Stack Frames (11A)

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Please send corrections (or suggestions) to youngwlim@hotmail.com.

This document was produced by using LibreOffice.

Based on

ARM System-on-Chip Architecture, 2nd 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

ARM assembler in Raspberry Pi
Roger Ferrer Ibáñez

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

Activation records (1)

a stack frame
a frame of data that gets pushed onto the stack.

a call stack
divided up into contiguous pieces called stack frames;
here, a stack frame would represent a function call and its argument data.

- return address
- arguments
- local variables.

architecture-dependent.

processor knows the size of each frame
and moves the stack pointer accordingly
as frames are pushed and popped off the stack.

https://stackoverflow.com/questions/10057443/explain-the-concept-of-a-stack-frame-in-a-nutshell

Activation records (2)

when your program is started,
the **call stack** has only one frame, that of the function **main**().
This is called the initial frame or the outermost frame.

each time a function is called,
  a new frame is added.
each time a function returns,
  the frame for that function invocation is eliminated.

for a recursive function,
there can be many frames for the same function.

the frame for the currently executing function
  is called the innermost frame.
  the most recently created frame

http://www.qnx.com/developers/docs/qnxcar2/index.jsp?topic=%2Fcom.qnx.doc.neutrino.prog%2Ftopic%2Fusing_gdb_StackFrames.html

Activation records (3)

Inside your program,
stack frames are identified by their addresses.
A stack frame consists of many bytes,
each of which has its own address;
each kind of computer has a convention for choosing one byte
whose address serves as the address of the frame.
Usually this address is kept in a register called the frame pointer register
while execution is going on in that frame.

http://www.qnx.com/developers/docs/qnxcar2/index.jsp?topic=%2Fcom.qnx.doc.neutrino.prog%2Ftopic%2Fusing_gdb_StackFrames.html

Activation records (4)

GDB assigns numbers to all existing stack frames,
starting with 0 for the innermost frame,
1 for the frame that called it, and so on upward.

These numbers don't really exist in your program;
they're assigned by GDB to give you
a way of designating stack frames in GDB commands.

http://www.qnx.com/developers/docs/qnxcar2/index.jsp?topic=%2Fcom.qnx.doc.neutrino.prog%2Ftopic%2Fusing_gdb_StackFrames.html

Activation records (5)

a call stack is
a stack data structure that stores information about
the active subroutines of a computer program.

This kind of stack is also known as an execution stack,
program stack, control stack, run-time stack, or machine stack,
and is often shortened to just "the stack".

Although maintenance of the call stack is important
for the proper functioning of most software,
the details are normally hidden and automatic
in high-level programming languages.
Many computer instruction sets provide
special instructions for manipulating stacks.

https://en.wikipedia.org/wiki/Call_stack

Activation records (6)

A call stack is used for several related purposes,
but the main reason for having one is
to keep track of the point to which each active subroutine
should return control when it finishes executing.

An active subroutine is one that has been called,
but is yet to complete execution,
after which control should be handed back
to the point of call.

Such activations of subroutines may
be nested to any level (recursive as a special case),
hence the stack structure.

https://en.wikipedia.org/wiki/Call_stack

Activation records (7)

For example, if a subroutine DrawSquare
calls a subroutine DrawLine from four different places,
DrawLine must know where to return
when its execution completes.

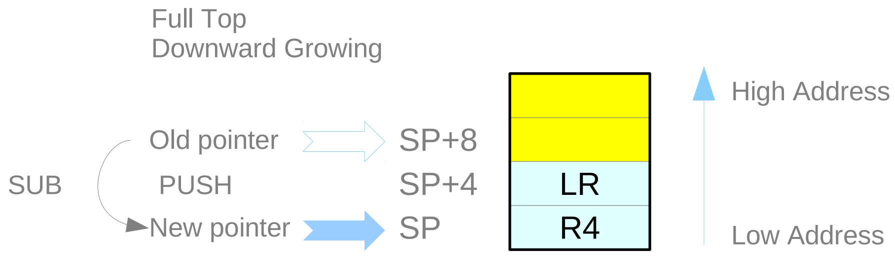
To accomplish this, the address following the instruction
that jumps to DrawLine, the return address,
is pushed onto the top of the call stack with each call.

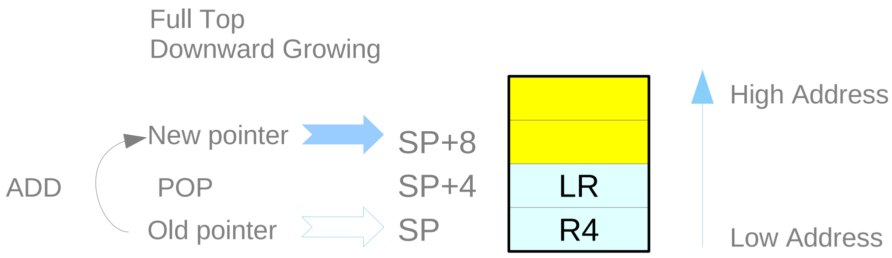
https://en.wikipedia.org/wiki/Call_stack

