Stack Frames (11A)

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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/

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
-

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 equal 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

LIFO Stack

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

SUB     R1, SP, #8        ; R1points 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
```

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}
```

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
```

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
```

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
```

4. Deallocation

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

Stack Frames

- Parameters
- Return address
- Saved registers
- Local variables

Stack Frames

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

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
```

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
```

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
```

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
```

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

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);
        }
}
```

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
```

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);
        }
}
```

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
```

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
}
```

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}
```

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
```

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
```

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}
```

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
```

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
```

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
```

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
```

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
```

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);
}
```

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
          STR       R0, [R1, #0x00]       ; z[0] = 6
          MOVS      R2, #0x02             ; value
          MOVS      R1, #0x01             ; index
          MOV       R0, SP                ; *pt
          BL.W      sub
          LDR       R1, [PC, #320]        ; R1 = &G
          STR       R0, [R1, #0x00]       ; store G
          ADD       SP, SP, #0x50         ; deallocates
          POP       {R4, PC}
```

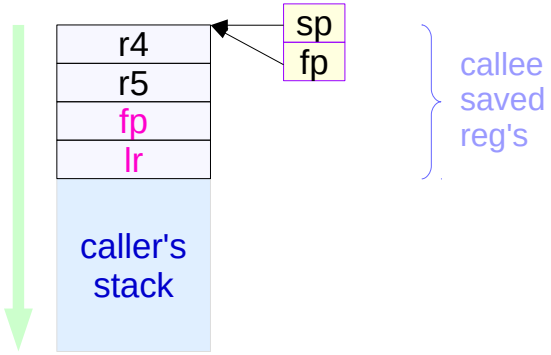
Callee Saved Registers

```
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 */
```

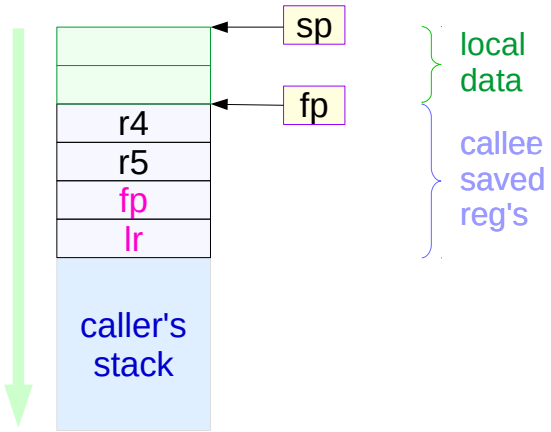
Dynamic Link

```
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
```

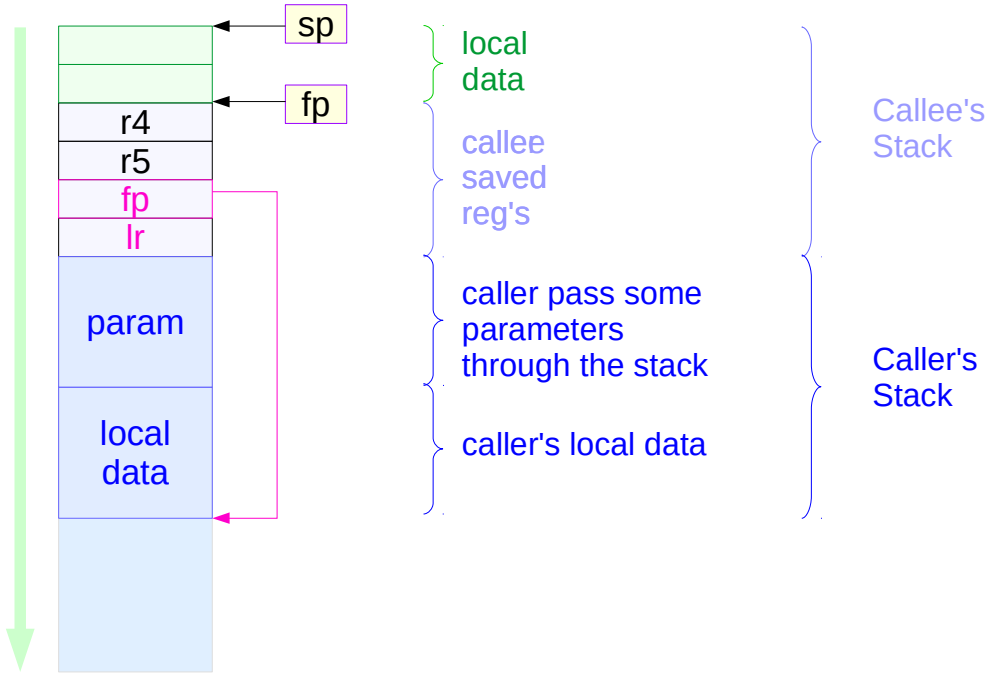


Local Data

