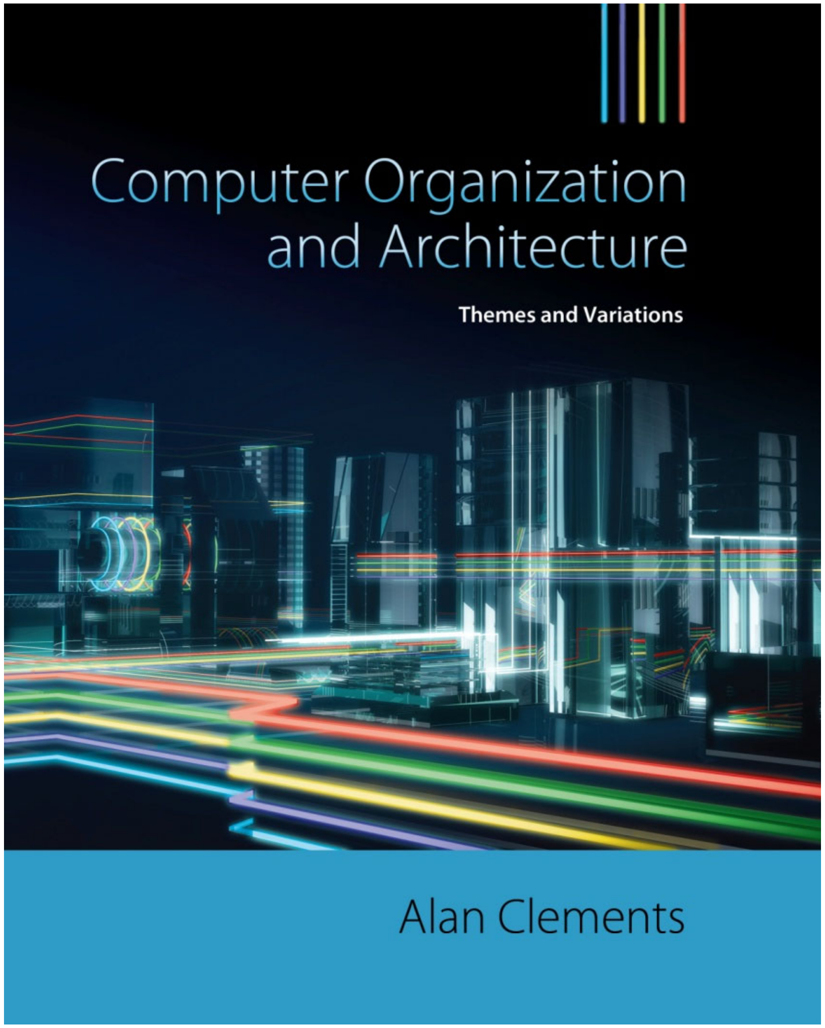
Part E

Chapter 3

Architecture and Organization



CENGAGE Learning

Subroutine Call and Return

子程序

- ❑ 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.

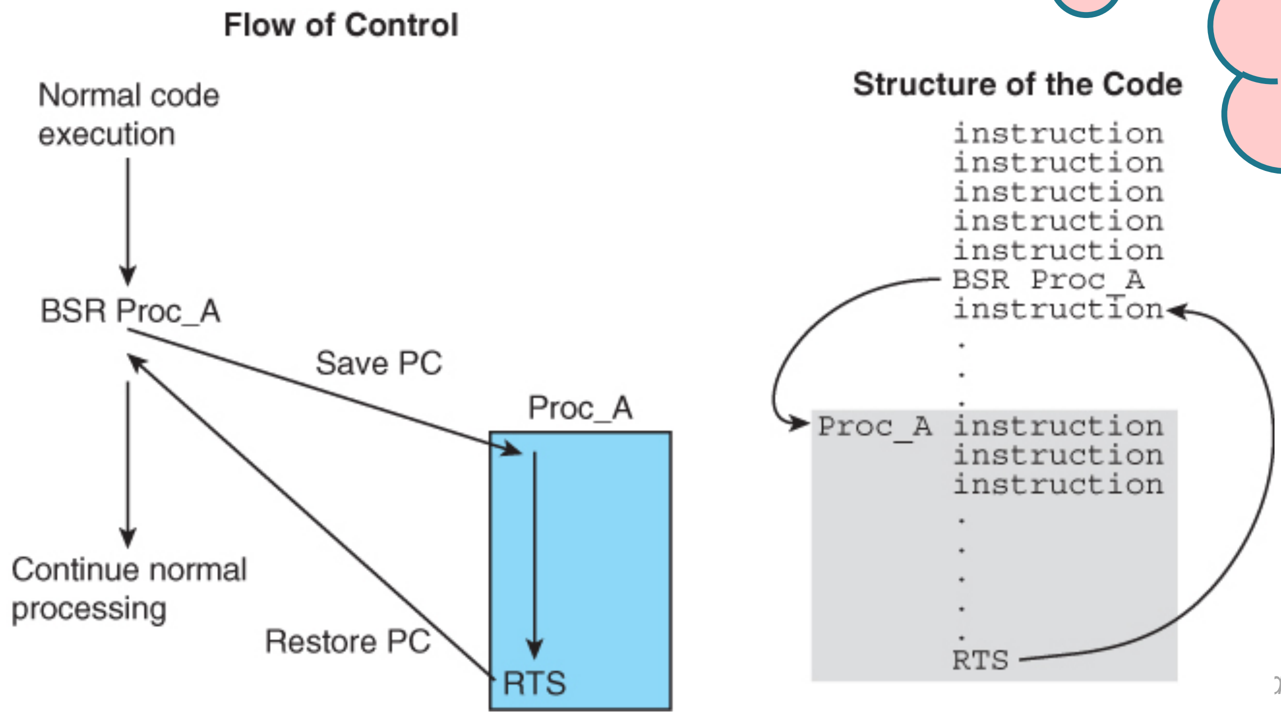
  1. A subroutine can be called from anywhere in the program.
  2. Once the subroutine is completed, it should return to the instruction directly after the subroutine calling location.

goes back to the main func

Subroutine Call and Return

- A *hypothetical* instruction *BSR Proc_A calls* subroutine *Proc_A*.
  - The processor R14(LR) saves the address of the next instruction to be executed in a safe place, and
  - loads the program counter R15(PC) 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



```
        instruction
        instruction
        instruction
        instruction
        instruction
        BSR Proc_A
        instruction
        .
        .
        .
Proc_A  instruction
        instruction
        instruction
        .
        .
        .
        .
        RTS
```

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.

So you have to manually add the return

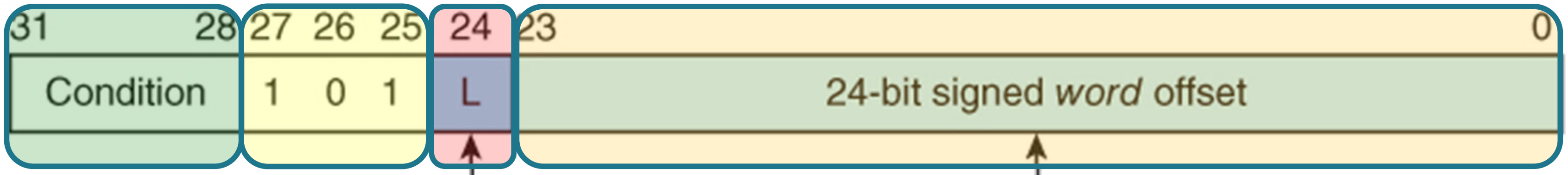
This is the main difference between B and BL

- ❑ 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*).

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"
```

Store the adderss of the next instruction in LR
To contine the program, just read LR.

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:

the excuting instruction.

```
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

  update flags.

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
      MOVL~~T~~E  r0,r0, LSL #5  ;ELSE if x < 0 THEN x = 32*x
      MOV    pc,lr          ;return by restoring saved PC
    = BX     lr
```

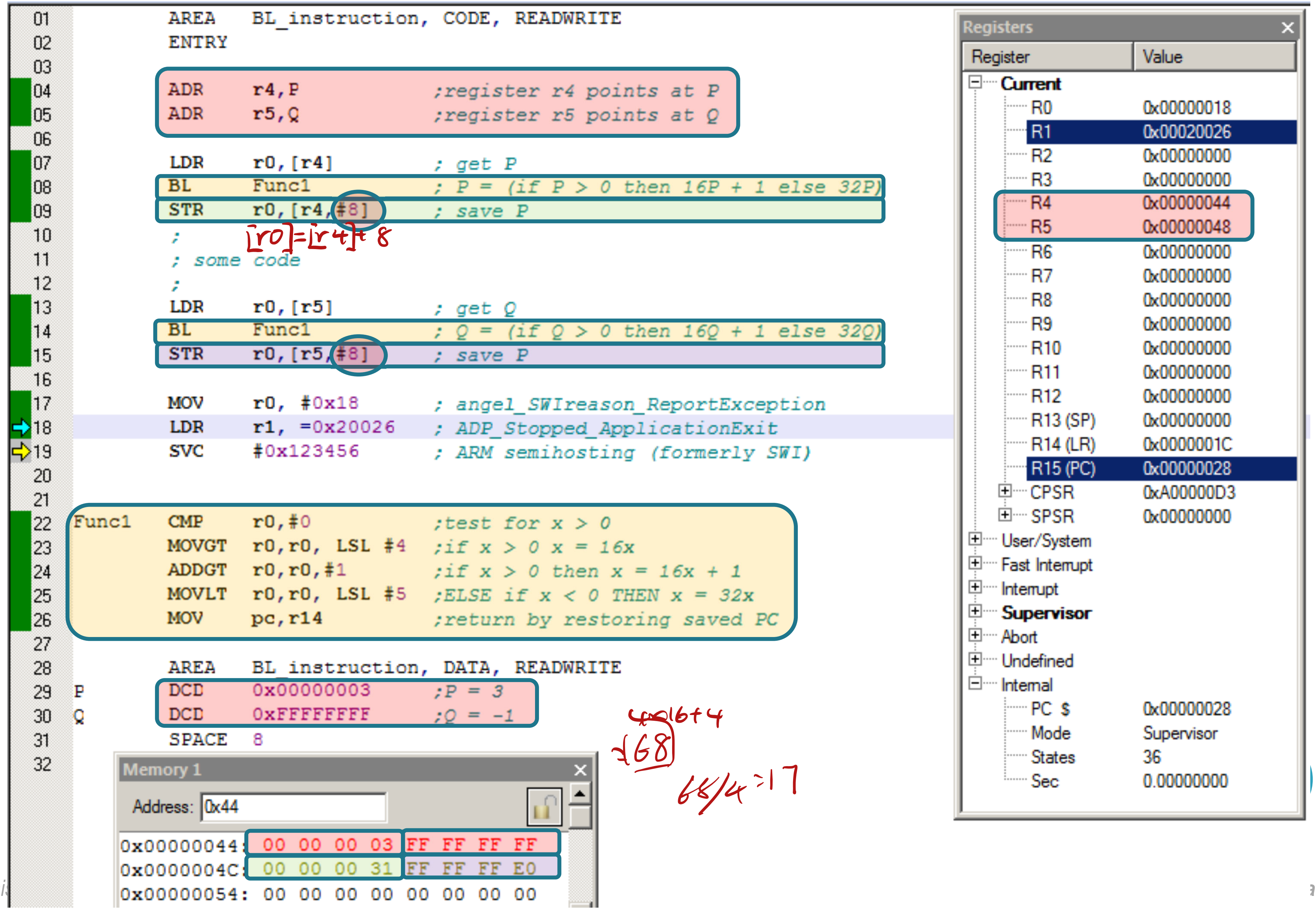
- ❑ Consider the following invocation of the above subroutine.

