Version Work in progress 2.00

UCSD CSE 30

Computer Organization and Systems Programming

Arm Assembly – Part 4

Cao-Slides, Credit: Keith Muller

Function Calls

Branch with Link (function call) instruction

```
bl label
```

bl	imm24

- Function call to the instruction with the address `label` (no local labels for functions)
  - imm24 number of instructions from pc+8 (24-bits)
  - label **any function label** in the current file, any function label that is defined as **.global** in any file that it is linked to, any C function that is not static

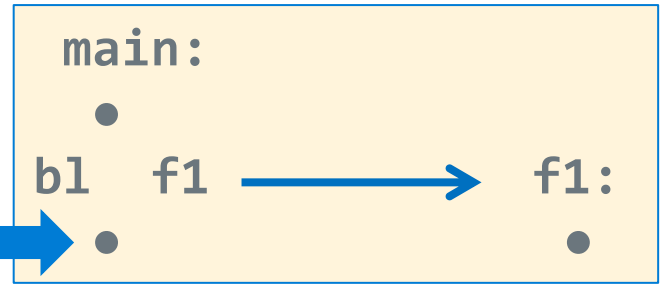
Branch with Link Indirect (function call) instruction

```
blx Rm
```

blx	Rm

- Function call to the instruction whose address is stored in Rm (Rm is a function pointer)
- bl and blx **both save** the address of the instruction **immediately** following the **bl** or blx instruction **in register lr** (link register is also known as r14)
- **The contents of the link register is the return address in the calling function**

(1) Branch to the instruction with the label f1
(2) copies the address of the instruction AFTER the bl in lr



Function Call Return

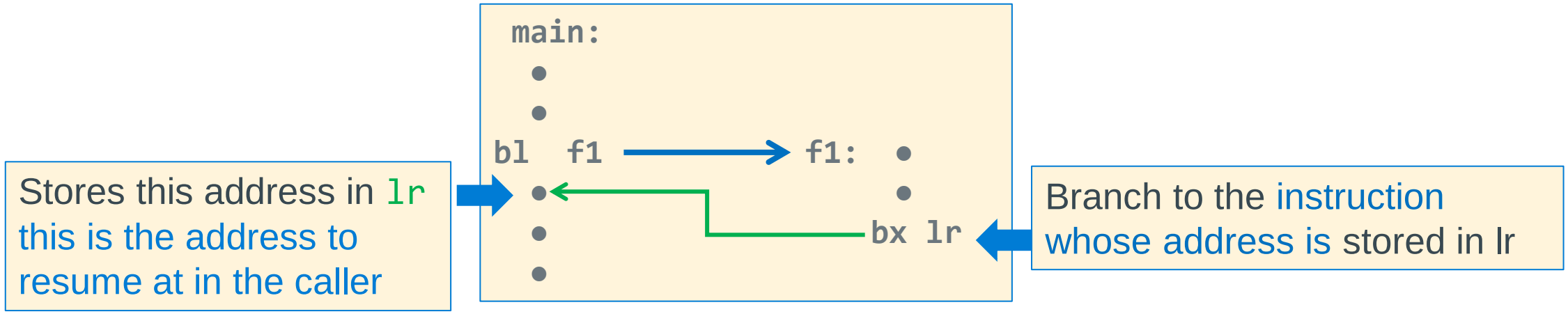
Branch & exchange (function return) instruction

```
bx lr
```

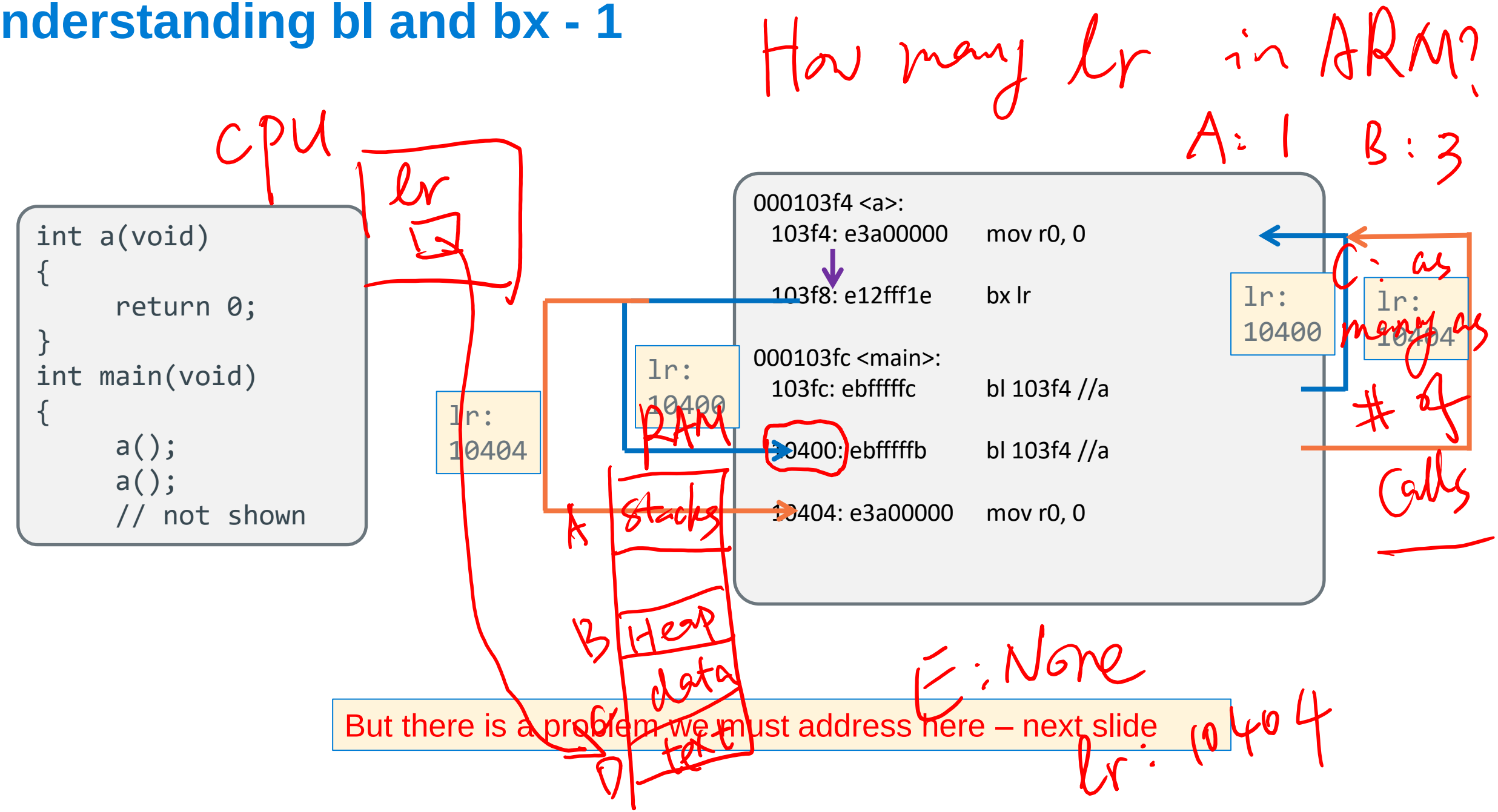
bx	Rn

```
// we will always use lr
```

- Causes a branch to the instruction **whose address is stored** in register <`lr`>
  - It copies `lr` to the PC
- This is often used to implement a return from a function call (exactly like a C return) when the function is called using either `bl label, or blx Rm`



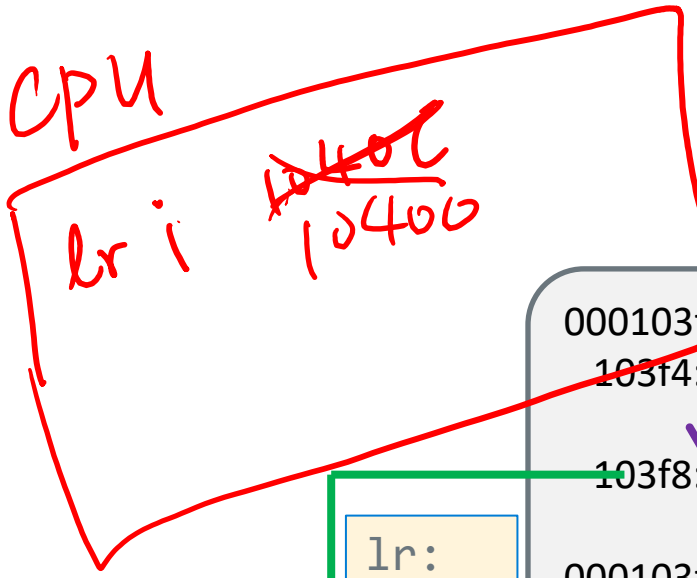
Understanding bl and bx - 1



Understanding bl and bx - 2

```
int b(void)
{
    return 0;
}
int a(void)
{
    b();
    return 0;
}
int main(void)
{
     a();
     a();
     // not shown
```

We need to preserve the lr!



Modifies the link register (lr), writing over main's return address
Cannot return to main()

```
000103f4 <b>:
   103f4: e3a00000     mov r0, 0
   103f8: e12fff1e     bx lr

000103fc <a>:
   103fc: ebfffffc     bl 103f4 <b>

   10400: e3a00000     mov r0, 0
   10404: e12fff1e     bx lr

00010408 <main>:
   10408: ebfffffb     bl 103fc <a>

   1040c: ebfffffa     bl 103fc <a>

   10410: e3a00000     mov r0, 0
```

lr: 10400

lr: 10400

lr: 1040c

lr: 10400

Uh No
Infinite loop!!!

Understanding bl and blx - 3

```
int a(void)
{
      return 0;
}

int (*func)() = a;

int main(void)
{
    (*func)();
    // not shown
```

But this has the same infinite loop problem when main() returns!

```
    .data
func:.word a // func initialized with address of a()

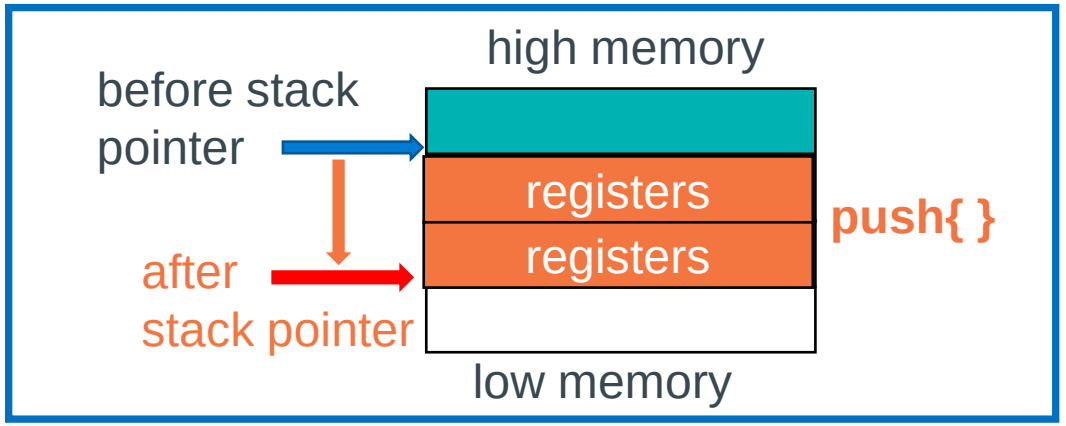
    .text
    .global a
    .type   a, %function
    .equ    FP_OFF, 4
a:
    mov     r0, 0
    bx      lr
    .size a, (. - a)

    .global main
    .type   main, %function
    .equ    FP_OFF, 4
main:
    ldr     r4, =func    // load address of func in r4
    ldr     r4, [r4]     // load contents of func in r4
    blx     r4                  // we lose the lr for main!
    // not shown
    bx          lr          // infinite loop!
```

