Version 1.13

UCSD CSE 30

Computer Organization and Systems Programming

Aarch32 Assembly – Part 5

Lecture 20 – November 29, 2022

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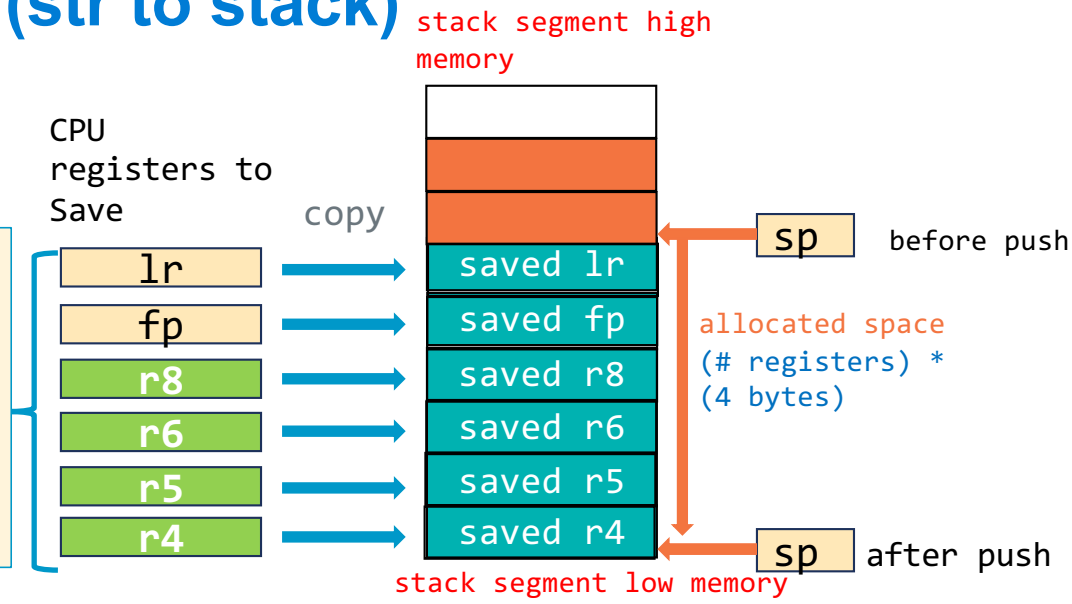
Frontier Exascale

push: Multiple Register Save (str to stack)

```
save registers
push{r4-r6, r8, fp, lr}
```

Registers are pushed on to the stack *in order* **right (high memory) to left (low memory)**

If you have no stack variables (later) then always push an **EVEN** number of registers!



- `push` copies the contents of the `{reg list}` to stack segment memory
- `push` **Also** subtracts (# of registers saved) * (4 bytes) from the `sp` to ***allocate*** space on the stack
  - sp = sp – (# registers_saved * 4)
- **this must always be true: sp % 8 == 0**

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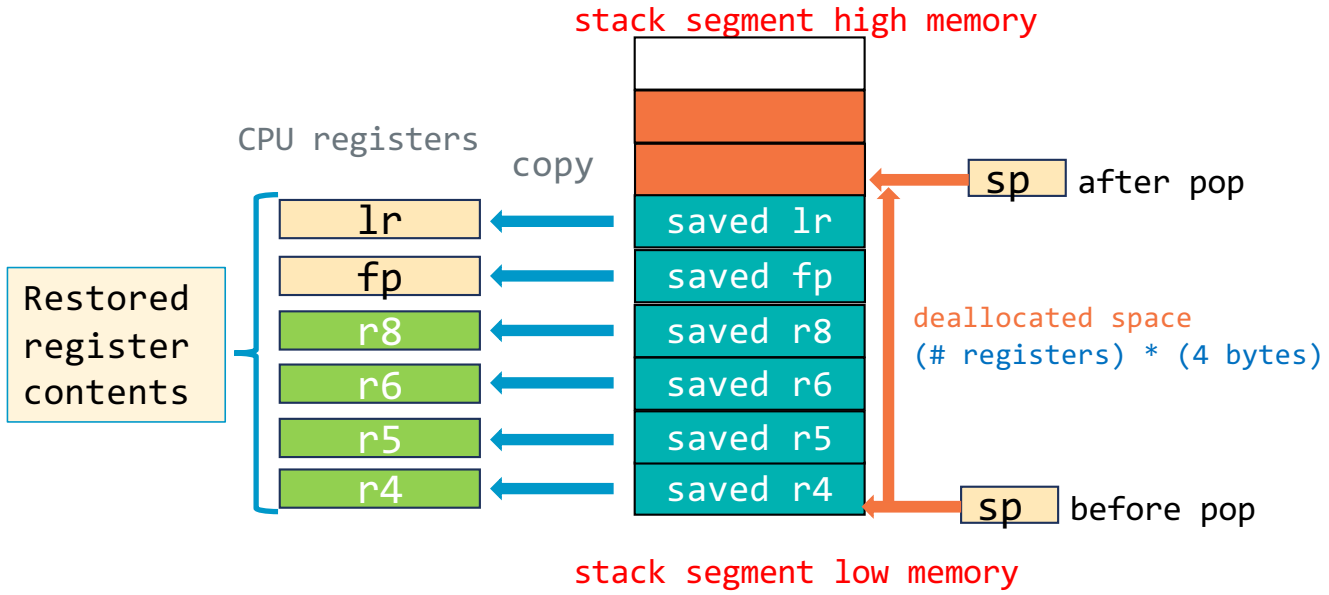
pop: Multiple Register Restore (ldr from stack)

```
restore registers
pop{r4-r6,r8,fp,lr}
```

Registers are **pop'd** from the stack *in order* **left (low memory) to right (high memory)**



- `pop` copies the contents of stack segment memory to the `{reg list}`
- `pop` **adds:** (# of registers restored) * (4 bytes) to `sp` to ***deallocate*** space on the stack
  - sp = sp + (# registers restored * 4)
- **Remember:** `{reg list}` must be the same in both the `push` and the corresponding `pop`

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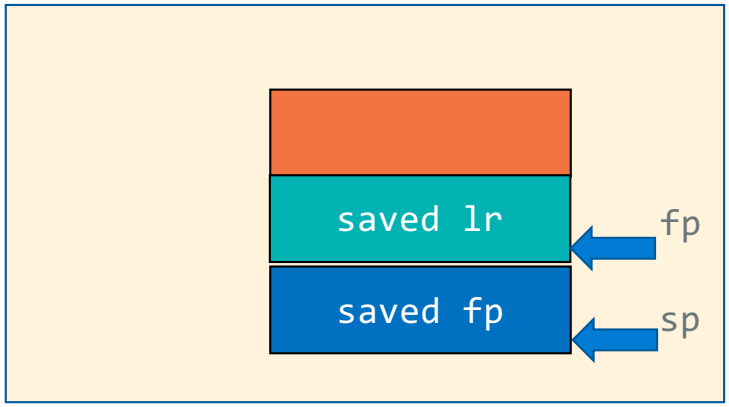
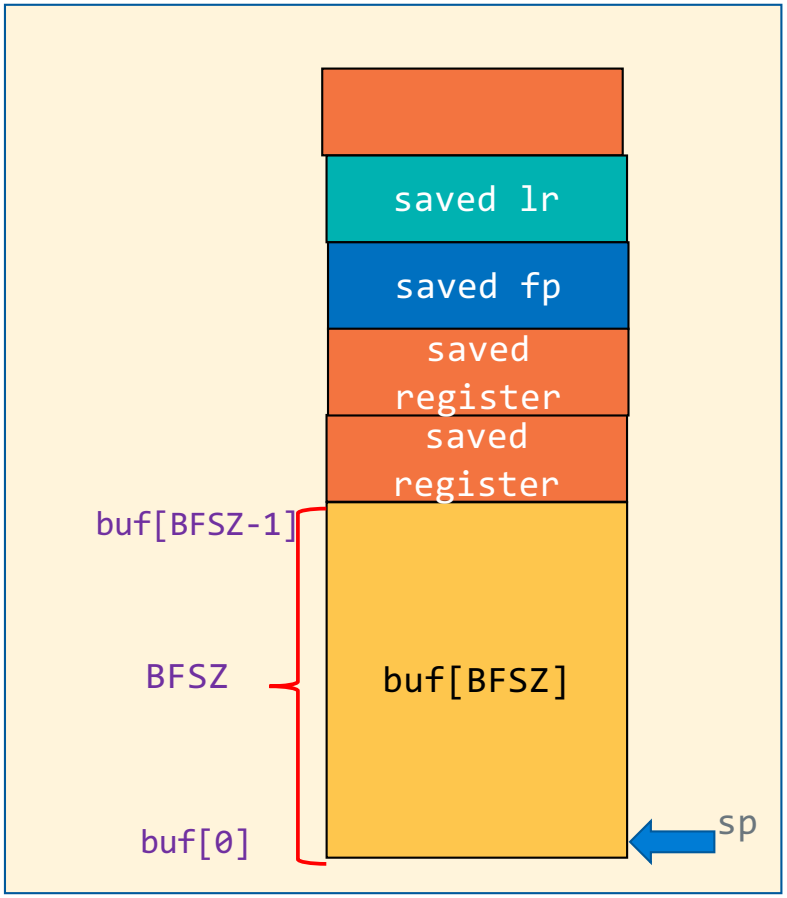
Local Variables are Part of Each Stack Frame

- Local variables are on the stack below the lowest numbered saved (pushed) register

```
#define BFSZ 4
int main(void)
{
  char buf[BFSZ]; // BFSZ bytes
...
```





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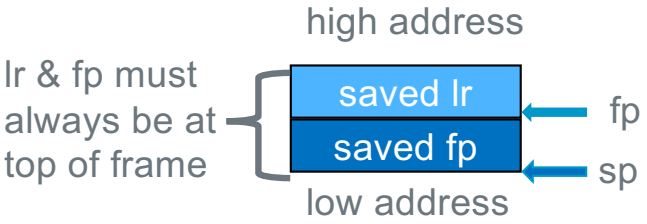
Stack Frame (Arm Arch32 Procedure Call Standards)

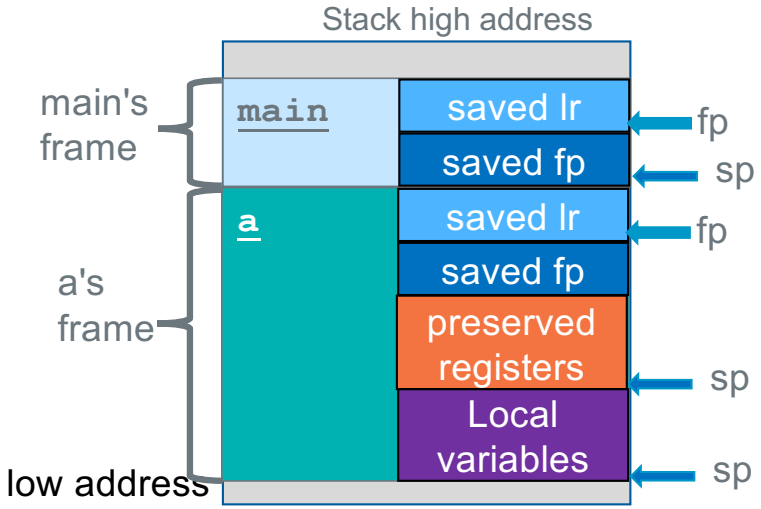
Stack Frame Requirements

- **Minimal frame: at function entry** `push {fp, lr}`
- The top two entries in a stack frame are always (1) saved lr, (2) saved fp
- `sp` points at top element in the stack (lowest byte address)
- `fp` points at the `lr` copy stored in the current stack frame
- **Stack frames MUST ALWAYS BE aligned to 8-byte addresses**
  - So, this must always be true: sp % 8 == 0



minimal frame above
Always save at least fp and lr and set fp at saved lr

```
int main(void)
{
     a();
     /* other code */
     return EXIT_SUCCESS;
}
int a(void)
{
    int x;
    int y;
    /* other code */
    return 0;
}
```



allocate stack space
SP = SP – "space"
grows "down"

deallocate stack space
SP = SP + "space"
shrinks "up"

Note slide has builds

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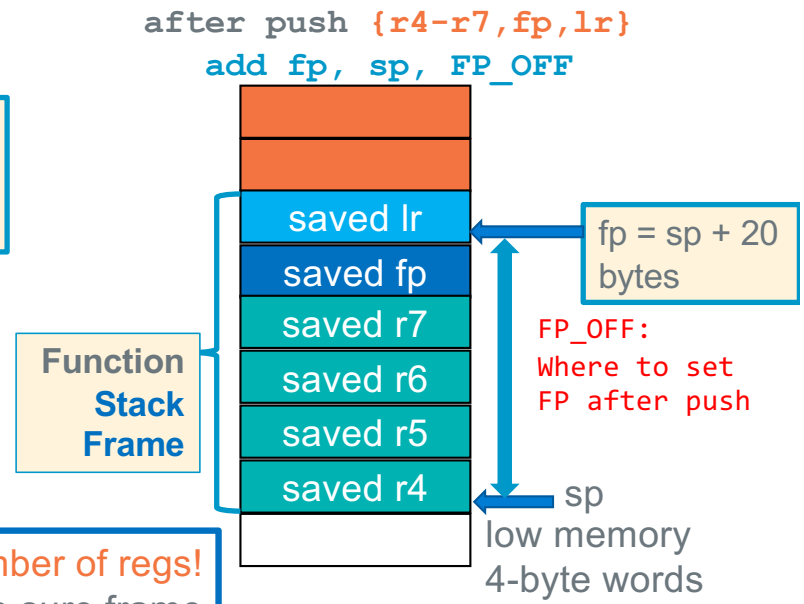
FP_OFF: Distance from FP to SP
Used to set FP at push and SP before pop

```
      // other code etc
        .equ    FP_OFF,  20
main:
       push    {r4-r7, fp, lr}
       add     fp, sp, FP_OFF
       …….
       sub     sp, fp, FP_OFF
       pop     {r4-r7, fp, lr}
       bx      lr
```

