Functions (10A)

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Based on

ARM System-on-Chip Architecture, 2^{nd} ed, Steve Furber

Introduction to ARM Cortex-M Microcontrollers
– Embedded Systems, Jonathan W. Valvano

Digital Design and Computer Architecture,
D. M. Harris and S. L. Harris

https://thinkingeek.com/arm-assembler-raspberry-pi/

Instructions for procedures

B {cond} label ; branch to label
BX {cond} Rm ; branch indirect to location specified by **Rm**
BL {cond} label ; branch to *subroutine* at label
BLX{cond} Rm ; branch to *subroutine* indirect specified by **Rm**

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BL (Branch and Link)

BL {cond} label ; branch to *subroutine* at label

The call to subroutine instruction
The address of the subroutine is specified by the label

Saves the the return address
(the address of the next instruction)
in the **LR** (Link Register, **R14**)

The range of the BL instruction is
-16MB to +16MB from the current instruction

May use W suffix to get the maximum branch range (width selection)

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BX (Branch eXchange)

BX {cond} Rm ; branch indirect to location specified by **Rm**

A branch indirect instruction

The branch instruction is specified by **Rm**

This instruction causes a UsageFault exception
If bit[0] of **Rm** is 0

Rm[0] = 1, the processor switched to the Thumb execution mode
Rm[1] = 0, the processor continues to the ARM execution mode

To return from subroutine

```
BX      LR
MOV     PC, LR
```

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Instructions for procedures

```
uint32_t    Num;

void Change1(void) {
    Num = Num + 25;
}

void main(void) {
    Num = 0;
    while (1) {
      Change1();
    }
}
```

```
uint32_t    Num;

void Change2(void) {
    if (Num <25600) {
        Num = Num + 25;
    }
}

void main(void) {
    Num = 0;
    while (1) {
        Change2();
    }
}
```

```
uint32_t    Num;

void Change3(void) {
    if (Num <100) {
        Num = Num + 1;
    } else {
        Num = -100;
    }
}

void main(void) {
    Num = 0;
    while (1) {
        Change3();
    }
}
```

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My notations

uint32_t Num =0;

address &NUM — content Num

In C,
Num is a content of a location

NUM **EQU** 0

address NUM — 0

In assembly,
NUM is an address of a location

```
LDR     R1, =Num  ; R1 = Num
```

considering R1
as the content of a location

then the value of the content R1 is
the address NUM

R1

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Using Change1 function

```
Change1:  LDR   R1, =Num        ; 5) R1 = Num (address)
          LDR   R0, [R1]        ; 6) R0 = [Num] (content)
          ADD   R0, R0, #25     ; 7) R0 = [Num] + 25
          STR   R0, [R1]        ; 8) [Num] = [Num] + 25
          BX    LR              ; 9) return

Main:     LDR   R1, =Num        ; 1) R1 = Num (address)
          MOV   R0, #0          ; 2) R0 = 0
          STR   R0, [R1]        ; 3) [Num] = 0
Loop:     BL    Change1         ; 4) call to Change
          B     Loop            ; 10) repeat
```

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Using Change2 function

```
Change2:  LDR   R1, =Num        ; R1 = Num
          LDR   R0, [R1]        ; R0 = [Num]
          CMP   R0, #25600      ;
          BHS   skip
          ADD   R0, R0, #25     ; R0 = [Num] + 25
          STR   R0, [R1]        ; [Num] = [Num] + 25
Skip:     BX    LR              ; return

Main:     LDR   R1, =Num        ; R1 = Num
          MOV   R0, #0          ; R0 = 0
          STR   R0, [R1]        ; [Num] = 0
Loop:     BL    Change2         ; call to Change
          B     Loop            ; repeat
```

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Using Change3 function

```
Change3:  LDR   R1, =Num       ; R1 = Num
          LDR   R0, [R1]       ; R0 = [Num]
          CMP   R0, #100       ;
          BGE   else
          ADD   R0, R0, #1     ; [Num] = [Num] + 1
          B     skip
else:     MOV   R0, #-100      ; R0 = -100
skip :    STR   R0, [R1]       ; [Num] = [Num] + 1 or -100
          BX    LR             ; return

Main:     LDR   R1, =Num       ; R1 = Num
          MOV   R0, #0         ; R0 = 0
          STR   R0, [R1]       ; [Num] = 0
Loop:     BL    Change3        ; call to Change
          B     Loop           ; repeat
```

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Pointer access to an array

Supporting Procedures

1. put parameters in a place where the procedure can access them
2. transfer control to the procedure
3. acquire the storage resources needed for the procedure
4. perform the desired task
5. put the result value in a place where the calling program can access it
6. return control to the points of origin, since a procedure can be called
   from several points in a program

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Argument registers and return register

R0, **R1**, **R2**, **R3** : four argument registers to pass parameters

Func (arg1, arg2, arg3, arg4)

R0 **R1** **R2** **R3**

the callee assumes that the caller provides
the necessary arguments in registers **R0**, **R1**, **R2**, **R3**

When more than 4 arguments are passed,
the extra arguments are passed on the stack,

the **SP** points to them at the entry to the function.

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Link register

LR : one link register containing the return address register
to the point of origin

The ***link*** portion of the name **LR** means that
an address or link is formed
that points to the calling site
to allow the procedure to return to the proper address

this link stored in register **LR** (**R14**) is called the return address

the return address is needed
because the same procedure could be called
from several parts of the program

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Instructions for procedures

BL ProcedureAddress

return address — ***BL*** *stores the return address to* ***LR*** *register*

PC+4 → LR

<u>transfer control</u> to the procedure

<u>jumps</u> to an address and simultaneously <u>saves</u> (links) the address of the following instruction in register **LR**

MOV PC, LR

<u>return control</u> to the points of origin

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Passing Arguments

```
int main (void)
{
        …
        leaf_example (1, 2, 3, 4);
        …
}
```

; g : **R0**, h : **R1**, i : **R2**, j : **R3**

```
MOV     R0, #1          ; g = 1
MOV     R1, #2          ; h = 2
MOV     R2, #3          ; i  = 3
MOV     R3, #4          ; j  = 4

BL      leaf_example
```

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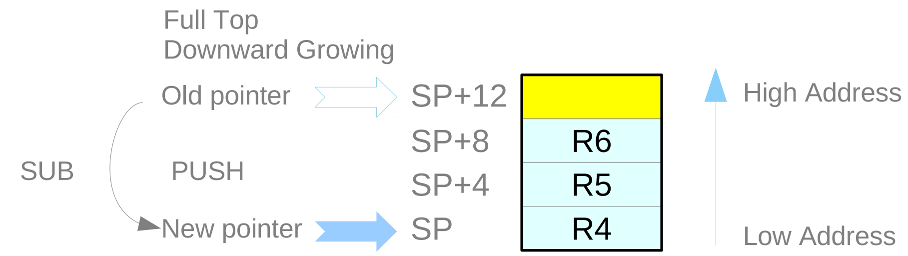
Function Prologue

```
int leaf_example (int g, int h, int i, int j)
{
        int f;
        f = (g + h) - (i+j);
        return f;
}
```



; g : **R0**, h : **R1**, i : **R2**, j : **R3**

```
SUB    SP, SP, #12     ; adjust stack to make room for 3 items
STR    R6, [SP, #8]    ; save register R6 for a later use    ; (g+h) - (i+j)
STR    R5, [SP, #4]    ; save register R5 for a later use    ; (i+j)
STR    R4, [SP, #0]    ; save register R4 for a later use    ; (g+h)
```

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Function Body

```
int leaf_example (int g, int h, int i, int j)
{
      int f;
      f = (g + h) - (i+j);
      return f;
}
```

```
ADD     R5, R0, R1        ; R5 = g + h
ADD     R6, R2, R3        ; R6 = i + j
SUB     R4, R5, R6        ; R4 = R5 - R6

MOV     R0, R4            ; returns f (R0 = R4)
```

