

# *Part E*

## CHAPTER 3

### Architecture and Organization



1

These slides are being provided with permission from the copyright for CS2208 use only. The slides must not be reproduced or provided to anyone outside of the class.

All download copies of the slides are for personal use only.  
Students must destroy these copies within 30 days after receipt of final course evaluations.

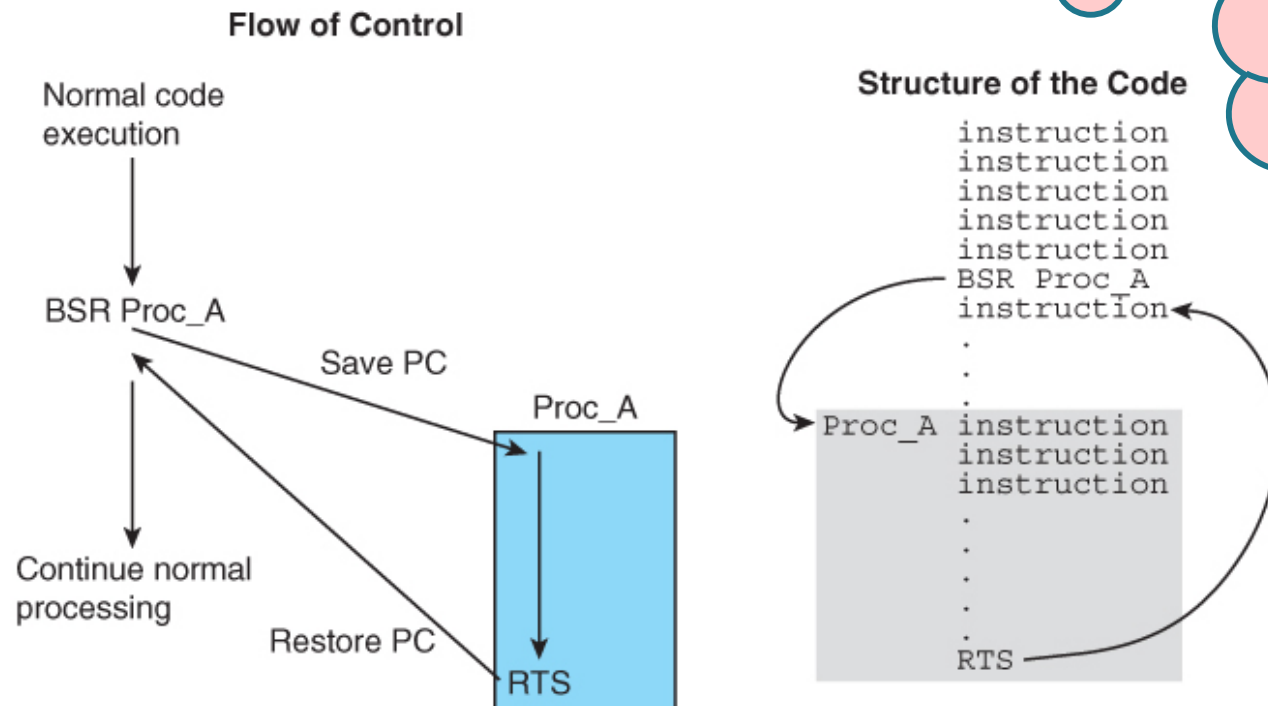
## Subroutine Call and Return

- ❑ A *subroutine* (a.k.a. *function*, *procedure*, and *subprogram*) is *a set of instructions* that *may be repeatedly called* by a program to do a given function.
- ❑ A *subroutine* gives the simplest form of program abstraction.
- ❑ There are two main characteristics in any subroutine.
  1. A subroutine can be called from anywhere in the program.
  2. Once the subroutine is completed, it should return to the instruction directly after the subroutine calling location.

# Subroutine Call and Return

- ❑ A *hypothetical* instruction *BSR Proc\_A* calls subroutine *Proc\_A*.
  - The processor **saves the address** of the next instruction to be executed in a safe place, and
  - **loads the program counter** with the address of the first instruction in the subroutine.
- ❑ At the end of the subroutine a *return from subroutine instruction*, *RTS*,
  - causes the processor to **return to the point immediately following the subroutine call**.

**FIGURE 3.40** The subroutine call and return



*BSR* and *RTS*  
are not ARM  
instructions

## ARM Support for Subroutines

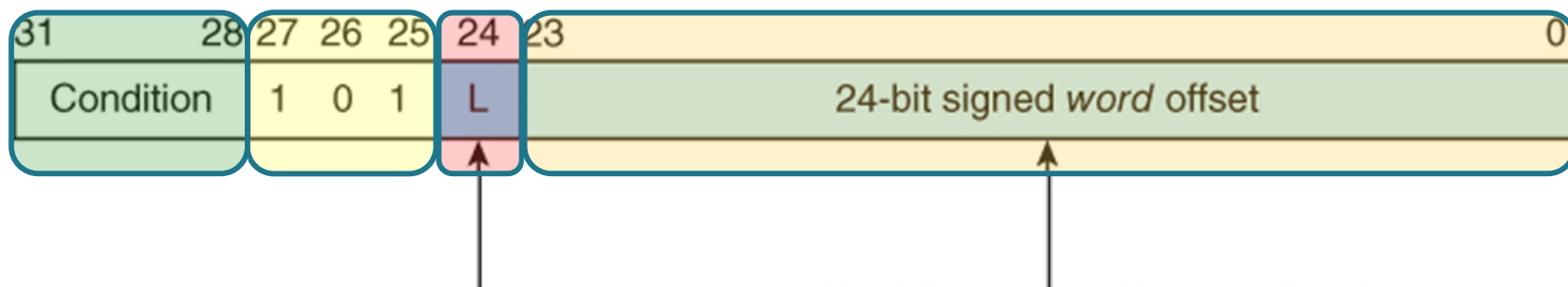
- ❑ **RISC** processors (including **ARM**) *do not provide* a *fully automatic* subroutine call/return mechanism like **CISC** processors.
- ❑ **ARM**'s *branch with link* instruction, **BL**,
  - automatically saves the return address in register **r14**.
- ❑ The branch instruction (Figure 3.41) has a 24-bit *signed* program counter relative offset (*word address offset*).