Function Prologue
always at top of function
saves regs and sets fp

Function Epilogue
always at bottom of function restores regs including the sp



# regs saved	FP_OFF in Bytes
2	4
3	8
4	12
5	16
6	20
7	24
8	28
9	32

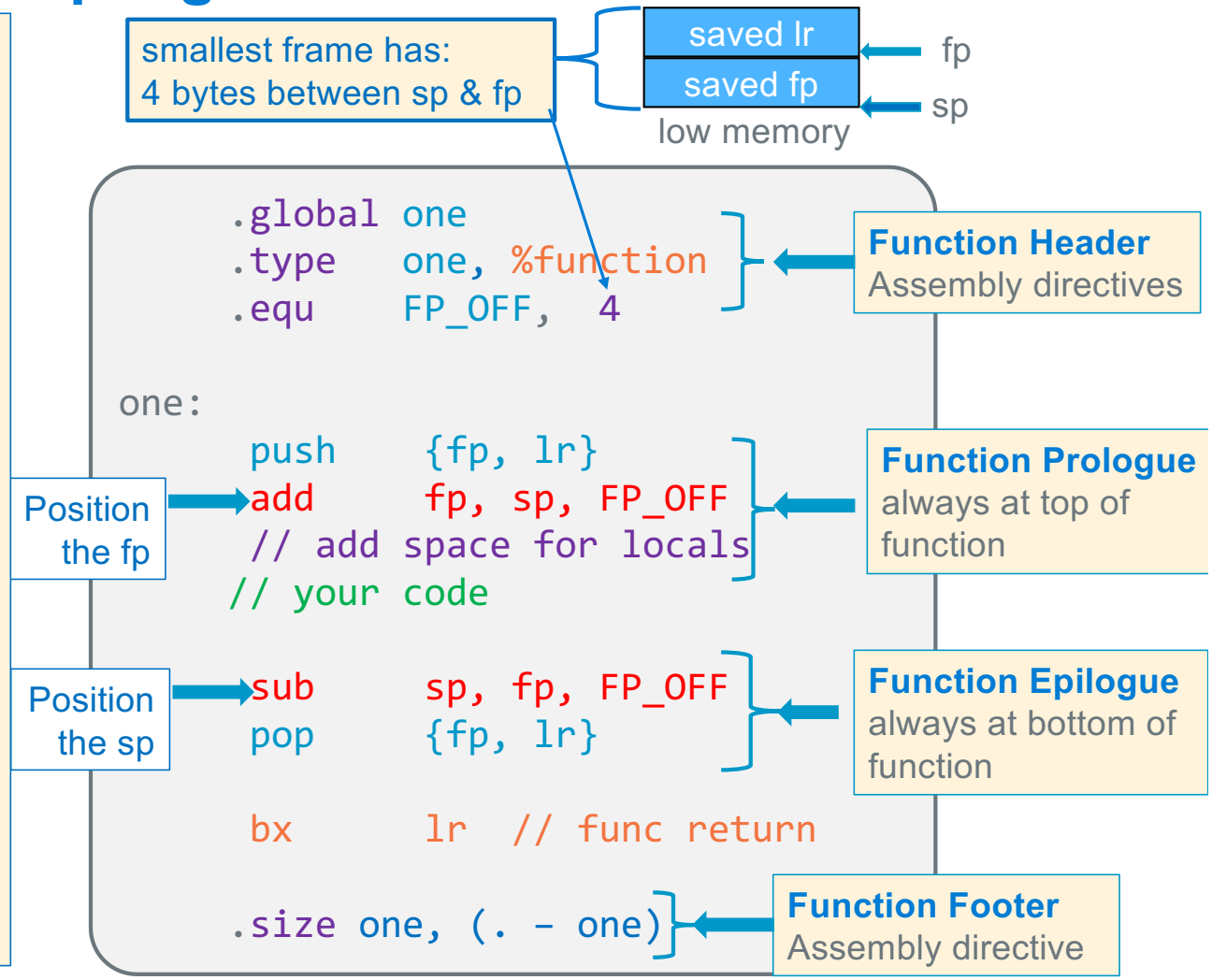
Means Caution, odd number of regs!
If odd number pushed, make sure frame is 8-byte aligned (later)
this must always be true: sp % 8 == 0

```
FP_OFF = (#regs - 1)*4 // -1 is lr offset from sp
Where # regs = #preserved + lr + fp
```

IMPORTANT: FP_OFF has **two** uses:
1. Where to set fp after prologue push (remember sp position)
2. Restore sp (deallocate locals) right before epilogue pop

Function Prologue and Epilogue: Minimum Stack Frame

- Each function has only one Prologue at the top of the function body and only one Epilogue at the bottom of the function body
- When you want to exit the function, set the return value in r0, and then branch (or fall through) to the epilogue
- Function entry (Function **Prologue**):
  1. save preserved registers
  2. set the fp to point at saved lr
  3. allocate space for locals (subtracts from sp)
- Function return (Function **Epilogue**):
  1. deallocate space for locals (adds to sp)
  2. restores preserved registers
  3. return to caller



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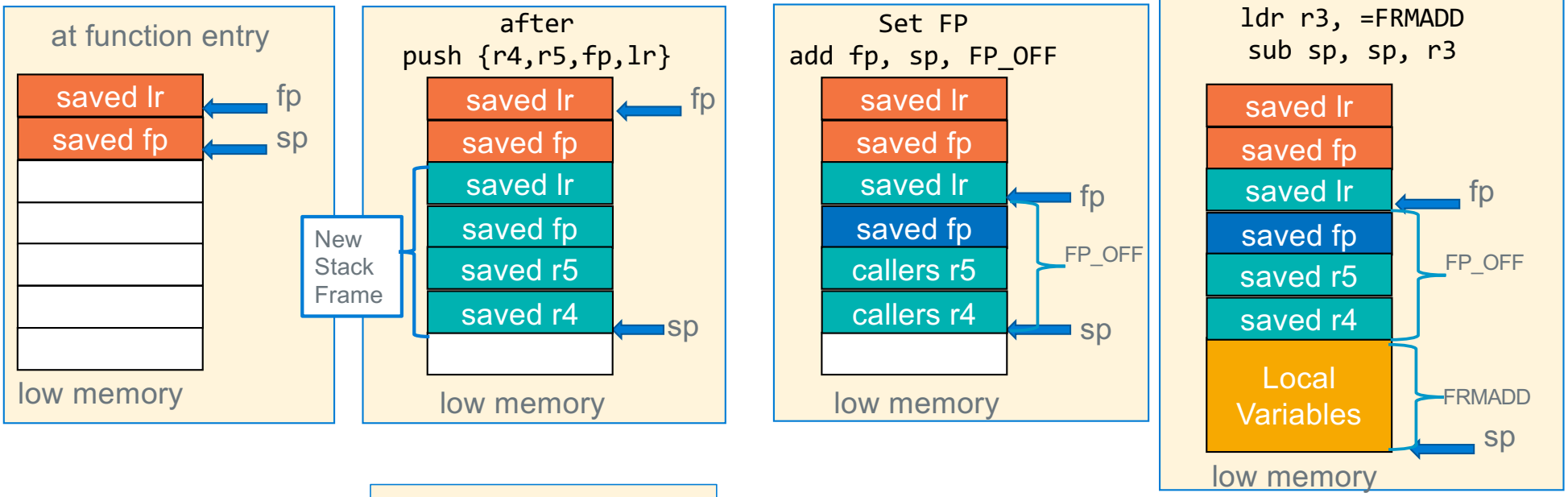
Function Prologue: Allocating the Stack Frame



Function was just called this how the stack looks
The orange blocks are part of the caller's stack frame

Function saves lr, fp using a `push` and only those preserved registers it wants to use on the stack
Do not push r12 or r13

Function moves the fp to point at the saved lr as required by the Aarch32 spec

Allocate Space for Local Variables

Part of function prologue

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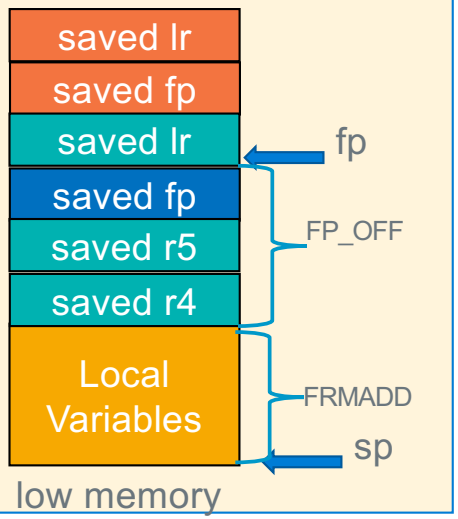
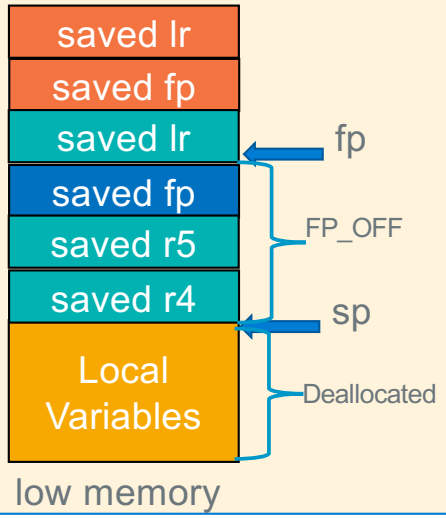
Function Epilogue: Deallocating the Stack Frame

Stack frame while during function body execution



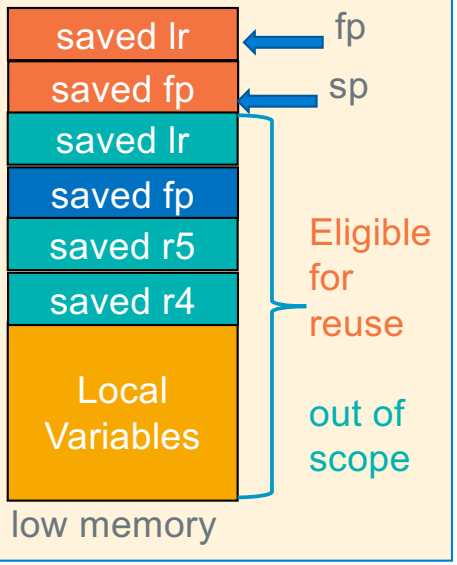
Use fp as a pointer to find local variables on the stack

Deallocate Space for locals
Put SP back so pop works
sub sp, fp, FP_OFF



Move SP back to where it was after the push in the prologue. So, the pop works properly (this also deallocates the local variables)

At function exit after
pop {r4,r5,fp,lr}



At function exit (in the function epilogue) the function uses pop to restore the registers to the values they had at function entry

Part of function epilogue

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Review Return Value and Passing Parameters to Functions

(Four parameters or less)

Register	*Function Call Use*
r0	1st parameter
r1	2nd parameter
r2	3rd parameter
r3	4th parameter

Register	*Function Return Value Use*
r0	8, 16 or 32-bit result, 32-bit address or least-significant half of a 64-bit result
r1	most-significant half of a 64-bit result

- Where `r0, r1, r2, r3` are arm registers, the function declaration is (first four arguments):

```
r0 = function(r0, r1, r2, r3)        // 32-bit return
r0, r1 = function(r0, r1, r2, r3)    // 64-bit return - long long
```

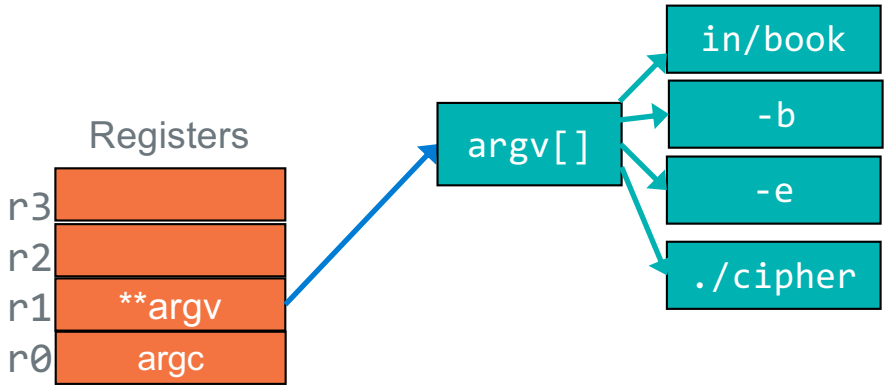
- Each **parameter and return value is limited to data that can fit in 4 bytes or less**
- You receive up to the first four parameters in these four registers
- You copy up to the first four parameters into these four registers before calling a function
- For parameter values using more than 4 bytes, a pointer to the parameter is passed (we will cover this later)
- **You MUST ALWAYS assume** that the called function will **alter the contents of all four registers: r0-r3**
- **Observation: When a function calls another function, the called function has the right to overwrite the first 4 parameters that were passed to it by the calling function**

Accessing argv from Assembly (stderr version)

```
    .extern printf
    .extern stderr
    .section .rodata
.Lstr:  .string "argv[%d] = %s\n"
    .text
    .global main    // main(r0=argc, r1=argv)
    .type   main, %function
    .equ    FP_OFF,     20
main:
    push    {r4-r7, fp, lr}
    add     fp, sp, FP_OFF
    ldr     r4, =stderr         // get the address of stderr
    ldr     r4, [r4]            // get the contents of stderr
    ldr     r5, =.Lstr          // get the address of .Lstr
    mov     r6, 0               // set indx = 0;
    mov     r7, r1              // save argv
.Lloop:
    // fprintf(stderr, "argv[%d] = %s\n", indx, argv[indx])
    ldr     r3, [r7]            // argv[indx]
    cmp     r3, 0               // check argv[indx]==NULL
    beq     .Ldone              // if so done
    mov     r2, r6              // indx
    mov     r1, r5              // "argv[%d] = %s\n"
    mov     r0, r4              // stderr
    bl      fprintf
    add     r6, r6, 1           // indx++
    add     r7, r7, 4           // argv++
    b       .Lloop
.Ldone:
    mov     r0, 0
    sub     sp, fp, FP_OFF
    pop     {r4-r7, fp, lr}
    bx      lr
```

