Chapter 6
Function Calling Mechanisms

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Overview

Slide 1

- Indirect branching
- Basic Mechanisms: call and return
- Argument passing
- C Functions
- Activation records
- Register windows on the SPARC

Indirect Branching

Slide 2

- Jump and link, *jmpl*
  - target of branch is specified using a SPARC addressing mode
  - like load instruction, no square brackets
  - address of jmpl instruction is saved in the destination register
- Synthetic instruction, *jmp* (destination register is %r0)
- Encoding: uses load/store format, op_3 is 111000

Implementing switch Statements

Slide 3

- Sample switch statement

```
switch (i) {
case 1:
    /* statement 1 */
    break;
case 2:
case 4:
    /* statement 2 */
    break;
case 6:
    /* statement 3 */
}
```

- Cascaded comparisons
- Branch table

Cascaded Comparisons

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```
        .seg    "text"
        sethi   %hi(i), %r2
        ldw     [%r2+%lo(i)], %r3
        cmp     %r3, 1
        bne     %xcc, try2
        nop                         ! branch delay slot
        ⋮                           ! code for stmt1
        bra     %xcc, last
        nop                         ! branch delay slot
```

Cascaded Comparisons (continued)

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```
try2:
        cmp     %r3, 2
        bre     %xcc, lab2
        nop                         ! branch delay slot
        cmp     %r3, 4
        bne     try3
        nop                         ! branch delay slot
lab2:
        ⋮                           ! code for stmt2
        bra     %xcc, last
        nop                         ! branch delay slot
```

Cascaded Comparisons (continued)

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```
try3:
        cmp     %r3, 6
        bne     %xcc, last
        nop                             ! branch delay slot
        ⋮                               ! code for stmt3
last:
```

Branch Table (the table)

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```
        .seg    "data"
tab:                                    ; initialize the branch table
        .word   lab1                    ; (i = 1) offset 0 → stmt1
        .word   lab2                    ; (i = 2) offset 1 → stmt2
        .word   last                    ; (i = 3) offset 2 → last
        .word   lab2                    ; (i = 4) offset 3 → stmt2
        .word   last                    ; (i = 5) offset 4 → last
        .word   lab3                    ; (i = 6) offset 5 → stmt3
```

Branch Table (branching)

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```
.seg    "text"
sethi   %hi(i), %r2
ldsw    [%r2+%lo(i)], %r3
cmp     %r3, 1
blt     %xcc, last          ! nothing to do
cmp     %r3, 6
bgt     last                ! nothing to do
set     tab−4, %r2          ! normalized table base address
sll     %r3, 2, %r3         ! scale the index
ldw     [%r2+%r3], %r4      ! %r4 holds target address
jmp     %r4
nop                         ! branch delay slot
```

Branch Table (the statements)

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```
lab1:
        ⋮                           ! code for stmt1
        bra     %xcc, last
        nop                         ! branch delay slot
lab2:
        ⋮                           ! code for stmt2
        bra     %xcc, last
        nop                         ! branch delay slot
lab3:
        ⋮                           ! code for stmt3
last:
```

Preliminaries

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- Functions
  - procedures
  - subroutines
- Arguments
  - formal arguments
  - actual arguments
  - parameters

Call and Return

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- Basic terminology
- Linkage
- Linking the return address
- The SPARC call instruction
- Saving the return address
- Saving the registers

Call and Return: Basic Terminology

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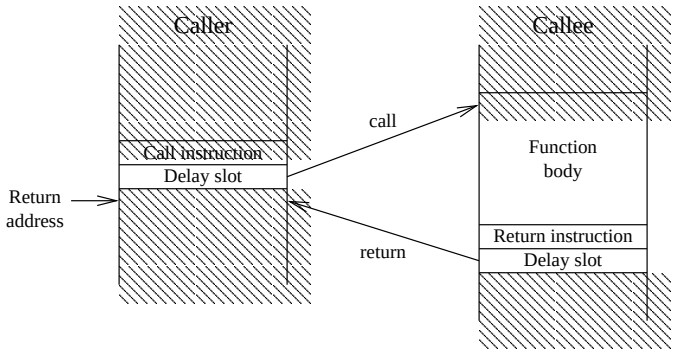

- Caller, Callee
- Function Call, Function Return
- Return address
- Function invocation