Activation records (1)

```
function:              ; Keep callee-saved registers

    push {r4, lr}      ; Keep the callee saved registers
    ...                ; code of the function
    pop {r4, lr}       ; Restore the callee saved registers
    bx lr              ; Return from the function
```





https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (2)

```
function:                      ; Keep callee-saved registers */

                               ; Keep the callee saved registers.
                               ; We added r5 to keep the stack 8-byte aligned
    push {r4, r5, fp, lr}      ; but the important thing here is fp */
    mov fp, sp                 ; fp ← sp. Keep dynamic link in fp */
    ...                        ; code of the function */
    mov sp, fp                 ; sp ← fp. Restore dynamic link in fp */
    pop {r4, r5, fp, lr}       ; Restore the callee saved registers.
                               ; This will restore fp as well */
    bx lr                      ; Return from the function */
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (3)

```
function:                      ; Keep callee-saved registers

                               ; Keep the callee saved registers.
                               ; We added r5 to keep the stack 8-byte aligned
    push{r4, r5, fp, lr}       ;  but the important thing here is fp
    mov fp, sp                 ; fp ← sp. Keep dynamic link in fp
    sub sp, sp, #8             ; Enlarge the stack by 8 bytes
      ...                      ; code of the function
    mov sp, fp                 ; sp ← fp. Restore dynamic link in fp
    pop {r4, r5, fp, lr}       ; Restore the callee saved registers.
                               ;  This will restore fp as well
    bx lr                      ; Return from the function
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (4)

```
void sq(int *c) {
    (*c) = (*c) * (*c);
}

sq:
    ldr r1, [r0]        ; r1 ← (*r0)
    mul r1, r1, r1      ; r1 ← r1 * r1
    str r1, [r0]        ; (*r0) ← r1
    bx lr               ; Return from the function
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (5)

```
int sq_sum5(int a, int b, int c, int d, int e) {
        sq(&a);
        sq(&b);
        sq(&c);
        sq(&d);
        sq(&e);
        return a + b + c + d + e;
}
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (6)

```
sq_sum5:
    push {fp, lr}          ; Keep fp and all callee-saved registers.
    mov fp, sp             ; Set the dynamic link

                           ; Allocate space for 4 integers in the stack
                           ; Keep parameters in the stack
    sub sp, sp, #16        ; sp ← sp - 16.
    str r0, [fp, #-16]     ; *(fp - 16) ← r0
    str r1, [fp, #-12]     ; *(fp - 12) ← r1
    str r2, [fp, #-8]      ; *(fp - 8) ← r2
    str r3, [fp, #-4]      ; *(fp - 4) ← r3
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (7)

```
/* At this point the stack looks like this
    | Value   |   Address(es)
    +--------+-----------------------
    |   r0    |  [fp, #-16], [sp]
    |   r1    |  [fp, #-12], [sp, #4]
    |   r2    |  [fp, #-8],  [sp, #8]
    |   r3    |  [fp, #-4],  [sp, #12]
    |   fp    |  [fp],       [sp, #16]
    |   lr    |  [fp, #4],   [sp, #20]
    |   e     |  [fp, #8],   [sp, #24]
    v
  Higher
  addresses
*/
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (8)

```
sub r0, fp, #16        ; r0 ← fp - 16
bl sq                  ; call sq(&a);
sub r0, fp, #12        ; r0 ← fp - 12
bl sq                  ; call sq(&b);
sub r0, fp, #8         ; r0 ← fp – 8
bl sq                  ; call sq(&c);
sub r0, fp, #4         ; r0 ← fp - 4
bl sq                  ; call sq(&d)
add r0, fp, #8         ; r0 ← fp + 8
bl sq                  ; call sq(&e)
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (9)

```
ldr r0, [fp, #-16]      ; r0 ← *(fp - 16). Loads a into r0
ldr r1, [fp, #-12]      ; r1 ← *(fp - 12). Loads b into r1
add r0, r0, r1          ; r0 ← r0 + r1
ldr r1, [fp, #-8]       ; r1 ← *(fp - 8). Loads c into r1
add r0, r0, r1          ; r0 ← r0 + r1
ldr r1, [fp, #-4]       ; r1 ← *(fp - 4). Loads d into r1
add r0, r0, r1          ; r0 ← r0 + r1
ldr r1, [fp, #8]        ; r1 ← *(fp + 8). Loads e into r1
add r0, r0, r1          ; r0 ← r0 + r1

mov sp, fp              ; Undo the dynamic link
pop {fp, lr}            ; Restore fp and callee-saved registers
bx lr                   ; Return from the function
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (10)

```
/* squares.s */
.data

.align 4
message: .asciz "Sum of 1^2 + 2^2 + 3^2 + 4^2 + 5^2 is %d\n"

.text

sq:
  <<defined above>>

sq_sum5:
  <<defined above>>

.globl main
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (11)

```
main:
    push {r4, lr}           ; Keep callee-saved registers

    ; Prepare the call to sq_sum5
    mov r0, #1              ; Parameter a ← 1
    mov r1, #2              ; Parameter b ← 2
    mov r2, #3              ; Parameter c ← 3
    mov r3, #4              ; Parameter d ← 4

    ; Parameter e goes through the stack,
    ; so it requires enlarging the stack
    mov r4, #5              ; r4 ← 5
    sub sp, sp, #8          ; Enlarge the stack 8 bytes,
                            ; we will use only the
                            ; topmost 4 bytes
    str r4, [sp]            ; Parameter e ← 5
    bl sq_sum5              ; call sq_sum5(1, 2, 3, 4, 5)
    add sp, sp, #8          ; Shrink back the stack
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