This is the main difference between B and BL

You may want to review slides 89 to 91 to remember how to encode and decode this 24-bit offset.

**FIGURE 3.41**

Encoding ARM's branch and branch-with-link instructions



The L-bit is 0 for a branch instruction and 1 for a branch with link instruction.

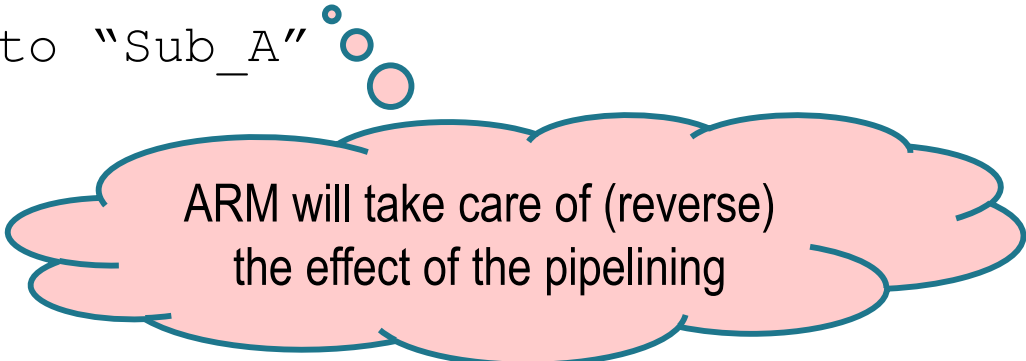
The 24-bit word offset is shifted left twice to create a 26-bit byte offset.

## ARM Support for Subroutines

- ❑ The *branch with link* instruction behaves like the branch instruction but the processor also copies the return address (i.e., the address of the next instruction to be executed following a return) into the link register **r14**.

- ❑ If you execute:

```
BL      Sub_A      ;save return address in r14  
          ;branch to "Sub_A"
```



ARM will take care of (reverse)  
the effect of the pipelining

- ❑ At the end of the subroutine, you return by
  - *copying the return address* in r14 to the program counter by executing:

```
MOV pc, lr
```

or

```
MOV r15, r14
```

## ARM Support for Subroutines

- ❑ Suppose that you want to evaluate the following expression several times in a program.

**if  $x > 0$  then  $x = 16*x + 1$  else  $x = 32*x$**

Should it be LT  
or LE?

- ❑ Assuming that **x** is loaded into **r0**, we can write :

```
Func1 CMP    r0, #0           ;test for x > 0
      MOVGT  r0, r0, LSL #4    ;if x > 0 x = 16*x
      ADDGT  r0, r0, #1        ;if x > 0 then x = 16*x + 1
      MOVLT  r0, r0, LSL #5    ;ELSE if x < 0 THEN x = 32*x
      MOV    pc, lr           ;return by restoring saved PC
```

- ❑ Consider the following invocation of the above subroutine.

```
LDR    r0, [r4]    ;get P
BL     Func1        ;First call
                     ;P = (if P > 0 then 16*P + 1 else 32*P)
STR    r0, [r4]    ;save P
```

Later on ...

```
LDR    r0, [r5]    ;get Q
BL     Func1        ;Second call
                     ;Q = (if Q > 0 then 16*Q + 1 else 32*Q)
STR    r0, [r5]    ; save Q
```



# ARM Support for Subroutines

```

01      AREA  BL_instruction, CODE, READWRITE
02      ENTRY
03
04      ADR    r4,P          ;register r4 points at P
05      ADR    r5,Q          ;register r5 points at Q
06
07      LDR    r0,[r4]       ; get P
08      BL     Func1         ; P = (if P > 0 then 16P + 1 else 32P)
09      STR    r0,[r4,#8]    ; save P
10      ;
11      ; some code
12      ;
13      LDR    r0,[r5]       ; get Q
14      BL     Func1         ; Q = (if Q > 0 then 16Q + 1 else 32Q)
15      STR    r0,[r5,#8]    ; save P
16
17      MOV    r0, #0x18     ; angel_SWIreason_ReportException
18      LDR    r1, =0x20026  ; ADP_Stopped_ApplicationExit
19      SVC    #0x123456     ; ARM semihosting (formerly SWI)
20
21
22      Func1  CMP    r0,#0   ;test for x > 0
23            MOVGT  r0,r0, LSL #4 ;if x > 0 x = 16x
24            ADDGT  r0,r0,#1   ;if x > 0 then x = 16x + 1
25            MOVLT  r0,r0, LSL #5 ;ELSE if x < 0 THEN x = 32x
26            MOV    pc,r14    ;return by restoring saved PC
27
28      AREA  BL_instruction, DATA, READWRITE
29      P
30      Q
31      SPACE 8
32

```

**Registers**

Register	Value
R0	0x00000018
R1	0x00020026
R2	0x00000000
R3	0x00000000
R4	0x00000044
R5	0x00000048
R6	0x00000000
R7	0x00000000
R8	0x00000000
R9	0x00000000
R10	0x00000000
R11	0x00000000
R12	0x00000000
R13 (SP)	0x00000000
R14 (LR)	0x0000001C
R15 (PC)	0x00000028
CPSR	0xA00000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	
Abort	
Undefined	
Internal	
PC \$	0x00000028
Mode	Supervisor
States	36
Sec	0.00000000

**Memory 1**

Address: 0x44

0x00000044:	00 00 00 03	FF FF FF FF
0x0000004C:	00 00 00 31	FF FF FF E0
0x00000054:	00 00 00 00	00 00 00 00

## Conditional Subroutine Calls

❑ **BL** instruction can be conditionally executed.

❑ **For example**

```
CMP r9,r4      ;if r9 < r4
```

```
BLLT ABC      ;then call subroutine ABC
```

❑ **BLLT** means

- **B**ranch
- with **L**ink
- execute on condition **L**ess **T**han



# Subroutine Call and Return

- ❑ An important application of the stack is to save the address to return to after executing the subroutine.
- A subroutine call can be implemented by
  - Pushing the return address onto the stack
  - Branching to the target address.
- Once the execution of the subroutine code is completed, a *return from subroutine* instruction is executed
  - Popping the return address from the stake
  - Copy the return address to the **PC** register

This is another method to implement a subroutine call, other than using R14.