Call and Return: Linkage

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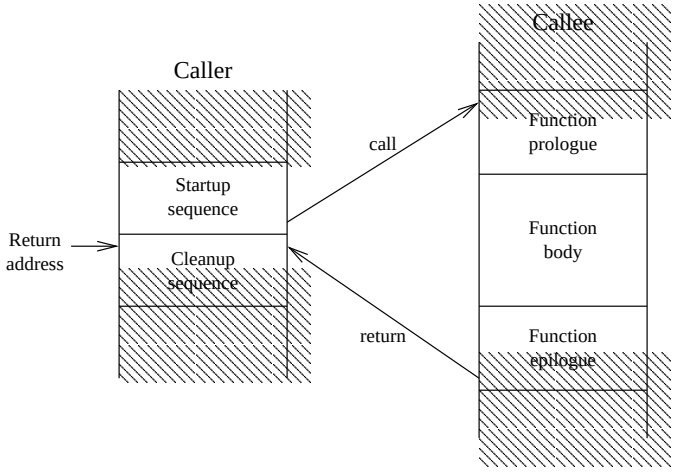

- Startup, Cleanup
- Prologue, Epilogue
- Calling convention

Call and Return: Linking the Return Address

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Startup sequence	Store the return address in %r15.
	Branch to the function.
Function prologue	*nothing*
Function epilogue	Branch to the address stored in %r15.
Cleanup sequence	*nothing*

Call and Return: Linking the Return Address (SPARC Code, using *jmp*)

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```
        set   ret, %r15      ! the startup sequence
        bra   %xcc, sub1     !
        nop                  ! delay slot
ret:
                             ! no cleanup sequence
        ⋮                    !
sub1:
                             ! no prologue
        ⋮                    ! the function body
        jmp   %r15           ! the epilogue
        nop
```

The *call* and *retl* Instructions

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- *call* saves address of call instruction in %r15
- *retl* (return from leaf) is a synthetic instruction

  jmpl %r15+8, %r0

Code Example

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```
        call   sub1   !
        nop           ! delay slot
                      ! no cleanup sequence
        ⋮             !
sub1:
                      ! no prologue
        ⋮             ! the function body
        retl          ! the epilogue
        nop
```

Encoding Call Instructions

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31 30 29	0
01	disp30

Field	Meaning
disp30	Displacement value in 30-bit 2's complement representation

The displacement is measured in instructions.

Call and Return: Saving the Return Address

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Startup sequence	Branch to the function (save the call address in *%r15*).
Function prologue	Save the value in *%r15* in a memory location.
Function epilogue	Restore the call address and return.
Cleanup sequence	*Nothing.*

Call and Return: Saving the Return Address (SPARC Code)

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```
        .seg    "data"
ret1:   .skip   4                       ! space to save the return addres
        .seg    "text"
sub1:
        sethi   %hi(ret1), %r1          ! prologue, save the return address
        stw     %r15, [%r1+%lo(ret1)]
        ⋮                               ! the function body
        call    sub2
        ⋮                               ! the function body
        sethi   %hi(ret1), %r1          ! epilogue, restore the return address
        lduw    [%r1+%lo(ret1)], %r15
        retl
        nop                             ! delay slot
```

Call and Return: Issues in Saving the Return Address

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- Saving return address not needed for *leaf* functions
- Simple strategy not sufficient for *cyclic* calling sequences
- Recursive functions have cyclic calling sequences

Call and Return: Saving the Registers

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- Nonintrusive strategy (callee saves)

Startup sequence	Branch to the function (save the call address in *%r15*).
Function prologue	For nonleaf functions, save *%r15* in memory.
	Save any registers used in the body of the function.
Function epilogue	Restore the registers saved in the prologue.
	Restore the call address and return.
Cleanup sequence	*Nothing.*

- Defensive (caller saves)
- Limit the registers saved

Call and Return: SPARC Register Usage

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Register(s)	Use	Volatility
%r0	Always zero	Unchanged
%r1–%r7	Temporaries	Volatile
%r8	Argument 1/Return Value	Volatile
%r9–%r13	Arguments 2 through 6	Volatile
%r14	Stack Pointer	Unchanged
%r15	Return Address	Volatile
%r16–%r29	Local and Input registers	Unchanged
%r30	Frame Pointer	Unchanged
%r31	Input register	Unchanged

Argument Passing

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- Pass-by-Value
- Pass-by-Value/Result
- Pass-by-Reference
- Contrasts

An Example: String Length

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- Assume the string starts at the location "str"
- Calling strlen