Function Prologue
always at top of function
saves regs and sets fp

```
 % ./cipher -e -b in/BOOK
argv[0] = ./cipher
argv[1] = -e
argv[2] = -b
argv[3] = in/BOOK
```



Function Epilogue
always at bottom of function Branch to this to exit the function
restores regs including the sp

Local Variables on the Stack

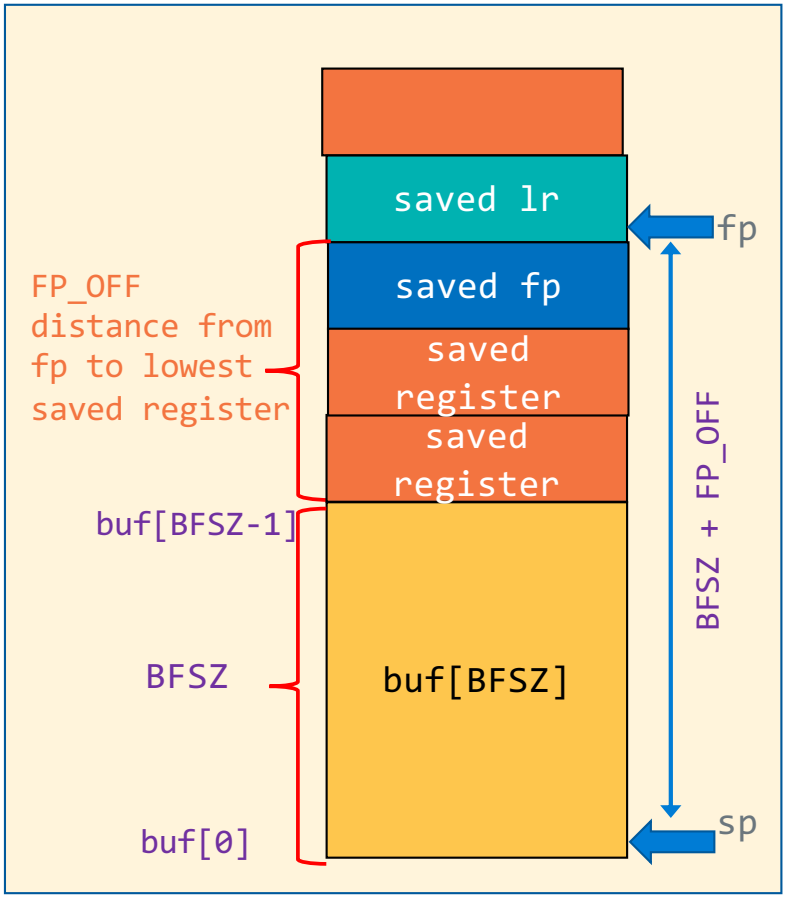
- Local variables are on the stack below the lowest numbered saved register
- frame pointer is used as a **pointer** to stack variables
- fp is the base register in ldr and str instructions
- Example load buf[0] into r4

```
#define BFSZ 4
int main(void)
{
  char buf[BFSZ]; // BFSZ bytes
...
```

  - FP_OFF = 12, BUFSZ = 4
  - Distance from FP is buf[0] is 12 + 4 = 16

```
ldrb r4, [fp, -16]
```

1. Calculate how much additional space is needed by all the local variables
2. **After the register save push, Subtract from the sp** the size of the variable in bytes (+ padding - later slides)



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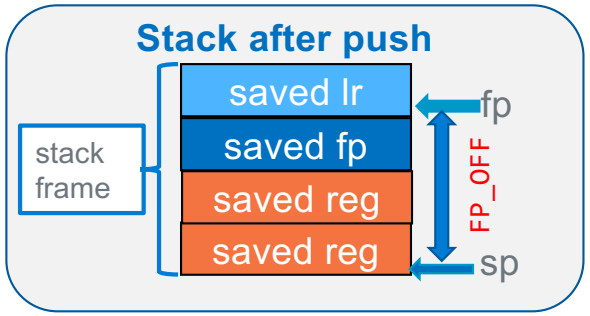
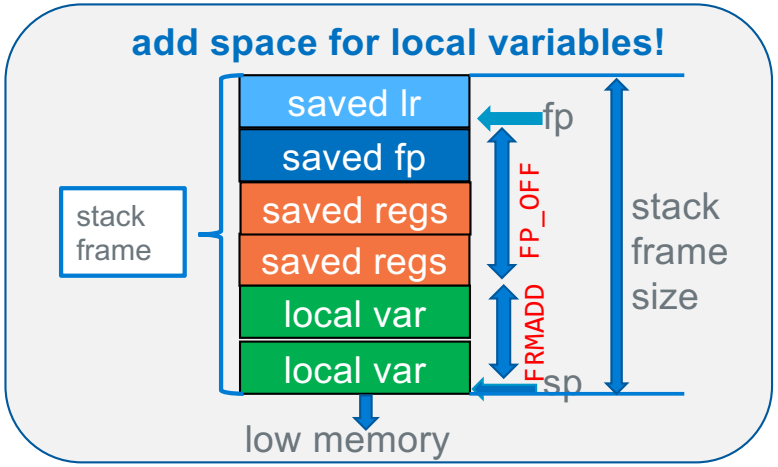
Function prologue with local variables




```
push    {fp, lr}
add     fp, sp, FP_OFF
```

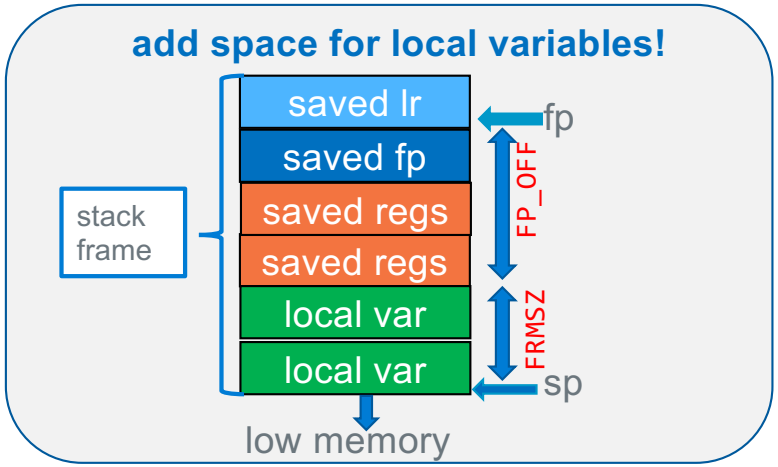


- move the sp to allocate space on the stack for local variables and outgoing parameters (later)

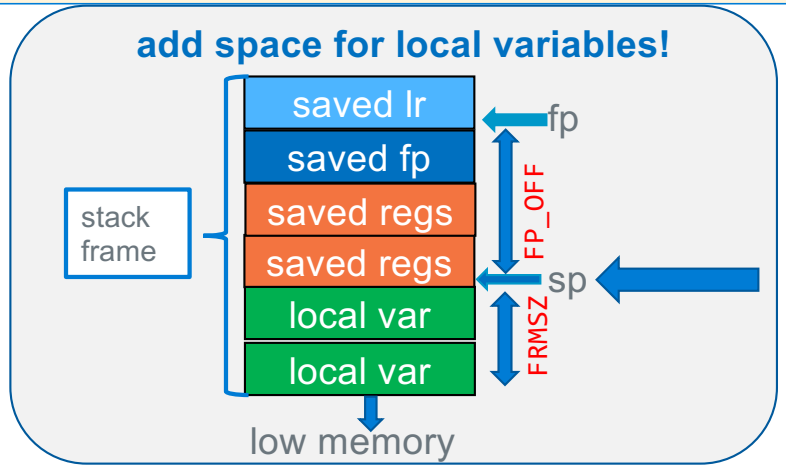
```
    .equ    FRMADD, 8
    push    {fp, lr}
    add     fp, sp, FP_OFF
    ldr     r3, =FRMADD // frames may be large
    sub     sp, sp, r3
// your code
```


x

Function epilogue with local variables



- For pop to restore the registers correctly:
  - sp must point at the last saved preserved register put on the stack by the save register operation: the push




```
        .equ    FRMADD, 8
        push    {fp, lr}
        add     fp, sp, FP_OFF
        ldr     r3, =FRMADD
        sub     sp, sp, r3
          // your code

        sub     sp, fp, FP_OFF
        pop     {fp, lr}

        bx      lr  // func return
```

- Return the **sp** (using the **fp**) to the same address it had after the push operation
  sub sp, fp, FP_OFF
- this works no matter how much space was allocated in the prologue

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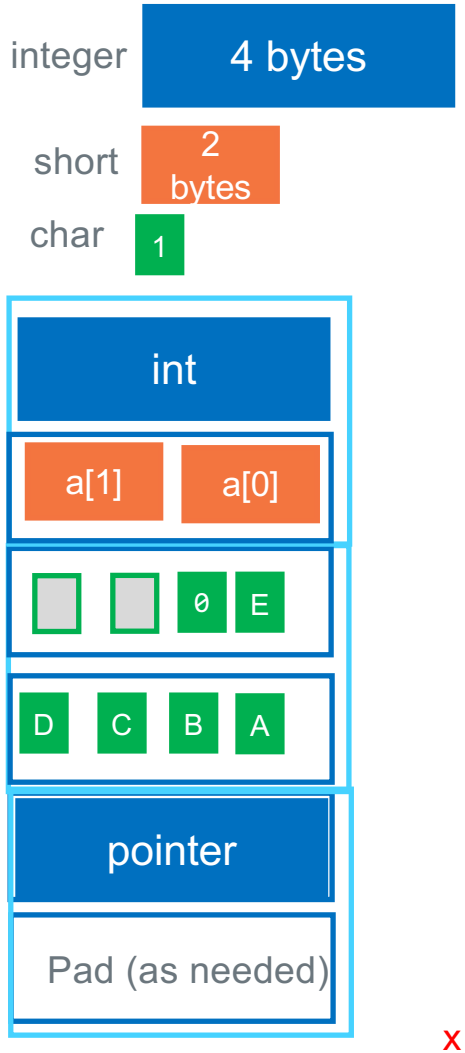
Stack Frame Design – Local Variables

- Arrays start at a 4-byte boundary (even arrays with only 1 element)
  - Exception: double arrays [ ] start at an 8-byte boundary
  - struct arrays are aligned to the requirements of largest member
- Space padding (0 or 4 bytes) when necessary is added at the high address end of a variables allocated space, based on the variable's alignment and the requirements of variable below it on the stack
- Single chars (and shorts) can be grouped together in same 4-byte word (following the alignment for the short)
- After all the variables have been allocated, add padding at stack frame bottom (low memory) so the total stack frame size (including all saved registers) is a multiple of 8 when the prologue is finished

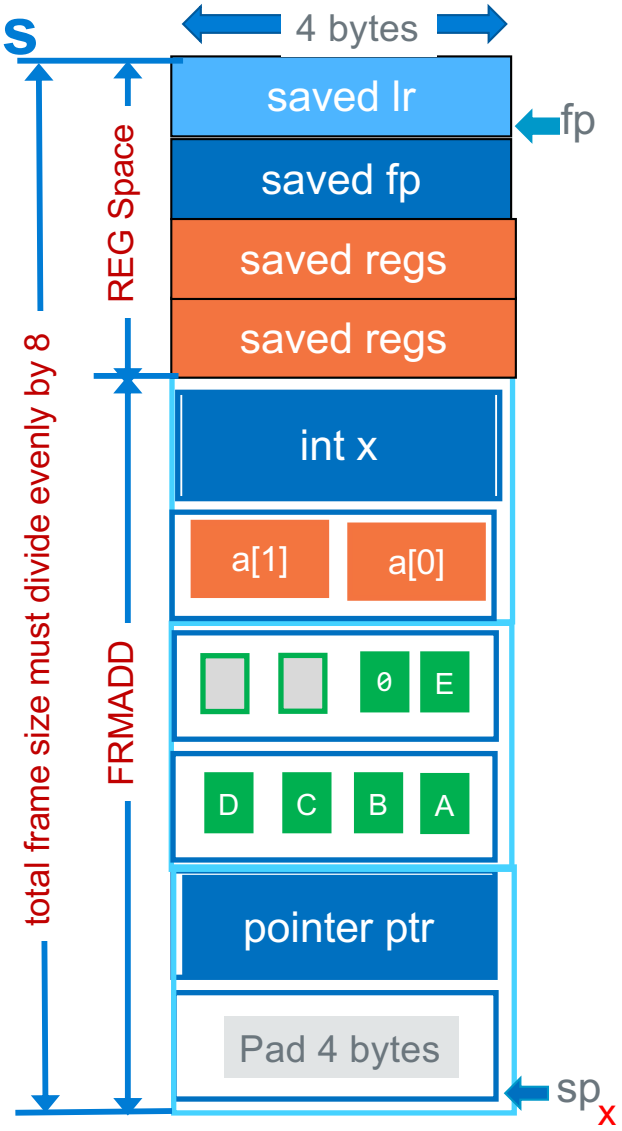


Step 1: Stack Frame Design – Local Variables

In this example we are allocating in order of variable definition, **no reordering**

```
int func(void)
{
    int x = 0;
    short st[2];
    char str[] ="ABCDE";
    char *ptr = &array[0];
```