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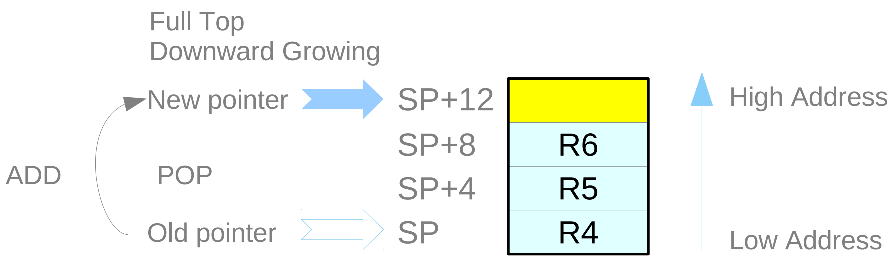
Function Epilogue

```
int leaf_example (int g, int h, int i, int j)
{
        int f;
        f = (g + h) - (i+j);
        return f;
}
```




```
LDR     R4, [SP, #0]     ; restore R4 for the caller
LDR     R5, [SP, #4]     ; restore R5 for the caller
LDR     R6, [SP, #8]     ; restore R6 for the caller
ADD     SP, SP, #12      ; adjust stack t delete 3 items

MOV     PC, LR           ; jump back to calling procedure
```

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Argument, scratch, variable, return result registers

R0, **R1**, **R2**, **R3**, **R12** :

argument or scratch registers
that are <u>not preserved</u> by the **callee** on a procedure call

R4, **R5**, **R6**, **R7**, **R8**, **R9**, **R10**, **R11** :

8 variable registers that <u>must be preserved</u> on a procedure call
(if used, the **callee** must save and restore them)

R0, **R1** :

return result registers
The called performs the calculations,
places the result (if any) in **R0** and **R1**
and returns control to the caller using **MOV PC, LR**

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Argument, scratch, variable, return result registers

Registers that is preserved across a procedure

- variable registers **r4 – r11**
- stack pointer register **sp**
- link register **lr**
- stack above the stack pointer

Registers that is not preserved across a procedure

- argument registers **r0 – r3**
- intra procedure call scratch register **r12**
- stack below the stack pointer

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ARM Register Conventions

Names	Reg No	Usage	preserved
a1-a2	0-1	Argument / return result/ scratch register	no
a3-a4	2-3	Argument / scratch register	no
v1-v8	4-11	Variables for local routine	yes
ip	12	Intra procedure call scratch register	no
sp	13	Stack pointer	yes
lr	14	Link register (Return address)	yes
pc	15	Program counter	n.a.

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Calling Convention (ARM32)

in the prologue, **push r4 ~ r11** to the stack,
push the return address in **r14** to the stack
(this can be done with a single **STM** instruction)

scratch registers to be used
LR

copy any passed arguments (in **r0 ~ r3**)
to the local scratch registers (**r4 ~ r11**);

r0 ~ r3 **r4 ~ r11**

allocate other local variables to the remaining
local scratch registers (**r4 ~ r11**);

r4 ~ r11

using **BL**, do calculations and / or call other subroutines
assuming **r0 ~ r3**, **r12** and **r14** will not be preserved;

put the result in **r0**;

In the epilogue, pop **r4 ~ r11** from the stack,
and pull the return address to the program counter **r15.**
(this can be done with a single **LDM** instruction)

https://en.wikipedia.org/wiki/Calling_convention#ARM_(A32)

PUSH, POP Synonyms

```
PUSH{cond}  reglist
POP{cond}   reglist
```

```
Synonyms
PUSH  =  STMDB R13!                  = STMFD R13!
POP   =  LDMIA R13! or even LDM      = LDMFD R13!
```

Assume

the base register SP (R13)

the adjusted address written back to the base register

registers are stored on the stack in numerical order

with the lowest numbered register at the lowest address.

Full Descending Stack with SP (=R13)

More than 4 arguments

the extra arguments are passed on the stack,
the SP points to them at the entry to the function.
In the prolog, you're pushing registers to be saved,
and this changes the SP, so you need to account for it.

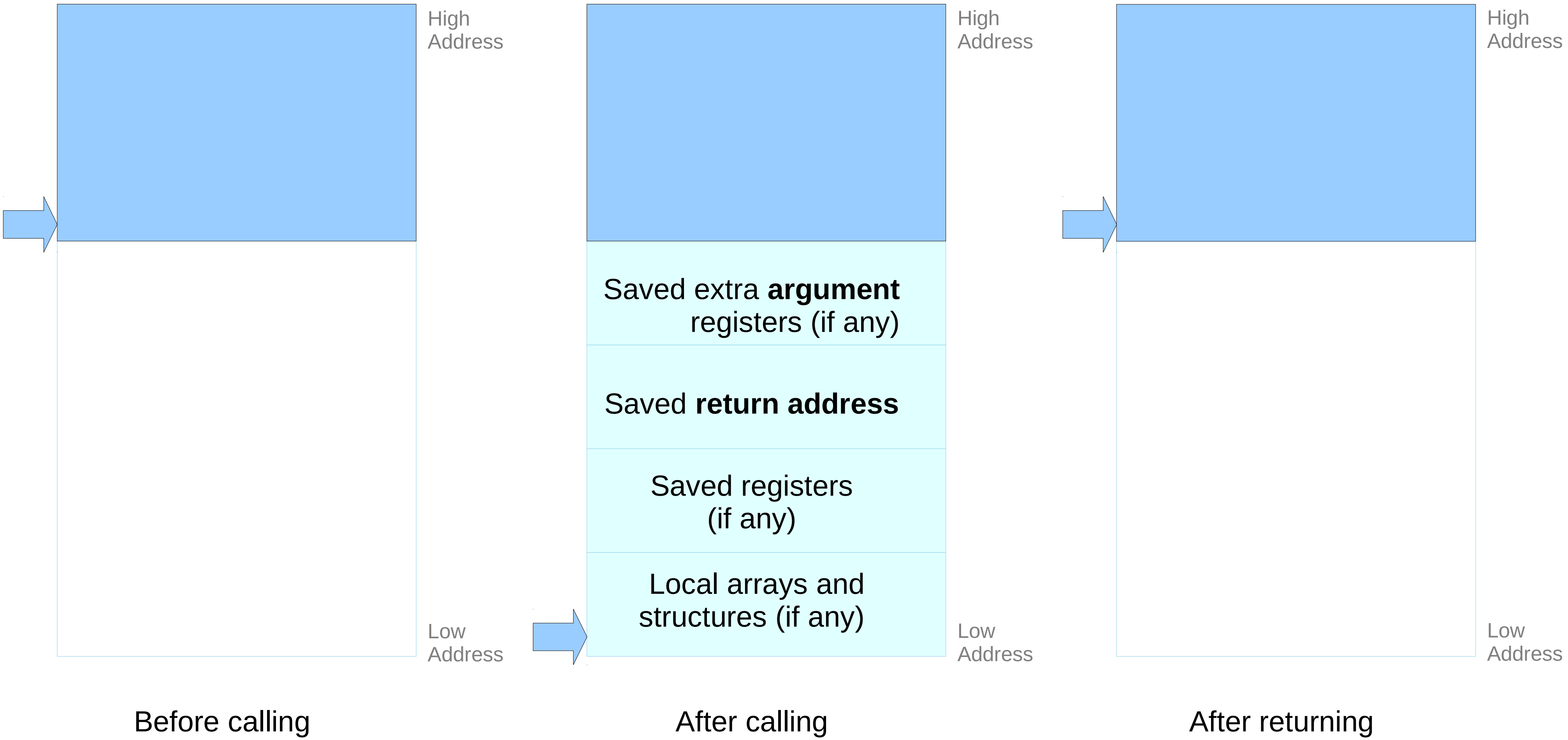
r4, **r5**, **r6**, **r7**, **r8** and **lr** are 6 registers,
so you need to adjust your SP offsets
by 6*4 = 24 bytes.

```
push {r4-r8,lr}          // 6 regs are pushed    // SP is decremented by 6*4 = 24 bytes
ldr r6, [sp, #(0+24)]    // get first stack arg
ldr r7, [sp, #(4+24)]    // get second stack arg
```

If you do more manipulations with SP, e.g. allocate space for stack vars, you might have to take that into account too.

https://stackoverflow.com/questions/15071506/how-to-access-more-than-4-arguments-in-an-arm-assembly-function