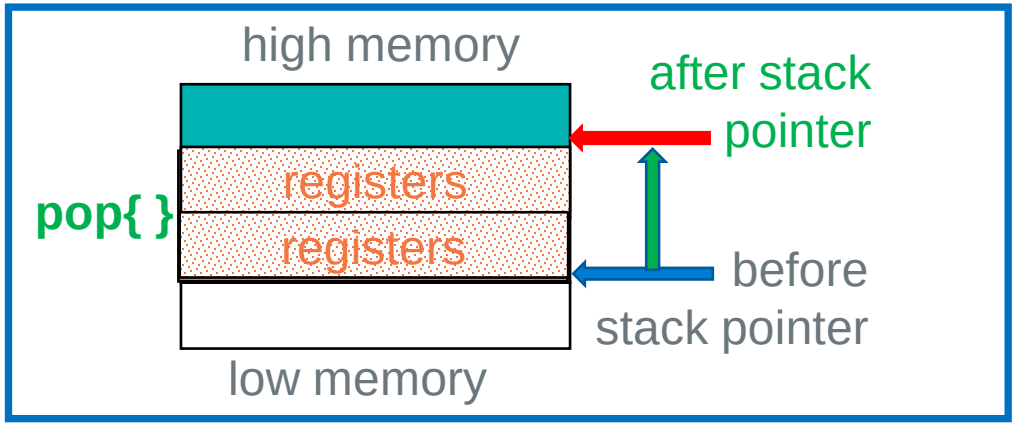
Preserving and Restoring Registers on the stack - 1

Operation	*Pseudo Instruction*	*Operation*
Push registers Function Entry	push *{reg list}*	sp = sp – 4 × #registers Copy registers to mem[sp]
Pop registers Function Exit	pop *{reg list}*	Copy mem[sp] to registers, sp = sp + 4 × #registers

push (multiple register `str` to memory operation)



push (multiple register `ldr` from memory operation)



Preserving and Restoring Registers on the Stack - 2

Operation	*Pseudo Instruction*	*Operation*
Push registers Function Entry	push *{reg list}*	sp = sp – 4 × #registers Copy registers to mem[sp]
Pop registers Function Exit	pop *{reg list}*	Copy mem[sp] to registers, sp = sp + 4 × #registers

- `{reg list}` is a **list of registers** in **numerically increasing order, left to right**

```
push {r4-r10, fp, lr}   // fp is r11, lr is r14
```

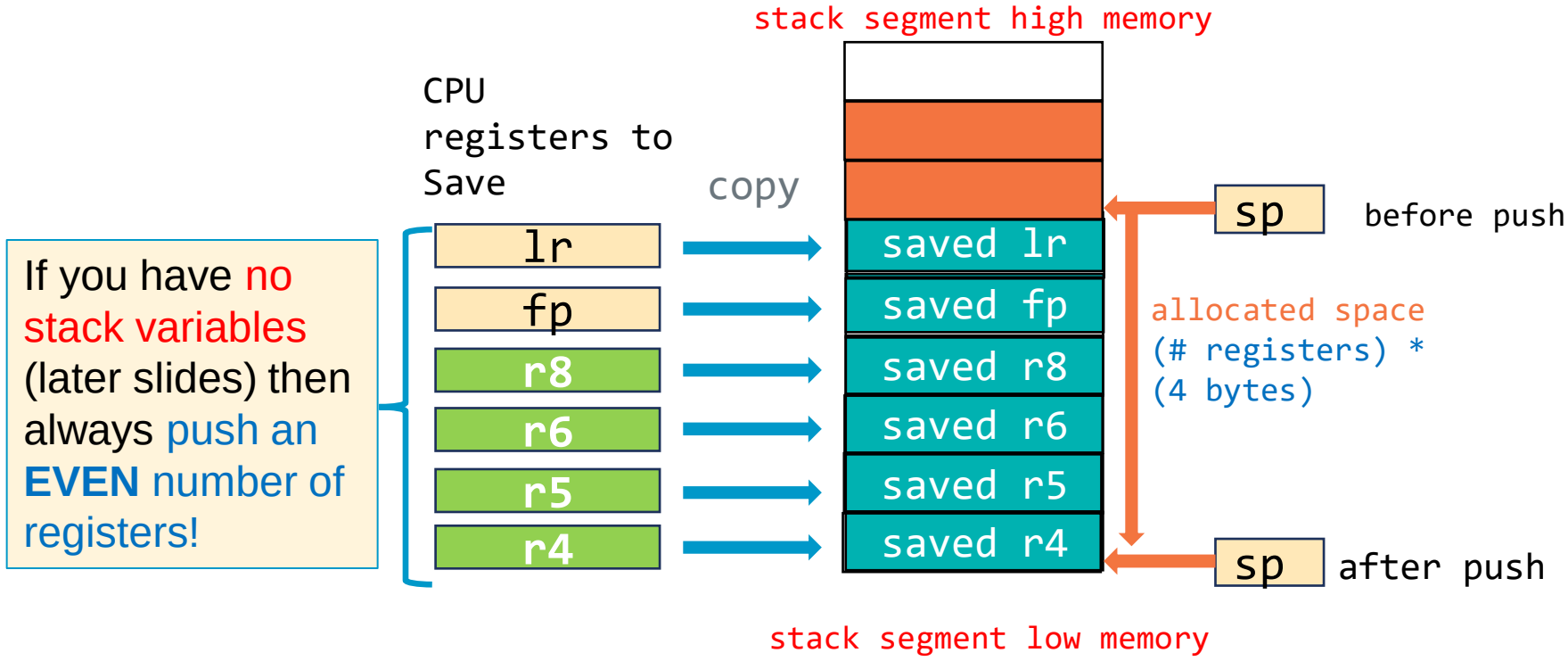
- Registers cannot be:
  1. duplicated in the list
  2. listed out of increasing numeric order (left to right)
- Register ranges can be specified `{r4, r5, r8-r10, fp, lr}`
- **Never!** `push/pop r12, r13, or r15`
  - the top two registers on the stack must always be `fp, lr` // ARM function spec – later slides

push: Multiple Register Save to the 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 slides) then always push an **EVEN** number of registers!

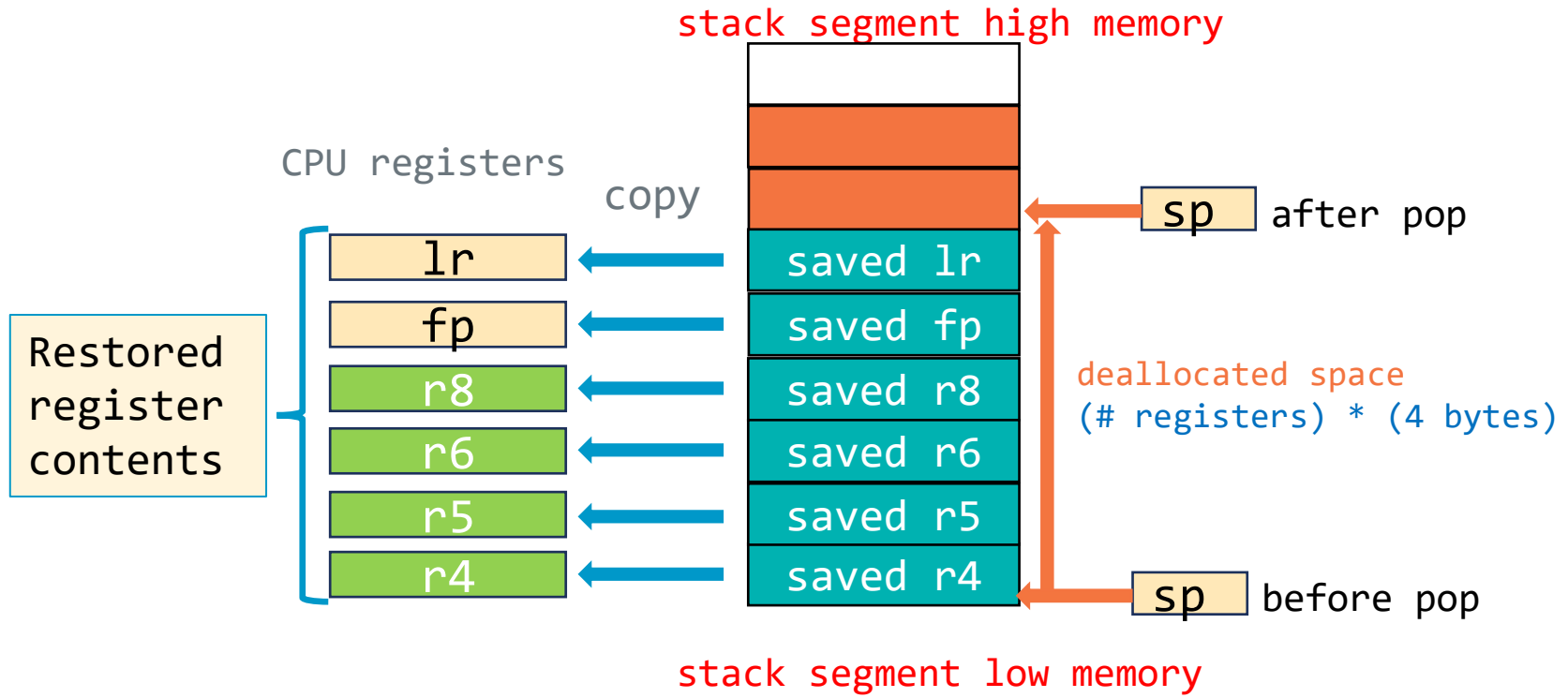


- `push` copies the contents of the `{reg list}` to stack segment memory
- `push` subtracts (# of registers saved) * (4 bytes) from the `sp` to ***allocate*** space on the stack
  - sp = sp – (# registers_saved * 4)
- **this must always be true: sp % 8 == 0**

pop: Multiple Register Restore from the stack

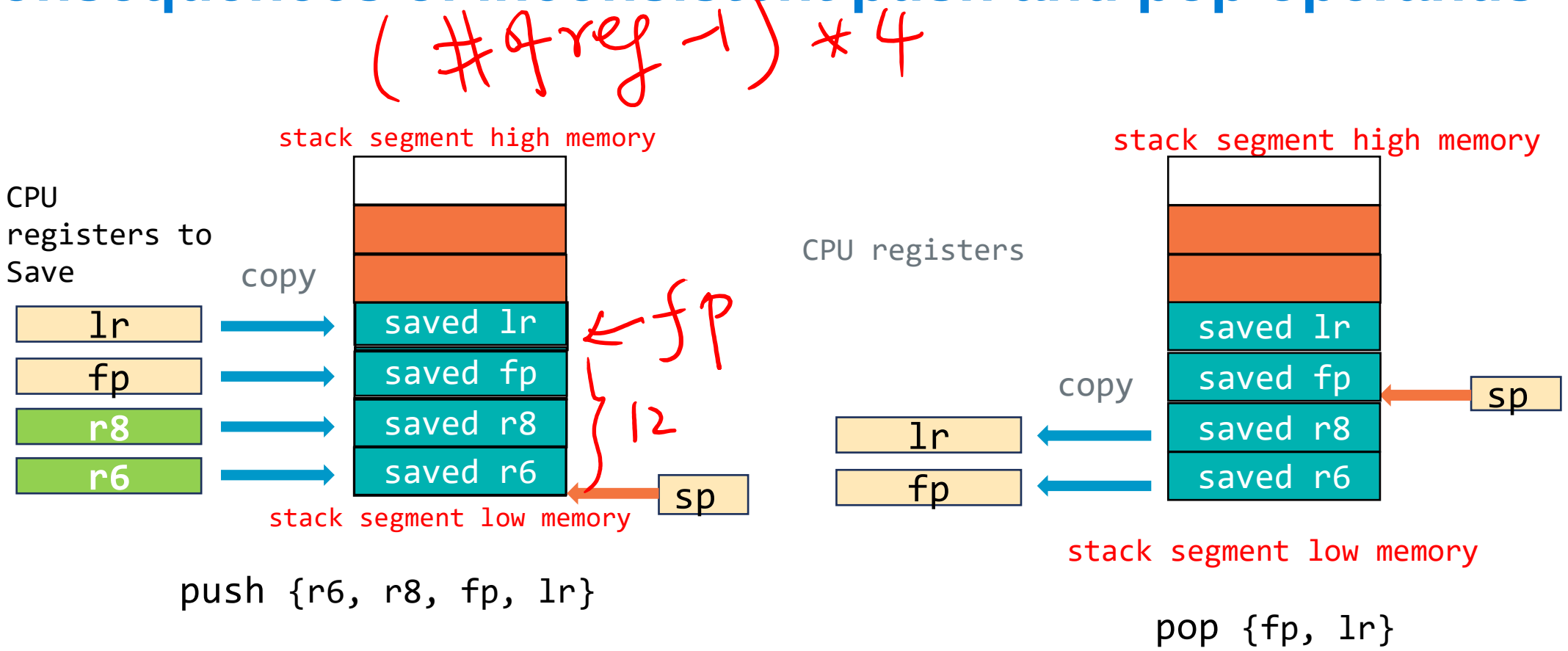
```
restore registers
pop {r4-r6, r8, fp, lr}
```