Activation records (12)

```
 ; Prepare the call to printf
mov r1, r0                          ; The result of sq_sum5
ldr r0, address_of_message
bl printf                           ; Call printf

pop {r4, lr}                        ; Restore callee-saved registers
bx lr
```

```
address_of_message: .word message

$ ./square
Sum of 1^2 + 2^2 + 3^2 + 4^2 + 5^2 is 55
```

https://thinkingeek.com/2013/02/07/arm-assembler-raspberry-pi-chapter-10/

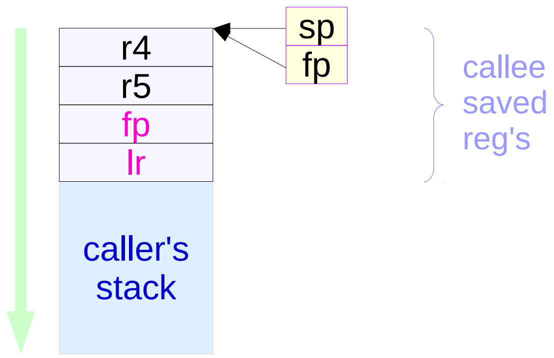
Callee Saved Registers

```
function:

push { r4, lr }    /* Keep the callee saved registers */
    code of the function
pop { r4, lr }              /* Restore the callee saved registers */
bx lr
/* Return from the function */
```

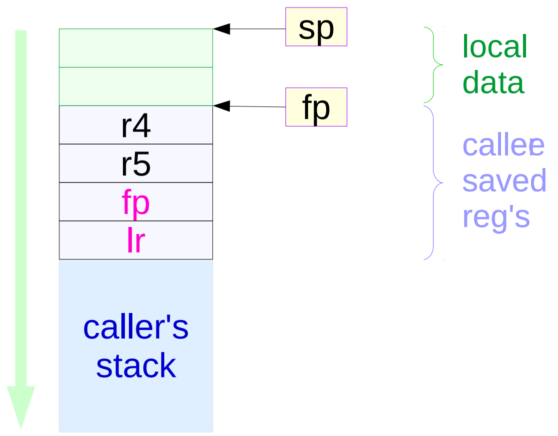
Dynamic Link

```
function:
push { r4, r5, fp, lr }
mov fp, sp                  /* fp ← sp . Keep dynamic link in fp */
    code of the function
mov sp, fp                  /* sp ← fp. Restore dynamic link in fp */
pop { r4, r5, fp, lr }
bx lr
```

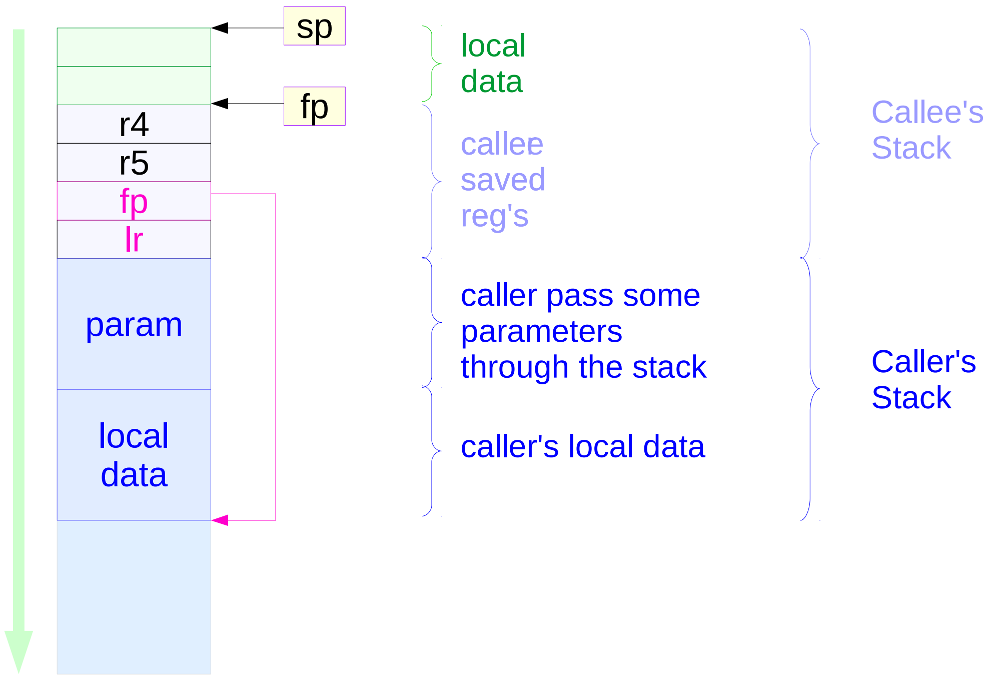


Local Data

```
function:
push { r4, r5, fp, lr }
sub sp, sp, #8          /* 8 bytes local data space */
mov fp, sp
    code of the function
mov sp, fp
pop { r4, r5, fp, lr }
bx lr
```