# Subroutine Call and Return

Occupied memory

Grows up

## Example

This is B. It is NOT BL

...  
...  
...

STR r15, [r13, #-4] !

B Target

...  
...

The proper return address

The address pushed onto the stake.

; assume that the stack grows towards  
; low addresses and the SP points at  
; the top item on the stack.  
; pre-decrement the stack pointer AND  
; push the return address on the stack  
; jump to the target address (B not BL)  
; to return here

Due to the pipeline effect, the PC value will not be the address of the current instruction. Instead, it will be current address +12. Yes, it is +12, not +8, as it is STR instruction

- Because ARM does not support a stack-based subroutine return mechanism, you would have to write:

LDR r12, [r13], #+4

; get saved PC and post-increment

; stack pointer

SUB r15, r12, #4

; fix PC and load into r15 to return

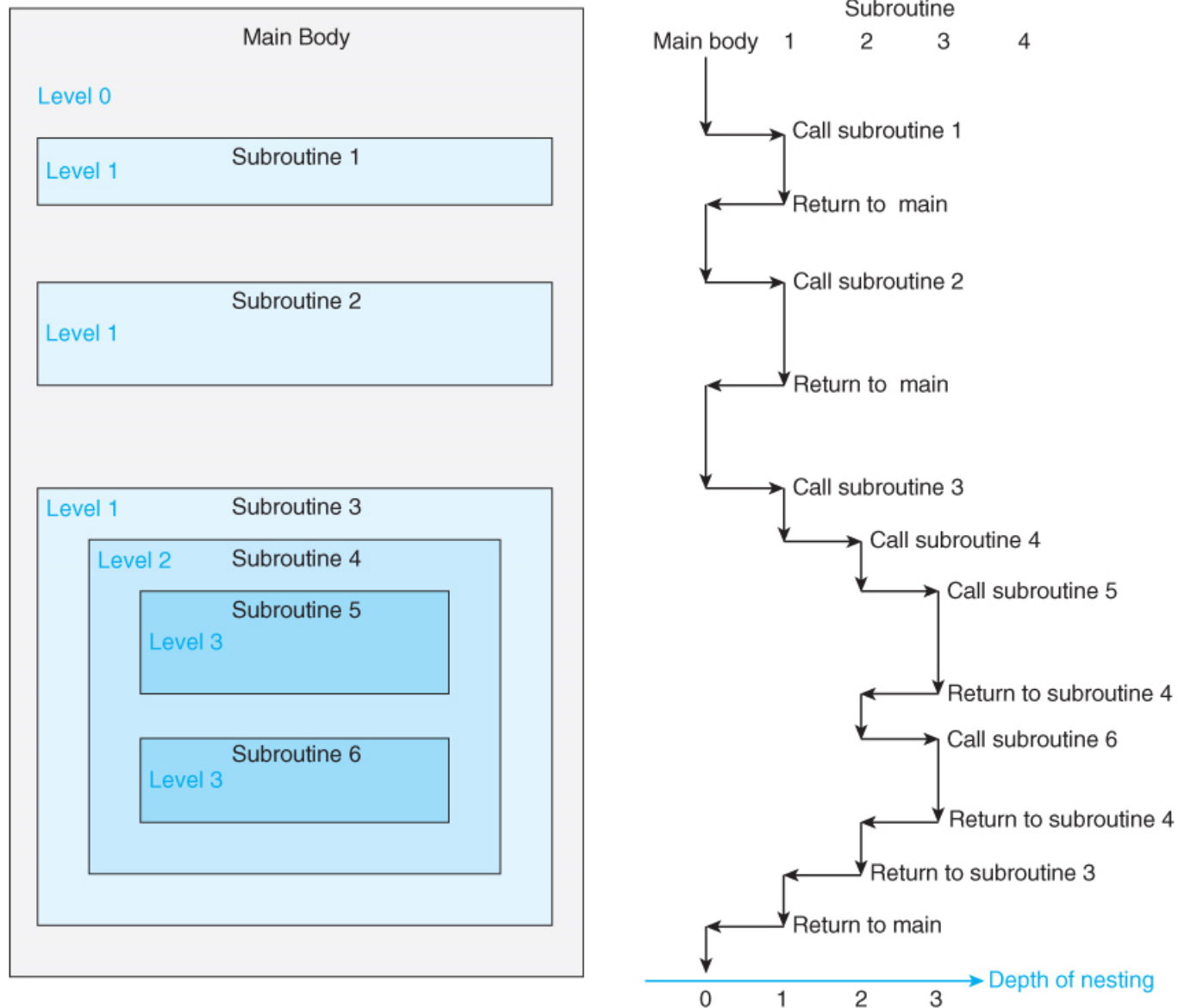
197

The 4 is subtracted to make the popped address pointing to the proper return address.

Why did not we copy the stack content directory to r15?