```
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



```
         AREA    BL_instruction, CODE, READWRITE
         ENTRY

         ADR     r4,P               ;register r4 points at P
         ADR     r5,Q               ;register r5 points at Q

         LDR     r0,[r4]            ; get P
         BL      Func1              ; P = (if P > 0 then 16P + 1 else 32P)
         STR     r0,[r4,#8]         ; save P
;
; some code
;
         LDR     r0,[r5]            ; get Q
         BL      Func1              ; Q = (if Q > 0 then 16Q + 1 else 32Q)
         STR     r0,[r5,#8]         ; save P

         MOV     r0, #0x18          ; angel_SWIreason_ReportException
         LDR     r1, =0x20026       ; ADP_Stopped_ApplicationExit
         SVC     #0x123456          ; ARM semihosting (formerly SWI)


Func1    CMP     r0,#0              ;test for x > 0
         MOVGT   r0,r0, LSL #4      ;if x > 0 x = 16x
         ADDGT   r0,r0,#1           ;if x > 0 then x = 16x + 1
         MOVLT   r0,r0, LSL #5      ;ELSE if x < 0 THEN x = 32x
         MOV     pc,r14             ;return by restoring saved PC

         AREA    BL_instruction, DATA, READWRITE
P        DCD     0x00000003         ;P = 3
Q        DCD     0xFFFFFFFF         ;Q = -1
         SPACE   8
```

[r0]=[r4]+8

4×16+4

=68

68/4=17

Register	Value
Current	
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

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
```

R13: stack pointer

R14: link register

when using B/BRL, return add will be store in R14.

B -> branch to the target add, and not update R14.

BL -> store the next instruction.

BLS -> switch to svm.

BX -> jump to the target add.

LDR : memory -> register

STR : register -> memory

MOV : register -> register

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
  - Branch
  - with Link
  - execute on condition Less Than

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.

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

  - Once the execution of the subroutine code is completed, a *return from subroutine* instruction is executed
    - Popping the return address from the ~~stake~~ stack
    - Copy the return address to the **PC** register

Grows up

Occupied memory

Subroutine Call and Return

- ❑ *Example*

This is B. It is NOT BL

```
...                  ;assume that the stack grows towards
...                  ;low addresses and the SP points at
...                  ;the top item on the stack.
STR r15,[r13,#-4]!   ;pre-decrement the stack pointer AND
                     ;push the return address on the stack
B   Target           ;jump to the target address (B not BL)
...                  ;to return here
...
```

The proper return address

The address pushed onto the stake.

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:

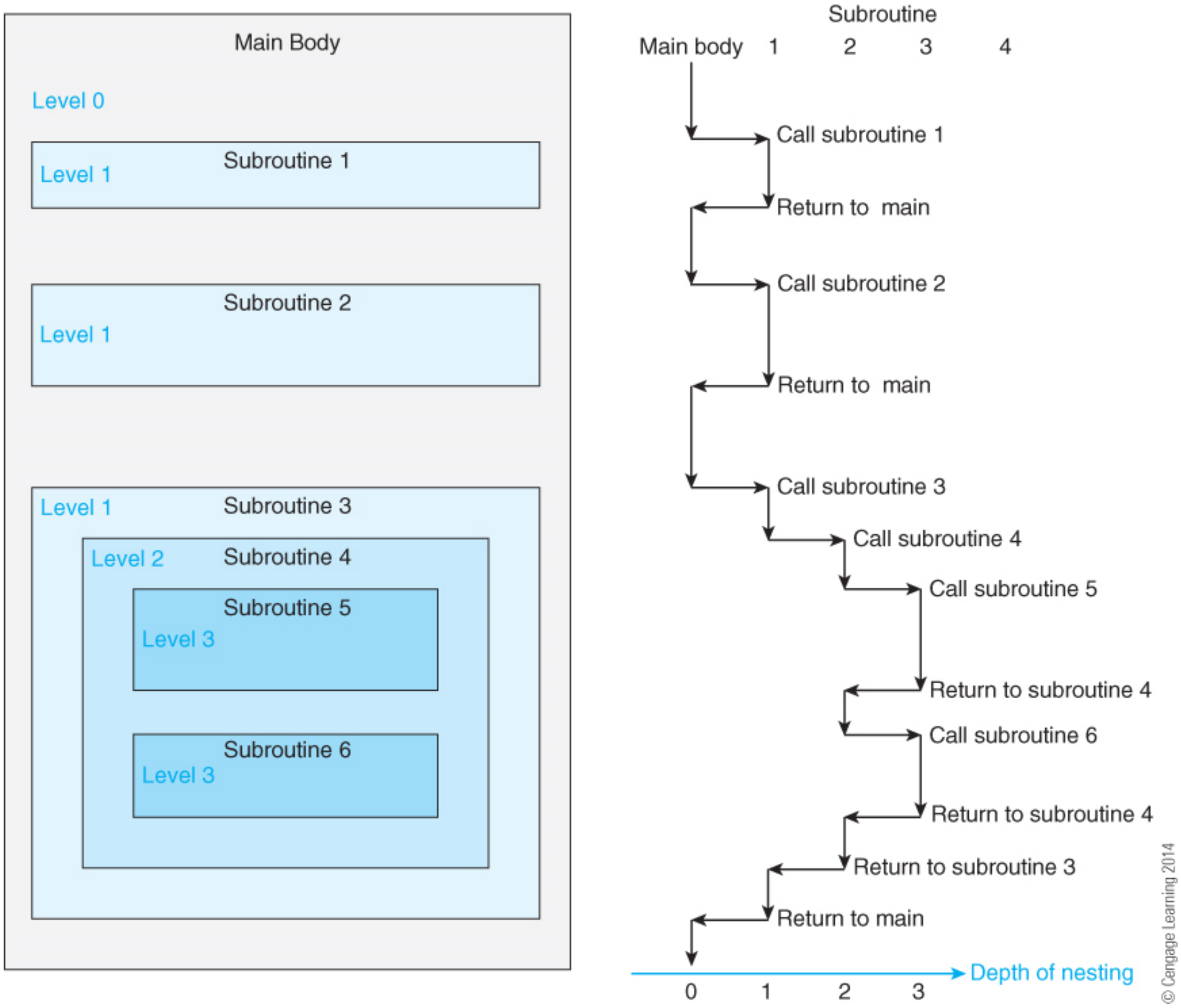
```
LDR r12,[r13],#+4     ;get saved PC and post-increment
                      ;stack pointer
SUB r15,r12,#4        ;fix PC and load into r15 to return
```

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

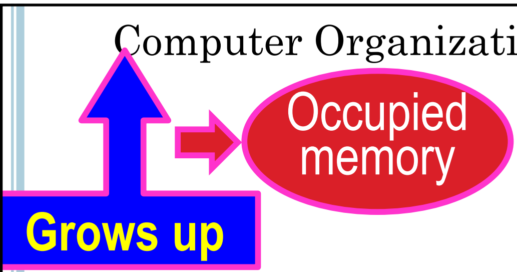
Why did not we copy the stack content directory to r15?

Nested subroutines

FIGURE 3.48 An example of nested subroutines

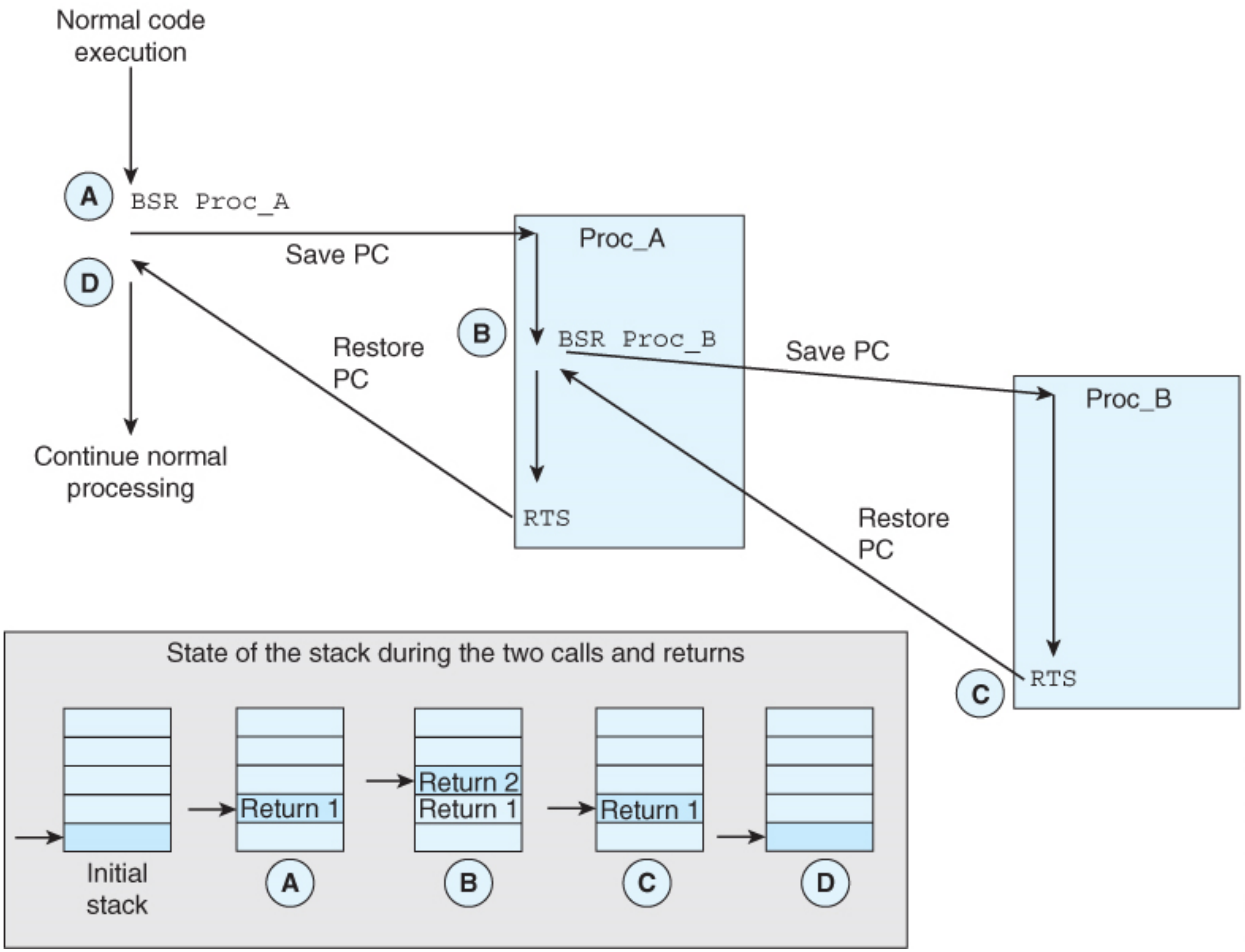


© Cengage Learning 2014

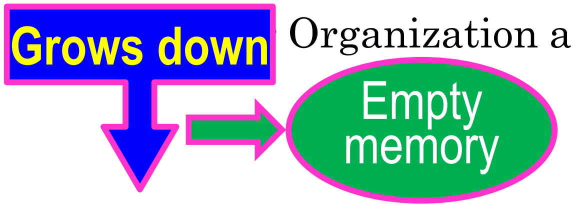


Example of nested subroutine

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.

LDM·
EA ->