```
set   str, %r8   ! put the argument in R8
call  strlen     ! call the function
nop              ! delay slot
⋮                ! %r8 holds the return value
```

- Pass-by-value

String Length: Body

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```
        .seg    "text"
strlen:
        clr     %r9                 ! initialize the result
  top:
        ldub    [%r8+%r9], %r10     ! load the next character
        cmp     %r10, 0             ! test for end of string
        bne,a   top
        inc     %r9                 ! one more character (delay slot)

        retl                        ! return
        mov     %r9, %r8            ! delay slot
```

Value/Result

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- AKA Copy-in/Copy-out
- Caller: copy inputs to argument registers; retrieve results from argument registers
- Callee: retrieve inputs from argument registers; put results in output registers
- Problem: %r8 holds the function return value, not the returned value of argument 1.
- We'll use %r9–%r13 for arguments

Strange Example

- Behavior
  - takes two arguments
  - returns the product of the two arguments
  - modifies the first argument by adding the value of the second
- Implementation

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```
        .seg    "text"
strange:
        ! the body
        mulx    %r9, %r10, %r8   ! calculate the result
        add     %r9, %r10, %r9   ! modify the first argument

        ! the epilogue
        retl                     ! return
        nop                      ! delay slot
```

Calling *strange*: value/result

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```
! z = strange( x, y ) – startup sequence
sethi   %hi(x), %r1
ldsw    [%r1+%lo(x)], %r9     ! first argument
sethi   %hi(y), %r1
call    strange
ldsw    [%r1+%lo(y)], %r10    ! second argument
! cleanup sequence
sethi   %hi(z), %r1
stw     %r8, [%r1+%lo(z)]     ! return value
sethi   %hi(x), %r1
stw     %r9, [%r1+%lo(x)]     ! first argument
```

Reference

- Caller passes the address of the argument, i.e., a reference to the argument
- Callee manipulates the argument directly
- Implementing *strange*

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```
strange:
        ldsw   [%r8], %r11          ! load value of first argument
        mulx   %r11, %r9, %r10      ! calculate the result
        add    %r11, %r9, %r11      ! calculate the sum
        stw    %r11, [%r8]          ! change the first argument

        ! the epilogue
        retl                        ! return
        mov    %r10, %r8            ! delay slot
```

Calling *strange*: reference

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```
! z = strange( x, y )
set     x, %r8                  ! the address of x
sethi   %hi(y), %r1             ! the value of y
call    strange
ldsw    [%r1+%lo(y)], %r9       ! delay slot
! cleanup sequence
sethi   %hi(z), %r1
stw     %r8, [%r1+%lo(z)]
```

Summary

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- Types of arguments: constant and variable
- Mechanisms: value, value/result, and reference
- Pass-by-value
  - appropriate for small constant arguments
  - called function should not alter the values passed by the caller
- Pass-by-value/result
  - appropriate for small variable arguments
  - caller's cleanup sequence stores the values of variable arguments
- Pass-by-value
  - appropriate for variable arguments and large constant arguments
  - called function should not alter the address values passed by the caller (i.e., addresses are passed by value)

C Functions

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- Function definition
  - header specifies return type and formal arguments
  - body is a compound statement and may declare "local" variables
- Arguments are always passed by value

  pass addresses to attain reference arguments

The *strange* Function in C

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```
int strange( int *p1, int p2 )
{
    int res;

    res = *p1 * p2;
    *p1 = *p1 + p2;
    return res;
}
```

Calling *strange* in C

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```
{
    int x, y, z;

    z = strange( &x, y );
}
```

Activation Records

- Limitations of using registers
  - large arguments (more than a register)
  - large number of arguments (more than %r8 through %r13)
  - large number of local variables (more than %r1 through %r7)
  - calling a function in a function body

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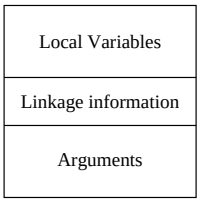
- Activation record



- Linkage information, linkage between caller and callee: return address, return value, etc.