Stack allocation



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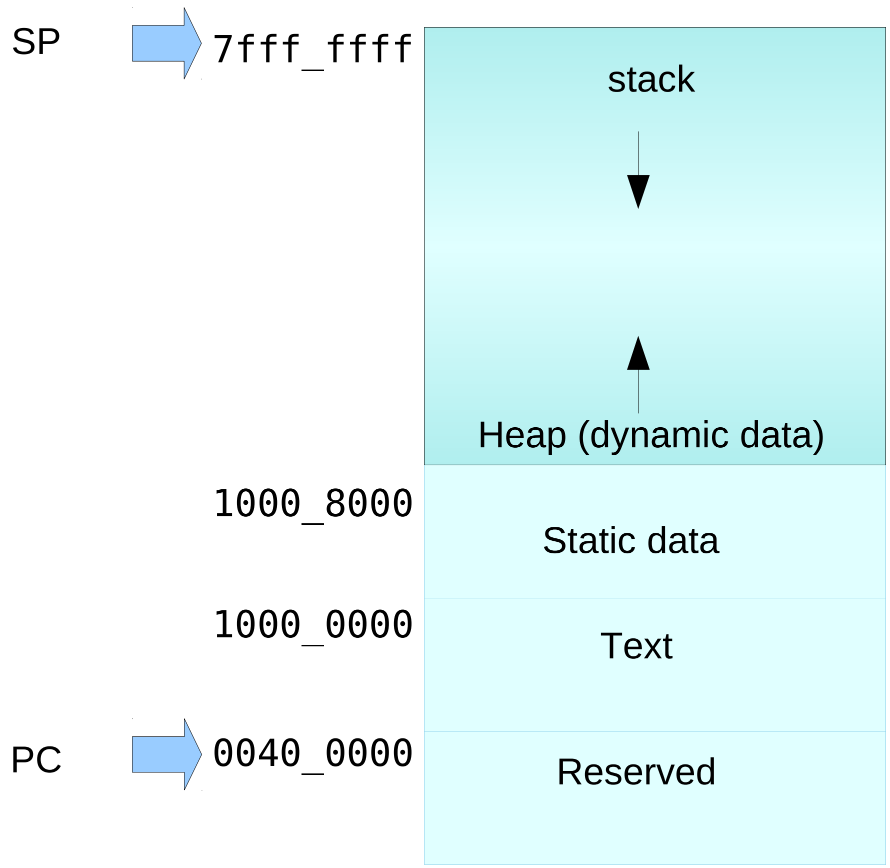
Memory map



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Recursive procedure

```
int fact (int n)
{
    if (n < 1) return (1);
    else return (n * fact(n-1));
}
```

```
    fact(3)
                fact(2)
                            fact(1)
                            return(1)
                return(2*1)
    return(3*2)
```

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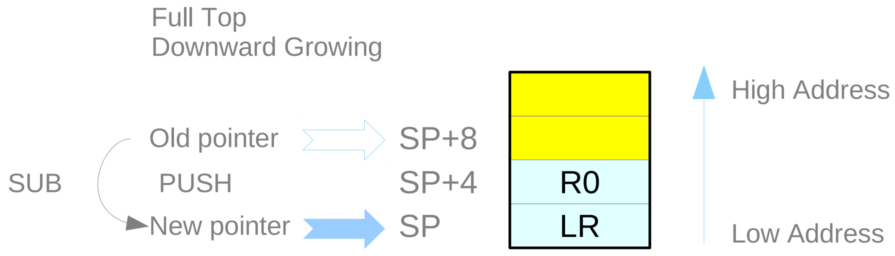
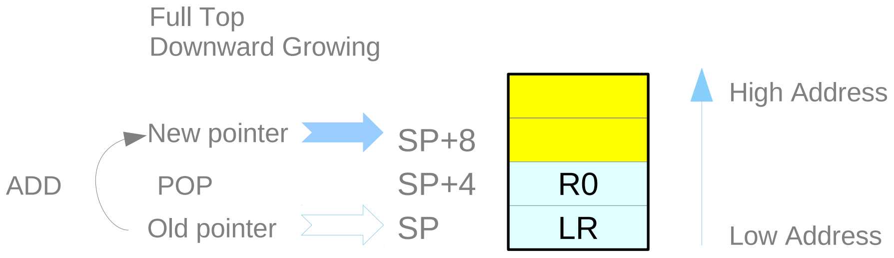
Recursive procedure

```
fact:
        SUB     SP, SP, #8          ; adjust stack for 2 items
        STR     LR, [SP, #0]        ; save the return address
        STR     R0, [SP, #4]        ; save the argument n

        CMP     R0, #1              ; compare n to 1
        BGE     L1                  ; if n >= 1, go to L1

        MOV     R0, #1              ; return 1
        ADD     SP, SP, #8          ; pop 2 items off stack
        MOV     PC, LR              ; return to the caller
```





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Recursive procedure

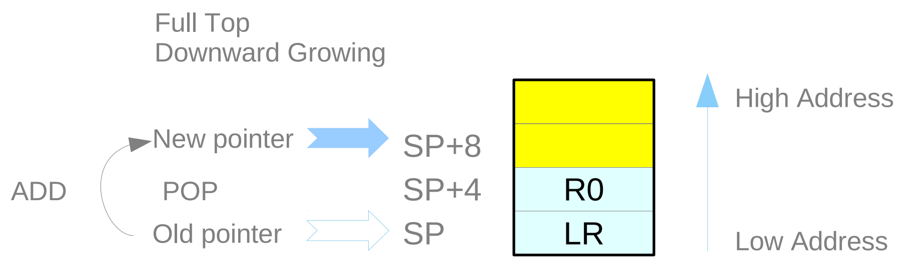
```
L1:
        SUB     R0, R0, #1          ; n >= 1 argument gets (n-1)
        BL      fact                ; call fact with (n-1)

        MOV     R12, R0             ; save the return value
        LDR     R0, [SP, #4]        ; return from BL ; restore argument n
        LDR     LR, [SP, #0]        ; restore the return address
        ADD     SP, SP, #8          ; adjust stack pointer to pop 2 items

        MUL     R0, R0, R12         ; return n * fact (n-1)
        MOV     PC, LR              ; return to the caller
```

Using a BL procedure call and a stack

R12 : IP Intra procedure call scratch register



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Recursive procedure

```
fact:   SUB  SP, SP, #8        ; adjust stack for 2 items
        STR  LR, [SP, #0]      ; save the return address
        STR  R0, [SP, #4]      ; save the argument n

        CMP  R0, #1            ; compare n to 1
        BGE  L1                ; if n >= 1, go to L1

        MOV  R0, #1            ; return 1
        ADD  SP, SP, #8        ; pop 2 items off stack
        MOV  PC, LR            ; return to the caller

L1:     SUB  R0, R0, #1        ; n >= 1 argument gets (n-1)
        BL   fact              ; call fact with (n-1)

        MOV  R12, R0           ; save the return value
        LDR  R0, [SP, #4]      ; return from BL ; restore argument n
        LDR  LR, [SP, #0]      ; restore the return address
        ADD  SP, SP, #8        ; adjust stack pointer to pop 2 items

        MUL  R0, R0, R12       ; return n * fact (n-1)
        MOV  PC, LR            ; return to the caller
```