```
      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
;------------------------------------------------------------
```

return add   next instruction
↓ to be read.

r13 +4

push lr to the stack.

-> save the address of return value.

What kind of stack is used here?

What is the maximum depth that can be called using this stack? 2

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`.

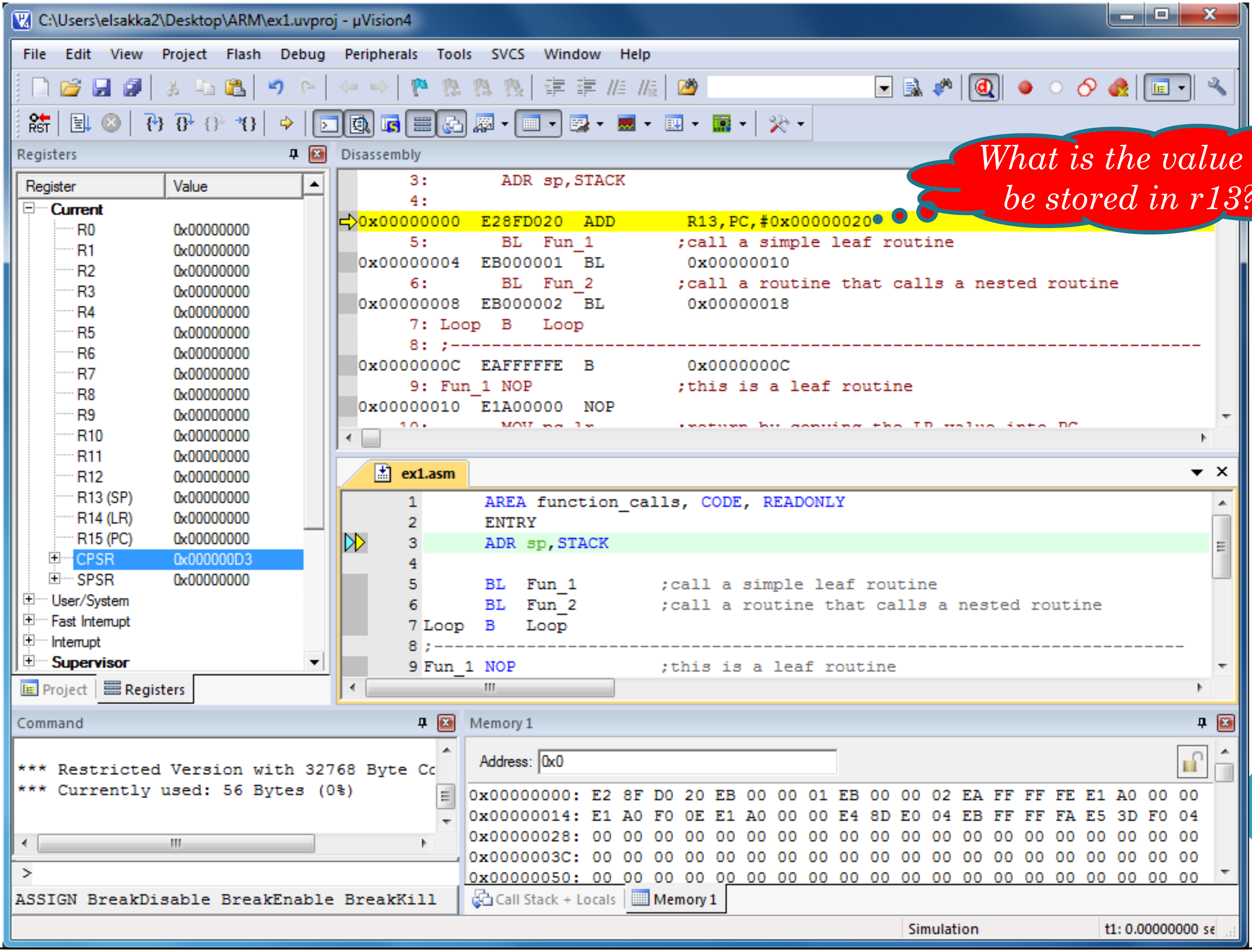
  STR lr [sp] , #4.

- ❑ 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.

  LDR pc [sp, #-4].

Leaf routines



C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
Registers
Disassembly
ex1.asm
Project
Registers
Command
Memory 1
Call Stack + Locals
Memory 1
Simulation
t1: 0.00000000 se

What is the value to be stored in r13?

Register	Value
Current	
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)	0x00000000
R14 (LR)	0x00000000
R15 (PC)	0x00000000
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	

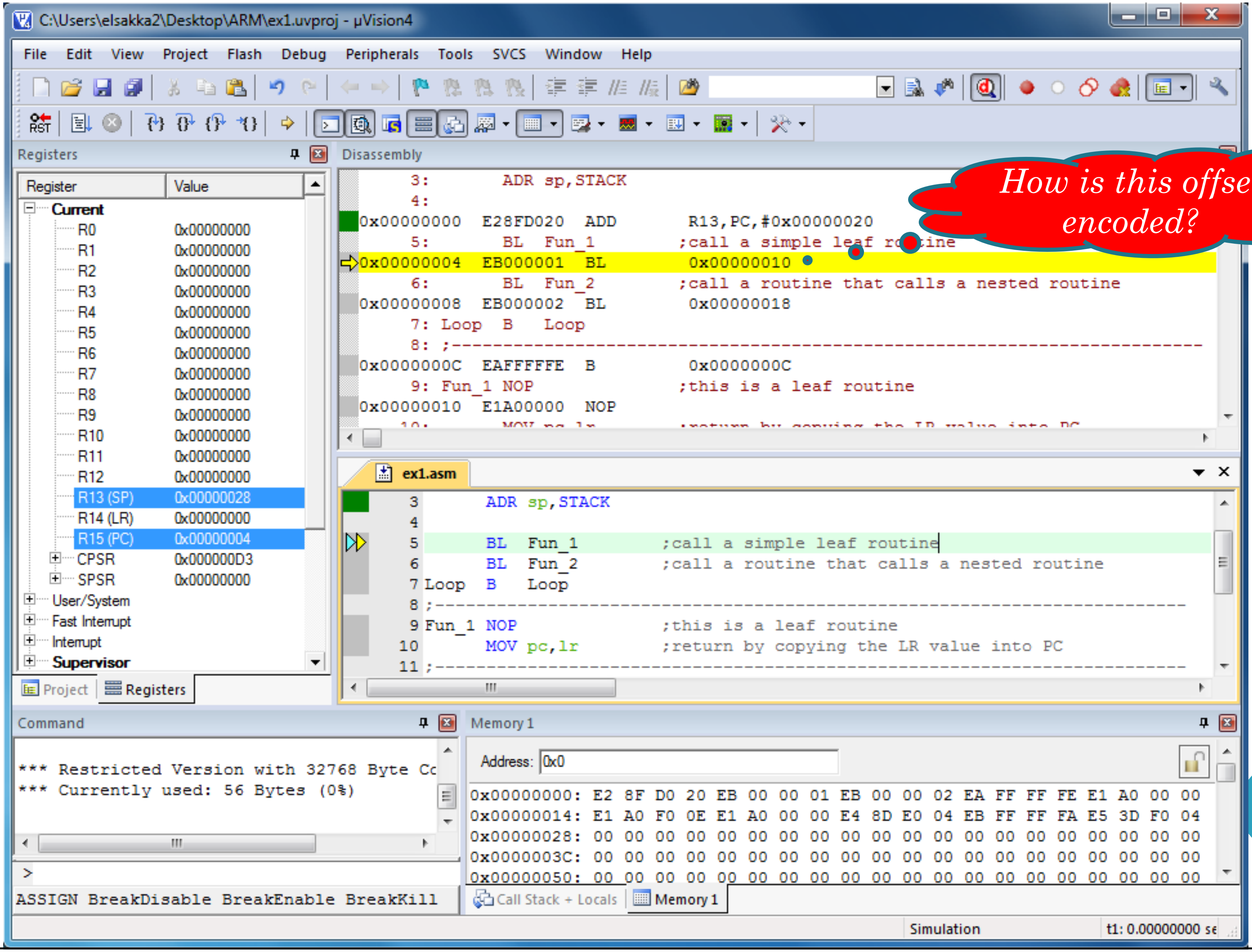
```
     3:        ADR sp,STACK
     4:
0x00000000  E28FD020  ADD       R13,PC,#0x00000020
     5:        BL  Fun_1        ;call a simple leaf routine
0x00000004  EB000001  BL        0x00000010
     6:        BL  Fun_2        ;call a routine that calls a nested routine
0x00000008  EB000002  BL        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
```

```
        AREA function_calls, CODE, READONLY
        ENTRY
        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
```

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

>
ASSIGN BreakDisable BreakEnable BreakKill
```

```
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 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
```

Leaf routines


C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
Registers
Disassembly
ex1.asm
Project
Registers
Command
Memory 1
Address:
Call Stack + Locals
Memory 1
Simulation

How is this offset encoded?