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**

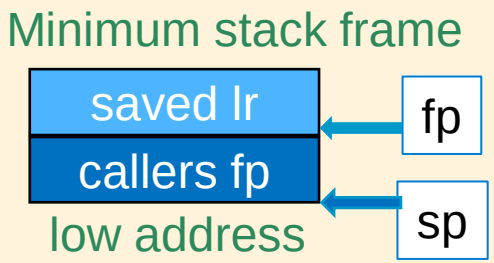
Consequences of inconsistent push and pop operands



- lr gets an address on the stack, likely segmentation fault

Minimum Stack Frame (Arm Arch32 Procedure Call Standards)

- **Minimal frame: allocating at function entry: `push {fp, lr}`**



- `sp` always points at top element in the stack (lowest byte address)
- `fp` always points at the bottom element in the stack
  - Bottom element is always the saved `lr` (contains the return address of caller)
  - A saved copy of callers fp is always the next element below the lr
  - fp will be used later when referencing stack variables
- **Minimal frame: deallocating at function exit: `pop {fp, lr}`**
- **On function entry**: sp must be 8-byte aligned (`sp % 8 == 0`)

equ FP_OFF, 4

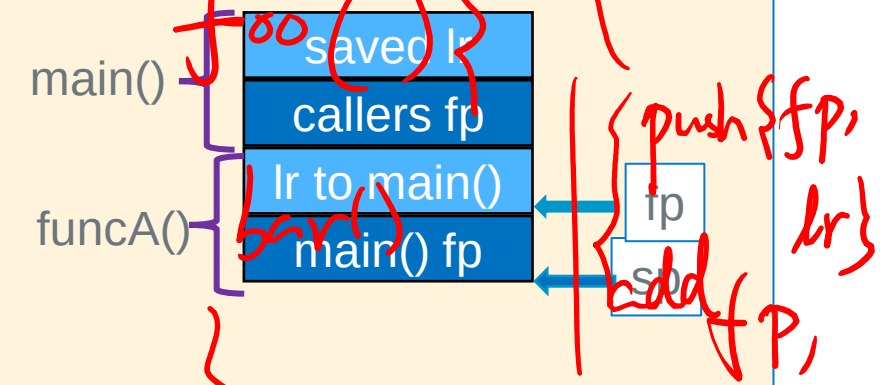
x

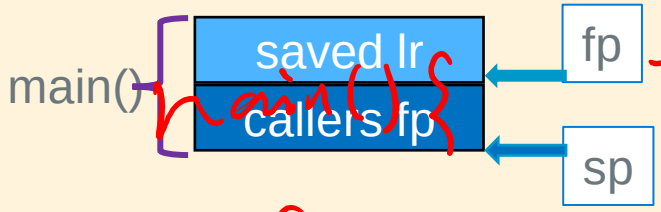
Minimum Stack Frame (Arm Arch32 Procedure Call Standards)

- Function entry (Function **Prologue**):
  1. create (activate) frame
  2. save preserved registers
  3. allocate space for locals
- Function return (Function **Epilogue**):
  1. deallocate space for locals
  2. restores preserved registers
  3. removes the frame

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

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



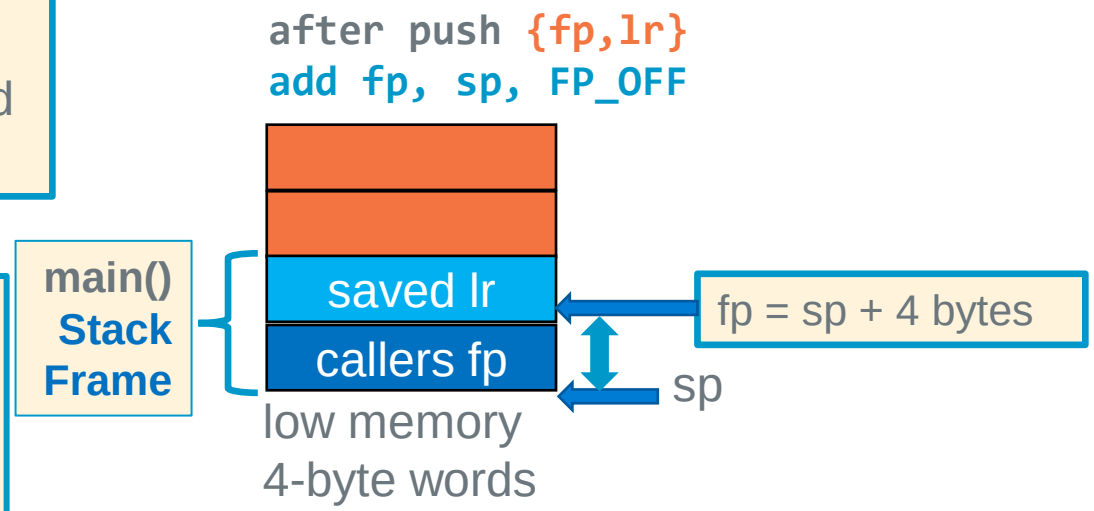


How to set the FP – Minimum Activation Frame

```
      // other code
        .equ    FP_OFF,  4
main:
      push    {fp, lr}
      add     fp, sp, FP_OFF
      …….
      sub     sp, fp, FP_OFF
      pop     {fp, lr}
      bx      lr
```

Function Prologue
always at top of function
push saves regs and allocates space by subtracting from sp and sets fp with the add

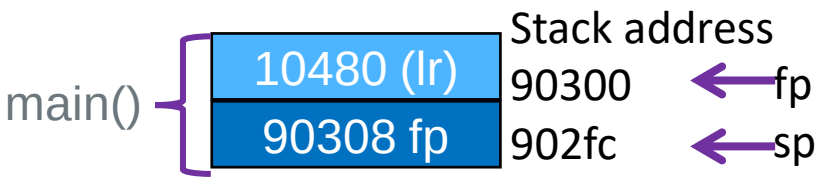
Function Epilogue
always at bottom of function pop restores regs fp, lr
and deallocates space by adding to sp



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

Using Minimal Stack Frames

```
int b(void)
{
    return 0;
}
int a(void)
{
    b();
    return 0;
}
int main(void)
{
     a();
     a();
```




```
000103f4 <b>:
   103f4: e92d4800     push {fp, lr}
   103f8: e28db004     add fp, sp, 4
   103fc: e3a00000     mov r0, 0
   10400: e24bd004     sub sp, fp, 4
   10404: e8bd4800     pop {fp, lr}
   10408: e12fff1e     bx lr


0001040c <a>:
   1040c: e92d4800     push {fp, lr}
   10410: e28db004     add fp, sp, 4
   10414: ebffffff6    bl 103f4 <b>
   10418: e3a00000     mov r0, 0
   1041c: e24bd004     sub sp, fp, 4
   10420: e8bd4800     pop {fp, lr}
   10424: e12fff1e     bx lr


00010428 <main>:
   10428: e92d4800     push {fp, lr}
   1042c: e28db004     add fp, sp, 4
   10430: ebffffff5    bl 1040c <a>
   10434: ebffffff4    bl 1040c <a>
// not shown
```


X

Using Minimal Stack Frames

```
int b(void)
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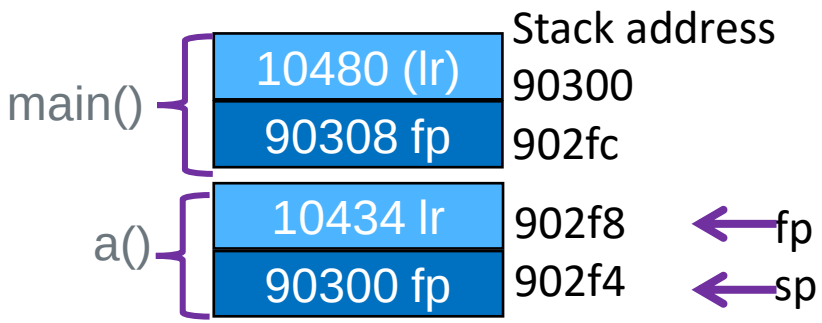


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// not shown
```

lr:
10434

X

Using Minimal Stack Frames

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    return 0;
}
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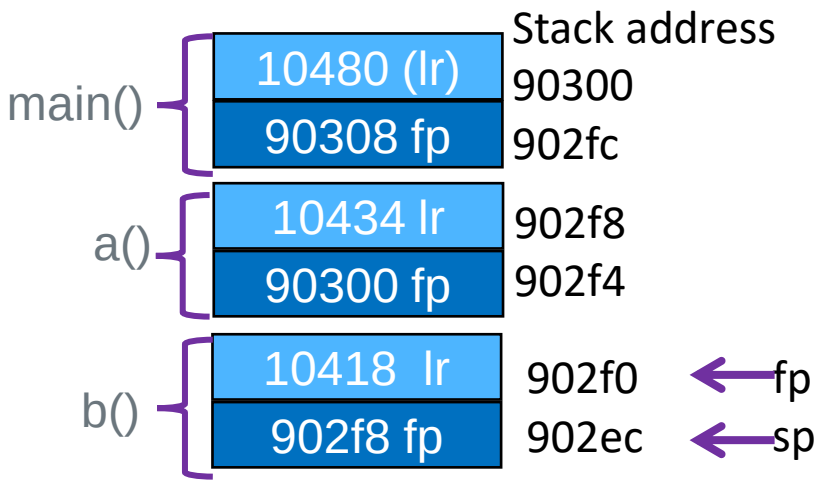
    return 0;
}
int main(void)
{
     a();
     a();
```

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// not shown
```

lr: 10418

lr: 10434

Using Minimal Stack Frames

```
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}
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    return 0;
}
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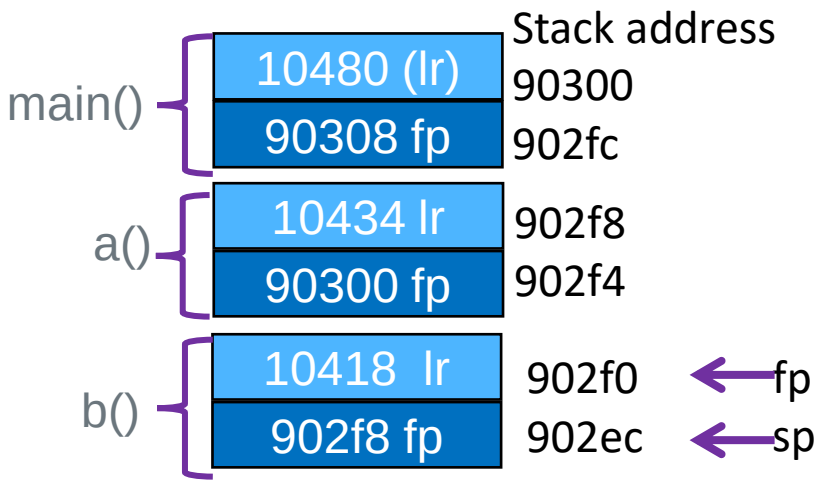
```

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// not shown
```

lr: 10418

lr: 10418

lr: 10434

Using Minimal Stack Frames