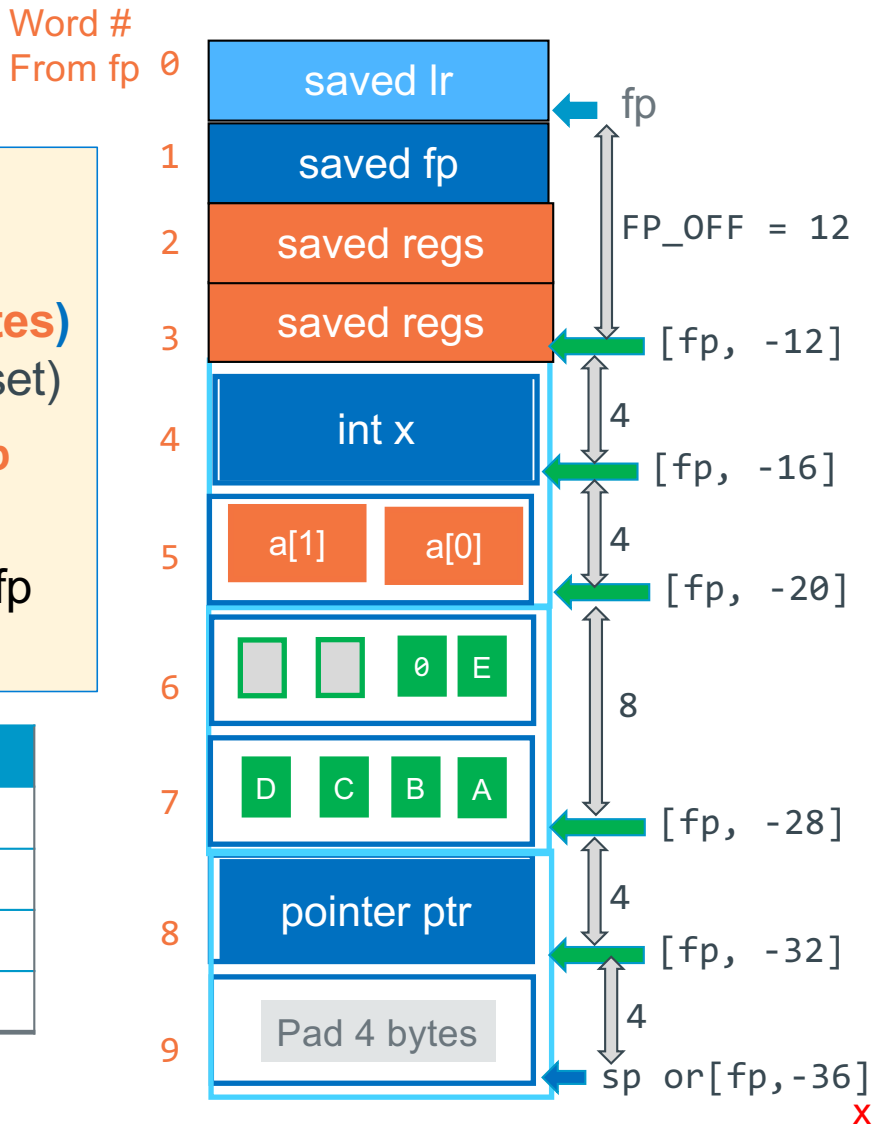
Variable name	Initial Value	Size bytes	Alignment pad to next	Total Size
int x	0	4	0	4
short a[]	??	2*2	0	4
char str[]	"ABCDE"	6	2	8
char *ptr	&array[0]	4	0	4
PAD Added		4		4
FRMADD (locals etc)	-----	-----	-----	24
Saved Register Space	-----	4 * 4	---	16
Total Frame Size				40



Accessing Stack Variables The Hard Way…..

- Access data stored in the stack
  - use `ldr/str` instructions
- **Use base register `fp` with offset (distance in bytes) addressing** (either register offset or immediate offset)
- No matter where in memory the stack is located, `fp` always points at saved `lr`)
- Word offset is a way to visualize the distance from fp for calculating offset values

Variable name	offset from fp	ldr instruction
`int x`	-16	`ldr r0, [fp, -16]`
`short a[]`	-20	`ldrsh r0, [fp, -20]`
`char str[]`	-28	`ldrb r0, [fp, -28]`
`char *ptr`	-32	`ldr r0, [fp, -32]`



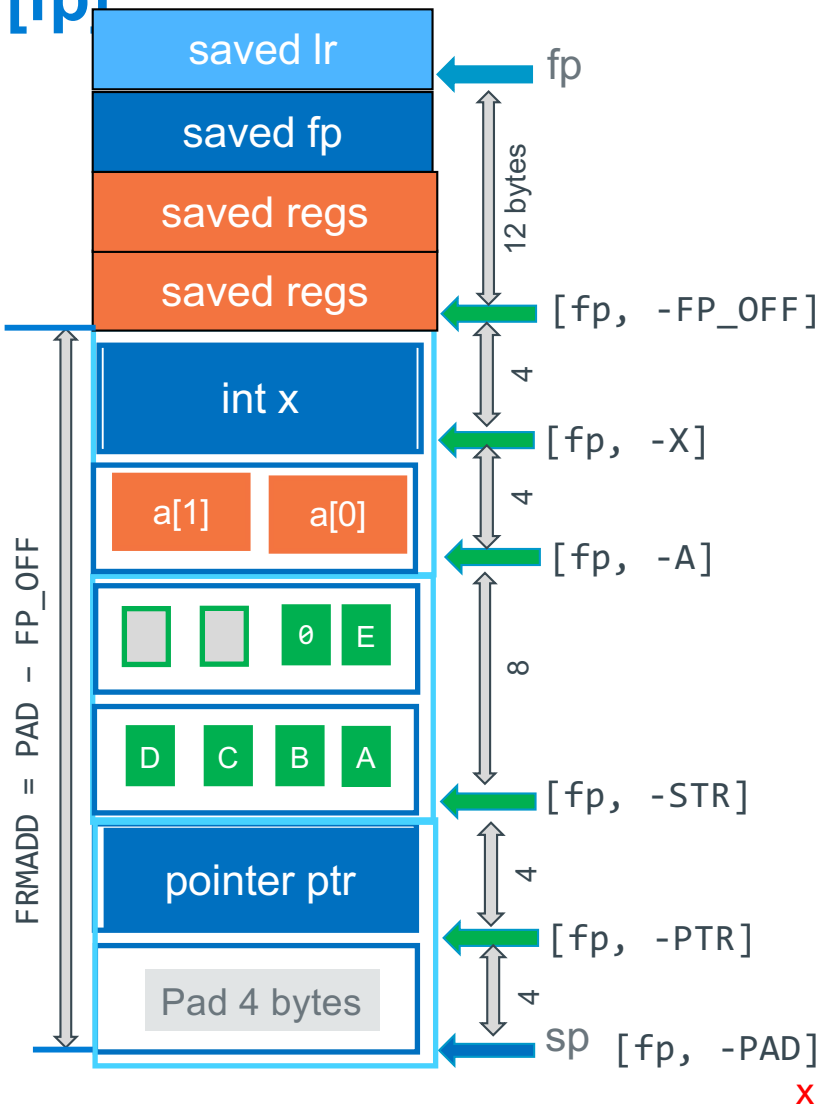
Step 2 Generate Distance offsets from [fp]

- Use the assembler to calculate the **distance** from the address contained in fp `[fp, -offset]`

```
.equ FP_OFF, 12
.equ X, 4+FP_OFF // X = 16
.equ A, 4+X      // A = 20
```

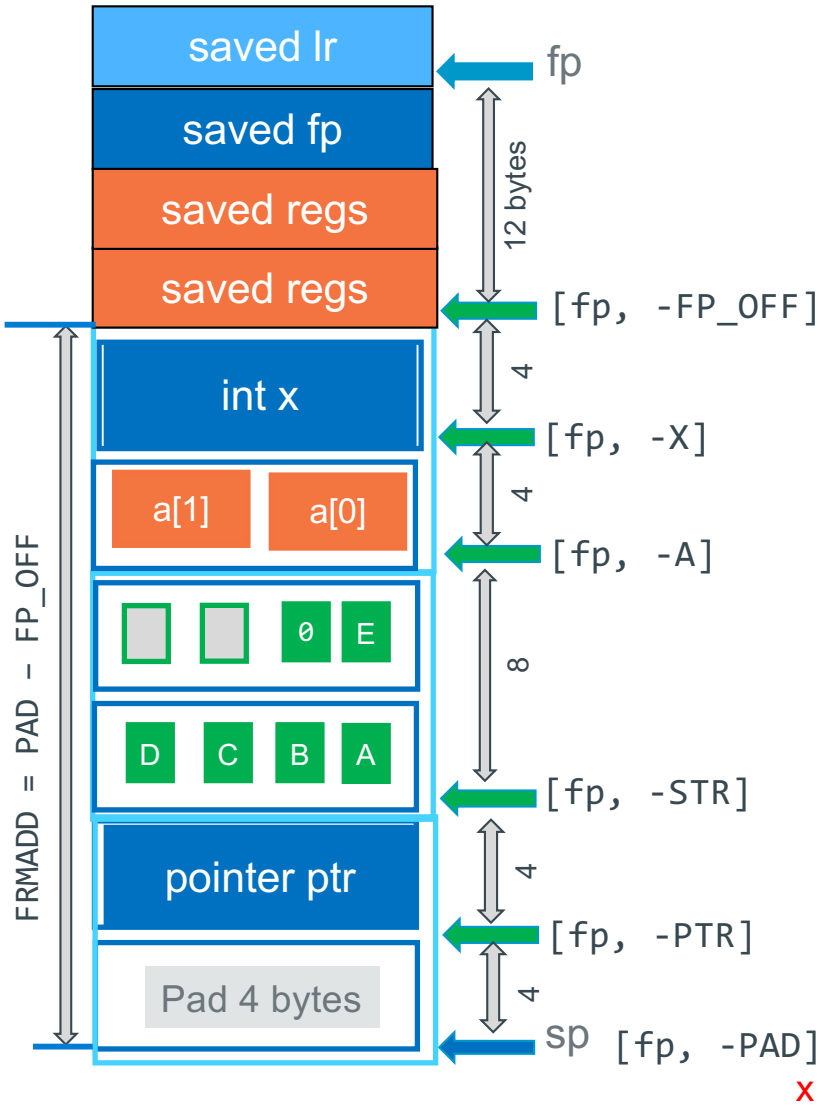
- Assign label names for each local variable
  - Each name is .equ to be the offset from fp

Variable name	Size	Name	expression size + prev	Distance from fp
Pushed regs-1	12	FP_OFF		12
int x	4	X	4 + FP_OFF	16
short a[]	4	A	4 + X	20
char str[]	8	STR	8 + A	28
char *ptr	4	PTR	4 + STR	32
PAD Added	4	PAD	4 + PTR	36
FRMADD		FRMADD	PAD-FP_OFF	24



Step 3 Allocate Space in the Prologue

```
    .global func
    .type   func, %function
    .equ      FP_OFF,      12
    .equ      X,           4 + FP_OFF
    .equ      A,           4 + X
    .equ      STR,         8 + A
    .equ      PTR,         4 + STR
    .equ      PAD,         4 + PTR
    .equ      FRMADD       PAD - FP_OFF
func:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
    ldr     r3, =FRMADD //frames can be large
    sub     sp, sp, r3 // add space for locals
    // rest of function code
    // no change to epilogue
    sub     sp, fp, FP_OFF  // deallocate locals
    pop     {r4, r5, fp, lr}
    bx      lr
    .size   func, (. - func)
```



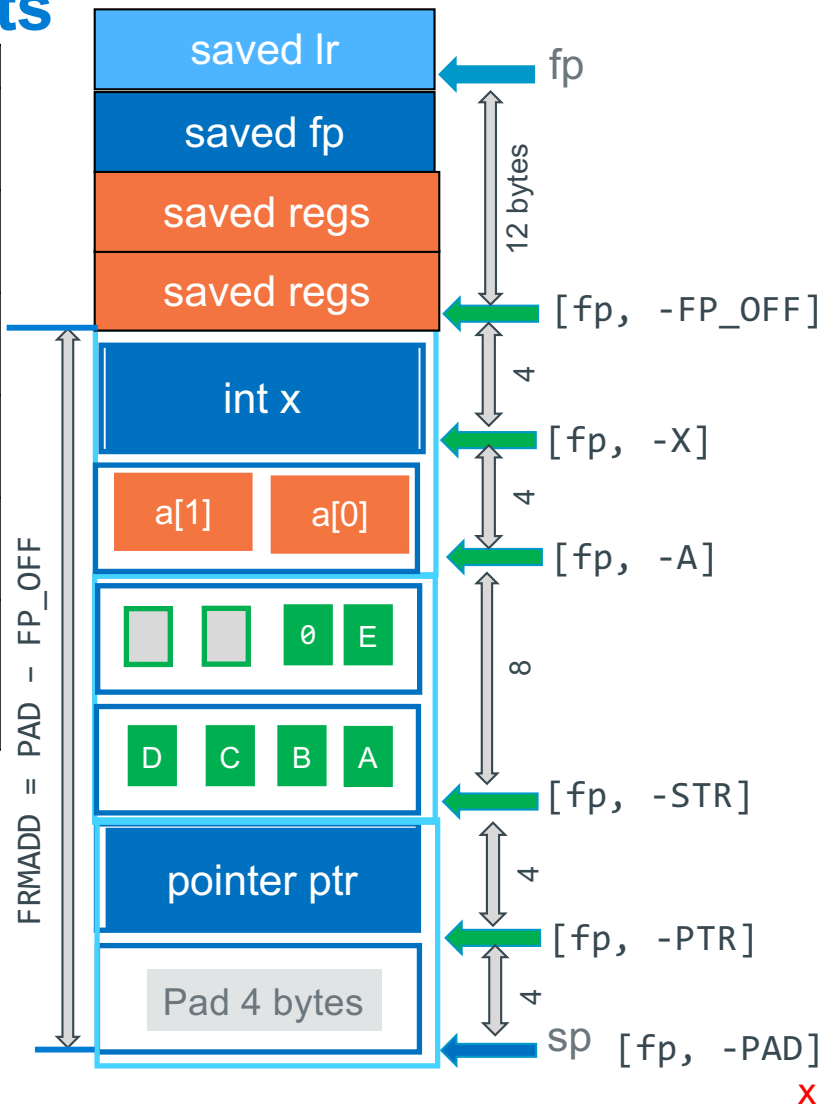
Accessing Stack using distance offsets

var	stack variable address into r0	stack variable contents into r0
x	ldr r0, =X sub r0, fp, r0	ldr r0, =X ldr r0, [fp, -r0]
a[0]	ldr r0, =A sub r0, fp, r0	ldr r0, =A ldrsh r0, [fp, -r0]
a[1]	ldr r0, =A - 2 sub r0, fp, r0	ldr r0, =A - 2 ldrsh r0, [fp, -r0]
str[1]	ldr r0, =STR - 1 sub r0, fp, r0	ldr r0, =STR - 1 ldrb r0, [fp, -r0]
ptr	ldr r0, =PTR sub r0, fp, r0	ldr r0, =PTR ldr r0, [fp, -r0]