Local Data and Parameters



Local Data Generating Examples

```
void sq(int *c)
{
        (*c) = (*c) * (*c);
}
```

```
int sq_sum5(int a, int b, int c, int d, int e)
{
        sq(&a);
        sq(&b);
        sq(&c);
        sq(&d);
        sq(&e);
        return a + b + c + d + e;
}
```

callee
function

- sq received a reference
- registers do not have an address
- allocate temporary local storage

```
...
    sq_sum5(1, 2, 3, 4, 5);
...
```

caller
function

Callee Function Code (1)

```
sq_sum5:
push { fp, lr }
mov fp, sp
sub sp , sp , #16

str r0, [ fp, #-16 ]      *( fp - 16 ) ← r0
str r1, [ fp, #-12 ]      *( fp - 12 ) ← r1
str r2, [ fp, #-8 ]       *( fp -  8 ) ← r2
str r3, [ fp, #-4 ]       *( fp -  4 ) ← r3

mov sp , fp
pop { fp, lr }
bx lr
```

```
sq:
ldr r1, [ r0 ]            r1 ← ( *r0 )
mul r1, r1, r1            r1 ← r1 * r1
str r1, [ r0 ]            ( *r0 ) ← r1
bx lr
```

```
sub r0, fp, #16           r0 ← fp - 16
bl sq                     call sq ( &a )
sub r0, fp, #12           r0 ← fp - 12
bl sq                     call sq ( &b )
sub r0, fp, #8            r0 ← fp - 8
bl sq                     call sq ( &c )
sub r0, fp, #4            r0 ← fp - 4
bl sq                     call sq ( &d )
add r0, fp, #8            r0 ← fp + 8
bl sq                     call sq ( &e )

ldr r0, [ fp, #-16 ]      r0 ← *( fp - 16 ) :a
ldr r1, [ fp, #-12 ]      r1 ← *( fp - 12 ) :b
add r0, r0, r1            r0 ← r0 + r1
ldr r1, [ fp, #-8 ]       r1 ← *( fp - 8 )  :c
add r0, r0, r1            r0 ← r0 + r1
ldr r1, [ fp, #-4 ]       r1 ← *( fp - 4 )  :d
add r0, r0, r1            r0 ← r0 + r1
ldr r1, [ fp, #8 ]        r1 ← *( fp + 8 )  :e
add r0, r0, r1            r0 ← r0 + r1
```

Callee Function Code (2)

```
sq_sum5:
push { fp, lr }
mov fp, sp
sub sp , sp , #16

str r0, [ fp, #-16 ]      *( fp - 16 ) ← r0
str r1, [ fp, #-12 ]      *( fp - 12 ) ← r1
str r2, [ fp, #-8 ]       *( fp -  8 ) ← r2
str r3, [ fp, #-4 ]       *( fp -  4 ) ← r3



mov sp , fp
pop { fp, lr }
bx lr
```

At this point the stack looks like this

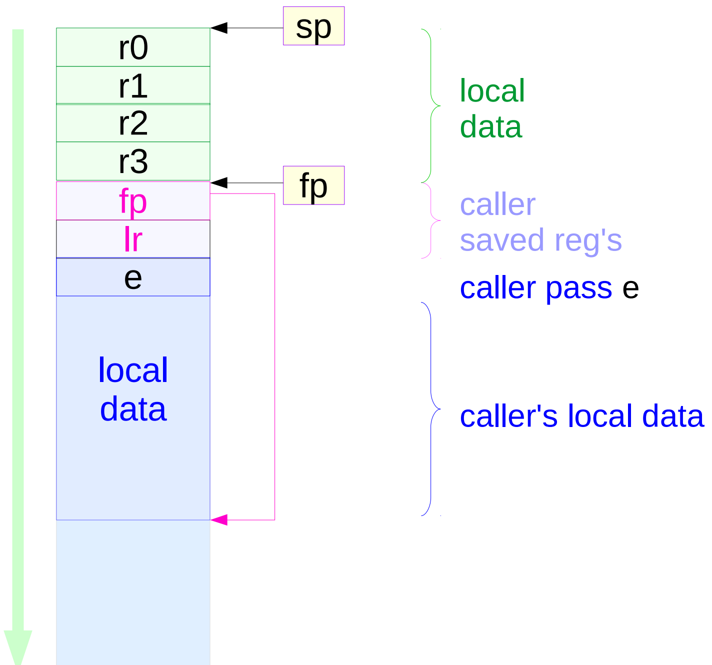
```
| Value | Address (es)
+--------+--------------------+--------------
|    r0 |  [ fp, #-16 ] ,     [sp]
|    r1 |  [ fp, #-12 ] ,     [sp , #4 ]
|    r2 |  [ fp, #-8 ] ,      [sp , #8 ]
|    r3 |  [ fp, #-4 ] ,      [sp , #12 ]
|    fp |  [ fp ] ,           [sp , #16 ]
|    lr |  [ fp, #4 ] ,       [sp , #20 ]
|    e  |  [ fp, #8 ] ,       [sp , #24 ]
v
Higher
addresses
```

local data

callee saved registers

caller passe parameters

Callee Function Code (3)




```
At this point the stack looks like this
| Value | Address (es)
+--------+-------------------+-------------
|    r0 |  [ fp, #-16 ] ,      [sp]
|    r1 |  [ fp, #-12 ] ,      [sp , #4 ]
|    r2 |  [ fp, #-8 ] ,       [sp , #8 ]
|    r3 |  [ fp, #-4 ] ,       [sp , #12 ]
|    fp |  [ fp ] ,            [sp , #16 ]
|    lr |  [ fp, #4 ] ,        [sp , #20 ]
|    e  |  [ fp, #8 ] ,        [sp , #24 ]
v
Higher
addresses
```

local data

callee saved registers

caller pass e parameters

Caller Function Code

```
.data
.align 4

message:
.asciz "Sum of 1^2 + 2^2 + 3^2 + 4^2 +
5^2 is %d\n"

.text

sq: <<defined above>>
sq_sum5: <<defined above>>

.globl main
main:

push { r4, lr }

pop { r4, lr }

bx lr
```

```
mov r0, #1        a ← 1
mov r1, #2        b ← 2
mov r2, #3        c ← 3
mov r3, #4        d ← 4

mov r4, #5        r4 ← 5

sub sp , sp , #8
str r4, [sp]      e ← 5

bl sq_sum5        sq_sum5 ( 1, 2, 3, 4, 5 )

add sp , sp , #8

mov r1, r0
ldr r0, address_of_message

bl printf

address_of_message: . word message
```

