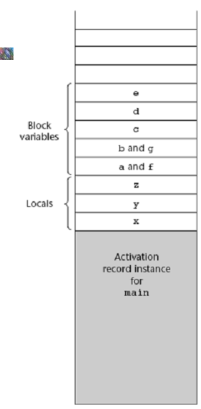
Implementing Blocks

- 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

Block locals

- Consider this skeletal program

```
void main(){
    int x,y,z
    while (. . .) {
        int a,b,c;
    }
        while (. . .) {
            int d,e;
        }
    while (. . .) {
        int f,g;
    }
}
```



Implementing Dynamic Scoping

- Two possible ways to implement dynamic scoping are called deep access and shallow access
- These are different from deep and shallow binding (different semantics) in that the semantics of dynamic scoping are unaltered by the access method

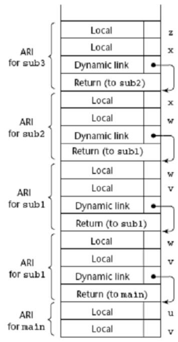
Implementing Dynamic Scoping

- *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

Deep Access Example

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

Where:
- **main calls sub1**
- **sub1 calls sub1**
- **sub1 calls sub2**
- **sub2 calls sub3**



Shallow Access for 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;
  …
}
```

	A			B
	A	C		A
MAIN_6	MAIN_6	B	C	A
u	v	x	z	w

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