Allocating Activation Records

- Need dynamic allocation to support cyclic calling sequences (recursion)
- Need variable sized allocation (different activation records have different sizes)

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- Fortunately we don't need general purpose allocation
  - allocations are associated with function calls
  - de-allocations are associated with function returns
  - functions returns are LIFO
  - we can use a stack of activation records

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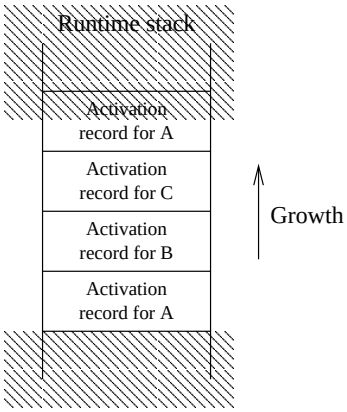
The Stack of Activation Records



A calls B, B calls C, C calls A

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Calling Convention

Startup	Allocate stack space for the argument portion of the activation record (include space for all arguments).
	Copy arguments (beyond the first 6) to the activation record.
	Branch to the function (storing the return address in *%r15*).
Prologue	Allocate stack space needed for linkage information and local variables.
	For nonleaf functions, save the value in *%r15* in the linkage part of the activation record.
	Save any nonvolatile registers used in the body of the function.
Epilogue	Restore the registers saved in the prologue.
	Restore the return address.
	Deallocate the stack space allocated in the prologue.
Cleanup	Deallocate the stack space allocated in the startup.

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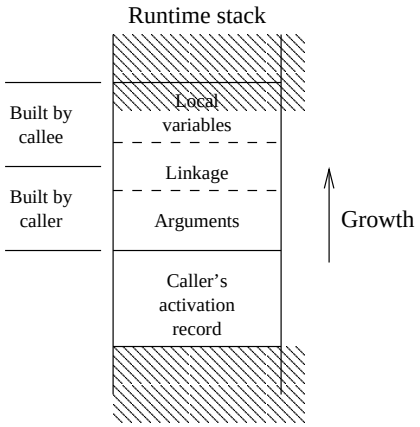
Graphical Interpretation



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The Stack Pointer

- Points to the top of the stack
- In SPARC assembly language %sp is an alias for %r14
- Details are operating system dependent
  - initialized by the OS when the program is loaded
  - minimal alignment is 8 (e.g., an extended word), OS may require more

Example

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- Translate x = f(y, &z, w);
- Assume that x, y, z, and w are 32-bit globals
- SPARC code

```
add     %sp, −16, %sp          ! allocate argument space
sethi   %hi(y), %r1            ! the value of y
ldw     [%r1+%lo(y)], %r8
set     z, %r9                 ! the address of z
sethi   %hi(w), %r1            ! the value of w
call    f
ldw     [%r1+%lo(w)], %r10     ! delay slot
! cleanup sequence
add     %sp, 16, %sp           ! deallocate argument space
sethi   %hi(x), %r1
stw     %r8, [%r1+%lo(x)]
```

The Frame Pointer

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- The stack pointer changes, the frame pointer doesn't
- Assume x, y, z, and w are at offsets 0, 4, 8, and 12, respectively
- SPARC code

```
! x = f( y, &z, w )
add     %sp, −16, %sp          ! allocate argument space
ldw     [%sp+4+16], %r8        ! the value of y
add     %sp, 8+16, %r9         ! the address of z
call    f
ldw     [%sp+12+16], %r10      ! delay slot
! cleanup sequence
add     %sp, 16, %sp           ! deallocate argument space
stw     %r8, [%sp+0]           ! save the return value
```

Graphical Interpretation

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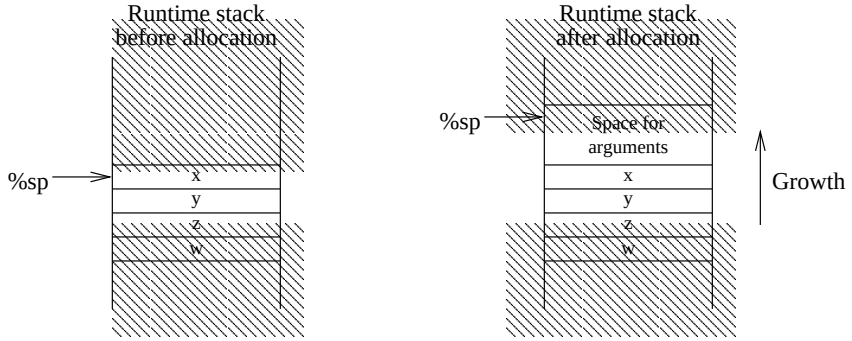