```
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]

local data

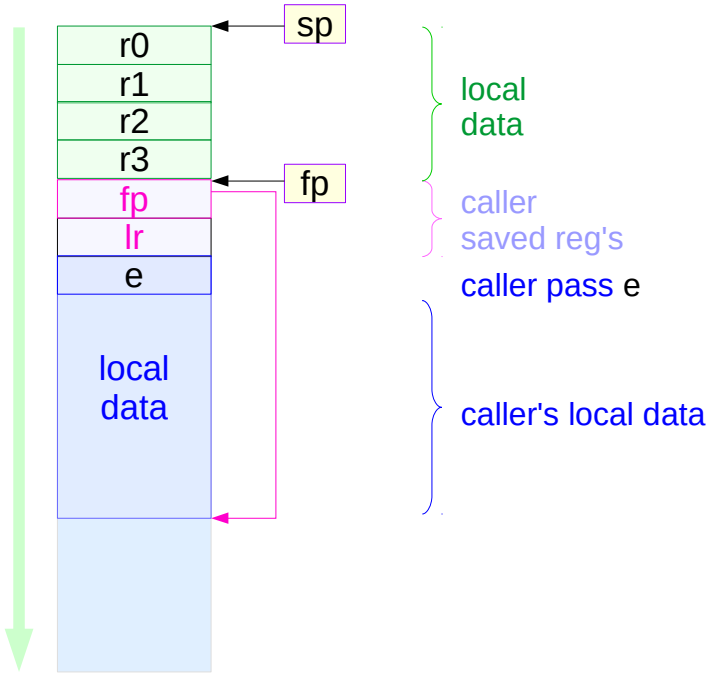
callee saved registers

caller passe parameters

v

Higher addresses

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

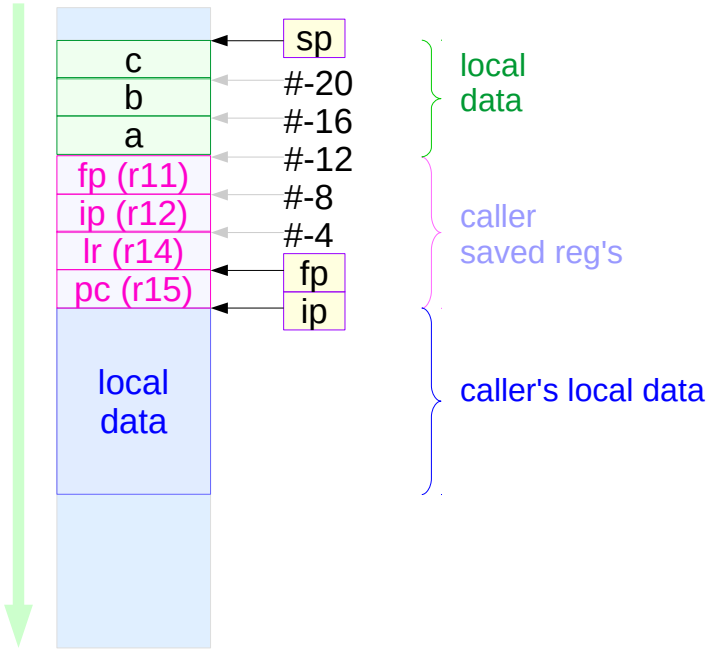
SP where the stack is
FP where the stack was

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}
```

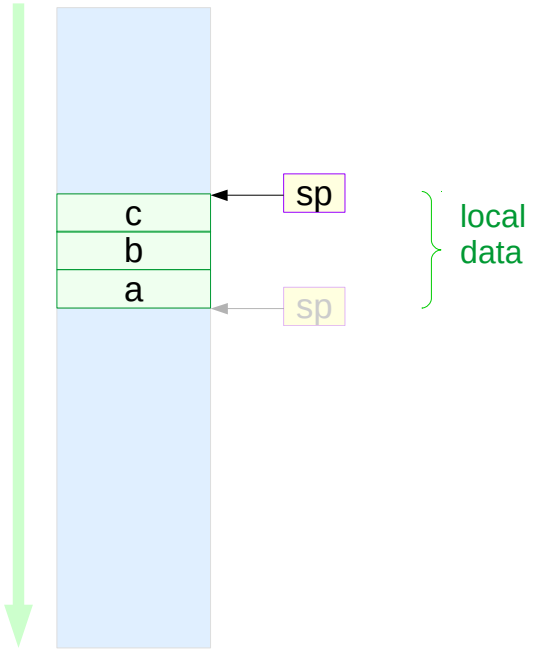



```
main()
{
  volatile int a, b, c;
  c = a + b;
}
```

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

Trigger.c

References

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[2] http://blog.bobuhiro11.net/2014/01-13-baremetal.html
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[4] https://www.cl.cam.ac.uk/projects/raspberrypi/tutorials/os/downloads.html