```
int b(void)
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}
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{
    b();
    return 0;
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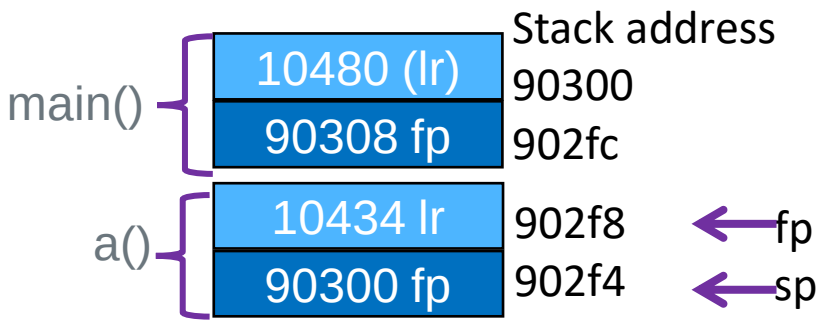
```

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   10434: ebffffff4   bl 1040c <a>
// not shown
```

lr: 10418

lr: 10418

lr: 10434

lr: 10418

lr: 10434

Using Minimal Stack Frames

```
int b(void)
{
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}
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{
    b();
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{
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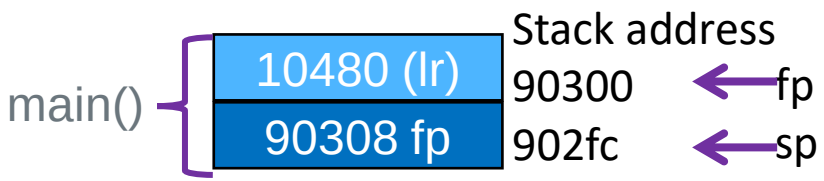
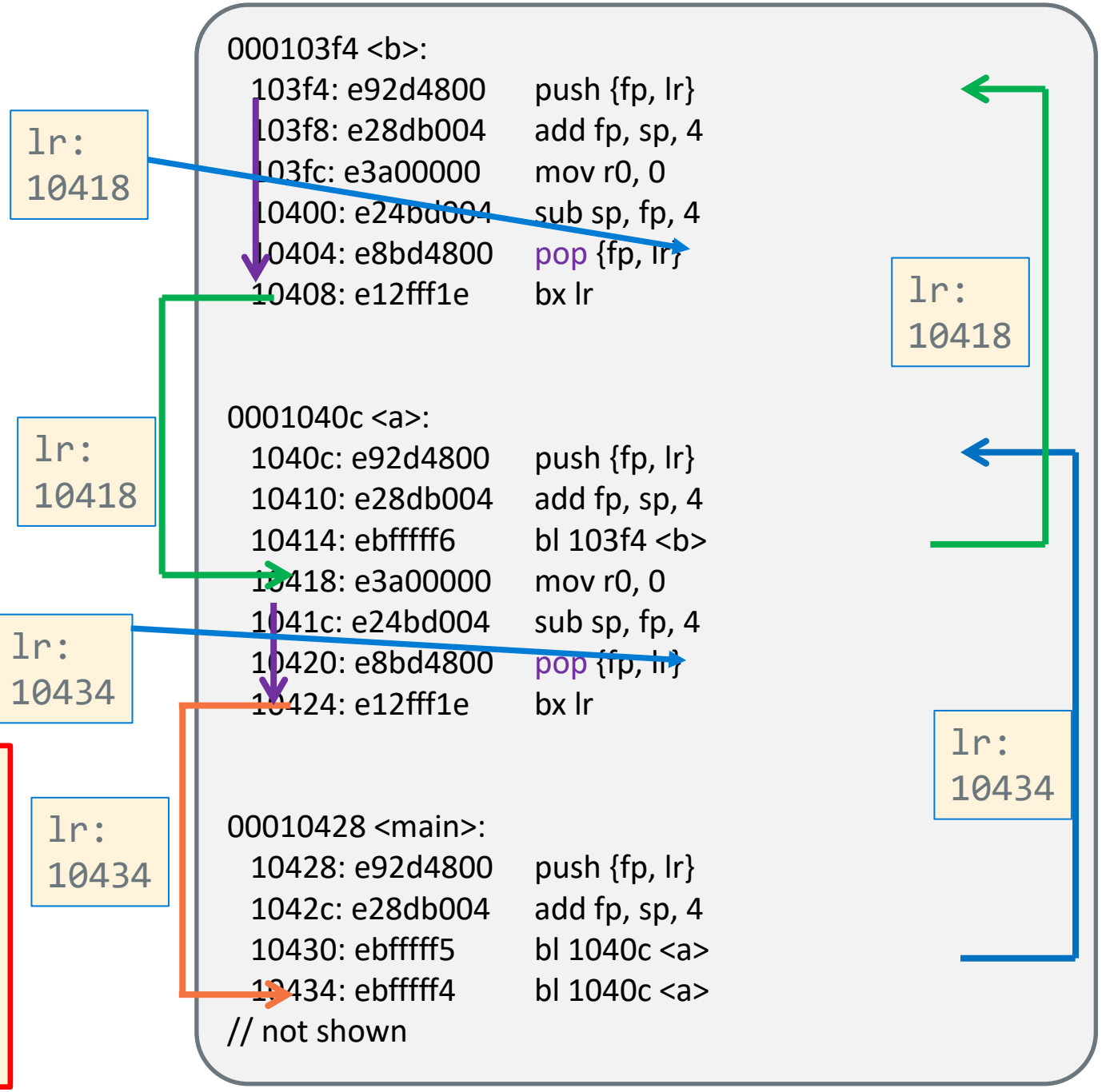
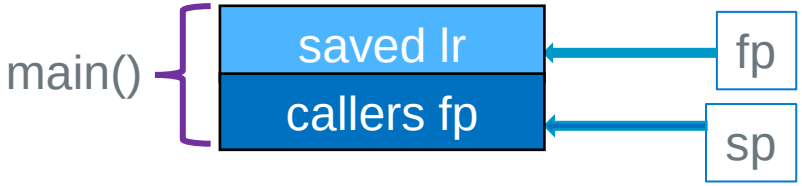


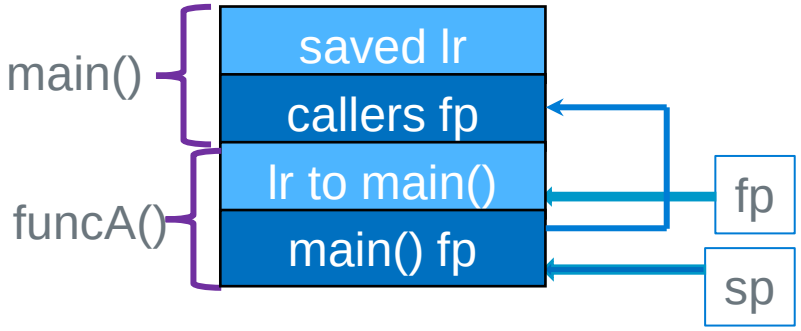
We are saving the lr on the stack on each function call and restoring it before returning.

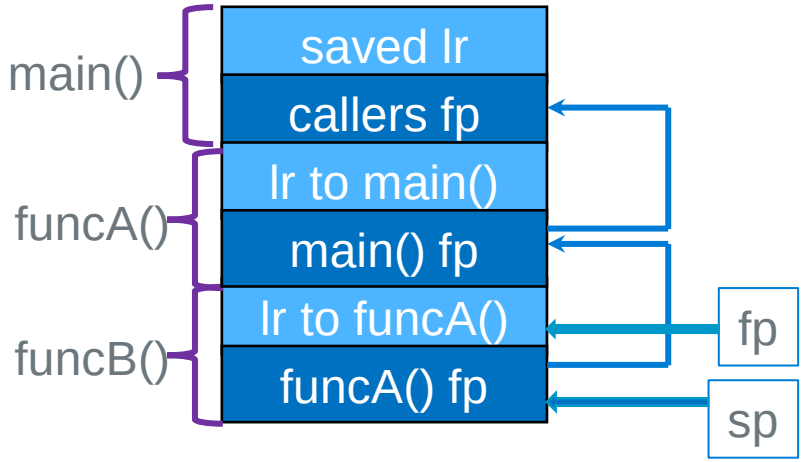
Result: NO infinite loop and we return to the correct instruction in the caller no matter how many functions we call.
Even recursion will work!

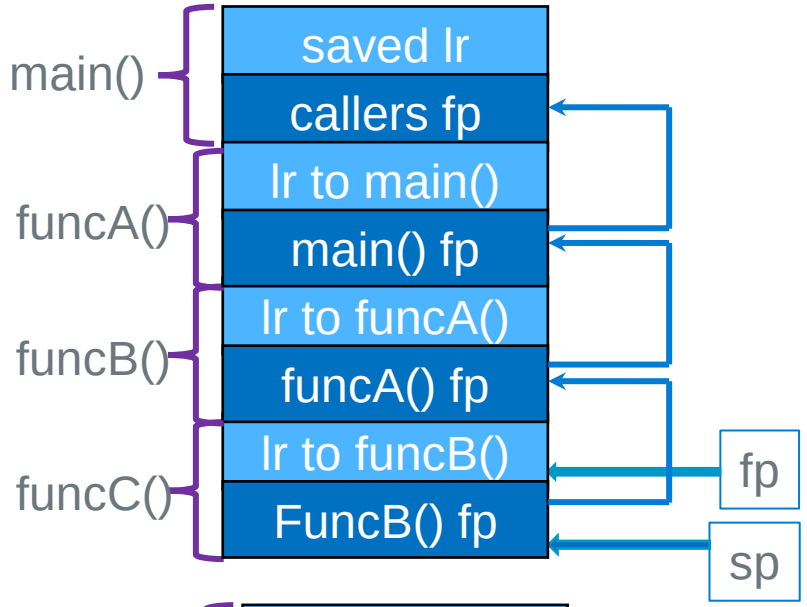


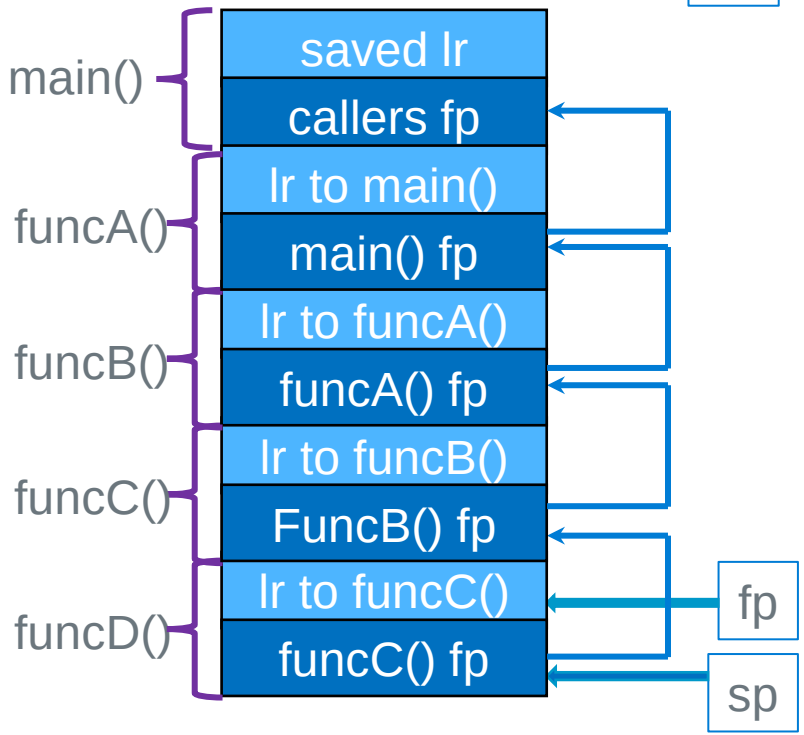
By following the saved fp, you can find each stack frame











How gdb finds stack frames

x

Registers: Requirements for Use

Register	*Function Call Use*	*Function Body Use*	*Save before use Restore before return*
r0	arg1 and return value	scratch registers	No
r1-r3	arg2 to arg4	scratch registers	No
r4-r10	preserved registers	contents preserved across function calls	Yes
r11/fp	stack frame pointer	Use to locate variables on the stack	Yes
r12/ip	may used by assembler with large text file	can be used as a scratch if really needed	No
r13/sp	stack pointer	stack space allocation	Yes
r14/lr	link register	contains return address for function calls	Yes
r15	Do not use	Do not use	No

- Any value you have in a preserved register before a function call **will still be there after the function returns**
- Contents are “preserved” across function calls

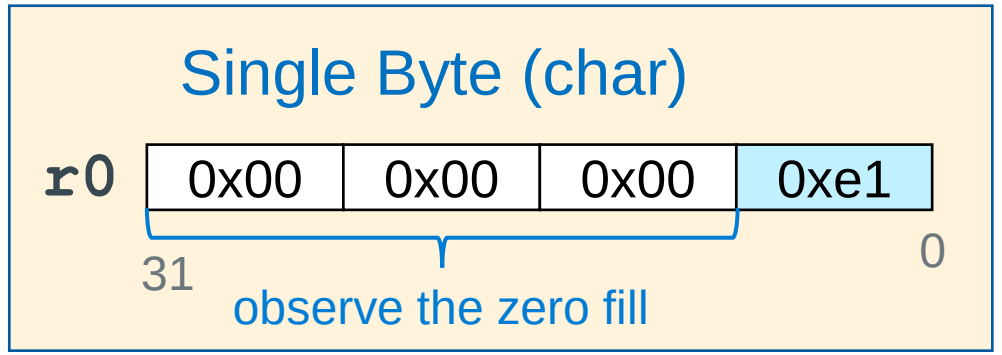
If the function wants to use a preserved register it must:

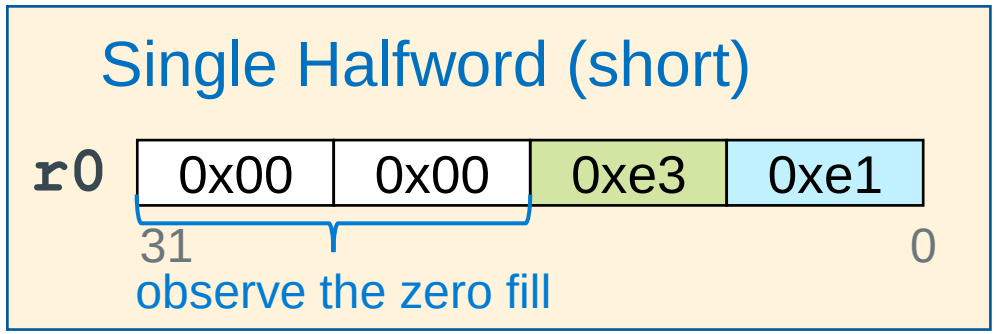
1. *Save* the value contained in the register at function entry
2. Use the register in the body of the function
3. *Restore* the original saved value to the register at function exit (before returning to the caller)

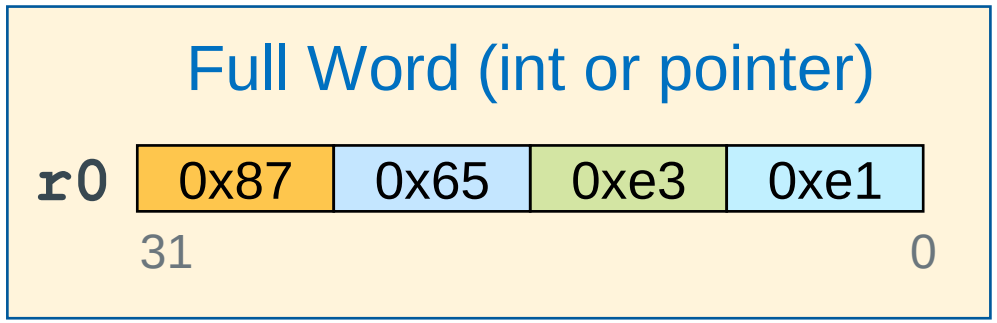
Argument and Return Value Requirements

- When passing or returning values from a function you must do the following:

1. Make sure that the values in the registers r0-r3 are in their properly aligned position in the register **based on data type**
2. Upper bytes in byte and halfword values in registers r0-r3 when passing arguments and returning values are zero filled







Global Variable access

var	global variable address into r0 (lside)	global variable contents into r0 (rside)	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]`

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

stderr	`ldr r0, =stderr`	`ldr r0, =stderr` `ldr r0, [r0]`	<do not write unless you really know what you are doing>
.Lstr	`ldr r0, =.Lstr`	`ldr r0, =.Lstr` `ldrb r0, [r0]`	<read only>