Register	Value
Current	
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	

```
     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
```

```
      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
;----------------------------------------------------------------------
```

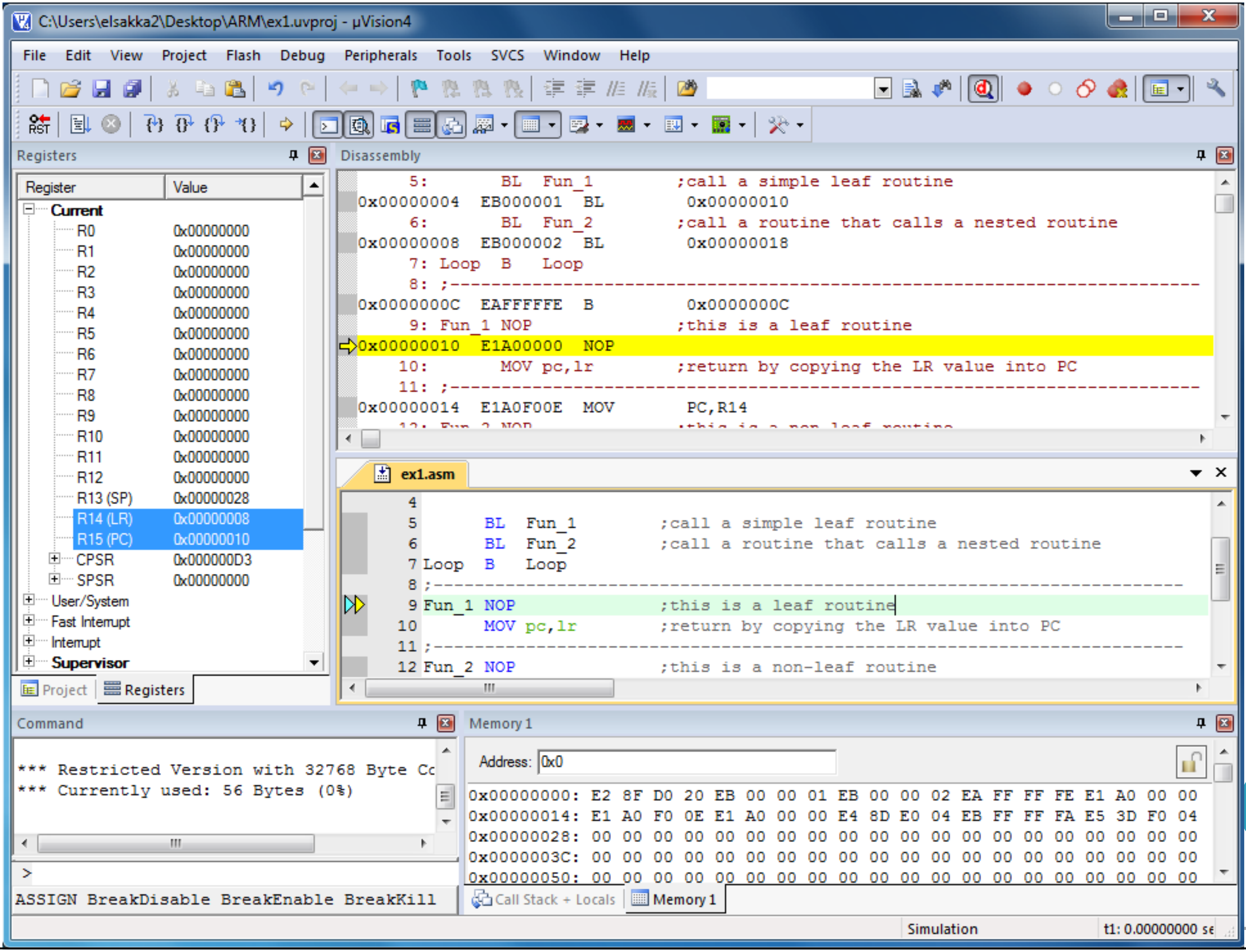
```
*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)
>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 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
```

t1: 0.00000000 se

Leaf routines



C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
RST
Registers
Disassembly
ex1.asm
Project
Registers
Command
Memory 1
Call Stack + Locals
Memory 1
Simulation
t1: 0.00000000 se

Register	Value
Current	
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	

```
      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
     11: ;-----------------------------------------------------------------------
0x00000014  E1A0F00E  MOV        PC,R14
     12: Fun_2 NOP                   ;this is a non-leaf routine
```

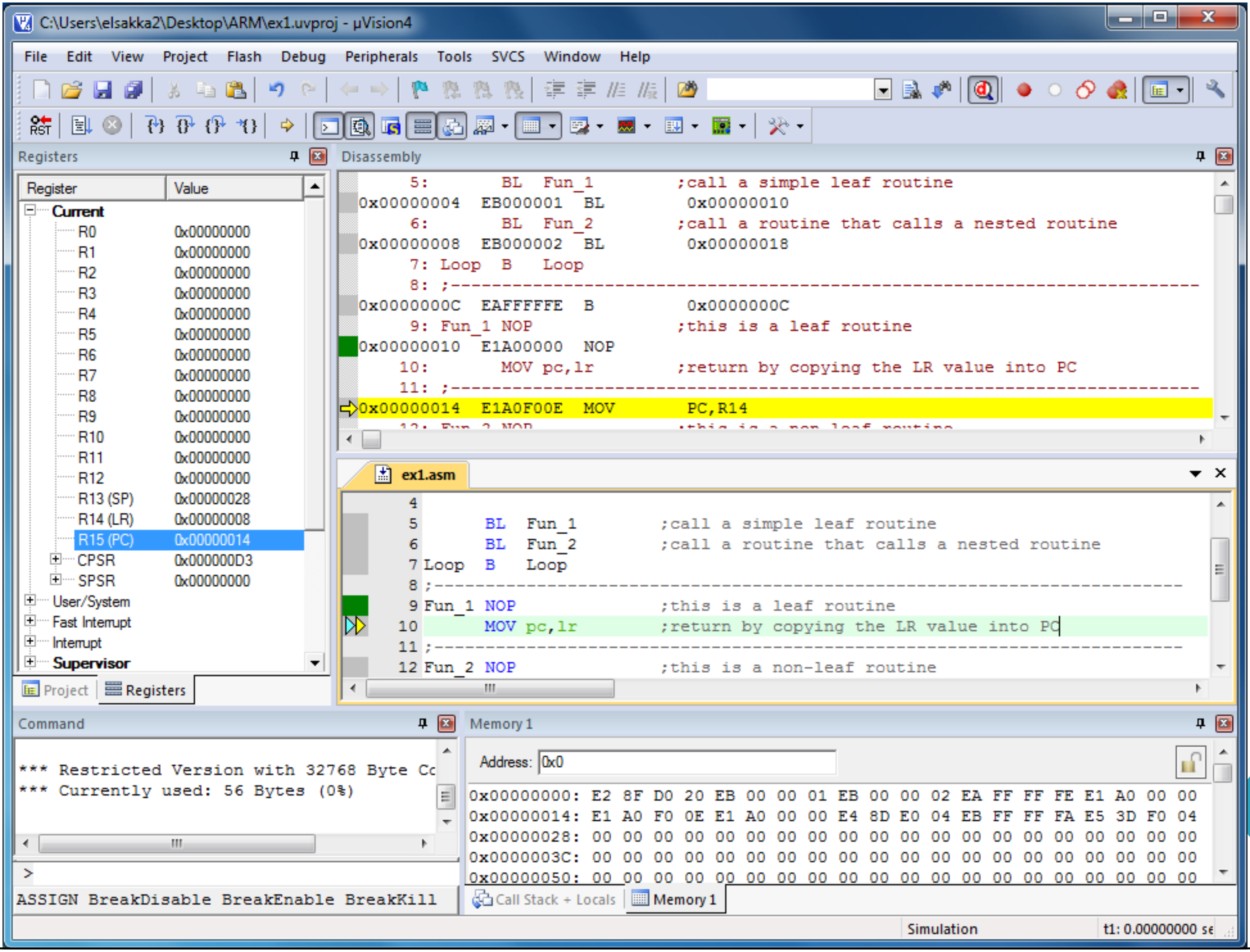
```

        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
```

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

>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 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
```

Leaf routines



C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
Registers
Disassembly
ex1.asm
Project
Registers
Command
Memory 1
Call Stack + Locals
Memory 1

Register	Value
Current	
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)	0x00000014
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	

```
     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
    11: ;---------------------------------------------------------------------
0x00000014  E1A0F00E  MOV        PC,R14
    12: Fun_2 NOP                   ;this is a non-leaf routine
```