Using a Frame Pointer

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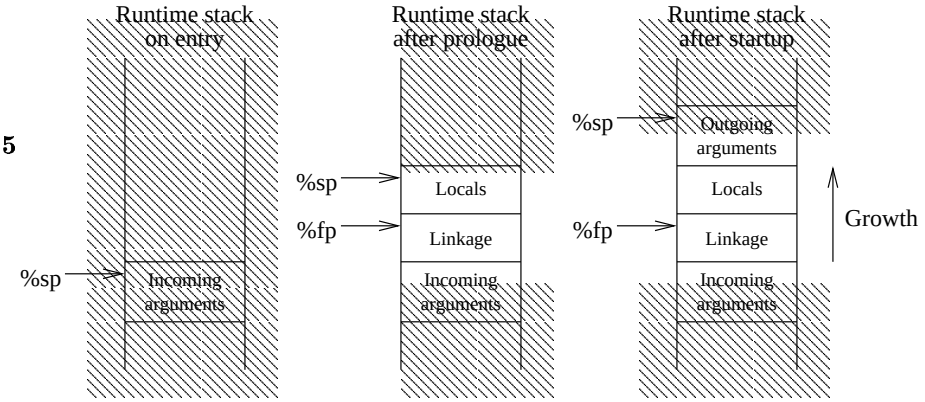
- In SPARC assembly language %fp is an alias for %r30
- Graphical Interpretation



- Arguments have positive offsets, locals have negative offsets

Example Using the Frame Pointer

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- Assume x, y, z, and w are at offsets −4, −8, −12, and −16, respectively
- SPARC code

```
! x = f( y, &z, w )
add   %sp, −16, %sp    ! allocate argument space
ldw   [%fp−8], %r8     ! the value of y
add   %fp, −12, %r9    ! the address of z
call  f
ldw   [%fp−16], %r10   ! delay slot
! cleanup sequence
add   %sp, 16, %sp     ! deallocate argument space
stw   %r8, [%fp−4]     ! save the return value
```

Calling Convention

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Startup	Allocate stack space for the argument portion of the activation record (include space for all arguments).
	Copy arguments (beyond the first 6) to the activation record.
	Branch to the function (storing the return address in *%r15*).
Prologue	Allocate stack space needed for linkage information and local variables.
	For nonleaf functions, save the return address (*%r15*) and the frame pointer (*%r30*)in the linkage part of the activation record.
	Save any nonvolatile registers used in the body of the function.
Epilogue	Restore the registers saved in the prologue.
	Restore the frame pointer and return address.
	Deallocate the stack space allocated in the prologue.
Cleanup	Deallocate the stack space allocated in the startup.

Example

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- Show prologue and epilogue for *fun1* with 48 bytes of local space
- SPARC code

```
fun1:
        ! the prologue
        stx   %r15, [%sp−8]   ! save the return address
        stx   %fp, [%sp−16]   ! save the frame pointer
        mov   %sp, %fp        ! establish the frame pointer
        add   %sp, −64, %sp   ! alloc space for linkage and locals
        ...
        ! the epilogue
        add   %sp, 64, %sp    ! deallocate stack space
        ldx   [%sp−8], %r15   ! restore the return address
        retl
        ldx   [%sp−16], %fp   ! restore frame pointer (delay slot)
```

Allocating Argument Space in the Prologue

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Startup	Copy arguments (beyond the first 6) to the activation record.
	Branch to the function (storing the return address in *%r15*).
Prologue	Allocate stack space for linkage information, local variables, and outgoing arguments.
	For nonleaf functions, save the return address (*%r15*) and frame pointer (*%r30*) in the linkage part of the activation record.
	Save any nonvolatile registers used in the body of the function.
Epilogue	Restore the registers saved in the prologue.
	Restore the frame pointer and return address.
	Deallocate the stack space allocated in the prologue.
Cleanup	*Nothing*