```
        .bss // from libc
stderr:.space 4  // FILE *
```

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

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

stdin, stdout and stderr are global variables

x

Assembler Directives: Label Scope Control (Normal Labels only)

```
.extern printf
.extern fgets
.extern strcpy
.global fbuf
```

`.extern <label>`

- **Imports** label (function name, symbol or a static variable name);
- An address associated with the label from another file can be used by code in this file

`.global <label>`

- **Exports** label (or symbol) to be visible outside the source file boundary (other assembly or c source)
- label is either a function name or a global variable name
- Only use with function names or static variables

- **Without** .global, labels are usually (depends on the assembler) **local to the file**

x

Example calling fprintf()

- `r0 = function(r0, r1, r2, r3)`

  `fprintf(stderr, "arg2", arg3, arg4)`
- create a literal string for arg2 which tells f**printf()** how to interpret the remaining arguments
- stdin, stdout, stderr are all global variable and are part of libc
  - these names are their lside (label names)
- to use them you must get their **contents** to pass to fprintf(), fread(), fwrite()

```
#include <stdio.h>
#include <stdlib.h>
int
main(void)
{
    int a = 2;
    int b = 3;
    int c;

    c = a + b;
    fprintf(stderr,"c=%d\n", c);

    return EXIT_SUCCESS;
}
```

We are going to put these variables in temporary registers

r0, r1, r2

three passed args in this use of fprintf

```
        .extern fprintf      //declare fprintf
        .section .rodata    // note the dots "."
.Lfst:  .string  "c=%d\n"
```

```
// part of the text segment below
        mov     r2, 2         // int a = 2;
        mov     r3, 3         // int b = 3;
        add     r2, r2, r3    // arg 3: int c = a + b;

        ldr     r0, =stderr   // get stderr address
        ldr     r0, [r0]      // arg 1: get stderr contents
        ldr     r1, =.Lfst    // arg 2: =literal address
        bl       fprintf
```

Preserved Registers: When to Use?

Register	*Function Call Use*	*Function Body Use*	*Save before use Restore before return*
r0	arg1 and return value	scratch registers	No
r1-r3	arg2 to arg4	scratch registers	No
r4-r10	preserved registers	contents preserved across function calls	Yes
r11/fp	stack frame pointer	Use to locate variables on the stack	Yes
r12/ip	may used by assembler with large text file	can be used as a scratch if really needed	No
r13/sp	stack pointer	stack space allocation	Yes
r14/lr	link register	contains return address for function calls	Yes
r15	Do not use	Do not use	No

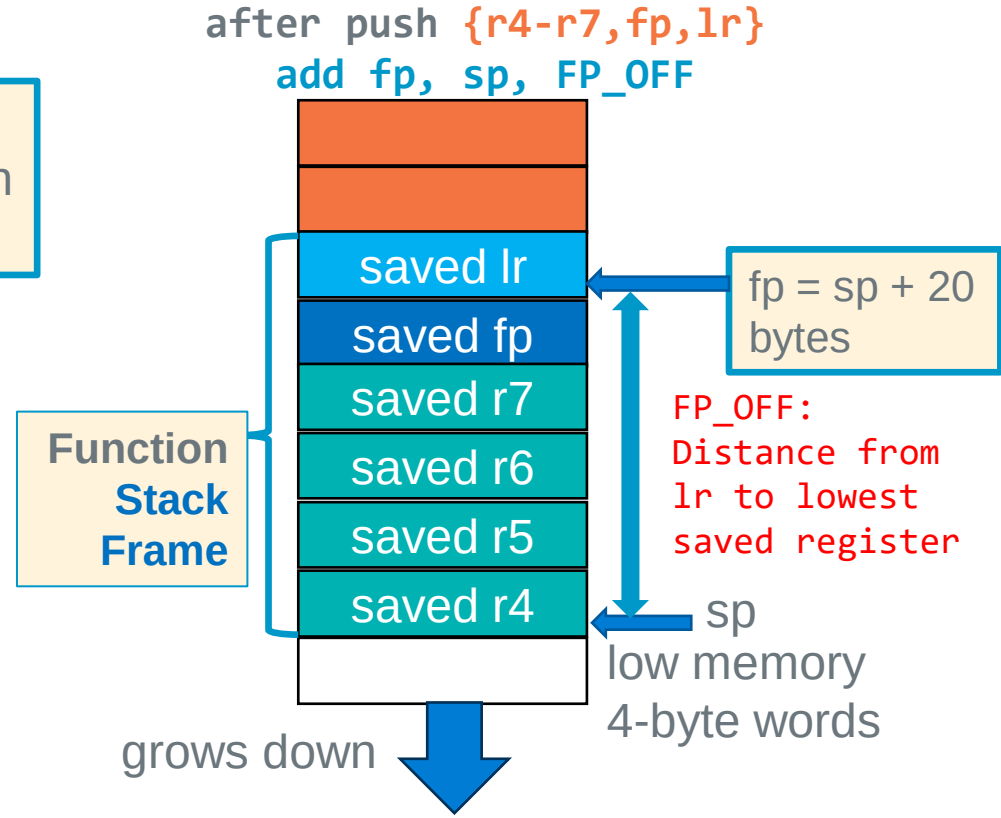
- When to use a preserved register in a function you are writing?
- Values that you want to protect from being changed by a function call
  - Local variables stored in registers
  - Parameters passed to you (in `r0-r3`) that you need to continue to use after calling another function

Saving Preserved registers and setting FP

```
      // 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 Distance from lr to lowest saved register
2	4
3	8
4	12
5	16
6	20
7	24
8	28
9	32

```
FP_OFF = (#regs saved - 1) * 4
```

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

Example: using preserved registers for local variables

```c
#include <stdio.h>
#include <stdlib.h>
int
main(void)
{
    int c; // use r0
    int count = 0;  // use r4

    while ((c = getchar()) != EOF) {

        putchar(c);
        count++;
    }

    printf("Echo count: %d\n", count);
    return EXIT_SUCCESS;
}
```

You must assume that both getchar() and putchar() alter r0-r3

r0

r0

r0 r1

```
        .extern getchar
        .extern putchar
        .section .rodata
.Lst:   .string  "Echo count: %d\n"

        .text
        .type   main, %function
        .global main
        .equ    EOF,            -1
        .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 */

        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

```
        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      //arg2
        ldr     r0, =.Lst   //arg1
        bl      printf
```

address of string literal variable

```
#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;
}
```

```
.Lst: .string  "Echo count: %d\n"
```

File header and footers are not shown

x

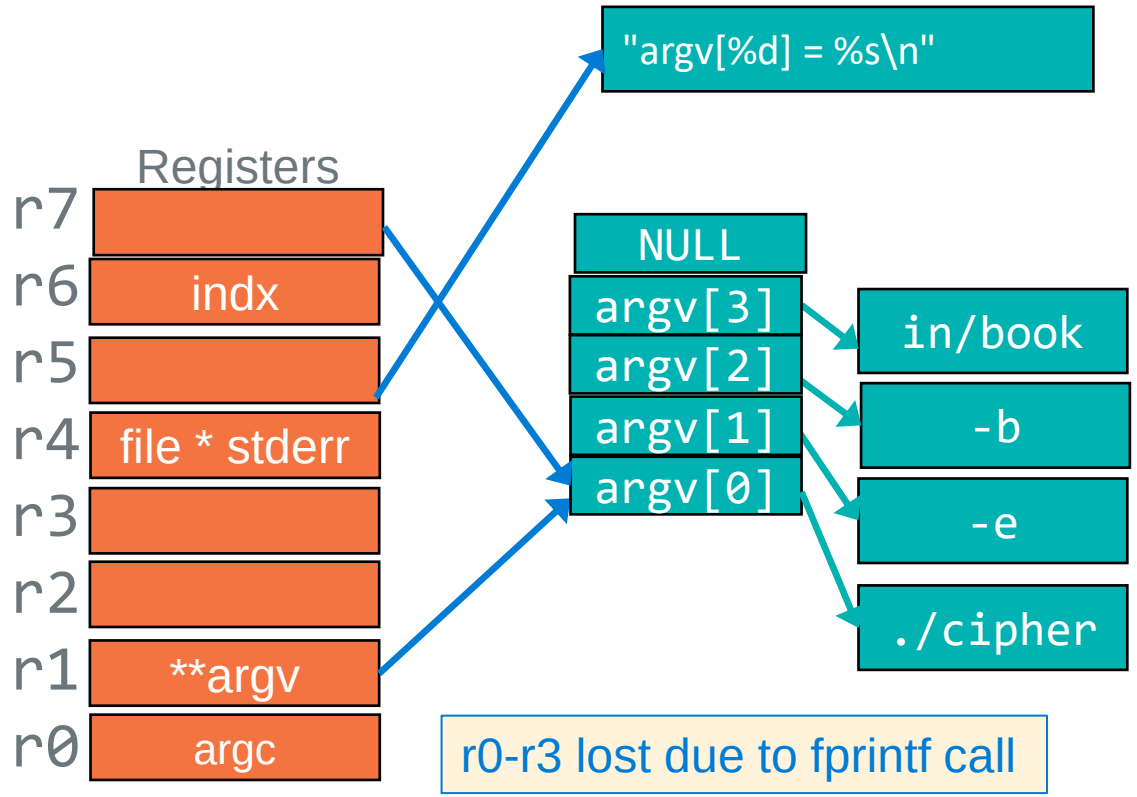
Accessing argv from Assembly (stderr version)

```
    .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
    mov     r7, r1          // save argv!
    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;