```

        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
```

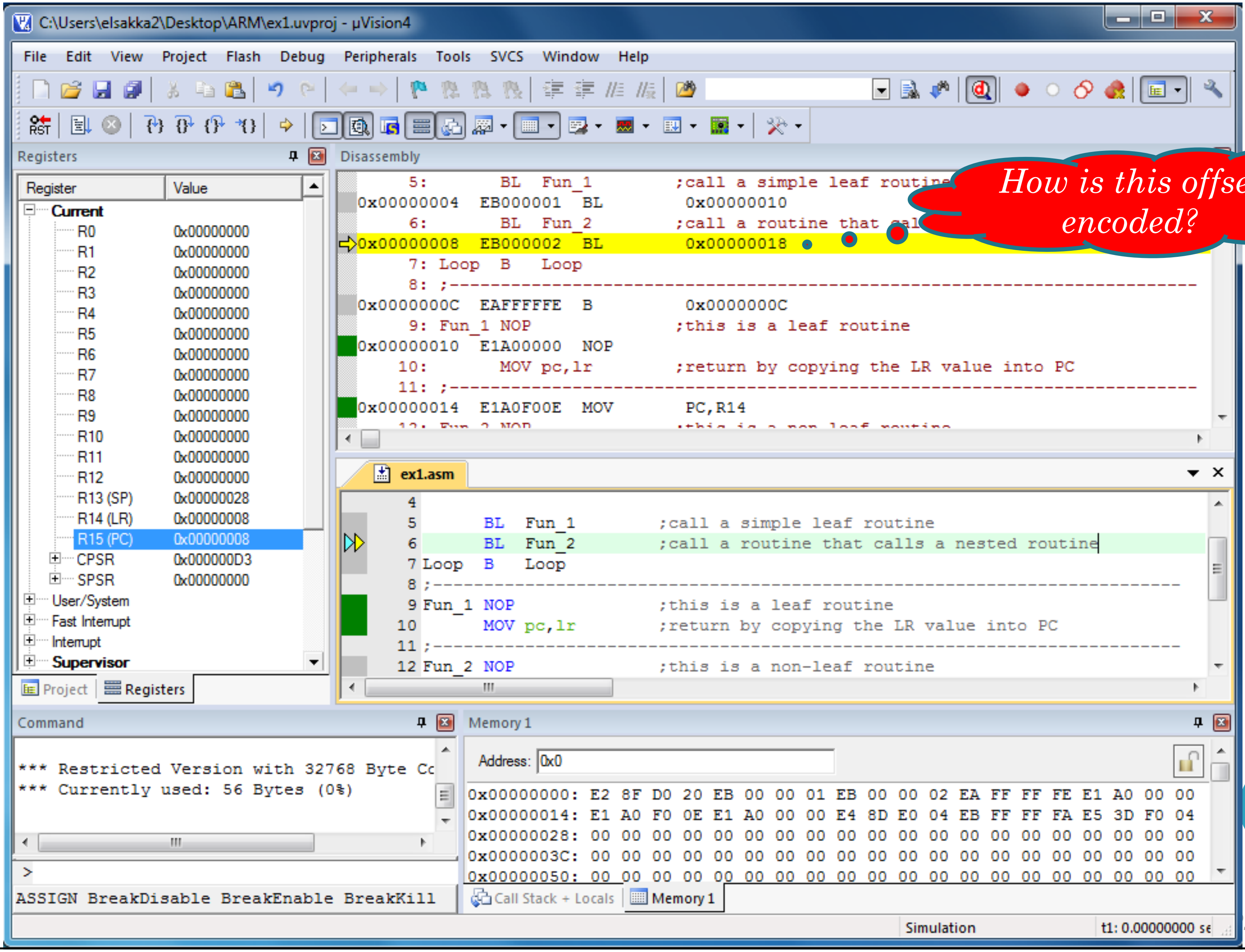
```
*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)

>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 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
```

Simulation t1: 0.00000000 se

Leaf routines



C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
Registers
Disassembly
ex1.asm
Command
Memory 1
Project
Registers
Call Stack + Locals
Simulation
t1: 0.00000000 se

How is this offset encoded?

Register	Value
Current	
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)	0x00000008
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	

```
     5:          BL   Fun_1          ;call a simple leaf routine
0x00000004  EB000001  BL          0x00000010
     6:          BL   Fun_2          ;call a routine that cal
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
    11: ;----------------------------------------------------------------------
0x00000014  E1A0F00E  MOV         PC,R14
```

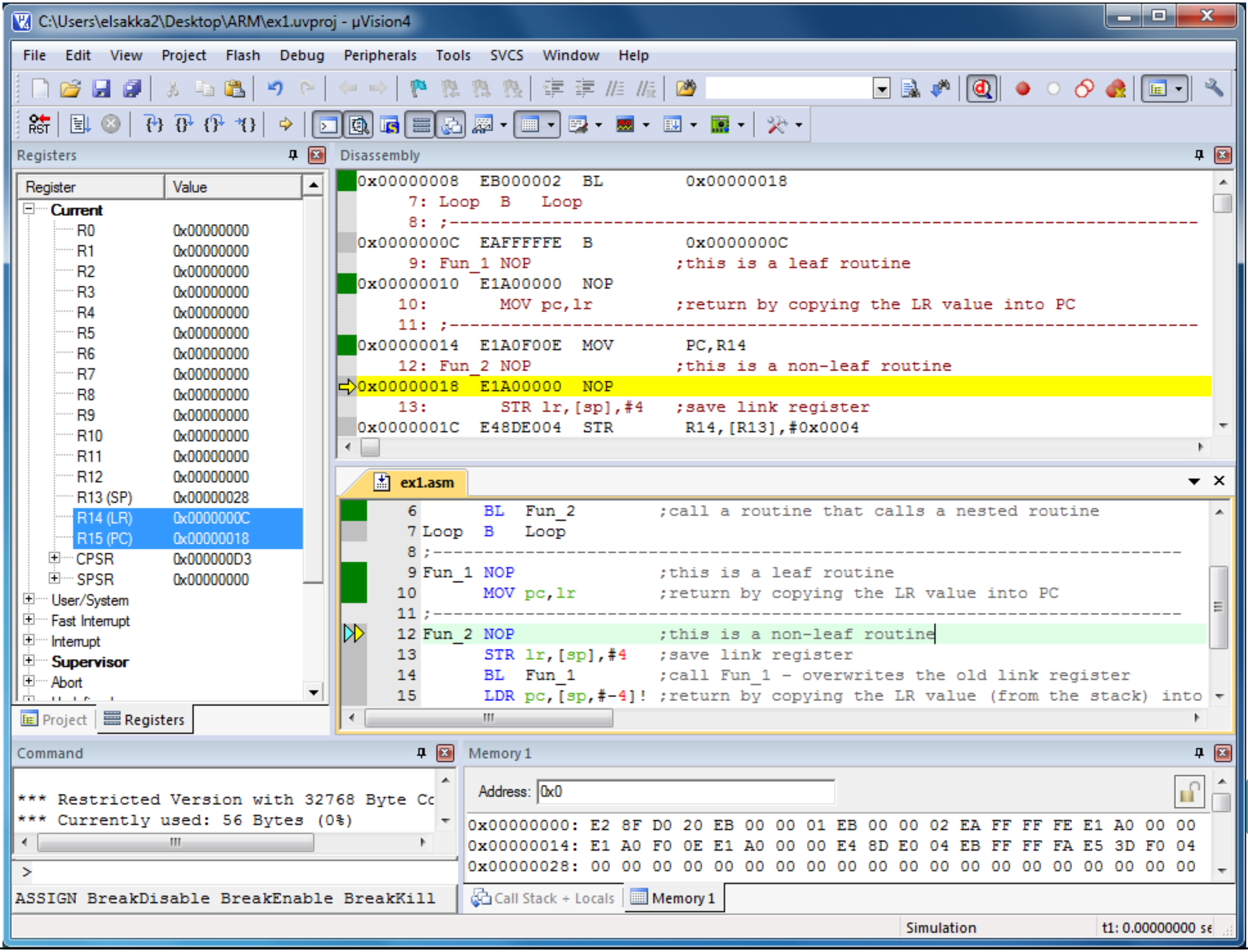
```
 4
 5        BL   Fun_1          ;call a simple leaf routine
 6        BL   Fun_2          ;call a routine that calls a nested routine
 7 Loop   B    Loop
 8 ;------------------------------------------------------------------------
 9 Fun_1  NOP                 ;this is a leaf routine
10        MOV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

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

>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 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
```

Leaf routines


C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
RST
Registers
Disassembly
ex1.asm
Project
Registers
Command
Memory 1
Call Stack + Locals
Memory 1
Simulation
t1: 0.00000000 se

Register	Value
Current	
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)	0x00000018
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	
Abort	

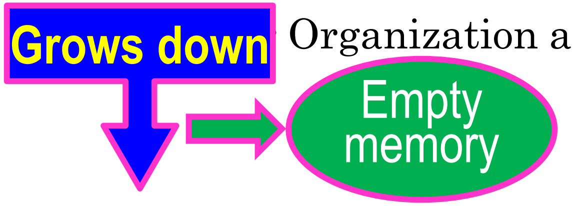
```
0x00000008  EB000002  BL         0x00000018
     7: Loop  B   Loop
     8: ;----------------------------------------------------------------------
0x0000000C  EAFFFFFE  B          0x0000000C
     9: Fun_1 NOP               ;this is a leaf routine
0x00000010  E1A00000  NOP
    10:        MOV pc,lr        ;return by copying the LR value into PC
    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
```