Graphical Interpretation

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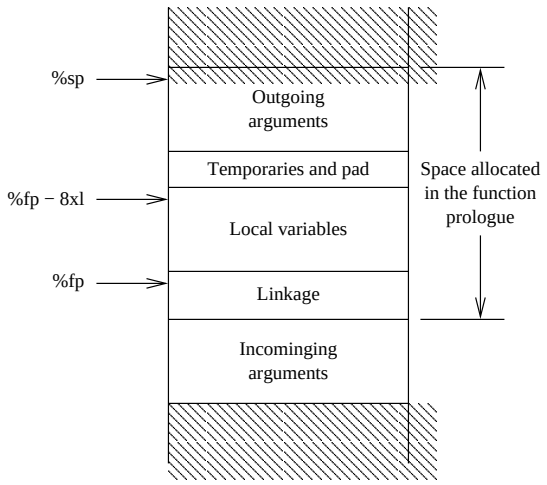

Register Windows on the SPARC

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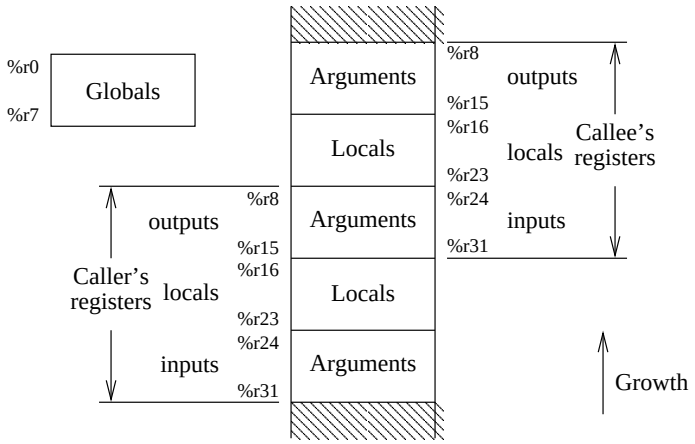

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Alternate Register Names

Basic names	Alternate names	Uses
%r0–%r7	%g0–%g7	Globals, shared by all functions
%r8–%r15	%o0–%o7	Outputs, output arguments and temporaries
%r16–%r23	%l0–%l7	Locals, temporaries
%r24–%r31	%i0–%i7	Inputs, input arguments

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Register Uses in Light of Register Windows

Register(s)	Use	Window usage
%r0	Always zero	%g0
%r1–%r7	Temporaries	Global registers
%r8	Argument 1/Return Value	Output registers
%r9–%r13	Arguments 2 through 6	Output registers
%r14	Stack Pointer	Output registers
%r15	Return Address	Output registers
%r16–%r23	Local registers	Local registers
%r24–%r29	Input registers	Input registers
%r30	Frame Pointer	Input, matches %r14
%r31	Input register	Input, matches %r15

Simpler Calling Convention

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Startup	Copy arguments (beyond the first 6) to the activation record. Branch to the function (storing the return address in *%r15*).
Prologue	For nonleaf functions, allocate a new set of registers saving the return address (*%r15*) and current stack pointer (*%r14*). Allocate stack space for local variables and outgoing arguments.
Epilogue	Deallocate the set of registers allocated in the prologue, restoring the old stack pointer and return address.
Cleanup	*Nothing*

SPARC Instructions

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- Save
  - allocate a register set (save caller's registers)
  - addition, sources from old regs, destination to new regs
  - frequently used to allocate stack space
  - prologue is one instruction, e.g.,

```
save   %sp, 128, %sp
```

- Restore
  - deallocate a register set (restore caller's registers)
  - also does and addition, but not often used
- Synthetic versions use %r0 for all operands
- Encoded using arithmetic format
  - op_3 is 111000 for save and 111001 for restore

The *ret* Instruction

- Using *retl*

```
! the epilogue
restore                 ! restore the caller's register set
retl                    ! return, using the caller's %r15
nop                     ! delay slot
```

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- Putting restore in the delay slot

```
! the epilogue
jmpl     %r31+8,%r0     ! return, using the caller's %r15
restore                 ! restore the caller's register set
```

- Using *ret*

```
! the epilogue
ret                     ! return, using the caller's %r15
restore                 ! restore the caller's register set
```

Stack Frame Organization

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