Using a BL procedure call and a stack

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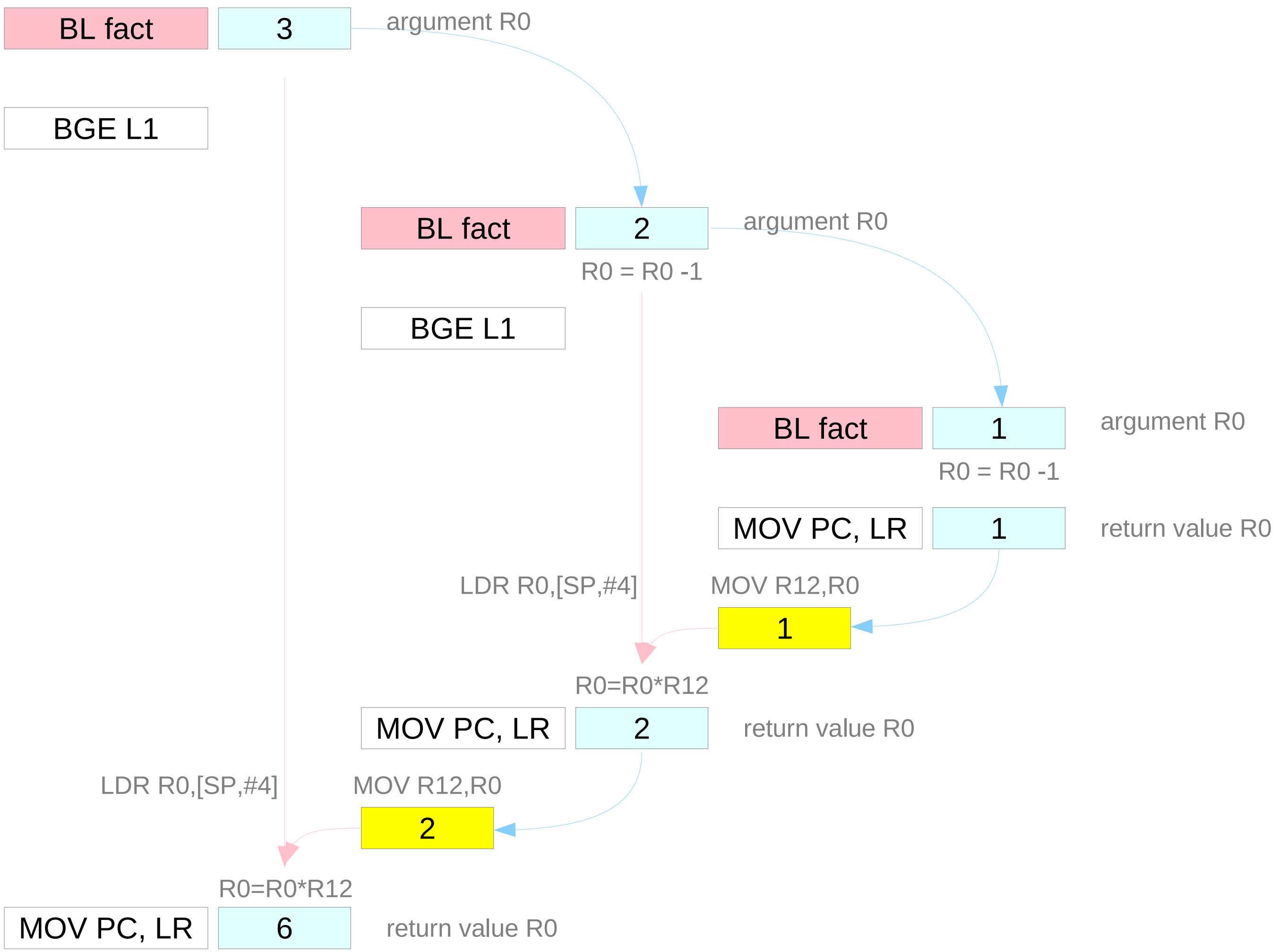
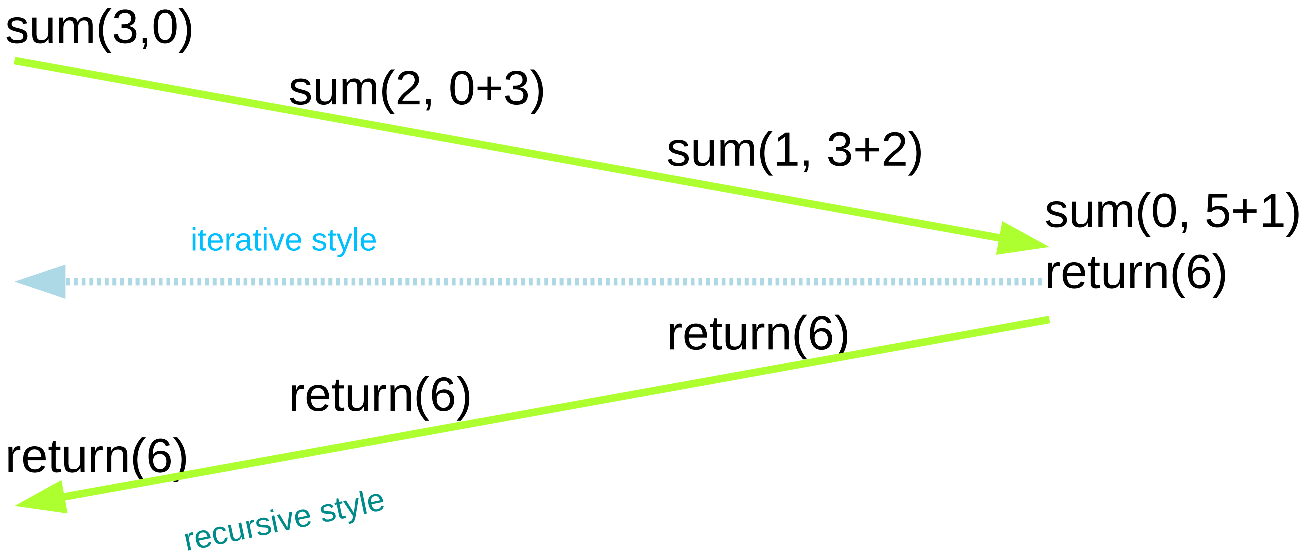
Recursive procedure



Recursive Procedure and Iterative Implementation

```
int sum (int n, int acc) {
    if (n > 0)
        return sum(n-1, acc+n);
    else
        return acc;
}
```



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Recursive Procedure and Iterative Implementation

```
sum:        CMP     R0, #0           ; test if n <= 0
            BLE     sum_exit         ; go to sum_exit if n <= 0;
            ADD     R1, R1, R0       ; add n to acc
            SUB     R0, R0, #1       ; subtract 1 from n
            B       sum              ; go to sum
sum_exit:
            MOV     R0, R1           ; return value acc
            MOV     PC, LR           ; return to caller
```

No BL procedure call

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String Copy Procedure

```
void strcpy (char x[], char y[])
{
    int i;

    i = 0;
    while ((x[i] = y[i]) != '\0')        // copy & test byte
        i += 1;
}
```

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String Copy Procedure

```
strcpy:  SUB    SP, SP, #4         ; adjust stack for 1 more item
         STR    R4, [SP, #0]       ; save R4
         MOV    R4, #0             ; i = 0 + 0
L1:      ADD    R2, R4, R1         ; address of y[i] in R2
         LDRBS  R3, [R2, #0]       ; R3 = y[i] and set condition flag
         ADD    R12, R4, R0        ; addressof x[i] in r12
         STRB   R3, [R12, #0]      ; x[i] = y[i]
         BEQ    L2                 ; if y[i] == 0, go to L2
         ADD    R4, R4, #1         ; i = i+1
         B      L1                 ; go to L1
L2       LDR    R4, [SP, #0]       ; y[i] == 0 : end of string, restore old R4
         ADD    SP, SP, #4         ; pop 1 word off stack
         MOV    PC, LR             ; return
```

No BL procedure call

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Swap (1)

```
void swap(int v[], int k)
{
    int temp;
    temp = v[k];
    v[k] = v[k+1];
    v[k+1] = temp;
}
```

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Swap (2) - using RN directive

```
v       RN  0   ; 1st argument address of v
k       RN  1   ; 2nd argument index k
temp    RN  2   ; local variable
temp2   RN  3   ; temporary for v[k+1]
vkAddr  RN  12  ; to hold address of v[k]
```

R0	v	; 1st argument address of v
R1	k	; 2nd argument index k
R2	temp	; local variable
R3	temp2	; temporary for v[k+1]
R12	vkAddr	; to hold address of v[k]

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Swap (3)

```
swap:   ADD     vkAddr, v, k, LSL #2        ; reg vkAddr = v + (k * 4)
                                            ; reg vkAddr has the address of v[k]
        LDR     temp, [vkAddr, #0]          ; temp = v[k]
        LDR     temp2, [vkAddr, #4]         ; temp2 = v[k+1]
                                            ; refers to next element of v
        STR     temp2, [vkAddr, #0]         ; v[k] = temp2
        STR     temp, [vkAddr, #4]          ; v[k+1] = temp

        MOV     PC, LR                      ; return to calling routine
```