```
      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 link register
      LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into
```

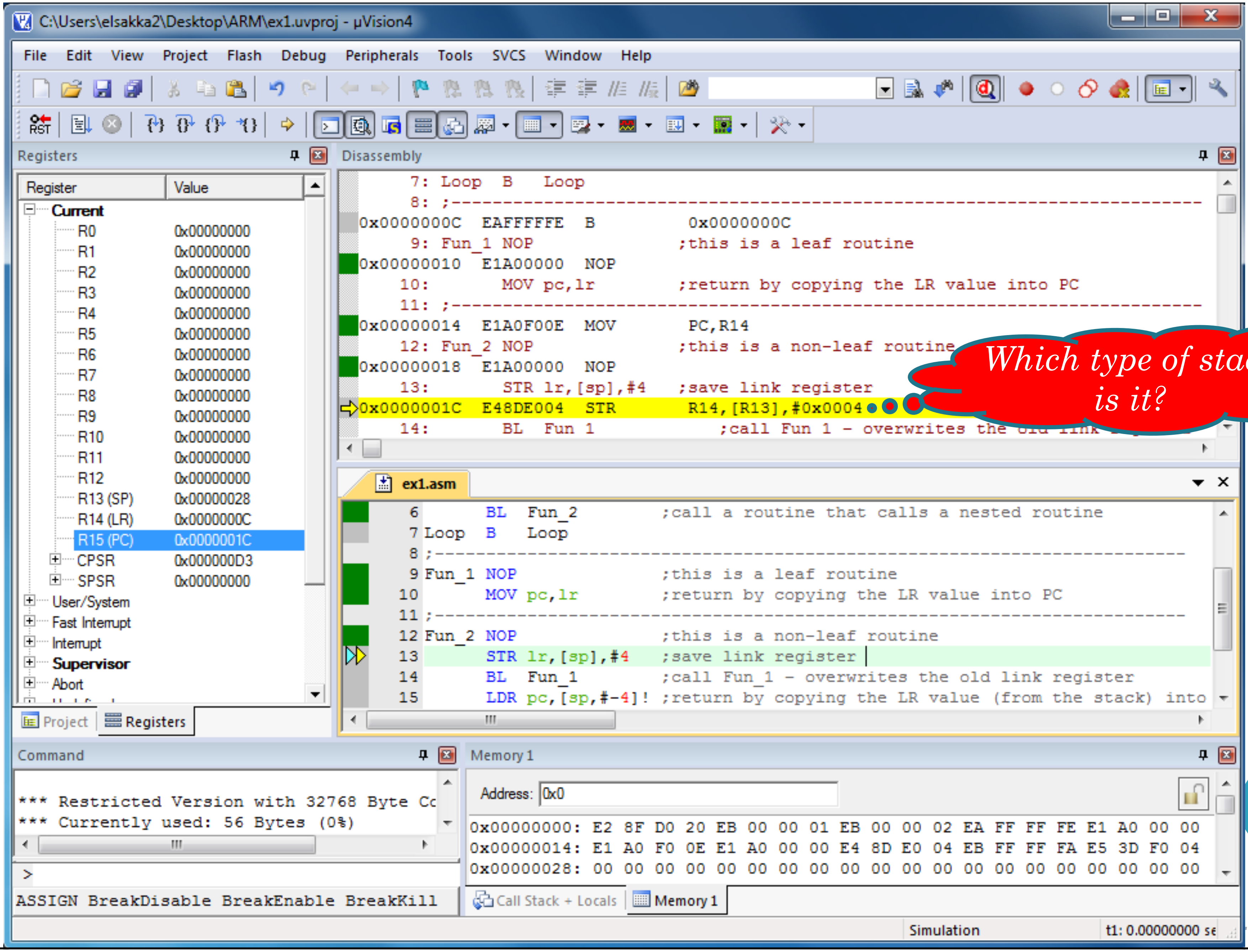
```
*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)
>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 00 00
```



Leaf routines


C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
Registers
Disassembly
ex1.asm
Project
Registers
Command
Memory 1
Call Stack + Locals
Memory 1
Simulation
t1: 0.00000000 se

Register	Value
Current	
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	

```
     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
    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
```

Which type of stack is it?

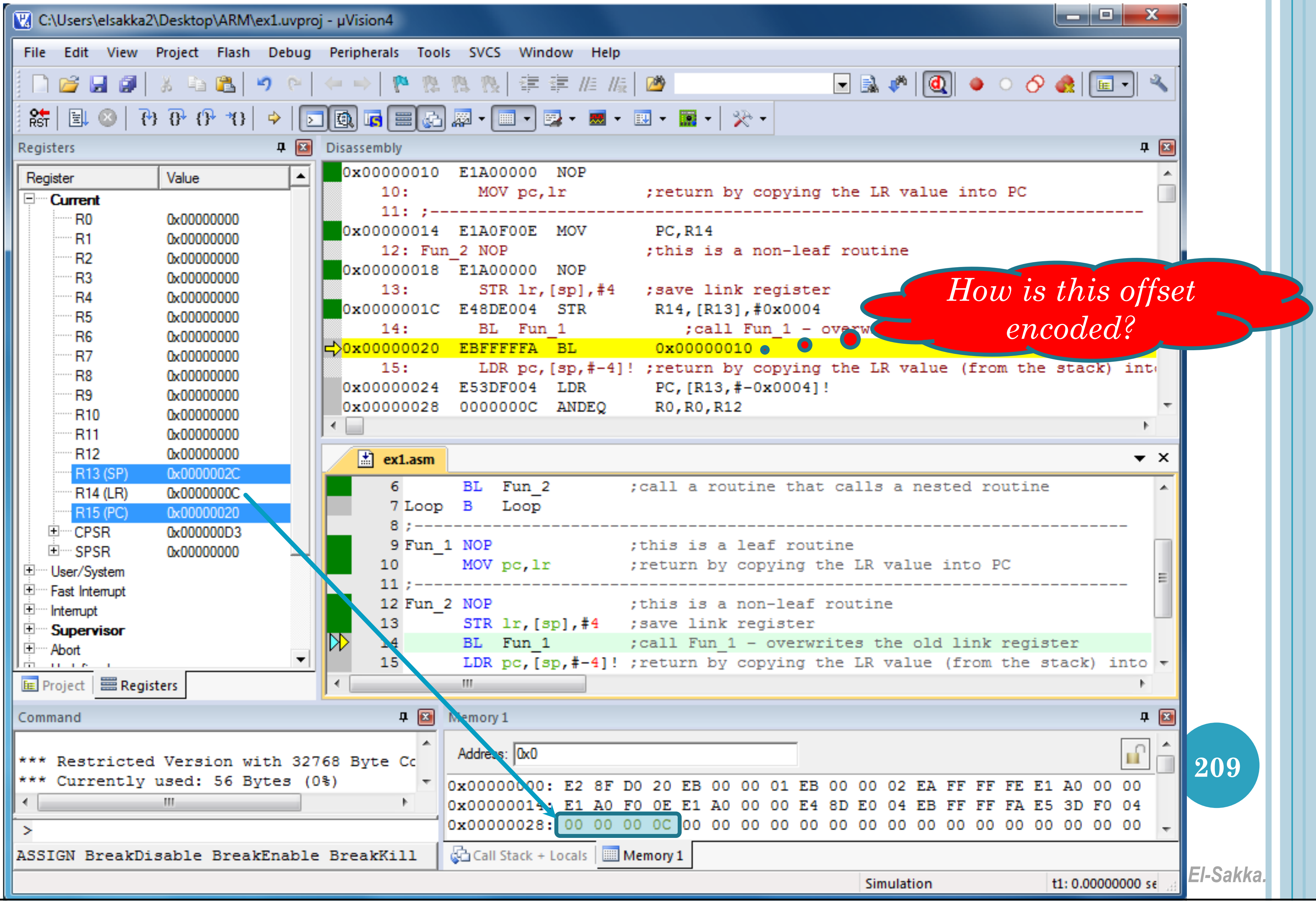
```
 6       BL   Fun_2         ;call a routine that calls a nested routine
 7 Loop  B    Loop
 8 ;-------------------------------------------------------------------
 9 Fun_1 NOP                ;this is a leaf routine
10       MOV  pc,lr         ;return by copying the LR value into PC
11 ;-------------------------------------------------------------------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

```
*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)
>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 00 00
```

Leaf routines


C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
Registers
Disassembly
ex1.asm
Project
Registers
Command
Memory 1
Call Stack + Locals
Simulation
t1: 0.00000000 se

Register	Value
Current	
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
User/System	
Fast Interrupt	
Interrupt	
Supervisor	
Abort	

```
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  EBFFFFFA  BL        0x00000010
    15:       LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) int
0x00000024  E53DF004  LDR       PC,[R13,#-0x0004]!
0x00000028  0000000C  ANDEQ     R0,R0,R12
```

```
        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 link register
        LDR   pc,[sp,#-4]! ;return by copying the LR value (from the stack) into
```

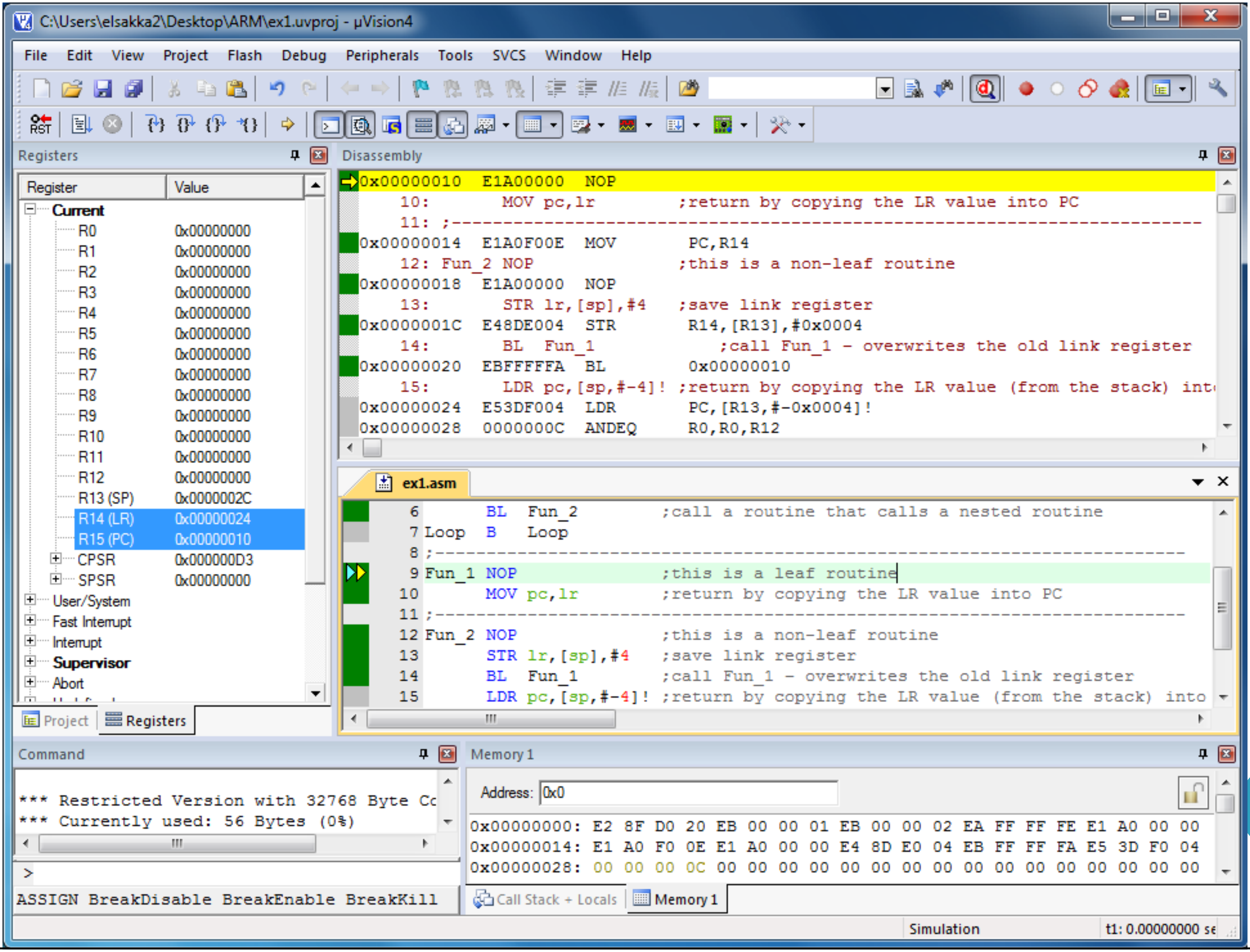
```
*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)

>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 00 00 00 00
```

How is this offset encoded?