# Nested subroutines

**FIGURE 3.48** An example of nested subroutines

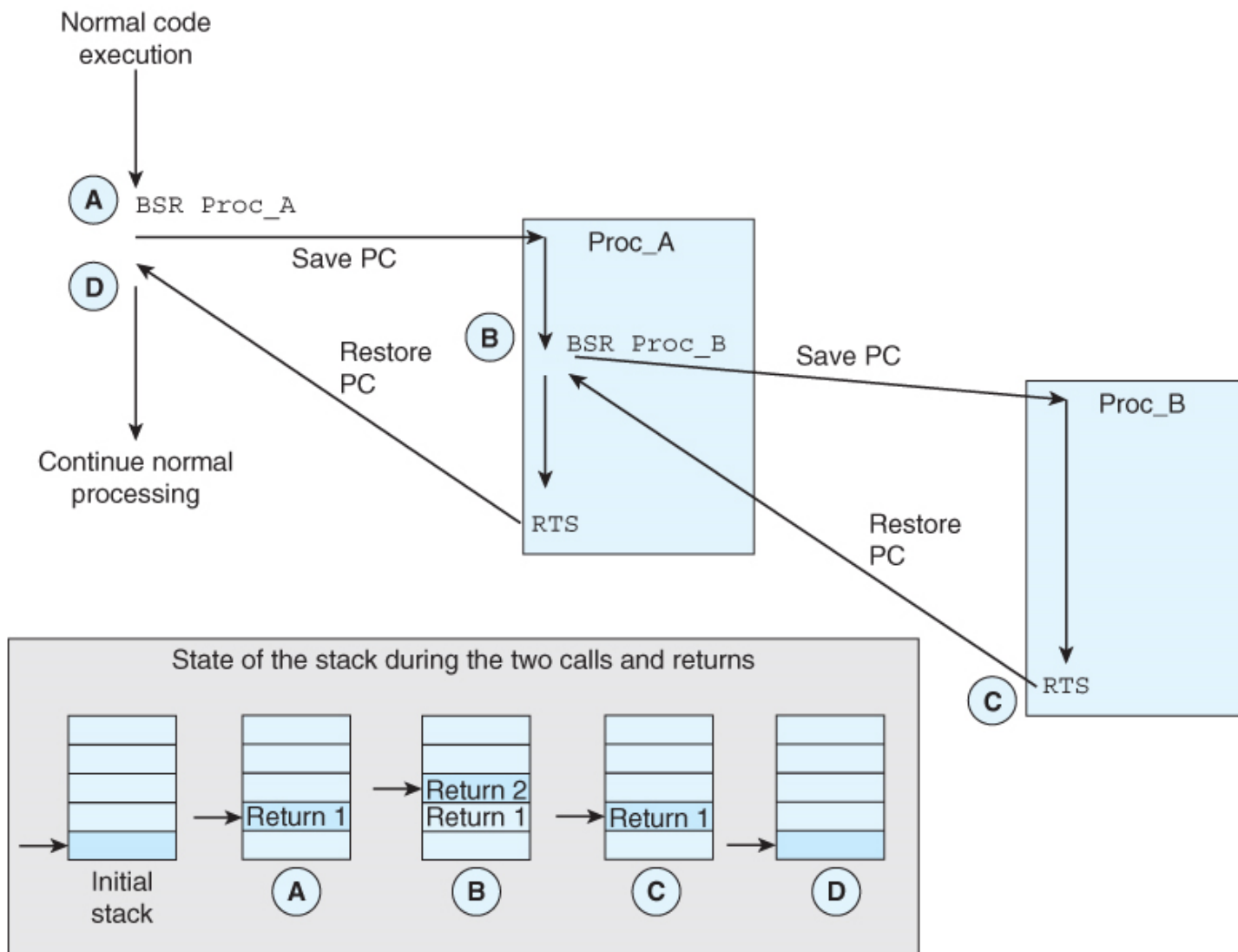


Occupied  
memory

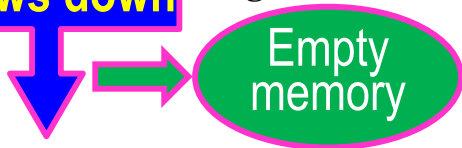
## Example of nested subroutine

FIGURE 3.49

The stack and nested subroutines (CISC processors)



© Cengage Learning 2014



## Leaf routines

- ❑ A *leaf routine* doesn't call another routine; it's at the end of the tree.
- ❑ If you call a *leaf routine* with **BL**,
  - the return address is saved in link register **r14**.
- ❑ A return to the calling point is made with a MOV **pc**, lr.
- ❑ If the routine is *not a leaf routine*, you *cannot* call another routine *without* first saving the link register.

```
ADR sp, STACK
```

```
BL Fun_1 ;call a simple leaf routine
```

```
BL Fun_2 ;call a routine that calls a nested routine
```

```
Loop B Loop
```

```
Fun_1 NOP ;this is a leaf routine
      MOV pc, lr ;return by copying the LR value into PC
```

```
Fun_2 NOP ;this is a non-leaf routine
      STR lr, [sp], #4 ;save link register
      BL Fun_1 ;call Fun_1 - overwrites the old LR
      LDR pc, [sp, #-4]! ;return by copying the LR value (from
                        ;the stack) into PC
```

```
STACK SPACE 0x10
```

What kind of stack is used here?

What is the maximum depth that can be called using this stack?

## Leaf routines

- ❑ Subroutine Fun\_1 is a leaf subroutine that does not call any other subroutine and, therefore, we don't have to worry about saving the link register, **r14**, and we can return by executing `MOV pc, lr`.
- ❑ Subroutine Fun\_2 contains a call to another subroutine (i.e., nested subroutine) and we have to save the link register in order to return from Fun\_2.
- ❑ The simplest way of *saving* the link register is to *push* it onto the stack.
- ❑ To return from Fun\_2, we *restore the pushed* **r14** into the program counter.

# Leaf routines

The screenshot shows the uVision4 IDE with the following components:

- Registers Panel:** Lists registers R0 through R15, CPSR, and SPSR. R13 (SP) is highlighted with a value of 0x00000000.
- Disassembly Panel:** Shows assembly code with comments:
 

```

3:      ADR sp,STACK
4:
0x00000000 E28FD020 ADD    R13,PC,#0x00000020
5:      BL  Fun_1      ;call a simple leaf routine
0x00000004 EB000001 BL     0x00000010
6:      BL  Fun_2      ;call a routine that calls a nested routine
0x00000008 EB000002 BL     0x00000018
7: Loop B  Loop
8: ;-----
0x0000000C EAffffFE B      0x0000000C
9: Fun_1 NOP           ;this is a leaf routine
0x00000010 E1A00000 NOP
10:      MOV pc,lr      ;return by moving the LR value into PC
      
```
- Source Panel (ex1.asm):** Shows the corresponding assembly source code with similar comments. Line 3, 'ADR sp,STACK', is highlighted in green.
- Command Panel:** Displays memory usage: '\*\*\* Restricted Version with 32768 Byte Cc' and '\*\*\* Currently used: 56 Bytes (0%)'.
- Memory Panel:** Shows a memory dump starting at address 0x0, with values like 0x00000000, 0x00000014, etc.