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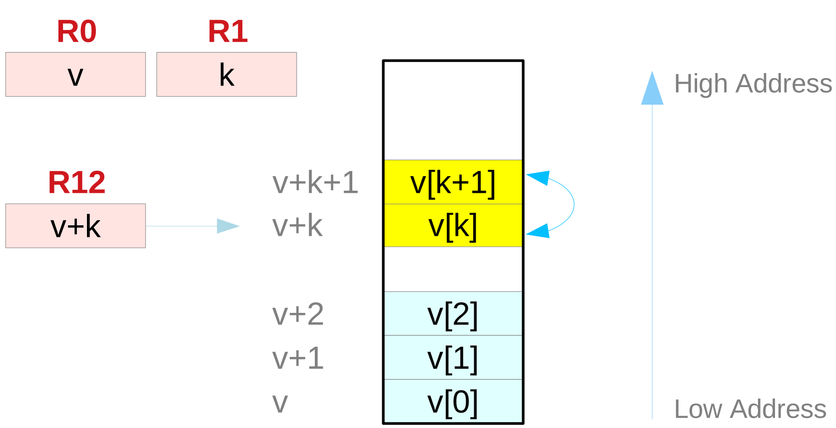
Swap (4)

```
swap:   ADD     R12, R0, R1, LSL #2     ; reg vkAddr = v + (k * 4)
                                        ; reg vkAddr has the address of v[k]
        LDR     R2, [R12, #0]           ; temp = v[k]
        LDR     R3, [R12, #4]           ; temp2 = v[k+1]
                                        ; refers to next element of v
        STR     R3, [R12, #0]           ; v[k] = temp2
        STR     R2, [R12, #4]           ; v[k+1] = temp

        MOV     PC, LR                  ; return to calling routine
```



R0	v	; 1st argument address of v
R1	k	; 2nd argument index k
R2	temp	; local variable
R3	temp2	; temporary for v[k+1]
R12	vkAddr	; to hold address of v[k]

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Sort (1)

```
void sort(int v[], int n)
{
    int i, j;
    for (i=0, i<n,  ++i) {
        for (j=i-1; j >= 0 && v[j] > v[j+1]) ; --j) {
            swap(v, j);
        }
    }
}
```

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Sort (2) – using RN directive

```
v       RN  0    ; 1st argument address of v
n       RN  1    ; 2nd argument index n
i       RN  2    ; local variable i
j       RN  3    ; local variable j
vjAddr  RN  12   ; to hold address of v[j]
vj      RN  4    ; to hold a copy of v[j]
vj1     RN  5    ; to hold a copy of v[j+1]
vcopy   RN  6    ; to hold a copy of v
ncopy   RN  7    ; to hold a copy of n
```

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Sort (3) outer loop

```
for (i=0, i<n,  ++i)
```

```
          MOV    i, #0            ; i =0
for1tst:  CMP    i, n             ; if i > n
          BGE    exit1            ; go to exit1 if i >= n
          * * *
          body of 1st for loop
          * * *
          ADD    i, i, #1         ; i += 1
          B      for1tst          ; branch to test of outer loop


exit1:           // restoring the registers
```

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Sort (4) inner loop

for (j=i-1; j >= 0 && v[j] > v[j+1]) ; --j)

```
          SUB   j, i, #1                 ; j = i -1
for2tst:  CMP   j, #0                    ; if j < 0
          BLT   exit2                    ; go to exit2 if j < 0
          ADD   vjAddr, v, j, LSL #2     ; reg vjAdr = v + (j * 4)
          LDR   vj, [vjAddr, #0]         ; reg vj = v[j]
          LDR   vj1, [vjAddr, #4]        ; reg vj = v[j+1]
          CMP   vj, vj1                  ; if vj < vj1
          BLE   exit2                    ; go to  exit2 if vj < vj1
          * * *
          body of 2nd for loop
          * * *
          SUB   j, j, #1                 ; j -= 1
          B     for2tst                  ; branch to test of outer loop
exit2:    ADD   R2, R2, #1               ; i += 1
          B     for1tst                  ; branch to test of outer loop
```

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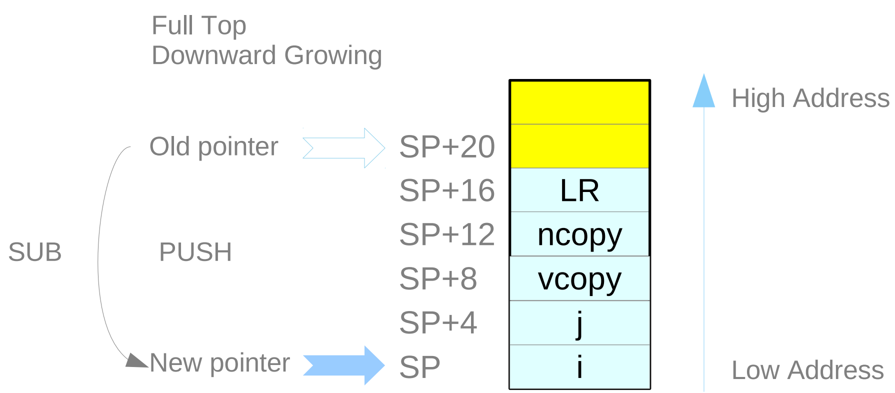
Sort (5) Saving registers

```
sort:   SUB    SP, SP, #20        ; make room on stack for 5 registers
        STR    LR, [SP, #16]      ; save LR on stack
        STR    ncopy, [SP, #12]   ; save ncopy on stack
        STR    vcopy, [SP, #8]    ; save vcopy on stack
        STR    j, [SP, #4]        ; save j on stack
        STR    i, [SP, #0]        ; save i on stack
```



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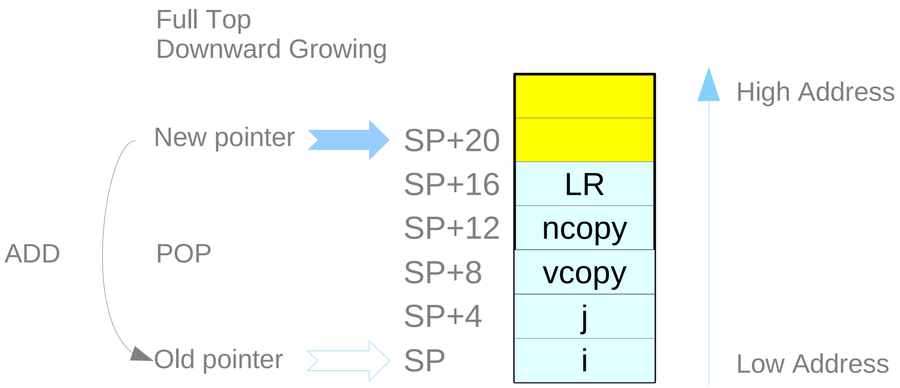
Sort (6) Restoring registers

```
exit1:  LDR   i, [SP, #0]          ; restore I from stack
        LDR   j, [SP, #4]          ; restore j from stack
        LDR   vcopy, [SP, #8]      ; restore vcopy from stack
        LDR   ncopy, [SP, #12]     ; restore ncopy from stack
        LDR   LR, [SP, #16]        ; restore LR from stack
        ADD   SP, SP, #20          ; restore stack pointer
```



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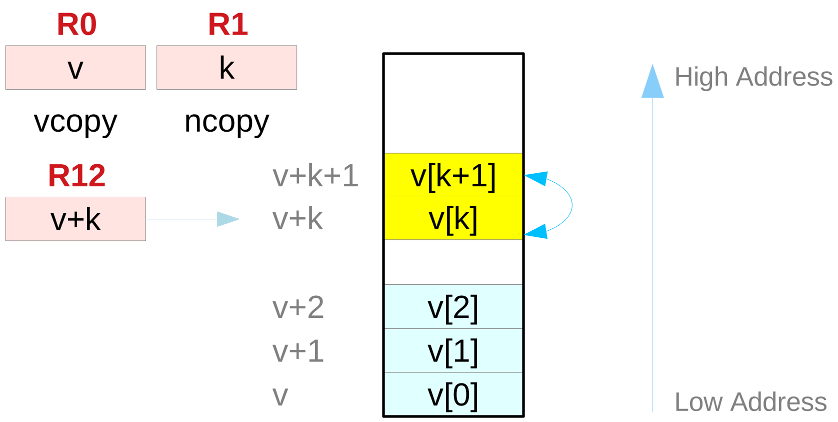
Sort (7) Calling swap

swap(v, j);

```
MOV    vcopy, v        ; copy parameter v into vcopy  (save R0)
MOV    ncopy, n        ; copy parameter n into ncopy  (save R1)

BL     swap

MOV    R0, vcopy       ; first swap parameter is v
MOV    R1, j           ; second swap parameter is j (new n)
```