*ptr	ldr r0, =PTR
	sub r0, fp, r0
	ldr r0, [r0]
		ldr r0, =PTR
		ldr r0, [fp, -r0]
		ldr r0, [r0]

var	write contents of r0 to stack variable
ptr	ldr r1, =PTR str r0, [fp, -r1]

*ptr	ldr r1, =PTR
	ldr r1, [fp, -r1]
	str r0, [r1]



Review: Loading and using Global Variables

- Tell the assembler to create and USE a literal table to obtain the address (Lvalue) of a label into a register:

  `ldr/str  Rd, =Label // Rd = address`

- *Example to the right: y = x;*

```
        .bss
y:      .space 4

        .data
x:      .word 200

        .text
        // function header
main:

        // load the address, then contents
        // using r2
        ldr r2, =x      // int *r2 = &x
        ldr r2, [r2]    // r2 = *r2;

        // &x was only needed once above
        // Note: r2 was a pointer then an int
        // no "type" checking in assembly!

        // store the contents of r2
        ldr r1, =y      // int *r1 = &y
        str r2, [r1]    // *r1 = r2
…
```

two step to **load** a **memory** variable

1. load the pointer to the memory
2. read (load) from *pointer

two steps **store** to a **memory** variable

1. load the pointer to the memory
2. write (store) to *pointer

x

Review: Global Variable access

var	*global variable address into r0*	*global variable contents into r0*	*contents of r0 into global variable*
x	`ldr r0, =x`	`ldr r0, =x` `ldr r0, [r0]`	`ldr r1, =x` `str r0, [r1]`

*x	`ldr r0, =x`
	`ldr r0, [r0]`
		`ldr r0, =x`
		`ldr r0, [r0]`
		`ldr r0, [r0]`
			`ldr r1, =x`
			`ldr r1, [r1]`
			`str r0, [r1]`

y	`ldr r0, =y`	`ldr r0, =y` `ldr r0, [r0]`	`ldr r1, =y` `str r0, [r1]`

stdin	`ldr r0, =stdin`	`ldr r0, =stdin`
		`ldr r0, [r0]`
			`ldr r1, =stdin`
			`str r0, [r1]`
			(example only, not recommended)

.Lstr	`ldr r0, =.Lstr`	`ldr r0, =.Lstr` `ldrb r0, [r0]`	<read only>

```
        .bss
y:      .space 4
stdin:.space 4  // FILE *
```

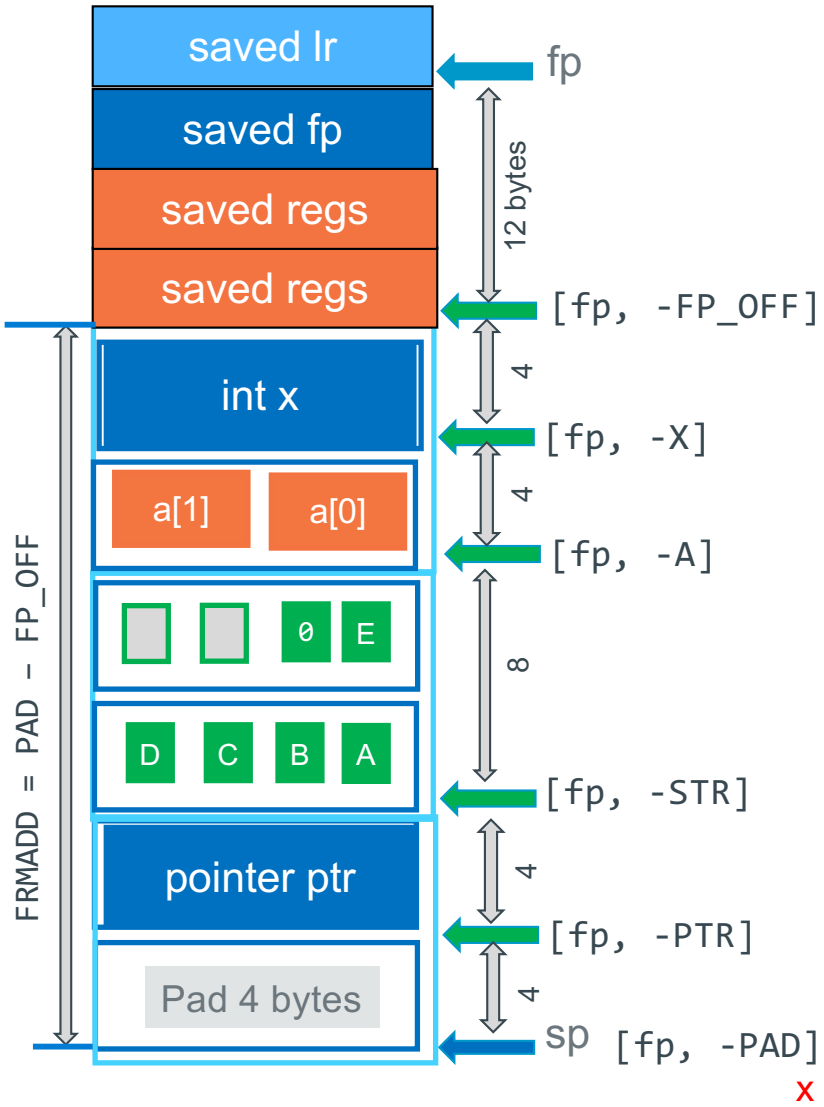
```
        .data
x:      .data y   //x = &y
```

```
        .section .rodata
.Lstr: .string "HI\n"
```

Step 4 Initialize the Local Variables

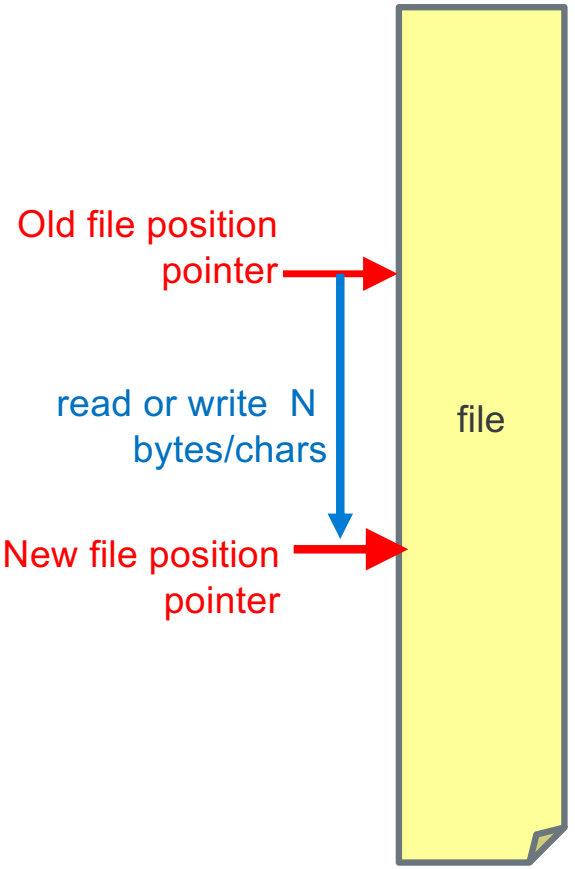
```
int func(void)
{
    int x = 0;
    short st[2];
    char str[] ="ABCDE";
    char *ptr = &(str[0]);
```

```
    mov     r4, 0
    ldr     r5, =X
    str     r4, [fp, -r5]

    ldr     r5, =STR
    sub     r5, fp, r5      // r5 = addr of STR
    ldr     r4, =PTR
    str     r5, [fp, -r4]   //ptr = &(str[0])
    mov     r4, 'A'
    strb    r4, [r5]
    mov     r4, 'B'
    add     r5, r5, 1
    strb    r4, [r5]
//…
```



C Stream Functions Array/block read/write

- Read/write ops *advance* the ***file position pointer*** from TOF towards EOF on each I/O
  - Moves towards EOF by number of bytes read/written
- `size_t fwrite(void *ptr, size_t size, size_t count, FILE *stream);`
  - Writes an array *ptr of *count* ***elements*** of ***size*** bytes from **stream**
  - *Updates the write file pointer forward by the number of bytes written*
  - returns number of elements written
    - Treat return != count as an error
- `size_t fread(void *ptr, size_t size, size_t count, FILE *stream);`
  - Reads an array *ptr of ***count elements*** of ***size*** bytes from *stream*
  - *Updates the read file pointer forward by the number of bytes read*
  - returns number of elements read,
    - Treat a return of 0 as being in EOF state
- **Set element size to 1 to return bytes read/written**
- EOF is **NOT a character in the file**, but a condition on the stream
- `int feof(FILE *stream)`
  - Returns non-zero at end-of-file for stream
- `int ferror(FILE *stream)`
  - Returns non-zero if error for stream



x

Version 1.13

UCSD CSE 30

Computer Organization and Systems Programming

Aarch32 Assembly – Part 5

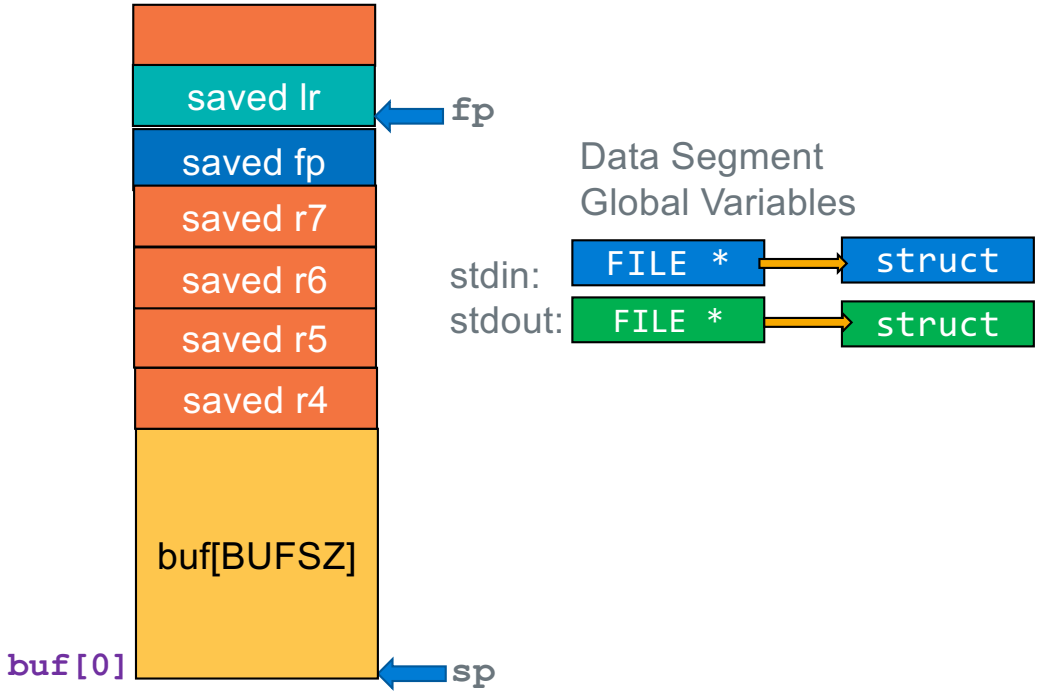
Lecture 21 – December 1, 2022

Keith Muller

Frontier Exascale

Passing Pointers to Stack Variables

```c
#include <stdio.h>
#include <stdlib.h>
#include <errno.h>
#define BUFSZ 4096
// copies input to output
int
main(void) {
    char buf[BUFSZ];
    size_t cnt;   // assign to a register only

    // read from stdin, up to BUFSZ bytes
    // and store them in buf
    // Number of bytes read is in cnt
    while ((cnt = fread(buf, 1, BUFSZ, stdin)) > 0) {
         // write cnt bytes from buf to stdout
        if (fwrite(buf, 1, cnt, stdout) != cnt) {
            return EXIT_FAILURE;
        }
    }
    return EXIT_SUCCESS;
}
```

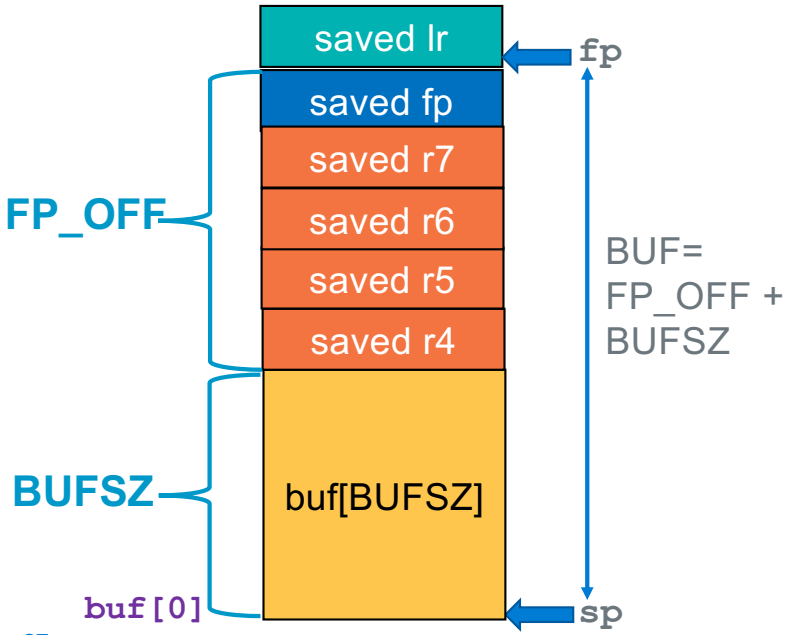



```
    .text
    .global main
    .type   main, %function    // stack frame below
    .equ    BUFSZ,      4096
    .equ    FP_OFF,     20          // fp offset in main stack frame
    .equ    BUF,        BUFSZ+FP_OFF// buffer
    .equ    PAD,        0+BUF       // Stack frame PAD
    .equ    FRMADD,     PAD-FP_OFF  // space for locals+passed args
```