A red callout bubble points to the instruction `ADD R13, PC, #0x00000020` with the text: "What is the value to be stored in r13?"



# Leaf routines

Registers

Register	Value
R0	0x00000000
R1	0x00000000
R2	0x00000000
R3	0x00000000
R4	0x00000000
R5	0x00000000
R6	0x00000000
R7	0x00000000
R8	0x00000000
R9	0x00000000
R10	0x00000000
R11	0x00000000
R12	0x00000000
R13 (SP)	0x00000028
R14 (LR)	0x00000000
R15 (PC)	0x00000004
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	

Disassembly

```

3:      ADR sp, STACK
4:
0x00000000 E28FD020 ADD    R13, PC, #0x00000020
5:      BL Fun_1          ;call a simple leaf routine
0x00000004 EB000001 BL     0x00000010
6:      BL Fun_2          ;call a routine that calls a nested routine
0x00000008 EB000002 BL     0x00000018
7: Loop B Loop
8: ;-----
0x0000000C EAffffFE B      0x0000000C
9: Fun_1 NOP              ;this is a leaf routine
0x00000010 E1A00000 NOP
10:     MOV pc, lr        ;return by copying the LR value into PC

```

ex1.asm

```

3      ADR sp, STACK
4
5      BL Fun_1          ;call a simple leaf routine
6      BL Fun_2          ;call a routine that calls a nested routine
7 Loop B Loop
8 ;-----
9 Fun_1 NOP              ;this is a leaf routine
10     MOV pc, lr        ;return by copying the LR value into PC
11 ;-----

```

Memory 1

Address	Value
0x00000000	E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
0x00000014	E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
0x00000028	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x0000003C	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x00000050	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

Command

```

*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)

```

ASSIGN BreakDisable BreakEnable BreakKill

Simulation t1: 0.00000000 sec

How is this offset encoded?

# Leaf routines

The screenshot displays the uVision4 IDE interface for a project named 'ex1.uvproj'. The main window shows the disassembly of assembly code. The Registers window on the left lists registers R0 through R15, with R14 (LR) and R15 (PC) highlighted. The Disassembly window shows instructions for Fun\_1 and Fun\_2. The ex1.asm window shows the source code for these routines. The Command window shows a message about a restricted version. The Memory window shows the memory dump starting at address 0x0.

**Registers:**

Register	Value
R0	0x00000000
R1	0x00000000
R2	0x00000000
R3	0x00000000
R4	0x00000000
R5	0x00000000
R6	0x00000000
R7	0x00000000
R8	0x00000000
R9	0x00000000
R10	0x00000000
R11	0x00000000
R12	0x00000000
R13 (SP)	0x00000028
R14 (LR)	0x00000008
R15 (PC)	0x00000010
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	

**Disassembly:**

```

5:      BL Fun_1      ;call a simple leaf routine
0x00000004 EB000001 BL      0x00000010
6:      BL Fun_2      ;call a routine that calls a nested routine
0x00000008 EB000002 BL      0x00000018
7: Loop B Loop
8: ;-----
0x0000000C EAffffff B      0x0000000C
9: Fun_1 NOP          ;this is a leaf routine
0x00000010 E1A00000 NOP
10:     MOV pc,lr      ;return by copying the LR value into PC
11: ;-----
0x00000014 E1A0F00E MOV      PC,R14
12: Fun_2 NOP          ;this is a non-leaf routine

```

**ex1.asm:**

```

4
5      BL Fun_1      ;call a simple leaf routine
6      BL Fun_2      ;call a routine that calls a nested routine
7 Loop B Loop
8 ;-----
9 Fun_1 NOP          ;this is a leaf routine
10     MOV pc,lr      ;return by copying the LR value into PC
11 ;-----
12 Fun_2 NOP          ;this is a non-leaf routine

```

**Command:**

```

*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)

```

**Memory:**

Address: 0x0

```

0x00000000: E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
0x00000014: E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
0x00000028: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x0000003C: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0x00000050: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

```

**Simulation:** t1: 0.00000000 s

# Leaf routines

The screenshot displays the uVision4 IDE interface for a project named 'ex1.uvproj'. The main window is divided into several panes:

- Registers:** A list of registers (R0-R15, CPSR, SPSR) with their current values. R15 (PC) is highlighted with a value of 0x00000014.
- Disassembly:** A list of assembly instructions with their addresses and comments. Instruction 11, `MOV PC, LR` at address 0x00000014, is highlighted in yellow. Comments indicate that this instruction returns by copying the LR value into the PC.
- ex1.asm:** A window showing the source assembly code. Instruction 11, `MOV pc,lr`, is highlighted in green, matching the instruction in the Disassembly window.
- Command:** A window showing the status of the simulation, including memory usage (32768 bytes available, 56 bytes used).
- Memory:** A window showing the memory contents at address 0x0. The instruction bytes for `MOV PC, LR` are visible at address 0x00000014.

The status bar at the bottom indicates the simulation is running, with a timer showing 0.00000000 seconds.