Using a BL procedure call and a stack

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Sort full listing (1)

Saving Registers

```
sort:       SUB   SP, SP, #20          ; make room on stack for 5 registers
            STR   LR, [SP, #16]        ; save LR on stack
            STR   R7, [SP, #12]        ; save ncopy on stack
            STR   R6, [SP, #8]         ; save vcopy on stack
            STR   R3, [SP, #4]         ; save j on stack
            STR   R2, [SP, #0]         ; save i on stack
```

Procedure Body

```
for1tst:
for2tst:
exit2:
```

R2	i	; local variable i
R3	j	; local variable j
R6	vcopy	; to hold a copy of v
R7	ncopy	; to hold a copy of n

Restoring Registers

```
exit1:
```

Procedure Return

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Sort full listing (2)

Procedure Body

```
          MOV  R6, R0               ; copy parameter v into vcopy  (save R0)
          MOV  R7, R1               ; copy parameter n into ncopy  (save R1)
          MOV  R2, #0               ; i = 0
for1tst:  CMP  R2, R1               ; if i > n
          BGE  exit1                ; go to exit1 if i >= n
          SUB  R3, R2, #1           ; j = i -1
for2tst:  CMP  R3, #0               ; if j < 0
          BLT  exit2                ; go to exit2 if j < 0
          ADD  R12, R0, R3, LSL #2  ; reg vjAdr = v + (j * 4)
          LDR  R4, [R12, #0]        ; reg vj = v[j]
          LDR  R5, [R12, #4]        ; reg vj = v[j+1]
          CMP  R4, R5               ; if vj < vj1
          BLE  exit2                ; go to  exit2 if vj < vj1
          MOV  R0, R6               ; first swap parameter is v
          MOV  R1, R3               ; second swap parameter is j
          BL   swap
          SUB  R3, R3, #1           ; j -= 1
          B    for2tst              ; branch to test of outer loop
exit2:    ADD  R2, R2, #1           ; i += 1
          B    for1tst              ; branch to test of outer loop
```

R0	v	; 1st argument address of v
R1	n	; 2nd argument index n
R2	i	; local variable i
R3	j	; local variable j
R12	vjAddr	; to hold address of v[j]
R4	vj	; to hold a copy of v[j]
R5	vj1	; to hold a copy of v[j+1]
R6	vcopy	; to hold a copy of v
R7	ncopy	; to hold a copy of n

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Sort full listing (3)

Restoring Registers

```
exit1:  LDR   R2, [SP, #0]     ; restore i from stack
        LDR   R3, [SP, #4]     ; restore j from stack
        LDR   R6, [SP, #8]     ; restore vcopy from stack
        LDR   R7, [SP, #12]    ; restore ncopy from stack
        LDR   LR, [SP, #16]    ; restore LR from stack
        ADD   SP, SP, #20      ; restore stack pointer
```

Procedure Return

```
        MOV   PC, LR           ; return to calling routine
```

```
R2   i      ; local variable i
R3   j      ; local variable j
R6   vcopy  ; to hold a copy of v
R7   ncopy  ; to hold a copy of n
```

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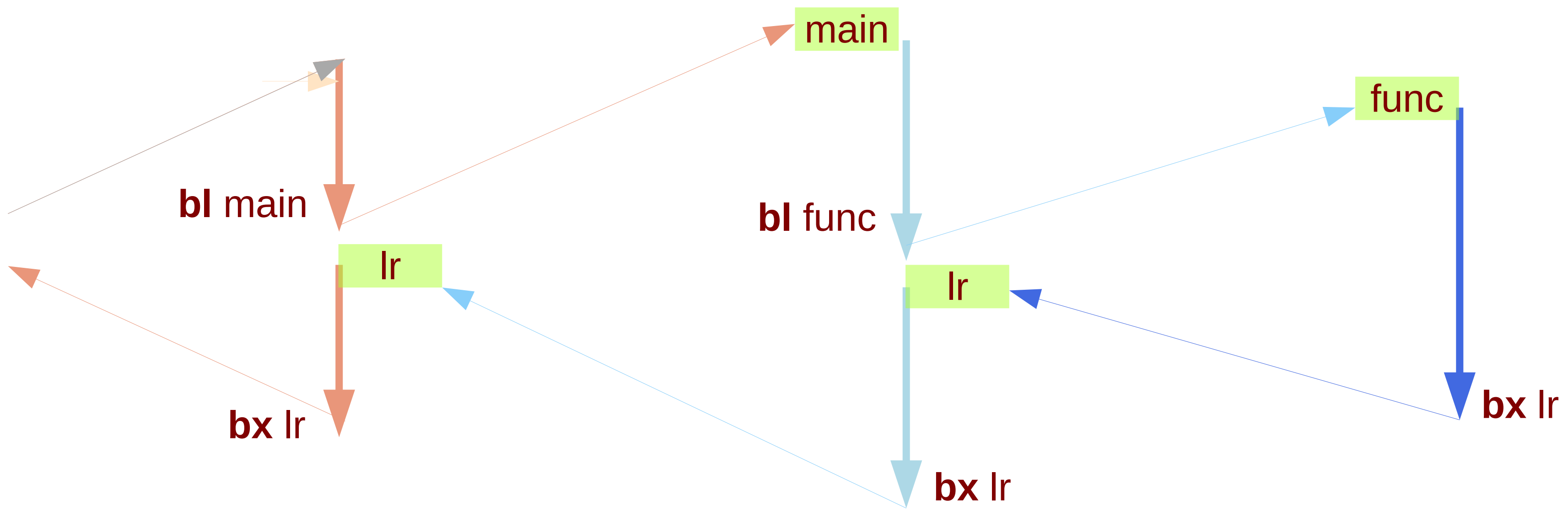
Saving and restoring of return address (1)

```
ldr r1, addr            ; r1 ← &address_of_return
str lr, [r1]            ; *r1 ← lr

bl func
                        ; lr ← address of next instruction
ldr r1, addr            ; r1 ← &address_of_return
ldr lr, [r1]            ; lr ← *r1
bx lr                   ; return from main
```

Nested function calls :
LR must <u>not</u> be overwritten



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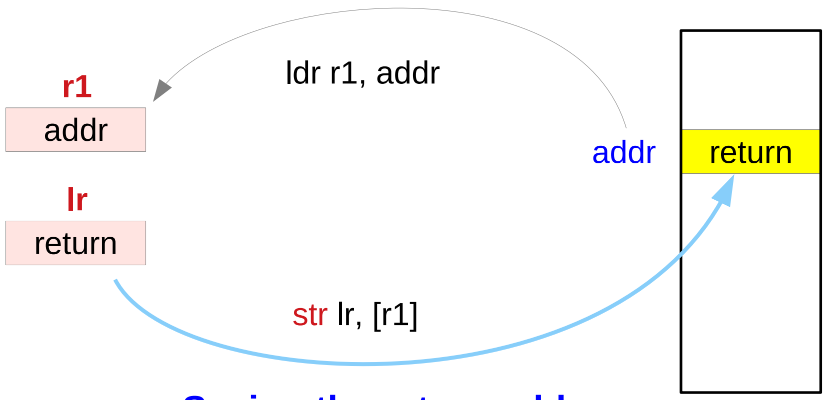
Saving and restoring of return address (2)