Reading and Writing bytes using C library routines fread() and fwrite()

```
    .text
    .global main
    .type   main, %function    // stack frame below, distances from fp
    .equ    BUFSZ,      4096
    .equ    FP_OFF,     20          // fp offset in main stack frame
    .equ    BUF,        BUFSZ+FP_OFF// buffer
    .equ    PAD,        0+BUF       // Stack frame PAD
    .equ    FRMADD,     PAD-FP_OFF  // space for locals+passed args
```

```
    // save values in preserved registers
    ldr     r4, =BUF     // distance from fp
    sub     r4, fp, r4   // pointer to buffer
    ldr     r5, =stdin   // standard input global
    ldr     r5, [r5]
    ldr     r6, =stdout  // standard output global
    ldr     r6, [r6]
```




```
    // fread(buffer, element_size, number of elements, FILE *)
    // fread(r0=buf, r1=1, r2=BUFSZ, r3=stdin)
    mov     r0, r4              // buf
    mov     r1, 1               // bytes
    mov     r2, BUFSZ           // cnt (or ldr r2, =BUFSZ)
    mov     r3, r5              // stdin
    bl      fread
    cmp     r0, 0               // check return value from fread
```

```
    // fwrite(buffer, element_size, number of elements, FILE *)
    // fwrite(r0=buf, r1=1, r2=cnt, r3=stdout)
    mov     r0, r4              // buf
    mov     r1, 1               // bytes
    mov     r2, r7              // cnt
    mov     r3, r6              // stdout
    bl      fwrite
    cmp     r0, r7               // check return value from fwrite
```

Passing Pointers to Stack Variables

```
#define BUFSZ 4096
int main(void) {
    char buf[BUFSZ];
    size_t cnt;   // assign to a register only

    while ((cnt = fread(buf, 1, BUFSZ, stdin)) > 0) {
        if (fwrite(buf, 1, cnt, stdout) != cnt) {
            return EXIT_FAILURE;
        }
    }
    return EXIT_SUCCESS;
}
```

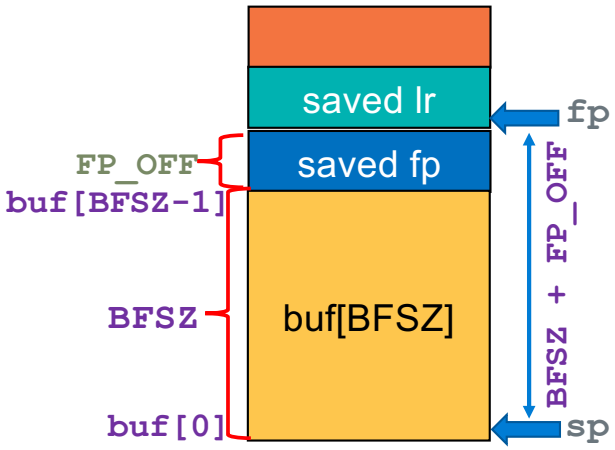
```
    .extern fread
    .extern fwrite
    .extern stdin
    .extern stdout
    .equ EXIT_FAILURE, 1

    .text
    .global main
    .type   main, %function

    .equ    BUFSZ,      4096
    .equ    FP_OFF,     20
    .equ    BUF,        BUFSZ + FP_OFF
    .equ    PAD,        0     + BUF
    .equ    FRMADD,     PAD-FP_OFF

// see right -->
.Ldone:
    sub     sp, fp, FP_OFF
    pop     {r4-r7, fp, lr}
    bx      lr

    .size   main, (. - main)
```

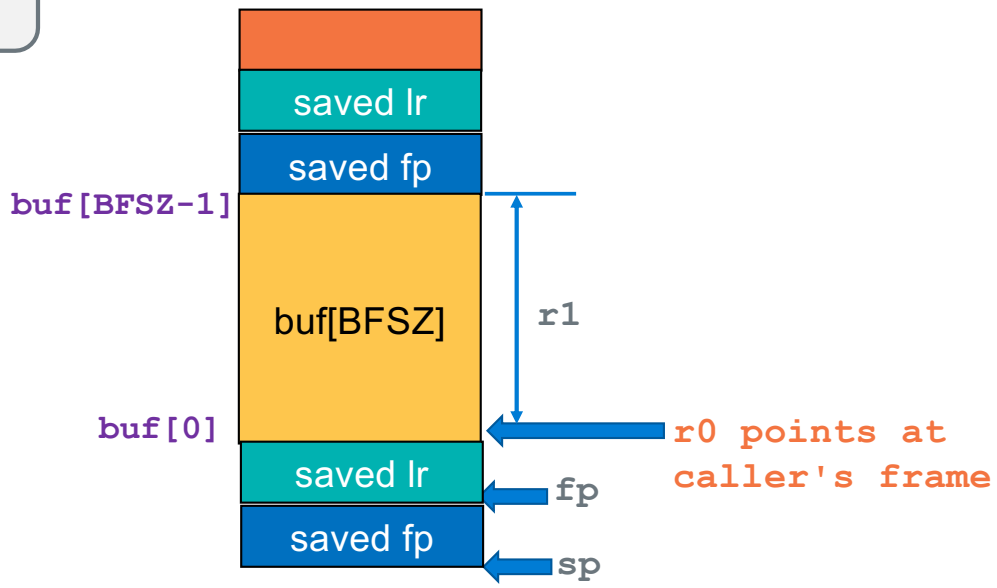
```
main:
    push    {r4-r7, fp, lr}
    add     fp, sp, FP_OFF          // set frame pointer
    ldr     r3, =FRMADD             // get frame size
    sub     sp, sp, r3              // allocate space

    // save values in preserved registers
    ldr     r4, =BUF                // distance from fp
    sub     r4, fp, r4              // pointer to buffer
    ldr     r5, =stdin              // standard input global
    ldr     r5, [r5]
    ldr     r6, =stdout             // standard output global
    ldr     r6, [r6]

.Lloop:
        // fread(r0=buf, r1=1, r2=BUFSZ, r3=stdin)
    mov     r0, r4                  // buf
    mov     r1, 1                   // bytes
    mov     r2, BUFSZ               // cnt (or ldr r2, =BUFSZ)
    mov     r3, r5                  // stdin
    bl      fread
    cmp     r0, 0
    ble     .Ldone
    mov     r7, r0                  // save cnt

          // fwrite(r0=buf, r1=1, r2=cnt, r3=stdout)
    mov     r0, r4                  // buf
    mov     r1, 1                   // bytes
    mov     r2, r7                  // cnt
    mov     r3, r6                  // stdout
    bl      fwrite
    cmp     r0, r7                  // did we write all the bytes?
    beq     .Lloop
    mov     r0, EXIT_FAILURE
.Ldone:
```

Writing Functions: Receiving a Pointer Parameter - 1

```
#define BFSZ 256 r0,        r1,        r2
void fillbuf(char *s, int len, char fill);
int main(void)
{
  char buf[BFSZ];
  fillbuf(buf, BFSZ, 'A');
  return EXIT_SUCCESS;
}
```

```
                                    r0,        r1,        r2
void fillbuf(char *s, int len, char fill)
{
    char *enptr = s + len;
    while (*s < enptr)
       *(s++) = fill;
}
```

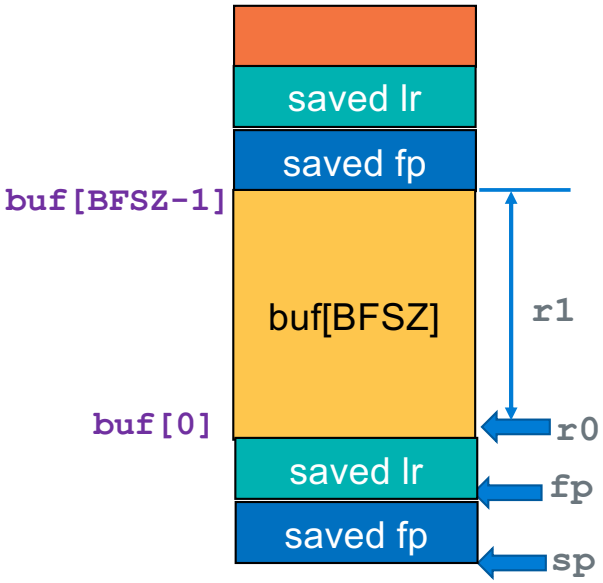




x

Writing Function: Receiving a Pointer Parameter - 2

```
void        r0,         r1,         r2
fillbuf(char *s, int len, char fill)
{
    char *enptr = s + len;
    while (s < enptr)
        *(s++) = fill;
}
```



Using r1 for endptr

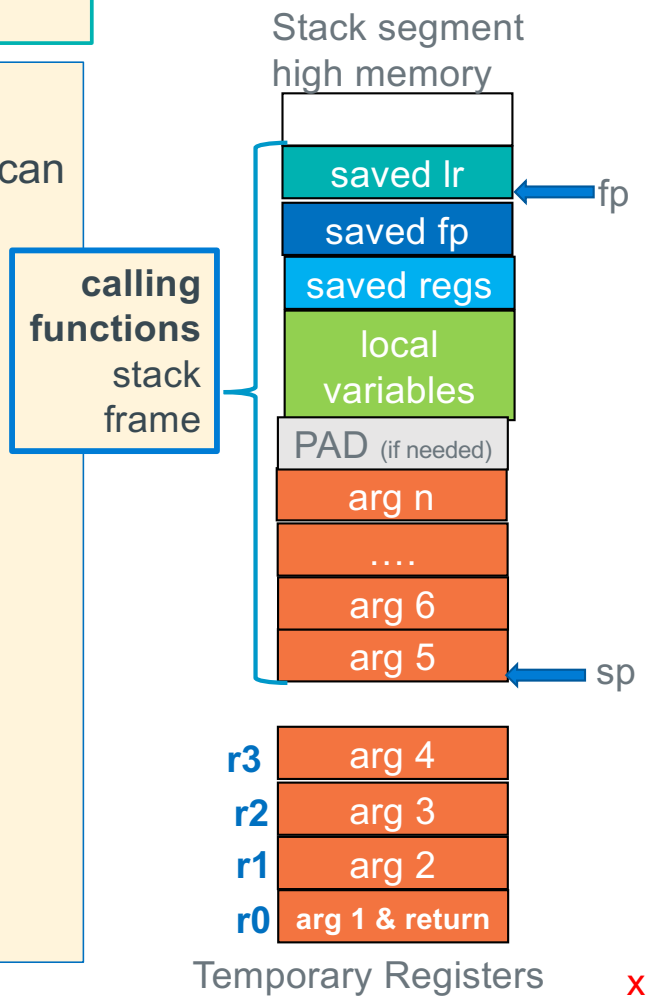
```
fillbuf:
    push    {fp, lr}        // stack frame
    add     fp, sp, FP_OFF  // set fp to base

    add     r1, r1, r0      // copy up to r1 = bufpt + cnt
    cmp     r0, r1          // are there any chars to fill?
    bge     .Ldone          // nope we are done

.Ldowhile:
    strb    r2, [r0]        // store the char in the buffer
    add     r0, 1           // point to next char
    cmp     r0, r1          // have we reached the end?
    blt     .Ldowhile       // if not continue to fill

.Ldone:
    sub     sp, fp, FP_OFF  // restore stack frame top
    pop     {fp, lr}        // restore registers
    bx      lr              // return to caller
```


x

Passing More Than Four Arguments – At the point of Call

```
r0 = function(r0, r1, r2, r3, arg5, arg6, … argn)
                arg1, arg2, arg3, arg4, ...
```

- **Args > 4 are in the caller's stack frame at SP (argv5), an up**
- Called functions have the right to change stack args just like they can change the register args!
  - Caller must assume **all args** including ones on the stack are changed by the caller
- Calling function prior to making the call
  1. Evaluate first four args: place resulting values in r0-r3
  2. Store Arg 5 and greater parameter values on the stack
- **One arg value per slot**! – NO arrays across multiple slots
  - chars, shorts and ints are directly stored
  - Structs (not always), and arrays are passed via a pointer
  - **Pointers** passed as output parameters usually contain an address ***that points at*** the stack, BSS, data, or heap



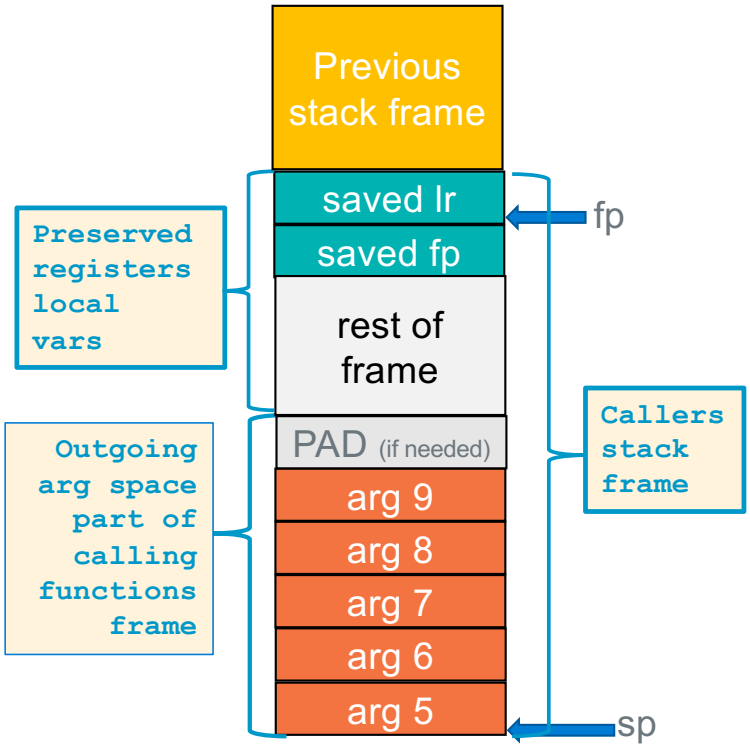
Calling Function: Allocating Stack Parameter Space

At the point of a function call (and obviously at the start of the called function):

1. sp must point at arg5
2. arg5 **must be at an 8-byte boundary**,
   a) **padding** to force arg5 alignment is **placed above** the last **argument the called function is expecting**

Approach: Extend the stack frame to include enough space for stack arguments function with the greatest arg count

1. Examine every function call in the body of a function
2. Find the function call with greatest arg count, Determines space needed for outgoing args
3. Add the space needed to the frame layout