# Leaf routines

The screenshot shows the µVision4 IDE with the following components:

- Registers Window:** Shows the current state of registers. R15 (PC) is highlighted with a value of 0x00000008.
- Disassembly Window:** Shows the assembly code. The instruction at address 0x00000008 is highlighted in yellow:
 

```

5:      BL Fun_1      ;call a simple leaf routine
0x00000004 EB000001 BL      0x00000010
6:      BL Fun_2      ;call a routine that calls
0x00000008 EB000002 BL      0x00000018
7:      Loop B      Loop
8:      ;-----
0x0000000C EAffffff B      0x0000000C
9:      Fun_1 NOP      ;this is a leaf routine
0x00000010 E1A00000 NOP
10:      MOV pc,lr      ;return by copying the LR value into PC
11:      ;-----
0x00000014 E1A0F00E MOV      PC,R14
12:      Fun_2 NOP      ;this is a non-leaf routine
      
```
- Source Window (ex1.asm):** Shows the corresponding assembly source code. The instruction at line 6 is highlighted in green:
 

```

4
5      BL Fun_1      ;call a simple leaf routine
6      BL Fun_2      ;call a routine that calls a nested routine
7      Loop B      Loop
8      ;-----
9      Fun_1 NOP      ;this is a leaf routine
10     MOV pc,lr      ;return by copying the LR value into PC
11     ;-----
12     Fun_2 NOP      ;this is a non-leaf routine
      
```
- Memory Window:** Shows the memory dump starting at address 0x0. The first two lines of memory are highlighted:
 

```

0x00000000: E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
0x00000014: E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
      
```
- Command Window:** Shows the status of the simulation:
 

```

*** Restricted Version with 32768 Byte Co
*** Currently used: 56 Bytes (0%)
      
```
- Bottom Bar:** Shows the simulation status: "Simulation" and "t1: 0.00000000 s".

A red callout bubble with the text "How is this offset encoded?" points to the offset 0x00000018 in the assembly code.

# Leaf routines

The screenshot shows the uVision4 IDE with the following components:

- Registers Panel:** Lists registers R0 through R15, CPSR, and SPSR. R14 (LR) is highlighted with a value of 0x0000000C, and R15 (PC) is highlighted with a value of 0x00000018.
- Disassembly Panel:** Shows assembly instructions with addresses and comments.
  - Address 0x00000008: `EB000002 BL 0x00000018` (7: Loop B Loop)
  - Address 0x0000000C: `EAffffffE B 0x0000000C` (9: Fun\_1 NOP ;this is a leaf routine)
  - Address 0x00000010: `E1A00000 NOP` (10: MOV pc,lr ;return by copying the LR value into PC)
  - Address 0x00000014: `E1A0F00E MOV PC,R14` (12: Fun\_2 NOP ;this is a non-leaf routine)
  - Address 0x00000018: `E1A00000 NOP` (13: STR lr,[sp],#4 ;save link register)
  - Address 0x0000001C: `E48DE004 STR R14,[R13],#0x0004`
- Source Panel (ex1.asm):** Shows the corresponding assembly source code.
  - Line 6: `BL Fun_2 ;call a routine that calls a nested routine`
  - Line 7: `Loop B Loop`
  - Line 9: `Fun_1 NOP ;this is a leaf routine`
  - Line 10: `MOV pc,lr ;return by copying the LR value into PC`
  - Line 12: `Fun_2 NOP ;this is a non-leaf routine`
  - Line 13: `STR lr,[sp],#4 ;save link register`
  - Line 14: `BL Fun_1 ;call Fun_1 - overwrites the old link register`
  - Line 15: `LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into`
- Command Panel:** Displays the message: `*** Restricted Version with 32768 Byte Co` and `*** Currently used: 56 Bytes (0%)`.
- Memory Panel:** Shows memory addresses and their corresponding hex values.
  - Address 0x0: 0x00000000: E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
  - Address 0x00000014: 0x00000014: E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
  - Address 0x00000028: 0x00000028: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
- Bottom Status Bar:** Shows "Simulation" and "t1: 0.00000000 s".



Grows down

Empty  
memory

## Leaf routines

Registers

Register	Value
R0	0x00000000
R1	0x00000000
R2	0x00000000
R3	0x00000000
R4	0x00000000
R5	0x00000000
R6	0x00000000
R7	0x00000000
R8	0x00000000
R9	0x00000000
R10	0x00000000
R11	0x00000000
R12	0x00000000
R13 (SP)	0x00000028
R14 (LR)	0x0000000C
R15 (PC)	0x0000001C
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	
Abort	

Disassembly

```
7: Loop B Loop
8: ;-----
0x0000000C EAffffff B 0x0000000C
9: Fun_1 NOP ;this is a leaf routine
0x00000010 E1A00000 NOP
10: MOV pc,lr ;return by copying the LR value into PC
11: ;-----
0x00000014 E1A0F00E MOV PC,R14
12: Fun_2 NOP ;this is a non-leaf routine
0x00000018 E1A00000 NOP
13: STR lr,[sp],#4 ;save link register
0x0000001C E48DE004 STR R14,[R13],#0x0004
14: BL Fun_1 ;call Fun_1 - overwrites the old link register
```

ex1.asm

```
6 BL Fun_2 ;call a routine that calls a nested routine
7 Loop B Loop
8 ;-----
9 Fun_1 NOP ;this is a leaf routine
10 MOV pc,lr ;return by copying the LR value into PC
11 ;-----
12 Fun_2 NOP ;this is a non-leaf routine
13 STR lr,[sp],#4 ;save link register
14 BL Fun_1 ;call Fun_1 - overwrites the old link register
15 LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into
```

Memory 1

Address: 0x0

0x00000000:	E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
0x00000014:	E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
0x00000028:	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

Command

\*\*\* Restricted Version with 32768 Byte Cc  
\*\*\* Currently used: 56 Bytes (0%)

ASSIGN BreakDisable BreakEnable BreakKill

Simulation t1: 0.00000000 se

Which type of stack  
is it?

# Leaf routines

The screenshot shows the uVision4 IDE with the following components:

- Registers Panel:**

Register	Value
R0	0x00000000
R1	0x00000000
R2	0x00000000
R3	0x00000000
R4	0x00000000
R5	0x00000000
R6	0x00000000
R7	0x00000000
R8	0x00000000
R9	0x00000000
R10	0x00000000
R11	0x00000000
R12	0x00000000
R13 (SP)	0x0000002C
R14 (LR)	0x0000000C
R15 (PC)	0x00000020
CPSR	0x000000D3
SPSR	0x00000000
- Disassembly Panel:**

```

0x00000010 E1A00000 NOP
10:      MOV pc,lr      ;return by copying the LR value into PC
11: ;-----
0x00000014 E1A0F00E MOV      PC,R14
12: Fun_2 NOP          ;this is a non-leaf routine
0x00000018 E1A00000 NOP
13:      STR lr,[sp],#4 ;save link register
0x0000001C E48DE004 STR      R14,[R13],#0x0004
14:      BL  Fun_1      ;call Fun_1 - overw
->0x00000020 EBFFFFFFA BL      0x00000010
15:      LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into
0x00000024 E53DF004 LDR      PC,[R13,#-0x0004]!
0x00000028 0000000C ANDEQ    R0,R0,R12
  