.Lloop:
    // fprintf(stderr, "argv[%d] = %s\n", indx, *argv)
    ldr     r3, [r7]        // arg 4: *argv
    cmp     r3, 0           // check *argv == NULL
    beq     .Ldone          // if so done
    mov     r2, r6          // arg 3: indx
    mov     r1, r5          // arg 2: "argv[%d] = %s\n"
    mov     r0, r4          // arg 1: stderr
    bl      fprintf
    add     r6, r6, 1       // indx++ for printing
    add     r7, r7, 4       // argv++ pointer
    b       .Lloop
.Ldone:
    mov     r0, 0
    sub     sp, fp, FP_OFF
    pop     {r4-r7, fp, lr}
    bx      lr
```

need to save r1 as we are calling a function - fprintf

observe the different increment sizes

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



r0-r3 lost due to fprintf call

```
fprintf(stderr, "argv[%d] = %s\n", indx, *argv);
```


X

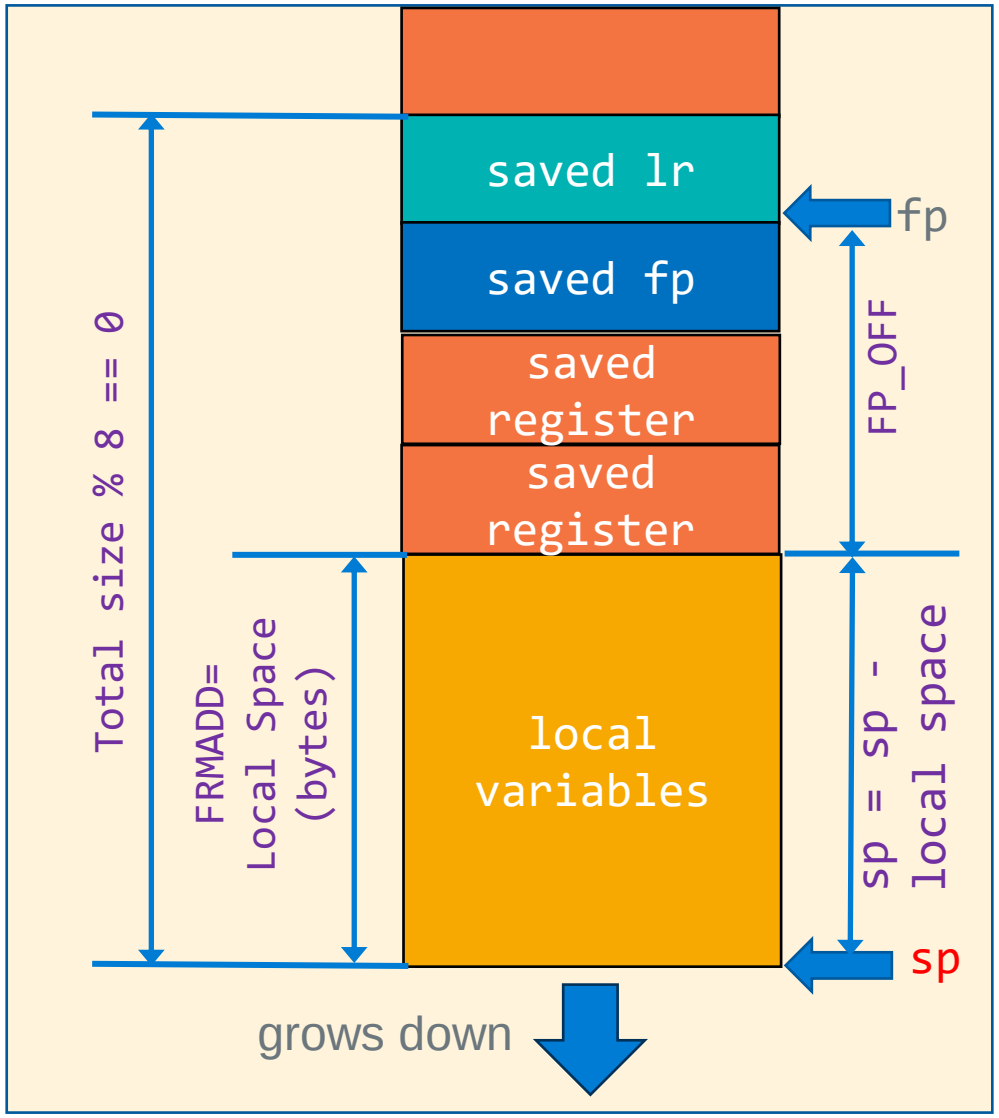
Local Variables on the Stack

- Space for local variables is allocated on the stack right below the lowest pushed register
  - Move the sp towards low memory by the total size of all local variables in bytes **plus padding**

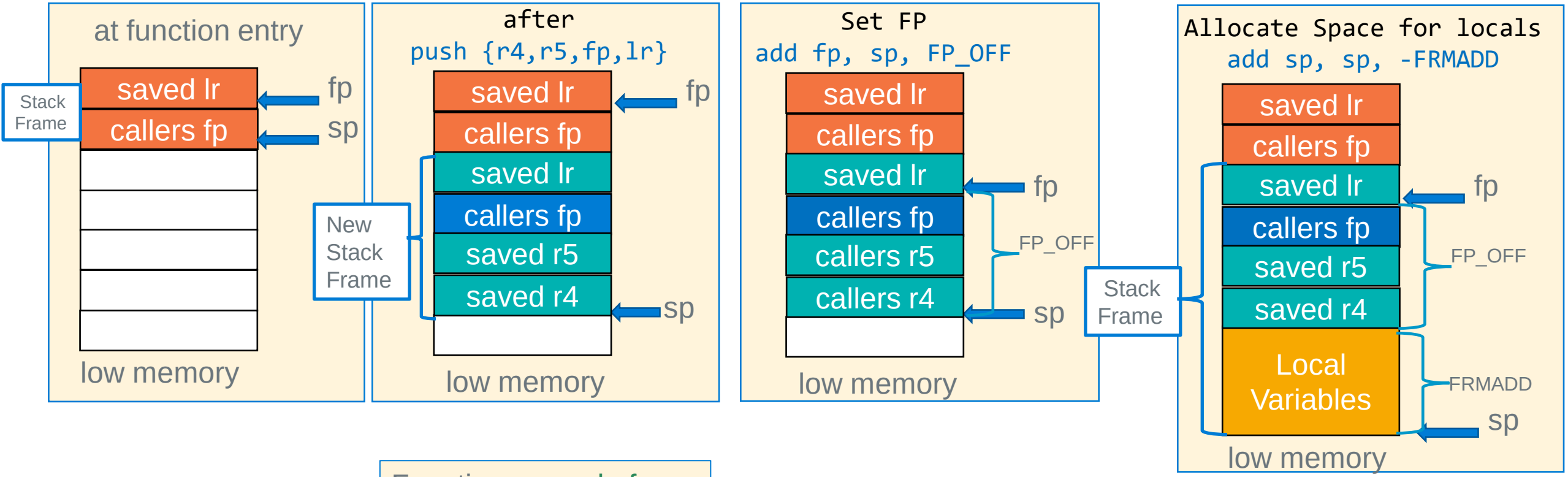
    FRMADD = total local var space (bytes) + padding
- Allocate the space after the register push by

  ```
  add   sp, sp, -FRMADD
  ```
- **Requirement:** on function entry, sp is always 8-byte aligned

  sp % 8 == 0
- **Padding (as required):**
  1. Additional space between variables on the stack to meet memory alignment requirements
  2. Additional space so the frame size is evenly divisible by 8
- fp (frame pointer) is used as a **pointer (base register)** to access all stack variables – later slides



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

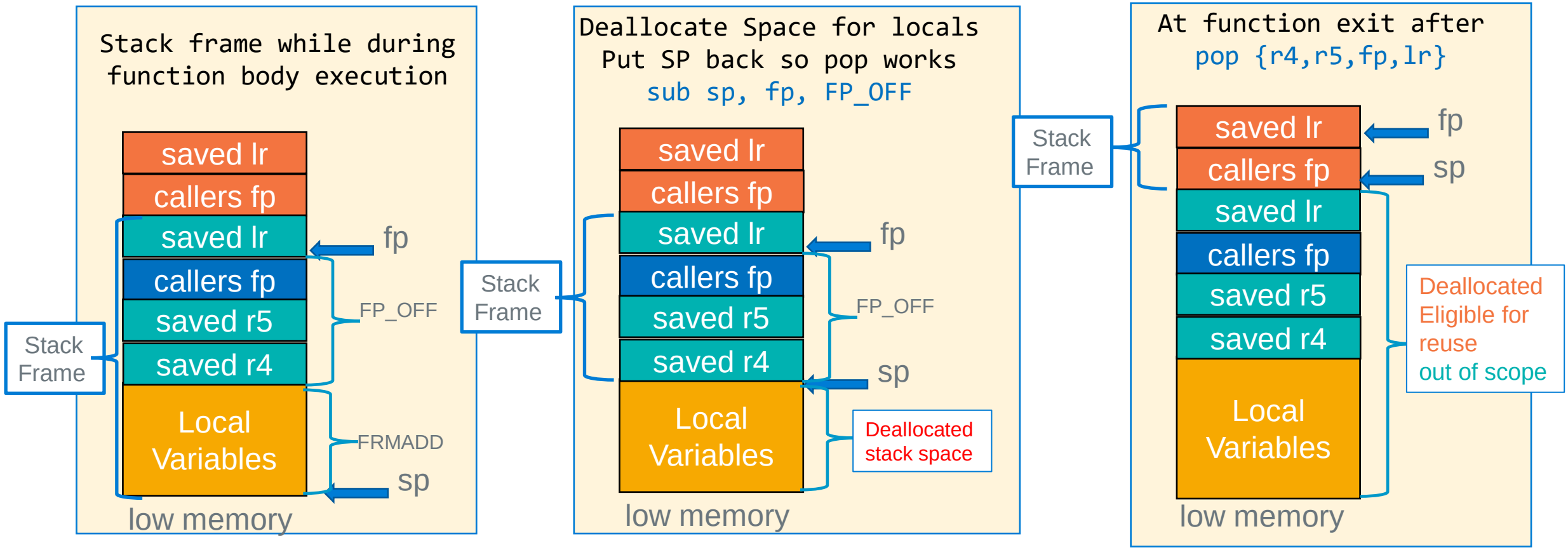
Function moves the fp to point at the saved lr as required by the Aarch32 spec

Allocate Space for Local Variables

Part of function prologue

x

Function Epilogue: Deallocating the Stack Frame



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

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

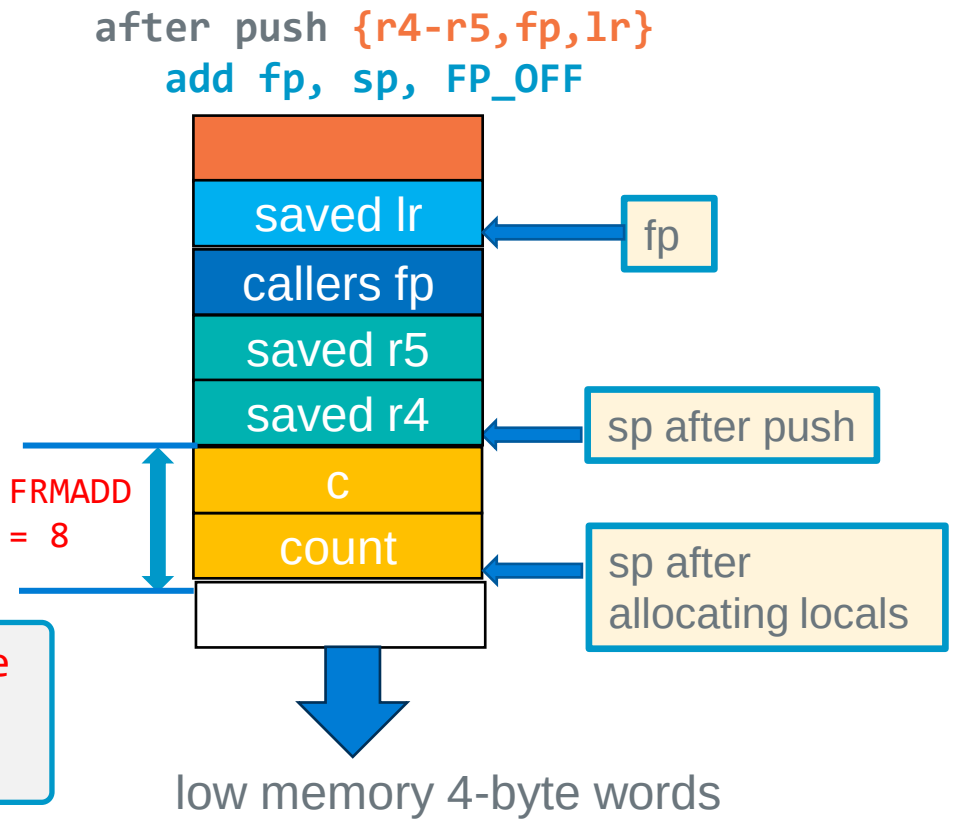
Part of function epilogue

Local Variables on the stack