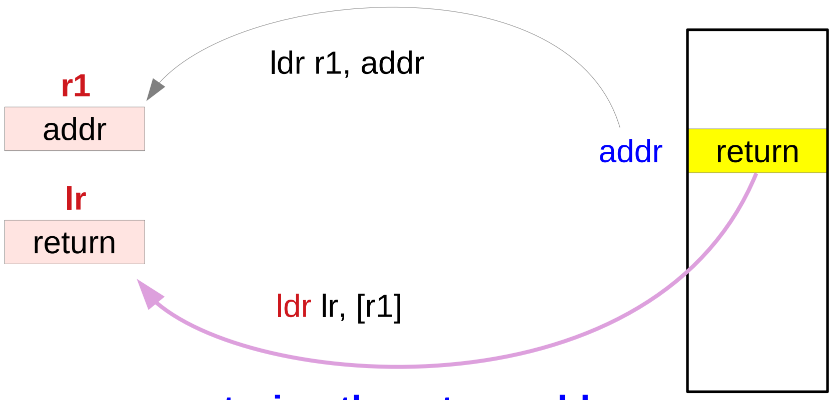
```
ldr r1, addr          ; r1 ← &address_of_return
str lr, [r1]          ; *r1 ← lr

bl func
                      ; lr ← address of next instruction
ldr r1, addr          ; r1 ← &address_of_return
ldr lr, [r1]          ; lr ← *r1
bx lr                 ; return from main
```

Instead of using a stack a memory location is used to save and restore LR



Saving the return address at addr



restoring the return address from addr

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Hello world (1)

```
; hello01.s
.data

greeting:
 .asciz "Hello world"

.balign 4
return: .word 0

.text
```

```
.global main
main:
    ldr r1, address_of_return          ;  r1 ← &address_of_return
    str lr, [r1]                       ;  *r1 ← lr

    ldr r0, address_of_greeting        ; r0 ← &address_of_greeting
                                       ; First parameter of puts

    bl puts                            ; Call to puts
                                       ; lr ← address of next instruction

    ldr r1, address_of_return          ; r1 ← &address_of_return
    ldr lr, [r1]                       ; lr ← *r1
    bx lr                              ; return from main

address_of_greeting:     .word greeting
address_of_return:       .word return

; External
.global puts
```

address	contents															
greeting	H	e	l	l	o		w	o	r	l	d	0				
return	0															

address	contents
address_of_greeting	greeting
address_of_return	return

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Hello world (2)

```
; printf01.s
.data

.balign 4
message1:        .asciz "Hey, type a number: "
                 ; First message

.balign 4
message2:        .asciz "I read the number %d\n"
                 ; Second message

.balign 4
scan_pattern :   .asciz "%d"
                 ; Format pattern for scanf

.balign 4
number_read:     .word 0
                 ; Where scanf will store the number read

.balign 4
return:          .word 0

.text

.global scanf
```

address	Byte 0 (LSByte)				Byte 1				Byte 2				Byte 3 (MSByte)			
message1	H	e	y	,		t	y	p	e		a		n	u	m	b
	e	r	:		0											
message2	I		r	e	a	d		t	h	e		n	u	m	b	e
	r		%	d	\	n	0									
scan_pattern	%	d	0													
number_read	0															
return	0															

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Hello world (3)

```
.global main
main:
    ldr r1, address_of_return          ; r1 ← &address_of_return
    str lr, [r1]                       ; *r1 ← lr

    ldr r0, address_of_message1        ; r0 ← &message1
    bl printf                          ; call to printf

    ldr r0, address_of_scan_pattern    ; r0 ← &scan_pattern
    ldr r1, address_of_number_read     ; r1 ← &number_read
    bl scanf                           ; call to scanf

    ldr r0, address_of_message2        ; r0 ← &message2
    ldr r1, address_of_number_read     ; r1 ← &number_read
    ldr r1, [r1]                       ; r1 ← *r1
    bl printf                          ; call to printf

    ldr r0, address_of_number_read     ; r0 ← &number_read
    ldr r0, [r0]                       ; r0 ← *r0

    ldr lr, address_of_return          ; lr ← &address_of_return
    ldr lr, [lr]                       ; lr ← *lr
    bx lr                              ; return from main using lr
```

```
message1:        .asciz "Hey, type a number: "
message2:        .asciz "I read the number %d\n"
scan_pattern :   .asciz "%d"
number_read:     .word 0
return:          .word 0
```

Using a BL procedure call
But no stack

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Hello world (4)

```
address_of_message1 :      .word message1
address_of_message2 :      .word message2
address_of_scan_pattern :  .word scan_pattern
address_of_number_read :   .word number_read
address_of_return :        .word return

; External
.global printf
```

address	contents
address_of_message1	message1
address_of_message2	message2
address_of_scan_pattern	scan_pattern
address_of_number_read	number_read
address_of_return	return

$ ./printf01
Hey, type a number: 123 ↴
I read the number 123

$ ./printf01 ; echo $?
Hey, type a number: 124 ↴
I read the number 124
124

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mult_by_5 function (1)

```
.balign 4
return2:            .word 0

.text

; mult_by_5 function

mult_by_5:
    ldr r1, address_of_return2          ; r1 ← &address_of_return
    str lr, [r1]                        ; *r1 ← lr

    add r0, r0, r0, LSL #2              ; r0 ← r0 + 4*r0

    ldr lr, address_of_return2          ; lr ← &address_of_return
    ldr lr, [lr]                        ; lr ← *lr
    bx lr                               ; return from main using lr

address_of_return2:     .word return2
```

address	contents
address_of_return2	return2

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mult_by_5 function (2)

```
; printf02.s
.data

.balign 4
message1:        .asciz "Hey, type a number: "
                 ; First message
.balign 4
message2:        .asciz "%d times 5 is %d\n"
                 ; Second message
.balign 4
scan_pattern :   .asciz "%d"
                 ; Format pattern for scanf
.balign 4
number_read:     .word 0
                 ; Where scanf will store the number read
.balign 4
return:          .word 0

.balign 4
return2:         .word 0
anf
```

	LSByte												MSByte			
	Byte 0				Byte 1				Byte 2				Byte 3			
address	contents															
message1	H	e	y	,		t	y	p	e		a		n	u	m	b
	e	r	:		0											
message2	%	d		t	i	m	e	s		5		%	d	\	n	0
scan_pattern	%	d	0													
number_read	0															
return	0															

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mult_by_5 function (3)

```
.global main
main:
    ldr r1, address_of_return          ; r1 ← &address_of_return
    str lr, [r1]                       ; *r1 ← lr

    ldr r0, address_of_message1        ; r0 ← &message1
    bl printf                          ; call to printf

    ldr r0, address_of_scan_pattern    ; r0 ← &scan_pattern
    ldr r1, address_of_number_read     ; r1 ← &number_read
    bl scanf                           ; call to scanf

    ldr r0, address_of_number_read     ; r0 ← &number_read
    ldr r0, [r0]                       ; r0 ← *r0
    bl mult_by_5

    mov r2, r0                         ; r2 ← r0
    ldr r1, address_of_number_read     ; r1 ← &number_read
    ldr r1, [r1]                       ; r1 ← *r1
    ldr r0, address_of_message2        ; r0 ← &message2
    bl printf                          ; call to printf

    ldr lr, address_of_return          ; lr ← &address_of_return
    ldr lr, [lr]                       ; lr ← *lr
    bx lr                              ; return from main using lr
```

```
message1:       .asciz "Hey, type a number: "
message2:       .asciz "%d times 5 is %d\n"
scan_pattern :  .asciz "%d"
number_read:    .word 0
return:         .word 0
return2:        .word 0
```

Using a BL procedure call
But no stack

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mult_by_5 function (4)

```
address_of_message1 :       .word message1
address_of_message2 :       .word message2
address_of_scan_pattern :   .word scan_pattern
address_of_number_read :    .word number_read
address_of_return :         .word return

; External
.global printf
```

address	contents
address_of_message1	message1
address_of_message2	message2
address_of_scan_pattern	scan_pattern
address_of_number_read	number_read
address_of_return	return

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Dynamic activation

```
int factorial(int n)
{
   if (n == 0)
      return 1;
   else
      return n * factorial(n-1);
}
```