APCS Register Use Convention

R11	fp	Frame Pointer
R12	ip	Scratch register / specialist use by linker
R13	sp	Lower end of current stack frame
R14	lr	Link address / scratch register
R15	pc	Program coutner

LR and FP Registers

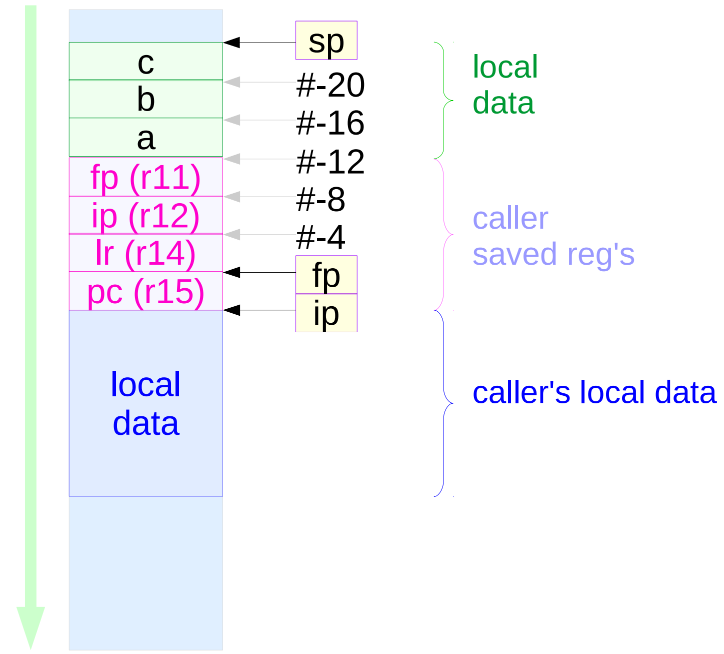
SP	where the stack is
FP	where the stack was
PC	where you are
LR	where you were

http://stackoverflow.com/questions/15752188/arm-link-register-and-frame-pointer

-fno-omit-frame-pointer

```
main:
mov     ip, sp
stmfd   sp!, { fp, ip, lr, pc }
sub     fp, ip, #4
sub     sp, sp, #12
ldr     r2, [fp, #-16]
ldr     r3, [fp, #-20]
add     r3, r3, r2
str     r3, [fp, #-24]
sub     sp, fp, #12
ldmfd   sp, {fp, sp, pc}
```

```
main()
{
  volatile int a, b, c;
  c = a + b;
}
```

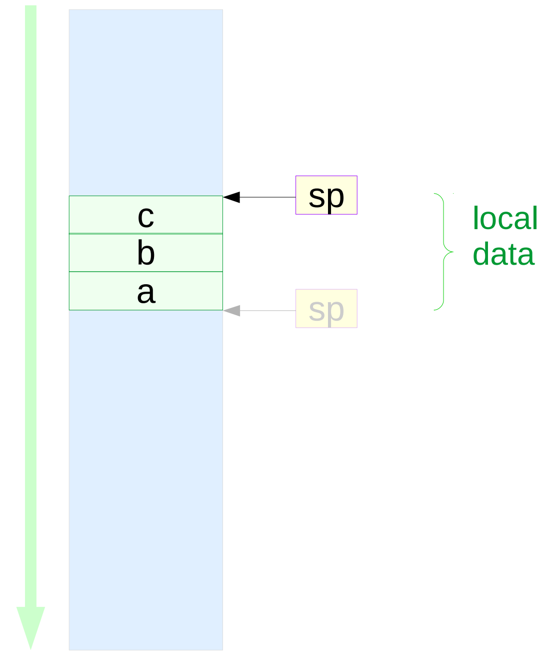


https://community.arm.com/thread/7092

-fomit-frame-pointer

```
main:
sub     sp, sp, #12
ldr     r2, [sp, #8]
ldr     r3, [fp, #4]
add     r3, r3, r2
str     r3, [sp, #0]
sub     sp, sp, #12
```

```
main()
{
  volatile int a, b, c;
  c = a + b;
}
```



https://community.arm.com/thread/7092

Local Variables

- Dynamic allocation / release allows for resue of RAM
- Limited scope of access (making it private) provides for data protection
- Only the program that created the local variable can access it
- Since an interrupt will save registers, the code is reentrant
- Since absolute addressing is not used, the code is relocatable

- We can use symbolic names for the variables making it easier to understand
- The number of variables is only limited by the size of the stack
- Because it is more general, it will be easier to add additional variables
-

Computer Organization and Design ARM Edition: The Hardware Software Interface by D. A. Patterson and J. L. Hennessy

Global Variables

```
void MyFunction (void) {
        static uint32_t count = 0;
        count++;
}
```