Rules: At point of call

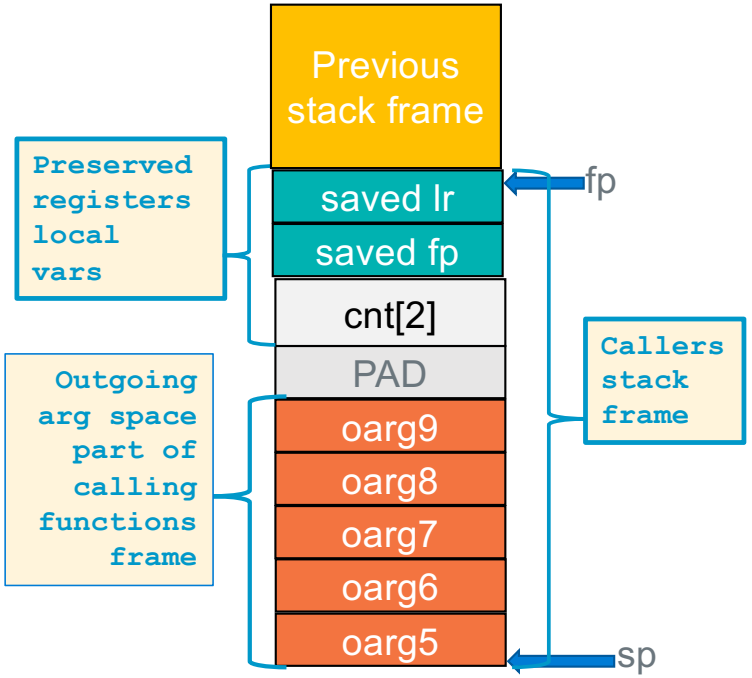
1. **arg5 must be pointed at by sp**
2. **SP must be 8-byte aligned**

x

Calling Function: Pass ARGS 5 and higher

```
.equ    FP_OFF,4
.equ    CNT,            8 + FP_OFF          // int cnt[2];
.equ    PAD,            4 + CNT          // added as needed
.equ    OARG9,          4 + PAD
.equ    OARG8,          4 + OARG9
.equ    OARG7,          4 + OARG8
.equ    OARG6,          4 + OARG7
.equ    OARG5,          4 + OARG6
.equ    FRMADD          OARG5 - FP_OFF
```

var	*write contents*
OARG5 = r1	ldr r0, =OARG5 //distance str r1, [fp, -r0]
OARG6 = &cnt	ldr r2, =CNT //distance sub r2, fp, r2 // &cnt ldr r0, =OARG6 //distance str r2, [fp, -r0]



Rules: At point of call

1. **arg5 must be pointed at by sp**
2. **SP must be 8-byte aligned**

x

Called Function: Retrieving Args From the Stack

- At function start and before the push{} the sp is at an 8-byte boundary
- **Args are in the caller's stack frame and arg 5 always starts at fp+4**
  - Additional args are higher up the stack, with one “slot” every 4-bytes
- This "algorithm" for finding args was designed to enable variable arg count functions like printf("conversion list", arg0, … argn);

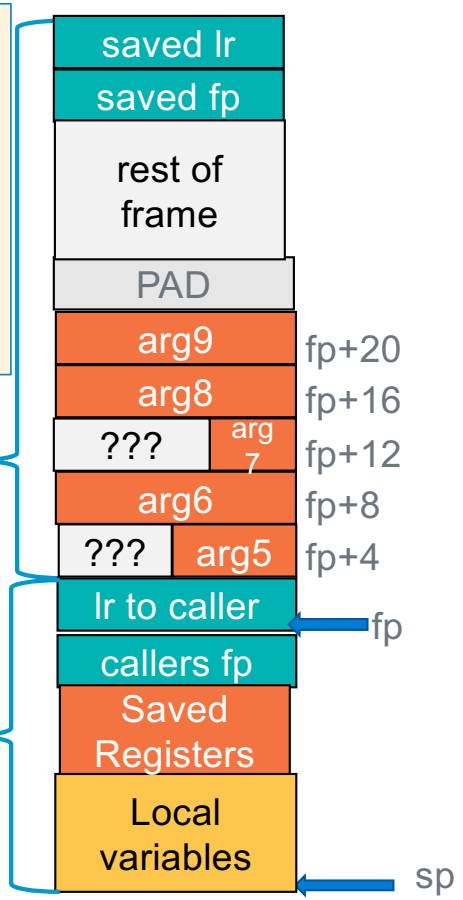
```
int func(int a1, int a2, int a3, int a4,
         short a5, int a6, char a7, int a8, int a9)
```

Constant	Offset	arm ldr /str statement
ARGN	(N-4)*4	ldr r4, [fp, ARGN]
ARG9	20	ldr r4, [fp, ARG9]
ARG8	16	ldr r4, [fp, ARG8]
ARG7	12	ldrb r4, [fp, ARG7]
ARG6	8	ldr r4, [fp, ARG6]
ARG5	4	ldrh r4, [fp, ARG5]

Callers Stack frame
no defined limit to number of args, keep going up stack 4 bytes at a time

Current Stack Frame

```
.equ ARG9,  20
.equ ARG8,  16
.equ ARG7,  12
.equ ARG6,   8
.equ ARG5,   4
```



Rule: Called functions always access stack parameters using a positive offset to the fp

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Determining the Passed Parameter Area on The Stack

- Find the function called by main with the largest number of parameters
- That function determines the size of the Passed Parameter allocation on the stack

```
int main(void)
{
    /* code not shown */
    a(g, h);

   /* code not shown */
    sixsum(a1, a2, a3, a4, a5, a6);

   /* code not shown */

   b(q, w, e, r);
   /* code not shown */
}
```

largest arg count is 6
allocate space for 6 - 4 = 2 arg slots

x

Passing More than Four Args – Six Arg Example

- Problem: Write and call a function that receives six integers and returns the sum
- First 4 parameters are in register r0 - r3 and the remaining argument are on the stack
- For this example, we will put all the locals on the stack

```
int main(void)
{
    int cnt = sixsum(1, 2, 3, 4, 5, 6);

    printf("the sum is %d\n", cnt);
    return EXIT_SUCCESS;
}
```

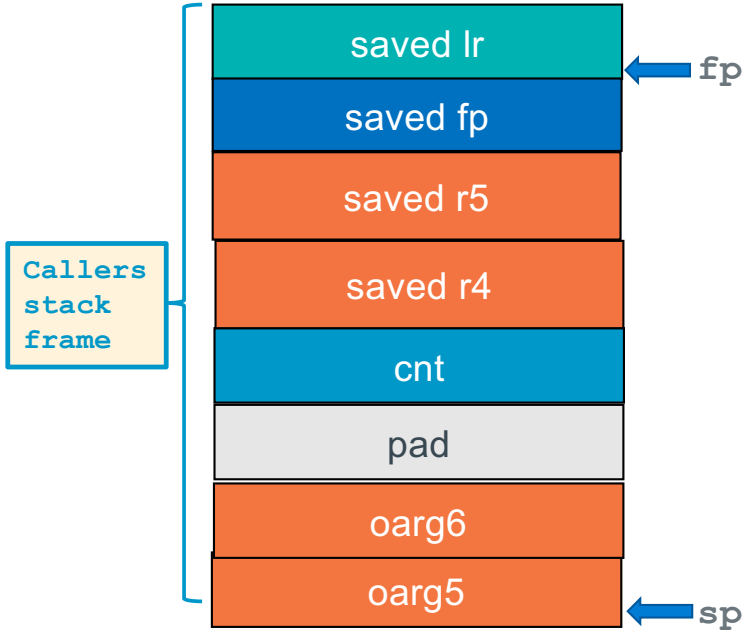
```
int
sixsum(int a1, int a2, int a3, int a4, int a5, int a6)
{
    return a1 + a2 + a3 + a4 + a5 + a6;
}
```


x

Calling Function > 4 Args - 1

```
int cnt = sixsum(1, 2, 3, 4, 5, 6);
```

```
        .equ    FP_OFF,         12  // local base
           // NAME,             SIZE + prev_name
        .equ    CNT,            4 + FP_OFF
        .equ    PAD,            4 + CNT
        .equ    OARG6,          4 + PAD
        .equ    OARG5,          4 + OARG6
        .equ    FRMADD          OARG5 - FP_OFF
```



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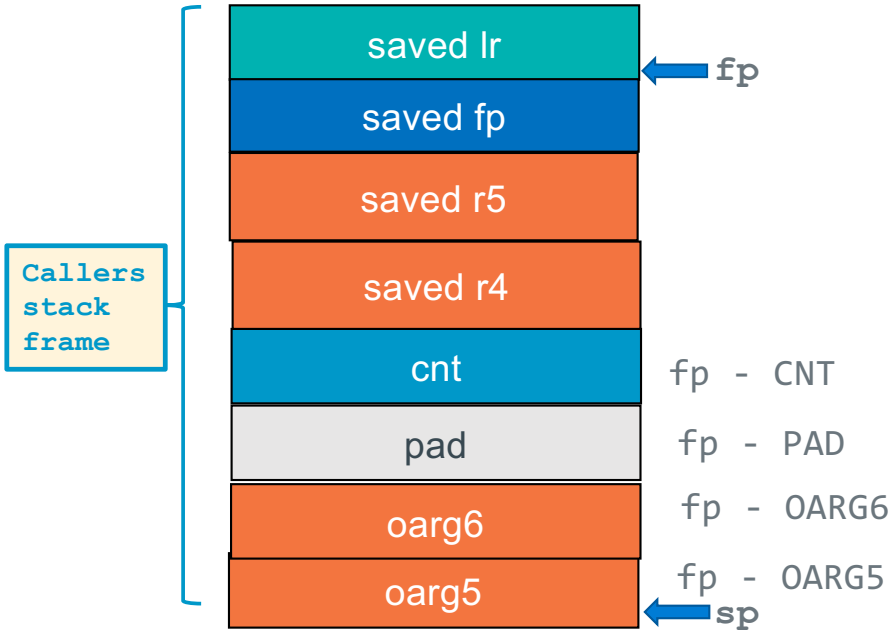
Calling Function > 4 Args - 2

```
int cnt = sixsum(1, 2, 3, 4, 5, 6);
```

```
.equ    FP_OFF, 12
.equ    CNT,            4 + FP_OFF
.equ    PAD,            4 + CNT
.equ    OARG6,          4 + PAD
.equ    OARG5,          4 + OARG6
.equ    FRMADD          OARG5 - FP_OFF
```




```
    .section .rodata
.Lpfstr: .string "the sum is %d\n"
```

```
main:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
    ldr     r3, =FRMADD
    sub     sp, sp, r3

    mov     r0, 6
    ldr     r5, =OARG6
    str     r0, [fp, -r5]   // arg6
    mov     r0, 5
    ldr     r5, =OARG5
    str     r0, [fp, -r5]   // arg5
    mov     r3, 4           // arg4
    mov     r2, 3           // arg3
    mov     r1, 2           // arg2
    mov     r0, 1           // arg1
    bl      sixsum

    ldr     r5, =CNT
    str     r0, [fp, -r5]  // update cnt on stack
    mov     r1, r0
    ldr     r0, =.Lpfstr
    bl      printf

    mov     r0, EXIT_SUCCESS
    sub     sp, fp, FP_OFF
    pop     {r4, r5, fp, lr}
    bx      lr
```

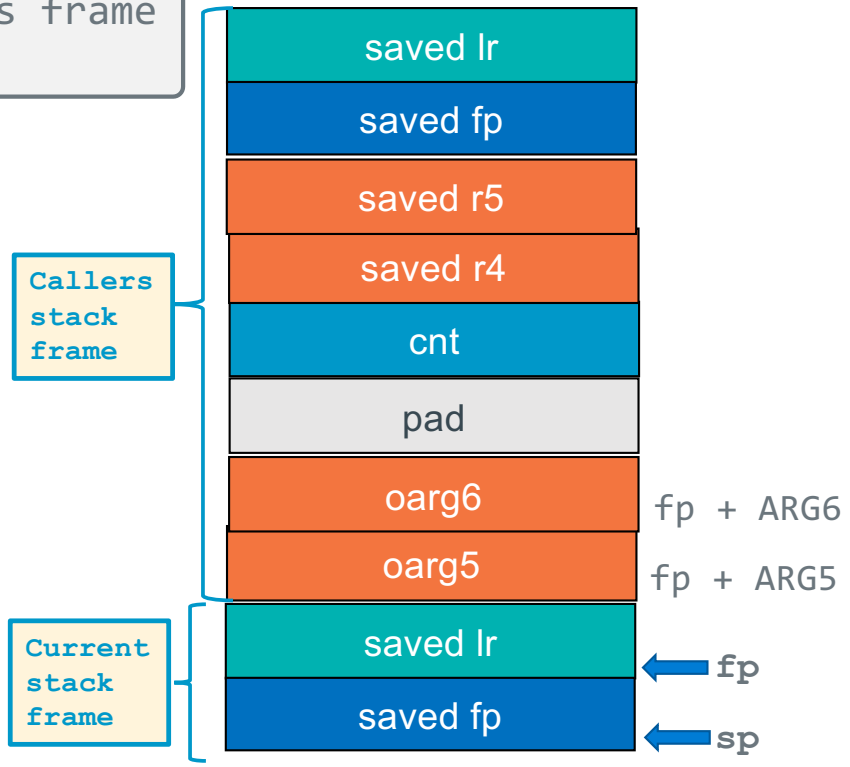

x

Called Function > 4 Args

```
int sixsum(int a1, int a2, int a3, int a4, int a5, int a6)
    return a1 + a2 + a3 + a4 + a5 + a6;
```

```
.equ   ARG6,         8 // offset into caller's frame
.equ   ARG5,         4 // offset into caller's frame
.equ   FP_OFF,       4 // local base
```

```
sixsum:
        push    {fp, lr}
        add     fp, sp, FP_OFF
        add     r0, r0, r1
        add     r0, r0, r2
        add     r0, r0, r3
        ldr     r1, [fp, ARG5]
        add     r0, r0, r1
        ldr     r1, [fp, ARG6]
        add     r0, r0, r1
        sub     sp, fp, FP_OFF
        pop     {fp, lr}
        bx      lr
```