```
int main(void)
{
    int c;
    int count = 0;
    // rest of code
}
```

```
 .text
    .type   main, %function
    .global main
   .equ    FP_OFF,    12
   .equ    FRMADD,     8
main:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
    add     sp, sp, -FRMADD
// but we are not done yet!
```

```
// when FRMADD values fail to assemble
        ldr r3, =-FRMADD
        add sp, sp, r3
```

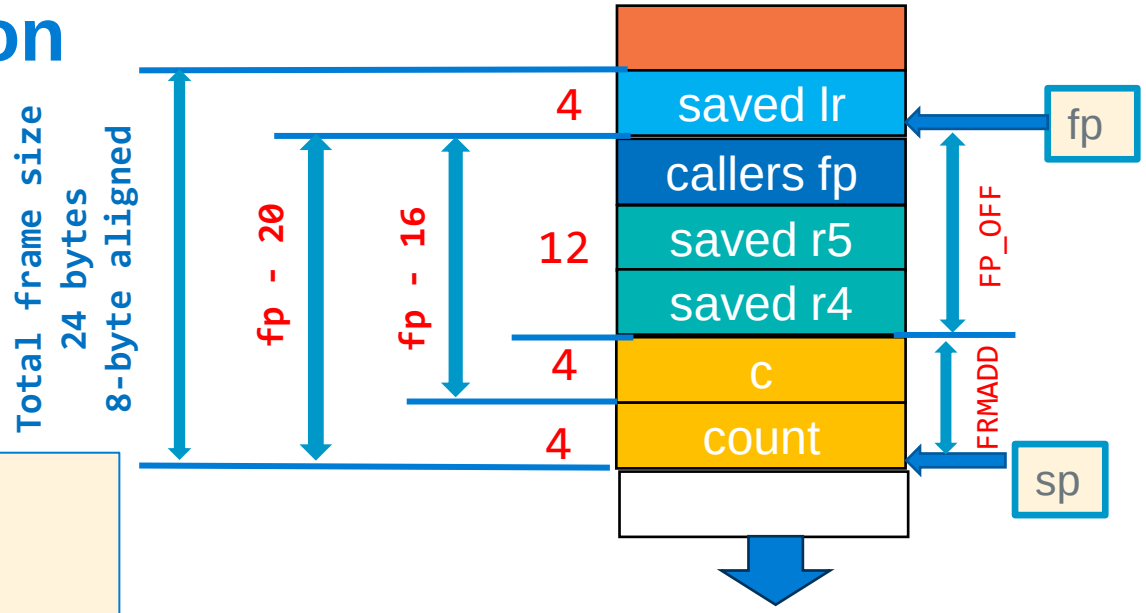


- Add space on the stack for each local
  - we will allocate space in same order the locals are listed the C function shown from high to low stack address
  - gcc compiler allocates from low to high stack addresses
  - Order does not matter for our use

- In this example we are allocating two variables on the stack
- When writing assembly functions, in many situations you may choose allocate these to registers instead

Accessing Stack Variables: Introduction

```
int main(void)
{
    int c;
    int count = 0;
    // rest of code
}
```



low memory 4-byte words

- TO Access data stored in the stack
  - use the **`ldr/str`** instructions
- **Use register `fp` with offset (negative distance in bytes) addressing** (use either register offset or immediate offset)
- ***No matter what address the stack frame is at***, `fp` always points at saved `lr`, so you can find a local stack variable by using an offset address from the contents of `fp`

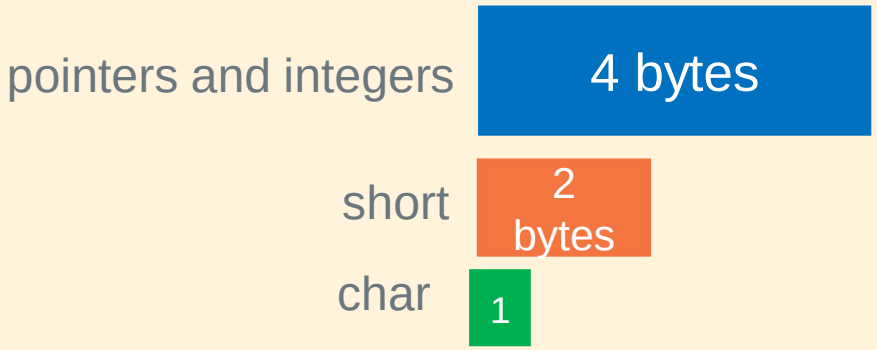
Variable	distance from fp	Read variable	Write Variable
`int c`	-16	`ldr r0, [fp, -16]`	`str r0, [fp, -16]`
`int count`	-20	`ldr r0, [fp, -20]`	`str r0, [fp, -20]`

```
 .text
    .type   main, %function
    .global main
   .equ    FP_OFF,     12
   .equ    FRMADD,      8
main:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
    add     sp, sp, -FRMADD
// but we are not done yet!
```

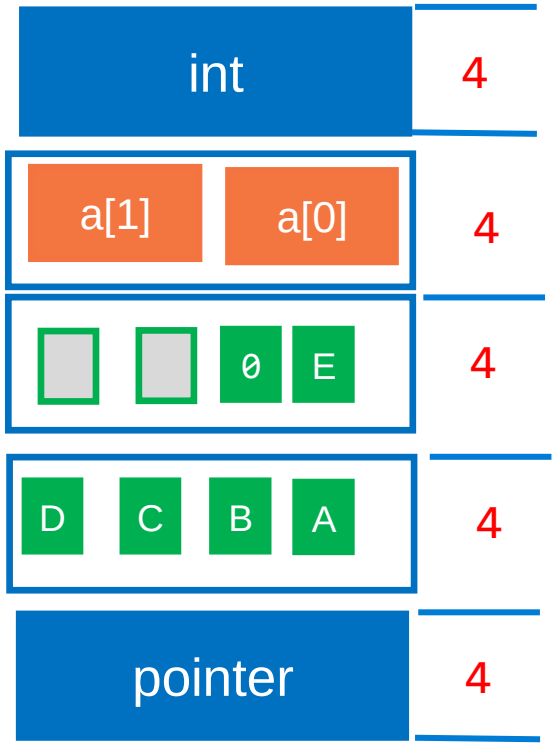

x

Stack Frame Design – Local Variables

- When writing an ARM equivalent for a C program, for CSE30 we will not re-arrange the order of the variables to optimize space (covered in the compiler course)
- 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
- Single chars (and shorts) can be grouped together in same 4-byte word (following the alignment for the short)
- Padding may be required (see next slide)

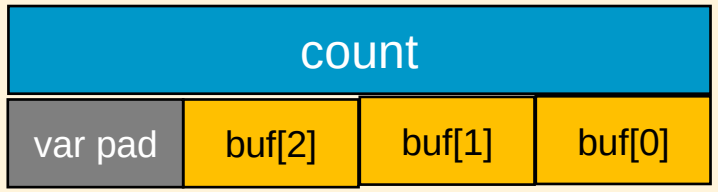


Rule: When the function is entered the stack is already 8-byte aligned

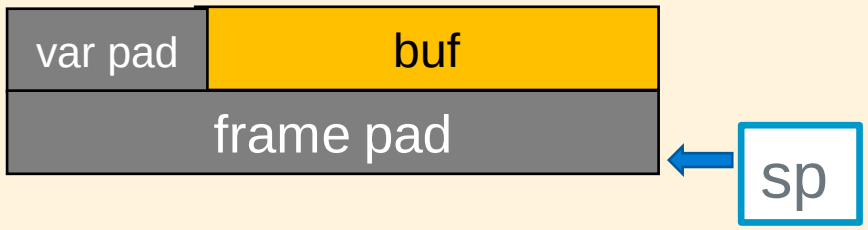


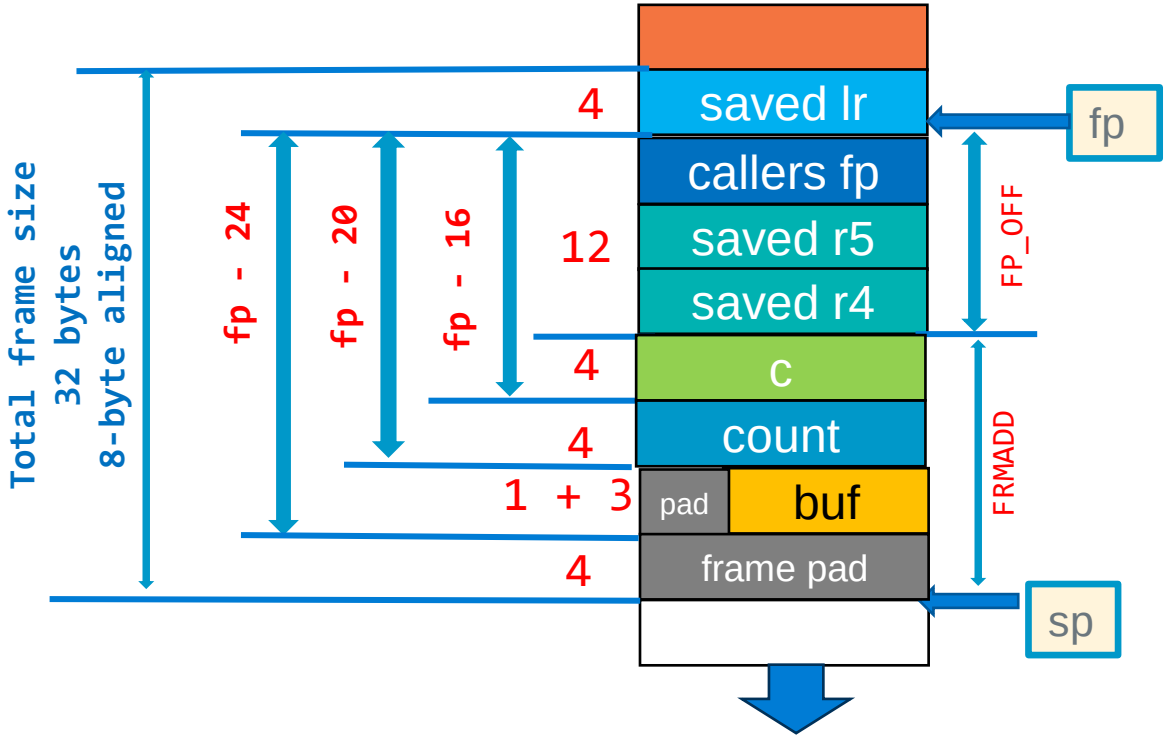
Stack Variables: Padding

- **Variable padding** – start arrays at 4-byte boundary and **leave unused space at end** (high side address) before the variable higher on the stack



- **Frame padding** – **add space below the last local variable** to keep 8-byte alignment





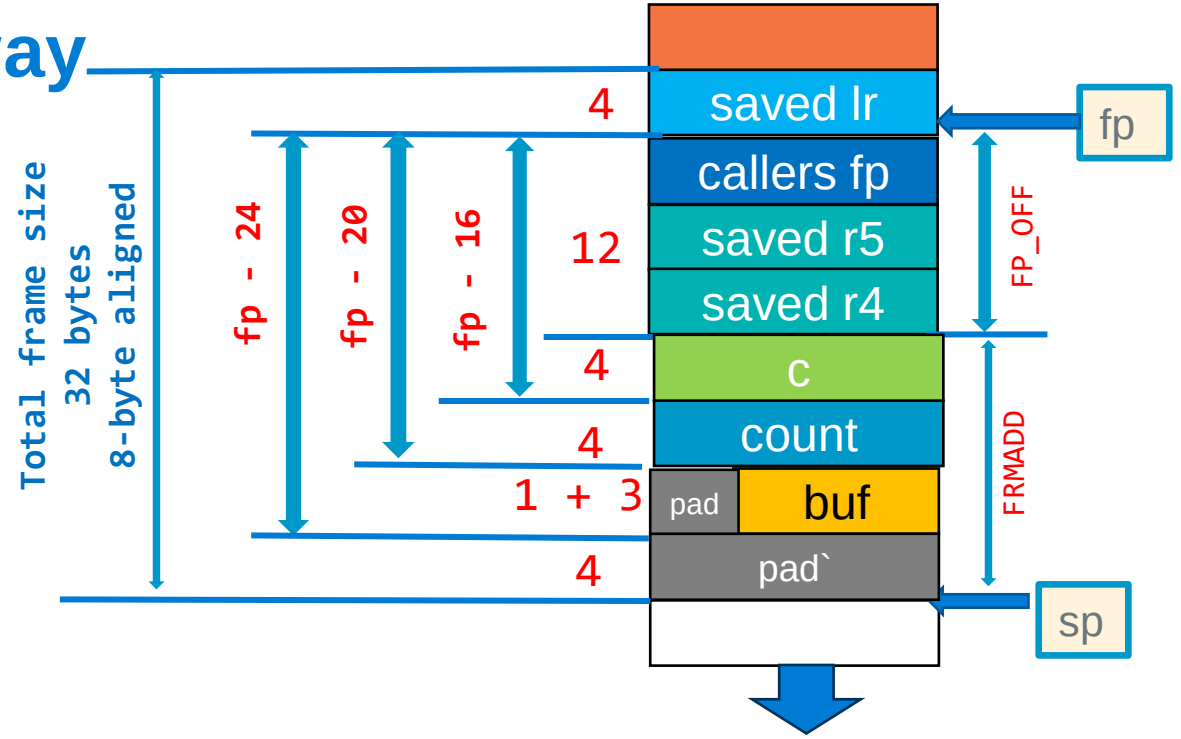