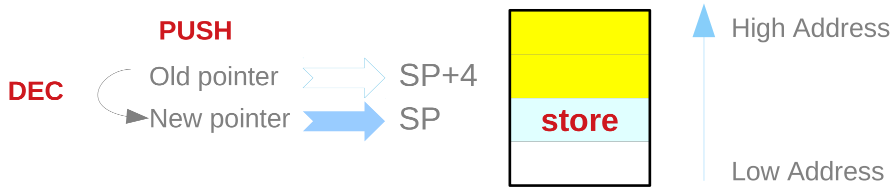
```
static int32_t myPrivateGlobalVariable; // accessible by this file only
void static MyPrivateFunction (void) {
}
```

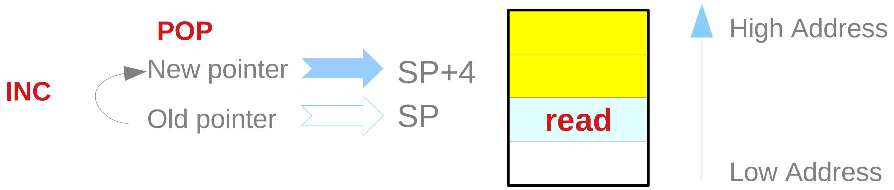
```
const int16_t Slope=21;
const uint8_t SinTable[8] = {0, 50, 98, 142, 180, 212, 236, 250};
```

LIFO Stack

- Program segments should have an matching number of pushes and pops
- Stack accesses (push or pop) should not be performed outside the allocation area
- Stack reads and writes should not be performed within the free area
- Stack push should first decrement SP by 4, then store the data
- Stack pop should first read the data, then increment SP by 4

Full Top Descending Stack





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DEC

LIFO Stack

```
LDR     R0, [SP, #4]     ; R0 = the next to the top bytes

SUB     R1, SP, #8       ; R1 points to the free area
STR     R0, [R1]         ; Store contents of R0 into free area (*** illegal ***)
LDR     R2, [R1]         ; Read contents of free area into R2 (*** illegal ***)


PUSH    {R0, R1}         ; Store contents of R0, R1 onto the stack
```

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Local variables on the stack

```
Func    PUSH    {R4, R5, R8, LR}        ; save registers as needed
        ; 1) allocate local variables
        ; 2) body of the function, access local variables
        ; 3) deallocate local variables
        POP     {R4, R5, R8, PC}
```

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Initializing a local array

```
void Set(void) {
	uint32_t data[10];
	int i;
	for (i=0; i<10; i++) {
		data[i] = i;
	}
}
```

```
Set     SUB     SP, SP, #40         ; 1) allocate 10 words
        MOVS    R0, #0x00           ; 2) i = 0
        B       test                ; 2)
Loop    LSL     R1, R0, #2          ; 2) 4*i
        STR     R0, [SP, R1]        ; 2) access
        ADDS    R0, R0, #1          ; 2) i++
Test    CMP     R0, #10             ; 2)
        ADD     SP, SP, #40         ; 3) deallocate
        BX      LR
```

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1. Binding

```
Sum     EQU     0          ; 32-bit local variable, stored on the stack
```

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2. Allocation

```
MOV     R0, #0
MOV     R1, #2
PUSH    {R0, R1}        ; allocate and initialize two 32-bit variables

SUB     SP, #8          ; allocate two 32-bit variables
```

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3. Access

```
LDR    R1, [SP, #sum]    ; R1 = sum
ADD    R1, R0            ; R1 = R0 + sum
STR    R1, [SP, #sum]    ; sum = R0 + sum

LDR    R0, [SP, #sum]    ; R0 = sum
LSR    R0, R0, #4
STR    R0, [SP, #sum]    ; sum = sum / 4
```

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4. Deallocation

```
ADD     SP, #4            ; deallocate sum
```

Stack Frames

- Parameters
- Return address
- Saved registers
- Local variables

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Stack Frames

```
uint32_t calc(void) {
    uint32_t        sum, n;
    for (n=1000; n>0; n--) {
        sum = sum + n;
    }
    return sum;
}
```

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Stack Frame Implementation Example 1 (1)

```
; *** binding phase ****
sum     EQU     0           ; 32-bit unsigned number
n       EQU     4           ; 32-bit unsigned number

; *** 1) allocation ***
calc    PUSH    {R4, LR}
        SUB     SP, #8          ; allocate n, sum
```

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Stack Frame Implementation Example 2 (2)

```
; *** 2) access ***
        MOV     R0, #0
        STR     R0, {R11, #sum]     ; sum = 0
        MOV     R1, #1000
        STR     R1, [R11, #n]       ; n = 1000
loop    LDR     R1, [R11, #n]       ; R1 = n
        LDR     R0, [R11, #sum]     ; R0 = sum
        ADD     R0, R1              ; R0 = sum + n
        STR     R0, [R11, #sum]     ; sum = sum + n
        LDR     R1, [R11, #n]       ; R1 = n
        SUBS    R1, #1              ; n-1
        STR     R1, [R11, #n]       ; n = n – 1
        BNE     loop

; *** 3) deallocation ***
        ADD     SP, #8              ; deallocation
        POP     {R4, R5, R11, PC}   ; R0 = sum
```

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Stack Frame Implementation Example 2 (1)

```
; *** binding phase ****
sum     EQU     0           ; 32-bit unsigned number
n       EQU     4           ; 32-bit unsigned number

; *** 1) allocation ***
calc    PUSH    {R4, R5, R11, LR}
        SUB     SP, #8          ; allocate n, sum
        MOV     R11, SP         ; frame pointer
```