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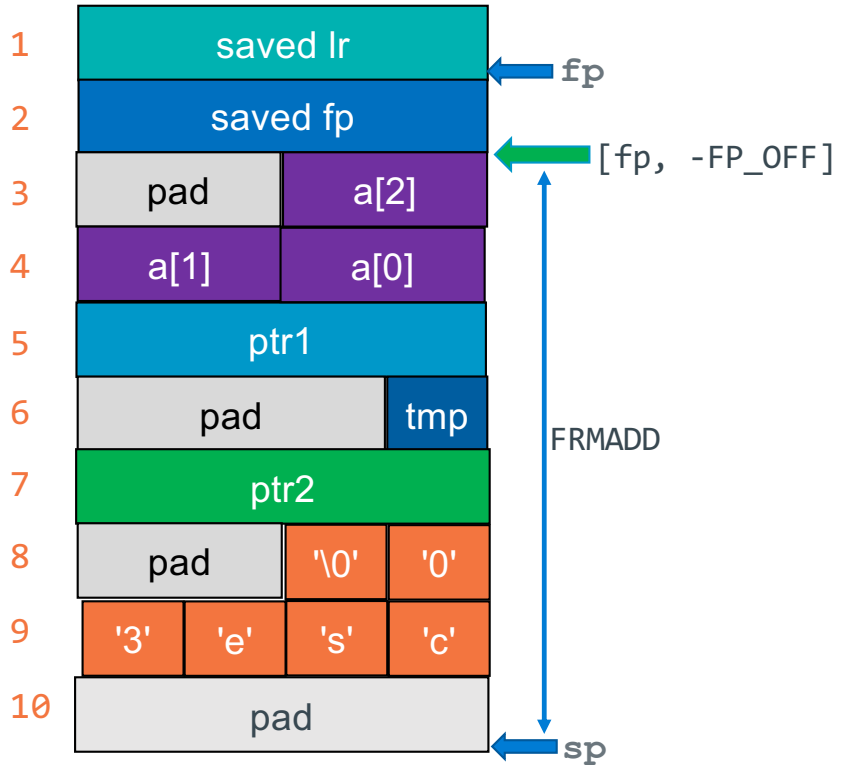
Extra Slides

Local Variables: Stack Frame Design Practice

Example shows allocation **without reordering** variables to optimize space

```
short a[3];
short *ptr1;
char tmp;
char *ptr2;
char nm[] = "cse30";
```

```
.equ   FP_OFF,       4  // Local base
// NAME,            SIZE + prev_name
.equ   A,            8 + FP_OFF
.equ   PTR1,         4 + A
.equ   TMP,          4 + PTR1
.equ   PTR2,         4 + TMP
.equ   NM,           8 + PTR2
.equ   PAD,          4 + NM
.equ   FRMADD        PAD - FP_OFF // for locals
```



When writing real code, you do not have to put all locals on the stack

- Place locals in registers if they fit, are accessed often, **and**
- You do not need their address (they are not an output variable in a function call)

x

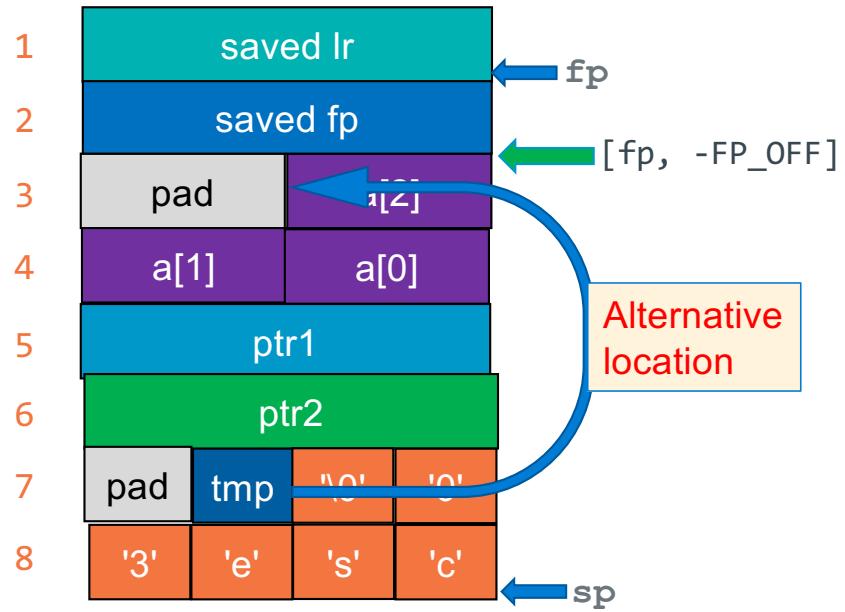
Local Variables: Stack Frame Design Reordering

Example shows allocation **with reordering** variables to optimize space

```
short a[3];
short *ptr1;
char *ptr2;
char tmp;
char nm[] = "cse30";
```

```
.equ   FP_OFF,        4  // Local base
// NAME,            SIZE + prev_name
.equ   A,             8 + FP_OFF
.equ   PTR1,          4 + A
.equ   PTR2,          4 + PTR1
.equ   TMP,           2 + PTR2
.equ   NM,            6 + TMP
.equ   PAD,           0 + NM // not needed
.equ   FRMADD         PAD - FP_OFF
```

size change



When writing real code, you do not have to put all locals on the stack

- Place locals in registers if they fit, are accessed often, **and**
- You do not need their address (they are not an output variable in a function call)

x

ARM Assembly Source File: Header and Footer

File Header
At the top of every ARM source file

```
        .arch   armv6          // armv6 architecture
        .arm                   // arm 32-bit instruction set
        .fpu    vfp            // floating point co-processor
        .syntax unified        // modern syntax
```

```
// Contents of the other memory segment include .text (your code)
```

File Footer
At the bottom of every ARM source file

```
.section .note.GNU-stack,"",%progbits // set stack/data non-exec
.end
        // everything past the .end is ignored!
        // Debugging notes etc
```

`.syntax unified`

- use the standard ARM assembly language syntax called ***Unified Assembler Language (UAL)***

`.section .note.GNU-stack,"",%progbits`

- tells the linker to **make the stack and all data segments not-executable** (no instructions in those sections) – security measure

`.end`

- at the end of the source file, everything written after the .end is ignored

x

Function Header and Footer Assembler Directives

function entry point
address of the first instruction in the function
Must not be a local label (does not start with .L)

```
                .text
Function        .global myfunc              // make myfunc global for linking
Header          .type   myfunc, %function   // define myfunc to be a function
                .equ    FP_OFF,  4          // fp offset in main stack frame
myfunc:
                // function prologue, stack frame setup
                // your code
                // function epilogue, stack frame teardown
Function        .size myfunc, (. - myfunc)
Footer
```

`.global function_name`

- Exports the function name to other files. **Required for main function,** optional for others

`.type name, %function`

- The `.type` directive sets the **type of a symbol/label name**
- `%function` specifies that **name** is a function (name is the address of the first instruction)

`equ FP_OFF, 4`

- Used for basic stack frame setup; the number 4 will change – later slides

`.size name, bytes`

- The `.size` directive is used to set the size associated with a symbol
- Used by the linker to exclude unneeded code and/or data when creating an executable file
- It is also used by the **debugger** gdb
- `bytes` **is best calculated as an expression: (period is the current address in a memory segment)**
  In CSE30 required use: `.size name, (. - name)`

x

Reference For PA8/9: C Stream Functions Opening Files

```
FILE *fopen(char filename[], const char mode[]);
```

- Opens a stream to the specified file in specified file access mode
  - returns NULL on failure – always check the return value; make sure the open succeeded!
- Mode is a string that describes the actions that can be performed on the stream:

"r'" Open for reading.

The stream is positioned at the beginning of the file. Fail if the file does not exist.

"w" Open for writing.

The stream is positioned at the beginning of the file. Create the file if it does not exist.

"a" Open for writing.

The stream is positioned at the end of the file. Create the file if it does not exist.

Subsequent writes to the file will always be at current end of file.

- An optional "+" following "r", "w", or "a" opens the file for both reading and writing

x

Reference: C Stream Functions Closing Files and Usage

```
int fclose(FILE *stream);
```

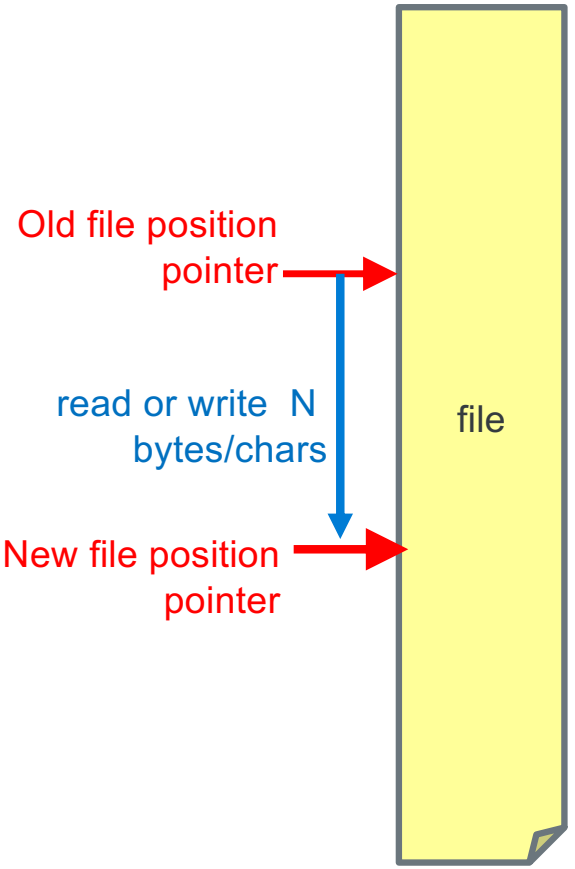
- Closes the specified stream, if open for writing, then forcing output to complete (eventually)
  - returns EOF on failure (often ignored as no easy recovery other than a message)

- Usage template for `fopen()` and `fclose()`
  1. Open a file with `fopen()` **always** checking the return value
  2. do i/o – keep calling stdio io routines
  3. close the file with `fclose()` when done with that I/O stream

x

C Stream Functions Array/block read/write

- Read/write ops *advance* the ***file position pointer*** from TOF towards EOF on each I/O
  - Moves towards EOF by number of bytes read/written
- `size_t fwrite(void *ptr, size_t size, size_t count, FILE *stream);`
  - Writes an array *ptr of *count* ***elements*** of ***size*** bytes from **stream**
  - *Updates the write file pointer forward by the number of bytes written*
  - returns number of elements written
    - Treat return != count as an error
- `size_t fread(void *ptr, size_t size, size_t count, FILE *stream);`
  - Reads an array *ptr of ***count elements*** of ***size*** bytes from *stream*
  - *Updates the read file pointer forward by the number of bytes read*
  - returns number of elements read,
    - Treat a return of 0 as being in EOF state
- **Set element size to 1 to return bytes read/written**
- EOF is **NOT a character in the file**, but a condition on the stream
- `int feof(FILE *stream)`
  - Returns non-zero at end-of-file for stream
- `int ferror(FILE *stream)`
  - Returns non-zero if error for stream

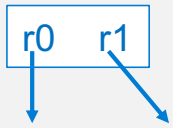


x

putchar/getchar
Setting up and Usage

```
#include <stdio.h>
#include <stdlib.h>
int
main(void)
{
    int c;
    int count = 0;

    while ((c = getchar()) != EOF) {
        putchar(c);
        count++;
    }
    printf("Echo count: %d\n", count);
    return EXIT_SUCCESS;
}
```




```
        .extern getchar
        .extern putchar
        .section .rodata
.Lfstr: .string  "Echo count: %d\n"
        .text
        .equ    EOF,         -1
        .type   main, %function
        .global main
        .equ    FP_OFF,    12
        .equ    EXIT_SUCCESS, 0
main:   push    {r4, r5, fp, lr}
        add     fp, sp, FP_OFF
        mov     r4, 0  //r4 = count

/* while loop code will go here */
.Ldone:
        mov     r1, r4 // count
        ldr     r0, =.Lfstr
        bl      printf
        mov     r0, EXIT_SUCCESS
        sub     sp, fp, FP_OFF
        pop     {r4, r5, fp, lr}
        bx      lr
        .size main, (. - main)
```

Putchar/getchar: The while loop

initialize count

pre loop test with a call to getchar()
if it returns EOF in r0 we are done

echo the character read with getchar and
then read another and increment count

did getchar() return EOF if not loop

saw EOF, print count

```
#include <stdio.h>
#include <stdlib.h>
int
main(void)
{
    int c;
    int count = 0;

    while ((c = getchar()) != EOF) {
        putchar(c);
        count++;
    }
    printf("Echo count: %d\n”, count);
    return EXIT_SUCCESS;
}
```

```
        mov     r4, 0  //count
        bl      getchar
        cmp     r0, EOF
        beq     .Ldone
.Lloop:
        bl      putchar
        bl      getchar
        add     r4, r4, 1
        cmp     r0, EOF
        bne     .Lloop
.Ldone:
        mov     r1, r4
        ldr     r0, =pfstr
        bl      printf
```

File header and footers are not shown

x

printing error messages in assembly

```
.Lmsg0: .string "Read failed\n"
        ldr     r0, =.Lmsg0                     // read failed print error
        bl      errmsg
```

```
        // int errmsg(char *errormsg)
        // writes error messages to stderr
        .type   errmsg, %function               // define to be a function
        .equ    FP_OFF,         4               // fp offset in stack frame
errmsg:
        push    {fp, lr}                        // stack frame register save
        add     fp, sp, FP_OFF                  // set the frame pointer

        mov     r1, r0
        ldr     r0, =stderr
        ldr     r0, [r0]
        bl      fprintf
        mov     r0, EXIT_FAILURE                // Set return value
        sub     sp, fp, FP_OFF                  // restore stack frame top
        pop     {fp, lr}                        // remove frame and restore
        bx      lr                              // return to caller
        // function footer
        .size   errmsg, (. - errmsg)            // set size for function
```


x

main.S Source File Showing a minimum stack frame