Leaf routines



C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
Registers
Disassembly
Project Registers
Command
Memory 1
Call Stack + Locals Memory 1
Simulation
t1: 0.00000000 se

Register	Value
Current	
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)	0x00000024
R15 (PC)	0x00000010
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	
Abort	

```
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) int
0x00000024  E53DF004  LDR        PC,[R13,#-0x0004]!
0x00000028  0000000C  ANDEQ      R0,R0,R12
```

ex1.asm

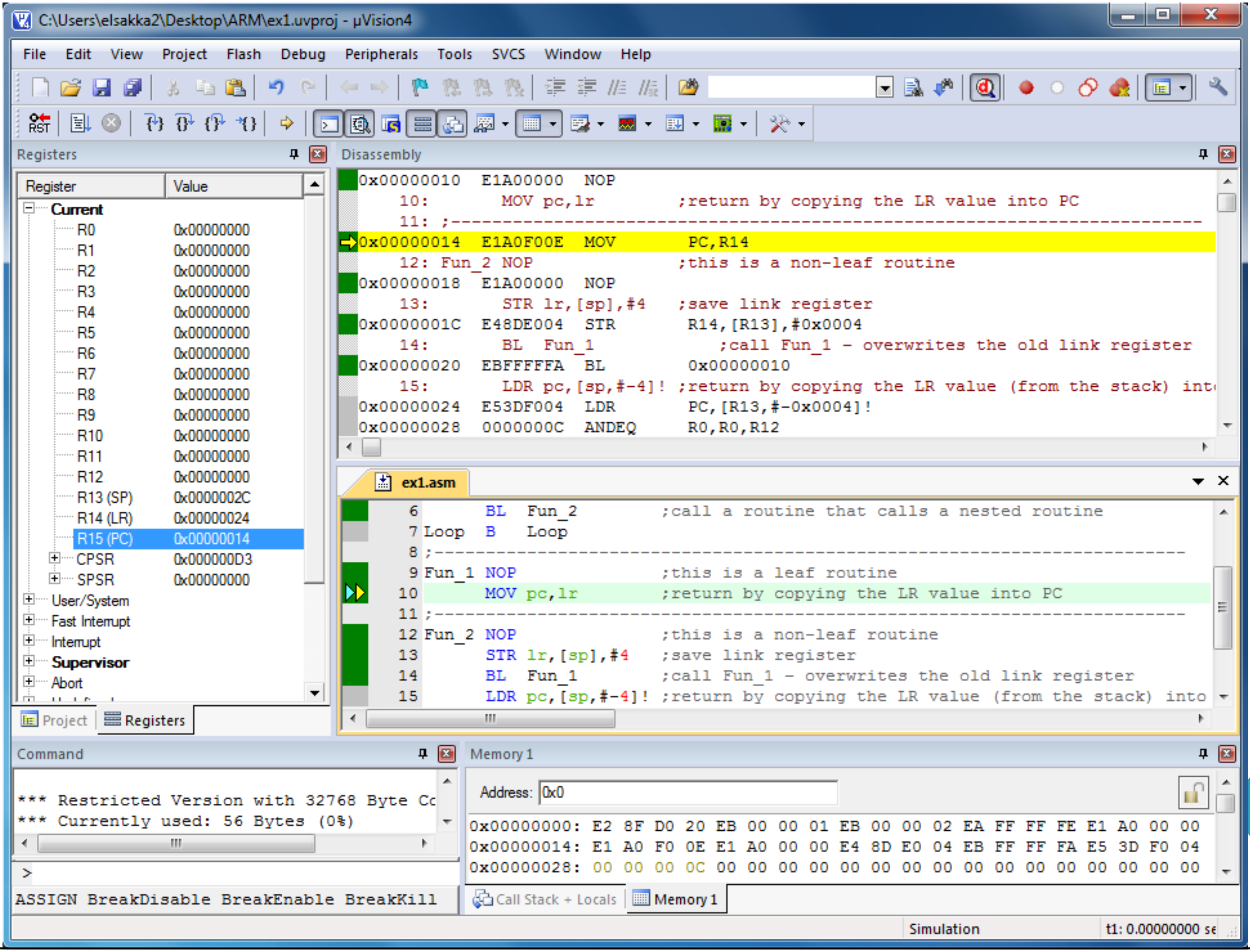
```
        BL    Fun_2         ;call a routine that calls a nested routine
  Loop  B     Loop
  ;-----------------------------------------------------------------------
  Fun_1 NOP                 ;this is a leaf routine
        MOV pc,lr           ;return by copying the LR value into PC
  ;-----------------------------------------------------------------------
  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 link register
        LDR pc,[sp,#-4]!    ;return by copying the LR value (from the stack) into
```

```
*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)
>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 00 00 00 00
```

Leaf routines



```
Register        Value
Current
  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)      0x00000024
  R15 (PC)      0x00000014
  CPSR          0x000000D3
  SPSR          0x00000000
User/System
Fast Interrupt
Interrupt
Supervisor
Abort
```

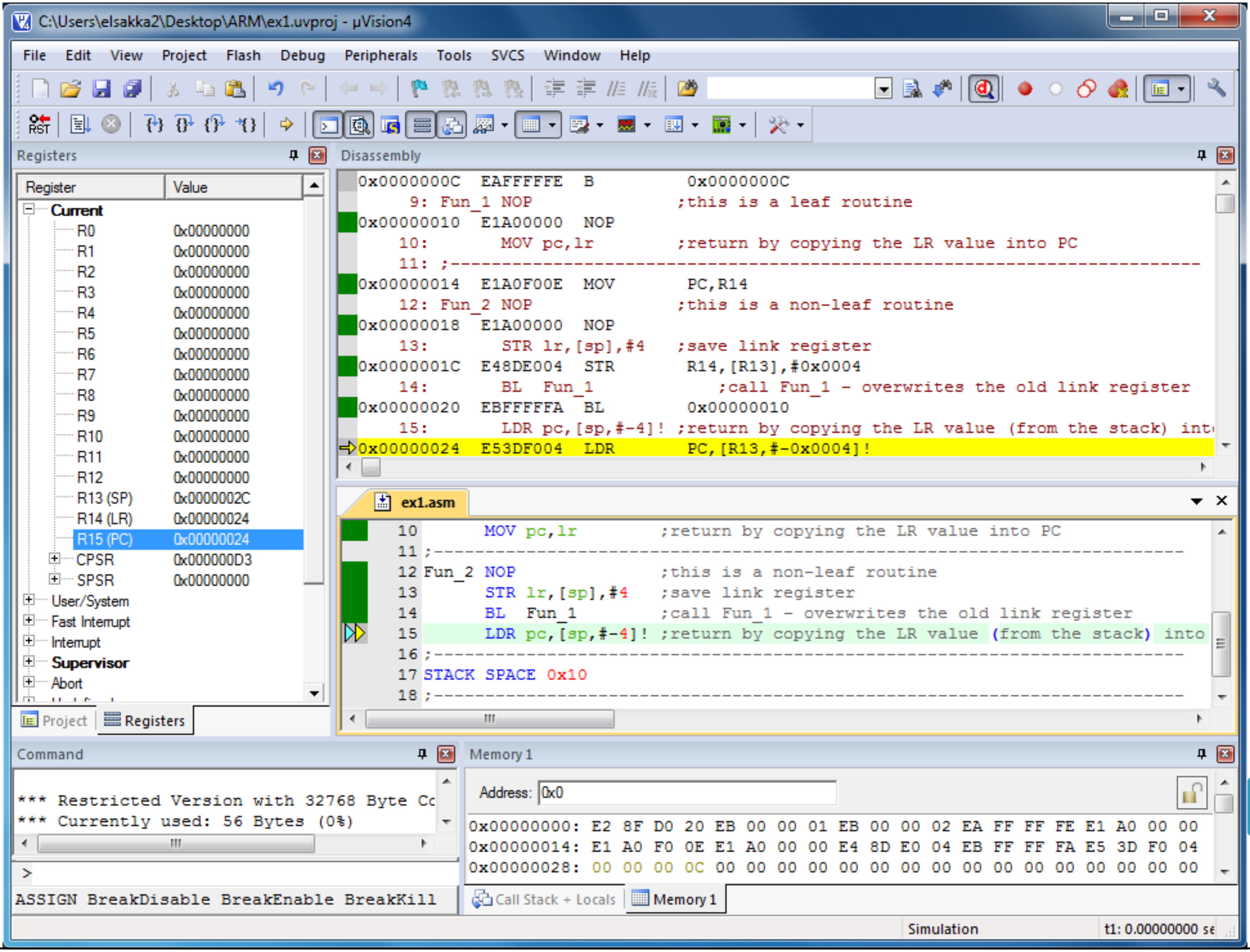
```
0x00000010  E1A00000  NOP
    10:       MOV pc,lr         ;return by copying the LR value into PC
    11: ;-------------------------------------------------------------------
0x00000014  E1A0F00E  MOV       PC,R14
    12: Fun_2 NOP               ;this is a non-leaf routine
0x00000018  E1A00000  NOP
    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) int
0x00000024  E53DF004  LDR       PC,[R13,#-0x0004]!
0x00000028  0000000C  ANDEQ     R0,R0,R12
```

```
       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 link register
       LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into
```