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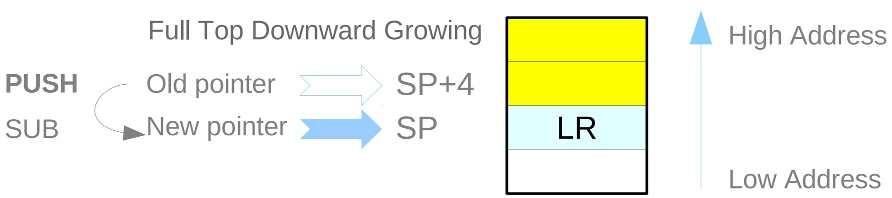
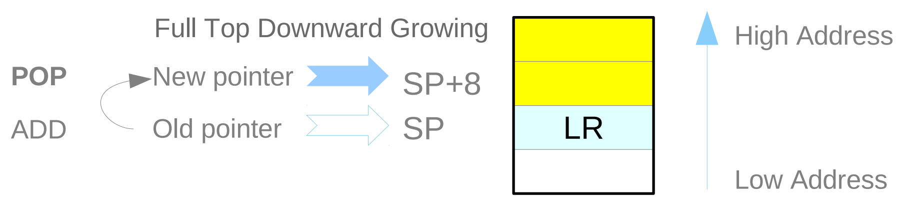
The stack

```
sub sp, sp, #4          ; sp ← sp - 4. This enlarges the stack by 8 bytes
str lr, [sp]            ; *sp ← lr

... // Code of the function

ldr lr, [sp]            ; lr ← *sp
add sp, sp, #4          ; sp ← sp + 4.
bx lr                   ; This reduces the stack by 8 bytes
                        ; effectively restoring the sp to its original value
```

```
str lr, [sp, #-4]!      ; preindex: sp ← sp - 4; *sp ← lr

... // Code of the function

ldr lr, [sp], #+4       ; postindex; lr ← *sp; sp ← sp + 4
bx lr
```





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Factorial implementation (1)

```
; factorial01.s
.data

message1:       .asciz "Type a number: "
format:         .asciz "%d"
message2:       .asciz "The factorial of %d is %d\n"

.text

factorial:

is_nonzero:

end:
```

LSByte | MSByte

address	Byte 0				Byte 1				Byte 2				Byte 3			
	contents															
message1	T	y	p	e		a		n	u	m	b	e	r	:	0	
format	%	d	0													
message2	T	h	e		f	a	c	t	o	r	i	a	l		o	f
		%	d		i	s		%	d	\	n	0				

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Factorial implementation (2)

```
.text

factorial:
    str lr, [sp,#-4]!       ; Push lr onto the top of the stack
    str r0, [sp,#-4]!       ; Push r0 onto the top of the stack
                            ; Note that after that, sp is 8 byte aligned
    cmp r0, #0              ; compare r0 and 0
    bne is_nonzero          ; if r0 != 0 then branch
    mov r0, #1              ; r0 ← 1. This is the return
    b end

is_nonzero:                 ; Prepare the call to factorial(n-1)
    sub r0, r0, #1          ; r0 ← r0 - 1
    bl factorial
                            ; After the call r0 contains factorial(n-1)
                            ; Load r0 (that we kept in th stack) into r1
    ldr r1, [sp]            ; r1 ← *sp
    mul r0, r0, r1          ; r0 ← r0 * r1

end:
    add sp, sp, #+4         ; Discard the r0 we kept in the stack
    ldr lr, [sp], #+4       ; Pop the top of the stack and put it in lr
    bx lr                   ; Leave factorial
```

Using a BL procedure call and a stack

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Factorial implementation (3)

```
.global main
main:
    str lr, [sp,#-4]!              ; Push lr onto the top of the stack
    sub sp, sp, #4                 ; Make room for one 4 byte integer in the stack
                                   ; In these 4 bytes we will keep the number
                                   ; entered by the user
                                   ; Note that after that the stack is 8-byte aligned
    ldr r0, address_of_message1    ; Set &message1 as the first parameter of printf
    bl printf                      ; Call printf

    ldr r0, address_of_format      ; Set &format as the first parameter of scanf
    mov r1, sp                     ; Set the top of the stack as the second parameter
                                   ; of scanf
    bl scanf                       ; Call scanf

    ldr r0, [sp]                   ; Load the integer read by scanf into r0
                                   ; So we set it as the first parameter of factorial
    bl factorial                   ; Call factorial
```

Using a BL procedure call and a stack

```
message1:     .asciz "Type a number: "
format:       .asciz "%d"
message2:     .asciz "The factorial of %d is %d\n"
```

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Factorial implementation (4)

```
mov r2, r0                          ; Get the result of factorial and move it to r2
                                    ; So we set it as the third parameter of printf
ldr r1, [sp]                        ; Load the integer read by scanf into r1
                                    ; So we set it as the second parameter of printf
ldr r0, address_of_message2         ; Set &message2 as the first parameter of printf
bl printf                           ; Call printf

add sp, sp, #+4                     ; Discard the integer read by scanf
ldr lr, [sp], #+4                   ; Pop the top of the stack and put it in lr
bx lr                               ; Leave main
```

Using a BL procedure call and a stack

```
address_of_message1:    .word message1
address_of_message2:    .word message2
address_of_format:      .word format
```

address	contents
address_of_message1	message1
address_of_message2	message2
address_of_format	format

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Factorial implementation (5)

```
factorial:
    str lr, [sp,#-4]!        ; Push lr onto the top of the stack
    str r4, [sp,#-4]!        ; Push r4 onto the top of the stack
                             ; The stack is now 8 byte aligned
    mov r4, r0               ; Keep a copy of the initial value of r0 in r4

    cmp r0, #0               ; compare r0 and 0
    bne is_nonzero           ; if r0 != 0 then branch
    mov r0, #1               ; r0 ← 1. This is the return
    b end

is_nonzero:                  ; Prepare the call to factorial(n-1)
    sub r0, r0, #1           ; r0 ← r0 - 1
    bl factorial

                             ; After the call r0 contains factorial(n-1)
                             ; Load initial value of r0 (that we kept in r4) into r1
    mov r1, r4               ; r1 ← r4
    mul r0, r0, r1           ; r0 ← r0 * r1

end:
    ldr r4, [sp], #+4        ; Pop the top of the stack and put it in r4
    ldr lr, [sp], #+4        ; Pop the top of the stack and put it in lr
    bx lr                    ; Leave factorial
```

Using a BL procedure call and a stack

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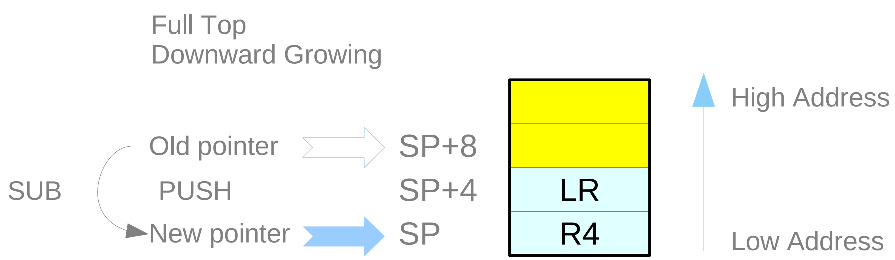
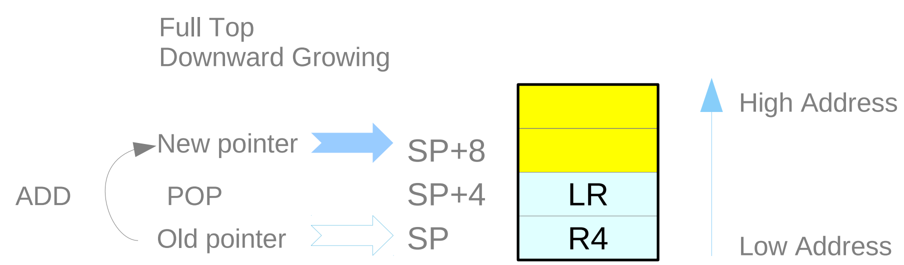
Factorial implementation (6)

```
str lr, [sp,#-4]!     ; Push lr onto the top of the stack
str r4, [sp,#-4]!     ; Push r4 onto the top of the stack

ldr r4, [sp], #+4     ; Pop the top of the stack and put it in r4
ldr lr, [sp], #+4     ; Pop the top of the stack and put it in lr

stmdb sp!, {r4, lr}   ; Push r4 and lr onto the stack

ldmia sp!, {r4, lr}   ; Pop lr and r4 from the stack

push {r4, lr}

pop {r4, lr}
```





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