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Stack Frame Implementation Example 2 (2)

```
; *** 2) access ***
        MOV     R0, #0
        STR     R0, {R11, #sum]         ; sum = 0
        MOV     R1, #1000
        STR     R1, [R11, #n]           ; n = 1000
loop    LDR     R1, [R11, #n]           ; R1 = n
        LDR     R0, [R11, #sum]         ; R0 = sum
        ADD     R0, R1                  ; R0 = sum + n
        STR     R0, [R11, #sum]         ; sum = sum + n
        LDR     R1, [R11, #n]           ; R1 = n
        SUBS    R1, #1                  ; n-1
        STR     R1, [R11, #n]           ; n = n – 1
        BNE     loop

; *** 3) deallocation ***
        ADD     SP, #8                  ; deallocation
        POP     {R4, R5, R11, PC}       ; R0 = sum
```

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Parameter Passing

Call by value	- safe, simple, good for small amounts of data
Call by reference	- parameter can be input or output, good for large amounts

Registers	- fast and simple
Stack	- flexible, good for large amounts of data
Global variables	- simple and poorstyle

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Call by value (1)

```
uint32_t next(uint32_t ang) {
        ang++;
        if (ang == 200) {
                ang = 0;
        }
        return ang;
}

void main (void) {
        uint32_t angle = 0;  // 0 to 199
        Stepper_Init();
        while (1) {
                Stepper_Step();
                angle = next(angle);
        }
}
```

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Call by value (2)

```
; R0 is the angle
next    ADD     R0, #1              ; add to copy
        CMP     R0, #200
        BNE     skip
        MOV     R0, #0              ; roll over
skip    BX      LR                  ; 0 to 199
angle   EQU     0
main    SUB     SP, #4              ; allocate
        MOV     R0, #0
        STR     #0, [SP, #angle]
        BL      Stepper_Init
loop    BL      Stepper_Step
        LDR     R0, [SP, #angle]    ; R0 = angle
        BL      next
        STR     R0, [SP, #angle]    ; update
        B       loop
```

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Call by reference A (1)

```
uint32_t next(uint32_t *pt) {
        (*pt) = (*pt) +1;
        if ((*pt) == 200) {
                (*pt) = 0;
        }
        return ang;
}

void main (void) {
        uint32_t angle = 0;  // 0 to 199
        Stepper_Init();
        while (1) {
                Stepper_Step();
                angle = next(angle);
        }
}
```

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Call by reference A (2)

```
; R0 is points to the angle
next    LDR     R1, [R0]            ; *pt
        ADD     R1, #1              ; increment
        CMP     R1 #200
        BNE     skip
        MOV     R1, #0              ; roll over
skip    STR     R1, [R0]            ; update
        BX      LR                  ; 0 to 199
angle   EQU     0
main    SUB     SP, #4              ; allocate
        MOV     R0, #0
        STR     #0, [SP, #angle]
        BL      Stepper_Init
loop    BL      Stepper_Step
        LDR     R0, [SP, #angle]    ; R0 = angle
        BL      next
        STR     R0, [SP, #angle]    ; update
        B       loop
```

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Call by reference B (1)

```
static int32_t Xx, Yy;              // position

void where(    int32_t *xpt,
               int32_t *ypt        ) {
      (*xpt) = Xx;                  // return Xx
      (*ypt) = Yy;                  // return Yy
}


void func(void) {
      int32_t myX, myY;
      where(&myX, &myY);
      // do something based on myX, myY
}
```

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Call by reference B (2)

```
Xx      SPACE      4              ; private to where
Yy      SPACE      4
where   LDR     R2, =Xx
        LDR     R2, [R2]          ; value of Xx
        STR     R2, [R0]          ; pass data
        LDR     R3, =Yy
        LDR     R3, [R3]          ; value of Yy
        STR     R3, [R1]          ; pass data
        BX      LR
myX     EQU     0                 ; 32-bit
myY     EQU     4
func    PUSH    {R4, LR}
        SUB     SP, #8            ; allocate
        MOV     R0, SP            ; R0 = &myX
        ADD     R1, SP, #myY ; R1 = &myY
        BL      where
        ; do something base on myX, myY
        ADD     SP, #8            ; deallocate
        POP     {R4, PC}
```

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Parameter Passing

```
; Reg R0 = Port A,      Reg R1 = Port B
; Reg R3 = PortC,       Reg R3 = Port D
getPorts        LDR         R0, =GPIO_PORTA_DATA_R
                LDR         R0, [R0]                         ; value of Port A
                LDR         R1, =GPIO_PORTB_DATA_R
                LDR         R1, [R1]                         ; value of Port B
                LDR         R2, =GPIO_PORTC_DATA_R
                LDR         R2, [R2]                         ; value of Port C
                LDR         R3, =GPIO_PORTD_DATA_R
                LDR         R3, [R3]                         ; value of Port D
                BX          LR
                *** calling sequence ***
                BL          getPorts
; Reg R0, R1, R2, R3 have four results
```

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Parameter Passing – (1) using registers

```
; Inputs:           R0, R1
; Outputs:          R2 = R0 – R1
Sub1      SUB       R2, R0, R1
          BX        LR


          LDR       R0, =A
          LDR       R0, [R0]          ; R0 has the value of A
          LDR       R1, =B
          LDR       R1, [R1]          ; R1 has the value of B
          BL        Sub1
          LDR       R0, =C
          STR       R2, [R0]          ; C = A – B
```