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

>
ASSIGN BreakDisable BreakEnable BreakKill
```

```
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
```

Leaf routines



C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
Registers
Disassembly
ex1.asm
Project
Registers
Command
Memory 1
Call Stack + Locals
Memory 1
Simulation
t1: 0.00000000 se

Register	Value
Current	
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)	0x00000024
R15 (PC)	0x00000024
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	
Abort	

```
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) int
0x00000024  E53DF004  LDR      PC,[R13,#-0x0004]!
```

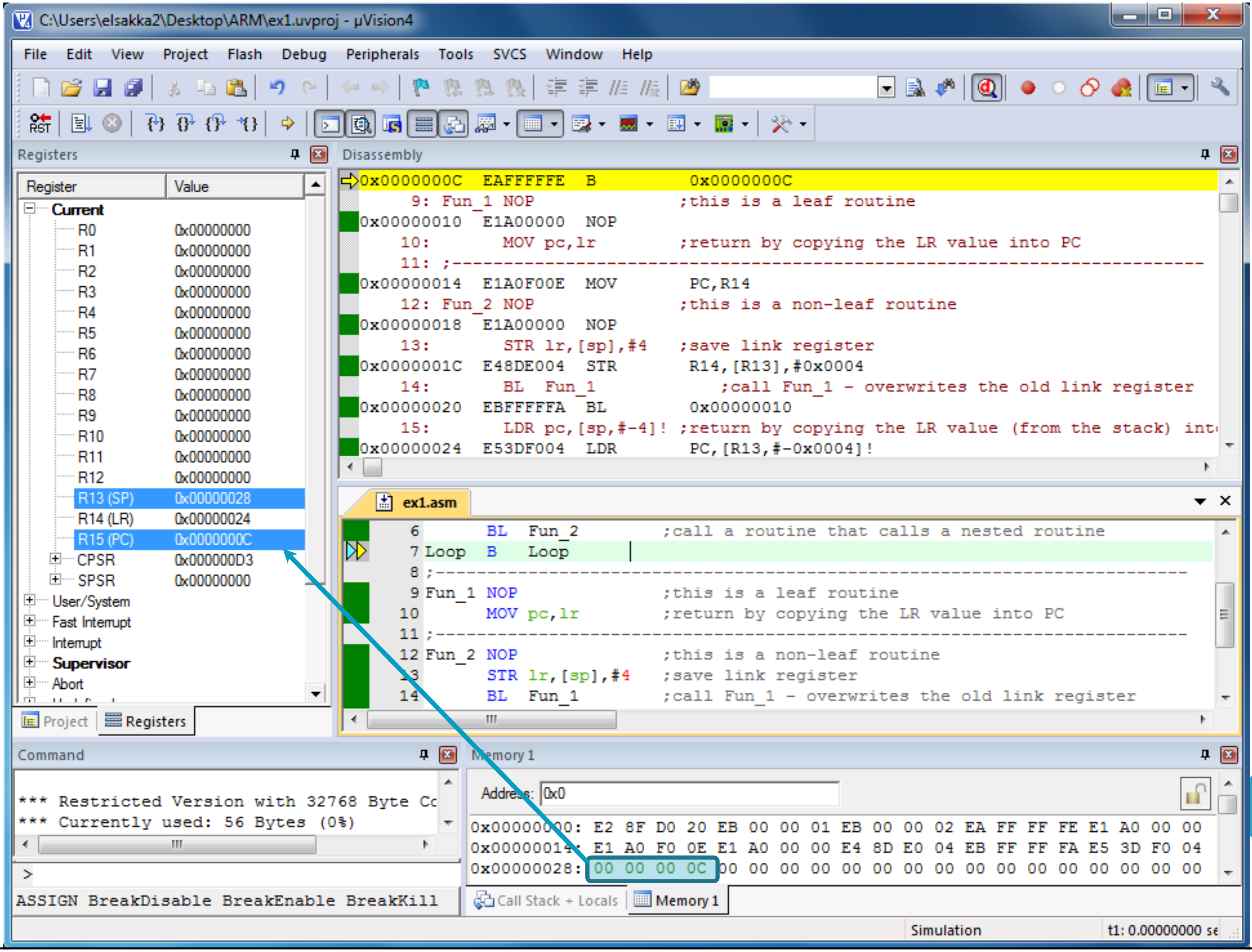
```
10       MOV pc,lr          ;return by copying the LR value into PC
11 ;---------------------------------------------------------------------
12 Fun_2 NOP                ;this is a non-leaf routine
13       STR lr,[sp],#4     ;save link register
14       BL  Fun_1          ;call Fun_1 - overwrites the old link register
15       LDR pc,[sp,#-4]! ;return by copying the LR value (from the stack) into
16 ;---------------------------------------------------------------------
17 STACK SPACE 0x10
18 ;---------------------------------------------------------------------
```

```
*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)
>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 00 00 00 00
```

Leaf routines



C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
Registers
Disassembly
ex1.asm
Project
Registers
Command
Memory 1
Call Stack + Locals
Simulation
t1: 0.00000000 se

Register	Value
Current	
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
User/System	
Fast Interrupt	
Interrupt	
Supervisor	
Abort	

```
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) int
0x00000024  E53DF004  LDR        PC,[R13,#-0x0004]!
```

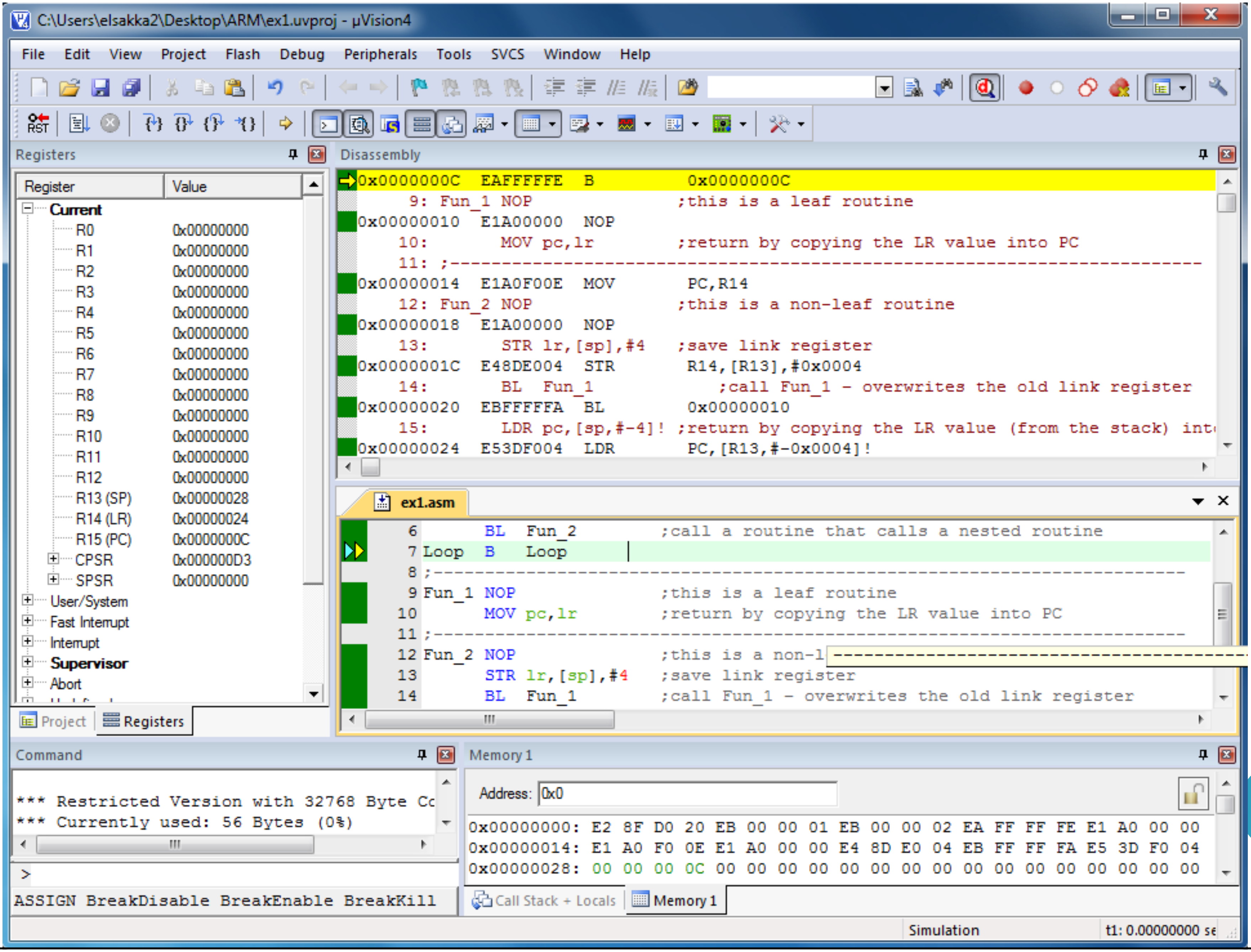
```
        BL    Fun_2          ;call a routine that calls a nested routine
Loop    B     Loop
;-----------------------------------------------------------------------
Fun_1   NOP                  ;this is a leaf routine
        MOV   pc,lr          ;return by copying the LR value into PC
;-----------------------------------------------------------------------
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 link register
```

```
*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)
>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 00 00 00 00
```

Leaf routines



C:\Users\elsakka2\Desktop\ARM\ex1.uvproj - µVision4

Register	Value
Current	
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
User/System	
Fast Interrupt	
Interrupt	
Supervisor	
Abort	

Disassembly:

```
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) int
0x00000024  E53DF004  LDR       PC,[R13,#-0x0004]!
```

ex1.asm:

```
      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-l-----------------------------
      STR lr,[sp],#4      ;save link register
      BL   Fun_1          ;call Fun_1 - overwrites the old link register
```

Command:

```
*** Restricted Version with 32768 Byte Cc
*** Currently used: 56 Bytes (0%)
>
ASSIGN BreakDisable BreakEnable BreakKill
```

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 0C 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

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
```

store
ST

multiple full descending
M F D

Load
LD

STMFD SP!, {R0~R7, LR}

← R0-R7,

start-add = sp - 9·4   9registers are push into the stack.

end-add = SP - 4 ← top of the stack: 1 position.

LDMFD SP!, {R0~R7, LR}

start_add = SP

end-add = sp + 9·4.

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:

SP

```
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