```
- Assembly Source Panel (ex1.asm):**

```

6      BL  Fun_2      ;call a routine that calls a nested routine
7 Loop B      Loop
8 ;-----
9 Fun_1 NOP          ;this is a leaf routine
10     MOV pc,lr      ;return by copying the LR value into PC
11 ;-----
12 Fun_2 NOP          ;this is a non-leaf routine
13     STR lr,[sp],#4 ;save link register
14     BL  Fun_1      ;call Fun_1 - overwrites the old link register
15     LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into
  
```
- Memory Panel:**

Address: 0x0

```

0x00000000: E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
0x00000014: E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
0x00000028: 00 00 00 0C 00 00 00 00 00 00 00 00 00 00 00 00
  
```

A red callout bubble asks: "How is this offset encoded?" pointing to the BL instruction at address 0x00000020. A blue arrow points from the R14 (LR) register value (0x0000000C) to the offset in the memory view (00 00 00 0C).



# Leaf routines

The screenshot shows the uVision4 IDE with the following components:

- Registers Window:** Lists registers R0 through R15, CPSR, and SPSR. R14 (LR) is highlighted with a value of 0x00000024. R15 (PC) is highlighted with a value of 0x00000010.
- Disassembly Window:** Shows assembly code starting at address 0x00000010. The first instruction is a NOP. Subsequent instructions include MOV pc,lr (return by copying the LR value into PC), MOV PC,R14, and a call to Fun\_2 (non-leaf routine). A call to Fun\_1 is also shown, which is identified as a leaf routine.
- Source Window (ex1.asm):** Shows the corresponding assembly source code. Fun\_1 is a leaf routine that saves the link register, calls Fun\_1 (overwriting the old link register), and returns by copying the LR value from the stack into the PC. Fun\_2 is a non-leaf routine that calls Fun\_1.
- Command Window:** Displays a message: "Restricted Version with 32768 Byte Code Memory. Currently used: 56 Bytes (0%)."
- Memory Window:** Shows memory addresses and their corresponding hex values. Address 0x00000000 contains E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00. Address 0x00000014 contains E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04. Address 0x00000028 contains 00 00 00 0C 00 00 00 00 00 00 00 00 00 00 00 00.

# Leaf routines

The screenshot displays the uVision4 IDE interface for an ARM project. The main window shows the disassembly of the assembly code. The Registers window on the left shows the current state of the registers, with R15 (PC) highlighted at address 0x00000014. The Disassembly window shows the following instructions:

```

0x00000010 E1A00000 NOP
10:      MOV pc,lr      ;return by copying the LR value into PC
11:      ;-----
0x00000014 E1A0F00E MOV    PC,R14
12: Fun_2 NOP          ;this is a non-leaf routine
0x00000018 E1A00000 NOP
13:      STR lr,[sp],#4  ;save link register
0x0000001C E48DE004 STR    R14,[R13],#0x0004
14:      BL  Fun_1       ;call Fun_1 - overwrites the old link register
0x00000020 EBFFFFFFA BL    0x00000010
15:      LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into PC
0x00000024 E53DF004 LDR    PC,[R13,#-0x0004]!
0x00000028 0000000C ANDEQ  R0,R0,R12
  
```

The ex1.asm source window shows the following assembly code:

```

6      BL  Fun_2       ;call a routine that calls a nested routine
7 Loop B    Loop
8      ;-----
9 Fun_1 NOP          ;this is a leaf routine
10     MOV pc,lr      ;return by copying the LR value into PC
11     ;-----
12 Fun_2 NOP        ;this is a non-leaf routine
13     STR lr,[sp],#4  ;save link register
14     BL  Fun_1       ;call Fun_1 - overwrites the old link register
15     LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into PC
  
```

The Command window shows the following text:

```

*** Restricted Version with 32768 Byte Code
*** Currently used: 56 Bytes (0%)
  
```

The Memory window shows the memory address 0x00000014 and the corresponding memory contents:

```

0x00000000: E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
0x00000014: E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
0x00000028: 00 00 00 0C 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  
```

The bottom status bar shows the simulation time: t1: 0.00000000 seconds.

# Leaf routines

The screenshot shows the uVision4 IDE with the following components:

- Registers Panel:** Lists registers R0 through R15 (PC), CPSR, and SPSR. R15 (PC) is highlighted with the value 0x00000024.
- Disassembly Panel:** Shows assembly instructions with addresses and comments.
  - Address 0x0000000C: `EAF FFF FE B` (NOP), comment: `;this is a leaf routine`
  - Address 0x00000010: `E1A 00 00 00` (NOP)
  - Address 0x00000014: `E1A 0F 00 E` (MOV PC, R14), comment: `;return by copying the LR value into PC`
  - Address 0x00000018: `E1A 00 00 00` (NOP), comment: `;this is a non-leaf routine`
  - Address 0x0000001C: `E48 DE 00 4` (STR R14, [R13], #0x0004), comment: `;save link register`
  - Address 0x00000020: `EB FFF FFA` (BL Fun\_1), comment: `;call Fun_1 - overwrites the old link register`
  - Address 0x00000024: `E53 DF 00 4` (LDR PC, [R13], #-0x0004), comment: `;return by copying the LR value (from the stack) into PC`
- Source Panel (ex1.asm):** Shows the corresponding assembly source code with line numbers 10 through 18.
- Command Panel:** Displays a message: `*** Restricted Version with 32768 Byte Code Memory *** Currently used: 56 Bytes (0%)`
- Memory Panel:** Shows memory addresses and their hexadecimal values:
  - Address 0x0: 0x00000000: E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
  - Address 0x14: 0x00000014: E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
  - Address 0x28: 0x00000028: 00 00 00 0C 00 00 00 00 00 00 00 00 00 00 00 00