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Parameter Passing – (2) using the stack

```
; Inputs:         In1 In2 on stack
; Outputs:        Out= In1 – In2 on stack
In1      EQU      8
In2      EQU      4
Out      EQU      0
Sub2     LDR      R0, [SP, #In1]
         LDR      R1, [SP, #In2]
         SUB      R2, R0, R1
         STR      R2, [SP, #Out]
         BX       LR

         LDR      R0, =A
         LDR      R0, [R0]          ; R0 has the value of A
         LDR      R1, =B
         LDR      R1, [R1]          ; R1 has the value of B
         PUSH     {R0, R1}          ; input parameters
         SUB      SP, #4            ; place for output
         BL       Sub2
         POP      {R2}              ; result
         LDR      R0, =C
         STR      R2, [R0]          ; C = A – B
         ADD      SP, #8            ; balance stack
```

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Parameter Passing – (3) using the stack (a)

```
; Inputs:          In1 In2 on stack
; Outputs:         Out= In1 – In2 on stack
In1      EQU       20
In2      EQU       16
Out      EQU       12
local    EQU       0
Sub3     PUSH      {R11, LR}
         SUB       SP, #4                ; allocate
         MOV       R11, SP               ; frame pointer
         LDR       R0, [R11, #In1]
         LDR       R1, [R11, #In2]
         SUB       R2, R0, R1
         STR       R2, [R11, #Out]
         ADD       SP, #4                ; deallocate
         POP       {R11, PC}
```

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Parameter Passing – (3) using the stack (b)

```
LDR    R0, =A
LDR    R0, [R0]        ; R0 has the value of A
LDR    R1, =B
LDR    R1, [R1]        ; R1 has the value of B
PUSH   {R0, R1}        ; input parameters
SUB    SP, #4          ; place for output
BL     Sub3
POP    {R2}            ; result
LDR    R0, =C
STR    R2, [R0]        ; C = A – B
ADD    SP, #4          ; deallocate stack
```

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Parameter Passing – (4) using global variables

```
; Inputs:          A, B
; Outputs:         C = A – B
Sub4     LDR       R0, =A
         LDR       R0, [R0]          ; R0 has the value of A
         LDR       R1, =B
         LDR       R1, [R1]          ; R1 has the value of B
         SUB       R2, R1, R0        ; A – B
         LDR       R0, =C
         STR       R0, [R0]
         BX        LR


         BL        Sub4
```

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Parameter Passing – (5) using memory locations

```
; Wait for Flag to become 1
Wait    LDR     R0, =Flag
Loop    LDR     R1, [R0]        ; R1 = Flag
        CMP     R1, #1
        BNE     loop            ; wait until 1
        MOV     R1, #0          ;
        STR     R1, [R0]        ; Flag = 0
        BX      LR


SysTick_Handler
        LDR     R0, =Flag       ; R0 = &Flag
        MOV     R1, #1
        STR     R1, [R0]        ; Flag = 1
        BX      LR              ; return form interrupt
```

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Compiler's local and global variable implementation (1)

Out = (99 * In) / 100;

```
LDR     R1, [PC, #208]        ; (R1 + 1)  = &In
MOVS    R2, #0x64             ; R2 = 100
LDRB    R0, [R1, #0x01]       ; R0 = In
ADD     R0, R0, R0, LSL #5    ; R0 = R0 + 32*R0 = 33 * In
ADD     R0, R0, R0, LSL #1    ; R0 = R0 + 2 *R0 = 99 * In
UDIV    R0, R0, R2            ; 99 * In / 100
STRB    R0, [R1, #0x02]       ; Out = 99 * In / 100
```

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Compiler's local and global variable implementation (1)

```
uint32_t combine (
        uint32_t     msb,
        uint32_t     lsb) {
        return msb << 8 + lsb;
}
```

```
Combine   MOV    R3, R0           ; R0 = msb
          ADD    R3, R1, #0x08    ; lsb + 8
          LSL    R0, R2, R3       ; msb << (8 + lsb)
          BX     LR
```

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Compiler's local and global variable implementation (2)

```
int32_t       G;            // global
int32_t sub(int32_t *pt          // R0
            int32_t index,       // R1
            int32_t values) {         // R2
      pt[index] -= value;
      return value;
}


Void main(void) {
      int32_t z[20];             //local
      G = 5;                     // access global
      z[0] = 6;                  // access local
      G = sub(z, 1, 2);
}
```

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Compiler’s local and global variable implementation (3)

```
; R0 is *pt          ; R1 is index
; R2 is value
Sub     MOV     R3, R0                  ; R3 is *pt
        LDR     R0, [R3, R1, LSL #2]    ;
        SUBS    R0, R0, R2
        STR     R0, [R3, R1, LSL #2]
        MOV     R0, R2                  ; return value
        BX      LR

Main    PUSH    {R4, LR}
        SUB     SP, SP, #0x50           ; allocate z
        MOVS    R0, #0x05
        LDR     R1, [PC, #340]          ; R1 = &G
        MOVS    R2
```

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Trigger.c

References

[1] http://wiki.osdev.org/ARM_RaspberryPi_Tutorial_C
[2] http://blog.bobuhiro11.net/2014/01-13-baremetal.html
[3] http://www.valvers.com/open-software/raspberry-pi/
[4] https://www.cl.cam.ac.uk/projects/raspberrypi/tutorials/os/downloads.html