# Leaf routines

The screenshot shows the uVision4 IDE with the following components:

- Registers Window:**

Register	Value
R0	0x00000000
R1	0x00000000
R2	0x00000000
R3	0x00000000
R4	0x00000000
R5	0x00000000
R6	0x00000000
R7	0x00000000
R8	0x00000000
R9	0x00000000
R10	0x00000000
R11	0x00000000
R12	0x00000000
R13 (SP)	0x00000028
R14 (LR)	0x00000024
R15 (PC)	0x0000000C
CPSR	0x000000D3
SPSR	0x00000000
- Disassembly Window:**

```

0x0000000C EAfffffe B 0x0000000C
9: Fun_1 NOP ;this is a leaf routine
0x00000010 E1A00000 NOP
10: MOV pc,lr ;return by copying the LR value into PC
11: ;-----
0x00000014 E1A0F00E MOV PC,R14
12: Fun_2 NOP ;this is a non-leaf routine
0x00000018 E1A00000 NOP
13: STR lr,[sp],#4 ;save link register
0x0000001C E48DE004 STR R14,[R13],#0x0004
14: BL Fun_1 ;call Fun_1 - overwrites the old link register
0x00000020 EBfffffa BL 0x00000010
15: LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into PC
0x00000024 E53DF004 LDR PC,[R13,#-0x0004]!

```
- ex1.asm Source Window:**

```

6 BL Fun_2 ;call a routine that calls a nested routine
7 Loop B Loop
8 ;-----
9 Fun_1 NOP ;this is a leaf routine
10 MOV pc,lr ;return by copying the LR value into PC
11 ;-----
12 Fun_2 NOP ;this is a non-leaf routine
13 STR lr,[sp],#4 ;save link register
14 BL Fun_1 ;call Fun_1 - overwrites the old link register

```
- Memory Window:**

Address: 0x0

0x00000000:	E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
0x00000014:	E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
0x00000028:	00 00 00 0C 00 00 00 00 00 00 00 00 00 00 00 00
- Command Window:**

\*\*\* Restricted Version with 32768 Byte Code Memory  
 \*\*\* Currently used: 56 Bytes (0%)

ASSIGN BreakDisable BreakEnable BreakKill
- Simulation Status:** Simulation, t1: 0.00000000 s



# Leaf routines

The screenshot displays the uVision4 IDE interface. The 'Registers' window on the left shows the current state of registers R0 through R15, with R13 (SP) at 0x00000028 and R14 (LR) at 0x00000024. The 'Disassembly' window shows the following code:

```

0x0000000C EAfffffe B 0x0000000C
9: Fun_1 NOP ;this is a leaf routine
0x00000010 E1A00000 NOP
10: MOV pc,lr ;return by copying the LR value into PC
11: ;-----
0x00000014 E1A0F00E MOV PC,R14
12: Fun_2 NOP ;this is a non-leaf routine
0x00000018 E1A00000 NOP
13: STR lr,[sp],#4 ;save link register
0x0000001C E48DE004 STR R14,[R13],#0x0004
14: BL Fun_1 ;call Fun_1 - overwrites the old link register
0x00000020 EBfffffa BL 0x00000010
15: LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into PC
0x00000024 E53DF004 LDR PC,[R13,#-0x0004]!
  
```

The 'ex1.asm' window shows the source code for these routines:

```

6 BL Fun_2 ;call a routine that calls a nested routine
7 Loop B Loop
8 ;-----
9 Fun_1 NOP ;this is a leaf routine
10 MOV pc,lr ;return by copying the LR value into PC
11 ;-----
12 Fun_2 NOP ;this is a non-leaf routine
13 STR lr,[sp],#4 ;save link register
14 BL Fun_1 ;call Fun_1 - overwrites the old link register
  
```

The 'Command' window at the bottom shows the status: '\*\*\* Restricted Version with 32768 Byte Code Memory \*\*\* Currently used: 56 Bytes (0%)'. The 'Memory' window shows the memory dump starting at address 0x0:

```

0x00000000: E2 8F D0 20 EB 00 00 01 EB 00 00 02 EA FF FF FE E1 A0 00 00
0x00000014: E1 A0 F0 0E E1 A0 00 00 E4 8D E0 04 EB FF FF FA E5 3D F0 04
0x00000028: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  
```

The status bar at the bottom indicates 'Simulation' and 't1: 0.00000000 sec'.

## Subroutines and Block Move Instructions

- ❑ All subroutines commonly use the same set of registers to save values, and this might cause problems.
  - Assume that a program used **R1** to store a temporary value.
  - Later, this program called a function.
  - The function also used **R1** to store a different value.
  - After returning from the function, the program will not have access to the original **R1** value that was there before calling the function.
  
- ❑ To solve this issue, the followings need to be done:
  - At the beginning of the function, the values of all registers that will be used in the function must be pushed onto a stack.
  - Just before returning from the function, all pushed values must be popped and loaded to the same registers.

## Subroutines and Block Move Instructions

- ❑ The **ARM**'s block move instructions can be used to
  - save register values once entering a subroutine and
  - restore registers just before returning from a subroutine.
- ❑ Consider the following ARM code:

```
BL      test                ;call test, save return
                                ;address in r14
...
test STMFD r13!, {r0-r4,r10} ;subroutine test, save working
                                ;registers
. body of code
.
LDMFD r13!, {r0-r4,r10}      ;subroutine completes,
                                ;restore the registers
MOV     pc, r14              ;copy the return address in
                                ;r14 to the PC
```



## Subroutines and Block Move Instructions

- ❑ If you are using a block move to restore registers from the stack, you can also include the program counter.

We can write:

```
test STMFD r13!, {r0-r4, r10, r14} ;save working registers
                                   ;and return address in r14
:
LDMFD r13!, {r0-r4, r10, r15} ;restore working registers
                              ;and put r14 in the PC
```

- ❑ At the beginning of the subroutine, we push the *link register r14* containing the return address onto the stack, and then at the end we pull the saved registers, including the value of the return address which is placed in the *PC*, to make the return.
  - By doing so, we reduced the size of this code by one instruction