```
int main(void)
{
    int c;
    int count = 0;
    char buf[] = "hi";
    // rest of code
}
```

```
 .text
    .type   main, %function
    .global main
   .equ    FP_OFF,    12
   .equ    FRMADD,    16
main:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
    add     sp, sp, -FRMADD
// but we are not done yet!
```

Accessing Stack Variables, the hard way

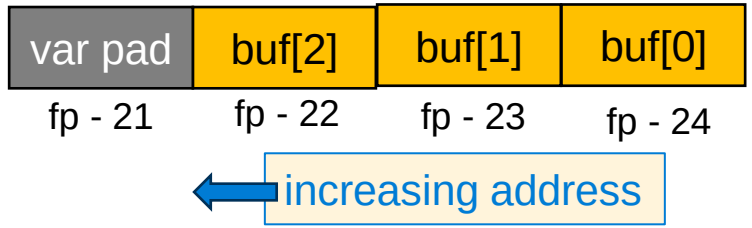
```
int main(void)
{
    int c;
    int count = 0;
    char buf[] = "hi";
    // rest of code
}
```

```
 .text
    .type   main, %function
    .global main
   .equ    FP_OFF,    12
   .equ    FRMADD,    16
main:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
    add     sp, sp, -FRMADD
// but we are not done yet!
```



char buf[ ] by usage with ASCII chars we will use strb (or make it unsigned char)

Variable	distance from fp	Read variable	Write Variable
int c	16	ldr r0, [fp, -16]	str r0, [fp, -16]
int count	20	ldr r0, [fp, -20]	str r0, [fp, -20]
char buf[0]	24	ldrb r0, [fp, -24]	strb r0, [fp, -24]
char buf[1]	23	ldrb r0, [fp, -23]	strb r0, [fp, -23]
char buf[2]	22	ldrb r0, [fp, -22]	strb r0, [fp, -22]



- **Calculating offsets is a lot of work to get it correct**
- It is also hard to debug
- There is a better way!

x

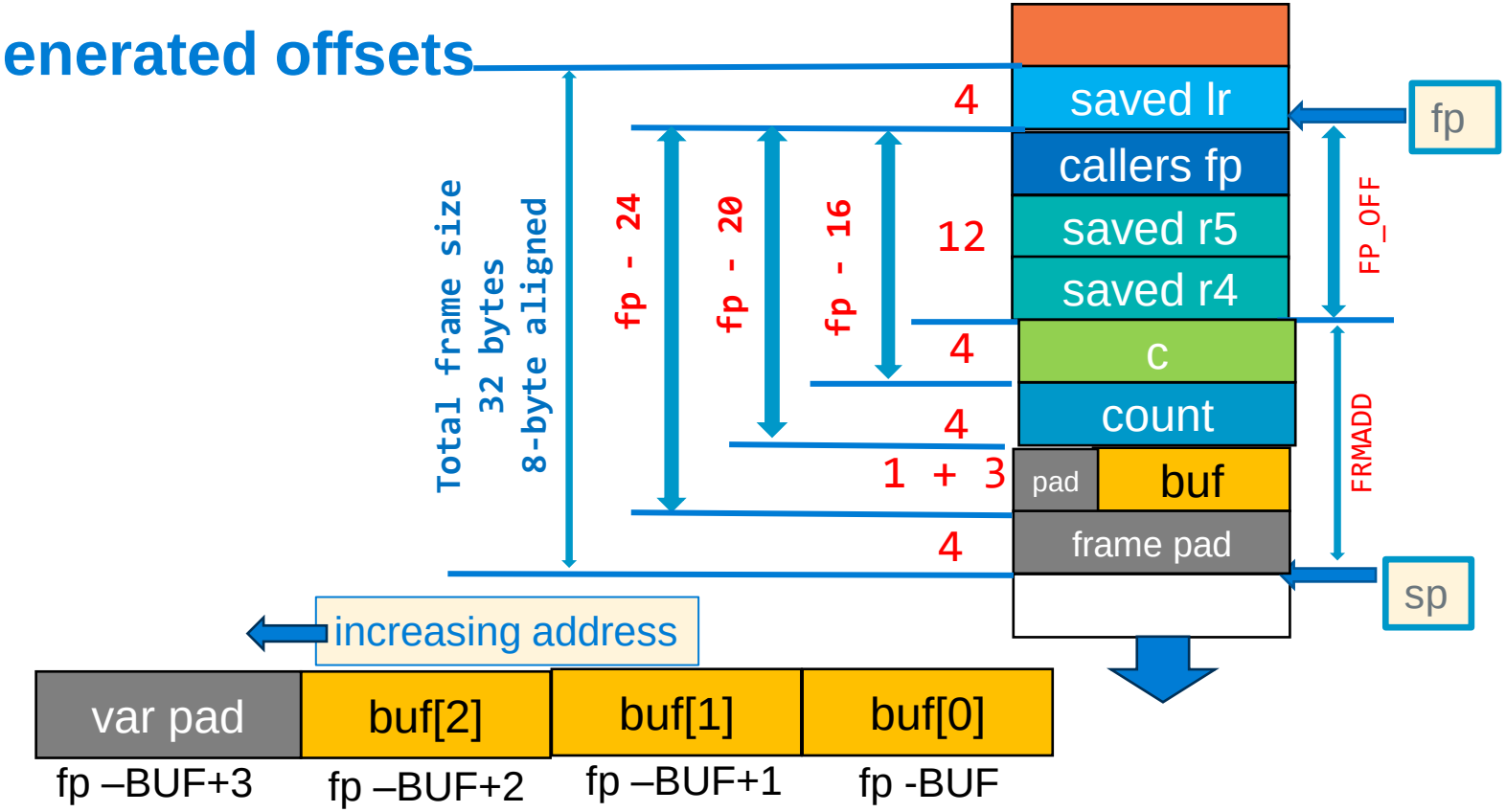
Best Practice: Use Assembler Generated offsets

```
.type   main, %function
.global main

.equ    FP_OFF,     12

.equ    C,          4 + FP_OFF
.equ    COUNT,      4 + C
.equ    BUF,        4 + COUNT
.equ    PAD,        4 + BUF
.equ    FRMADD,     PAD - FP_OFF
// FRMADD =  28 - 12 = 16
```

pushed reg fp distance

Prior allocation distance

variable size in bytes



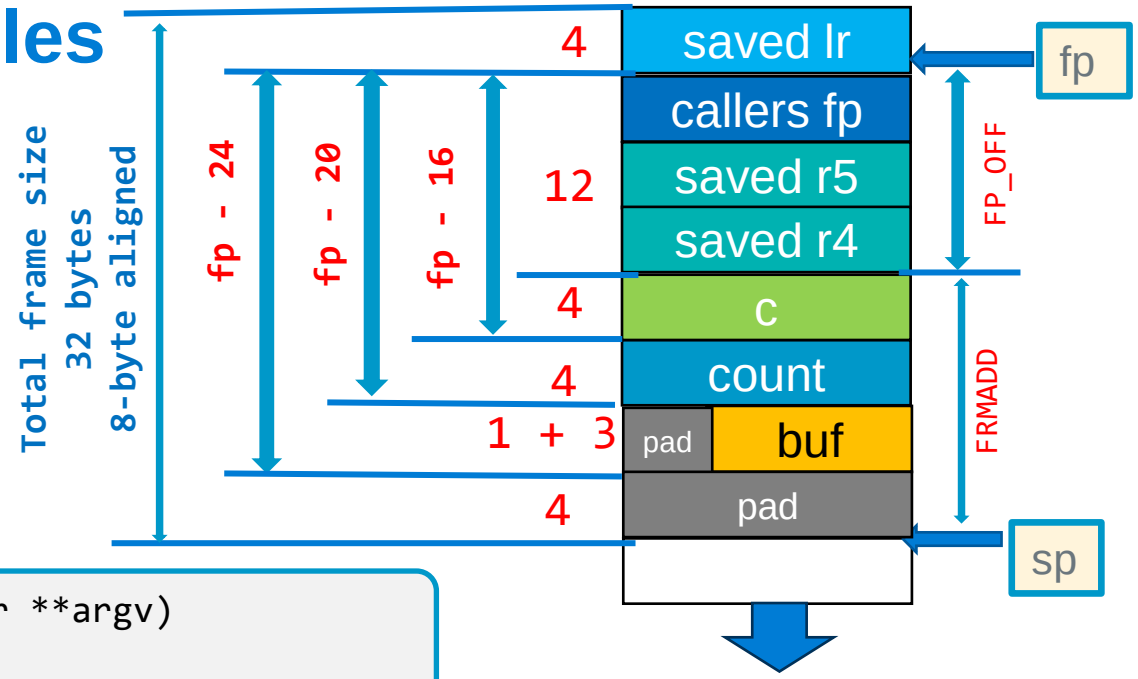
Variable	distance from fp	Address on Stack	Read variable	Write Variable
int c	C	add r0, fp, -C	ldr r0, [fp, -C]	str r0, [fp, -C]
int count	COUNT	add r0, fp, -COUNT	ldr r0, [fp, -COUNT]	str r0, [fp, -COUNT]
char buf[0]	BUF	add r0, fp, -BUF	ldrb r0, [fp, -BUF]	strb r0, [fp, -BUF]
char buf[1]	BUF-1	add r0, fp, -BUF+1	ldrb r0, [fp, -BUF+1]	strb r0, [fp, -BUF+1]
char buf[2]	BUF-2	add r0, fp, -BUF+2	ldrb r0, [fp, -BUF+2]	strb r0, [fp, -BUF+2]

Initializing and Accessing Stack variables

```
    .section .rodata
.Lmess: .string "%d %d %s\n"
    .extern printf
    .text
    .type   main, %function
    .global main
    .equ    FP_OFF,     12
    .equ    C,          4 + FP_OFF
    .equ    COUNT,      4 + C
    .equ    BUF,        4 + COUNT
    .equ    PAD,        4 + BUF
    .equ    FRMADD,     PAD - FP_OFF
main:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
    add     sp, sp, -FRMADD
    // nothing to do for C
    mov     r2, 0
    str     r2, [fp, -COUNT]
    strb    r2, [fp, -BUF+2]
    mov     r2, 'h'
    strb    r2, [fp, -BUF]
    mov     r2, 'i'
    strb    r2, [fp, -BUF+1]

    ldr     r0, =.Lmess         // arg1
    ldr     r1, [fp, -C]        // arg2
    ldr     r2, [fp, -COUNT]    // arg3
    add     r3, fp, -BUF        // arg4
    bl      printf
```

passes contents of stack var C

passes address of a stack variable buf




```
int main(int argc, char **argv)
{
    int c;
    int count = 0;
    char buf[] = "hi";
    printf("%d %d %s\n", c, count, buf);
    // rest of code
```

pass stack address

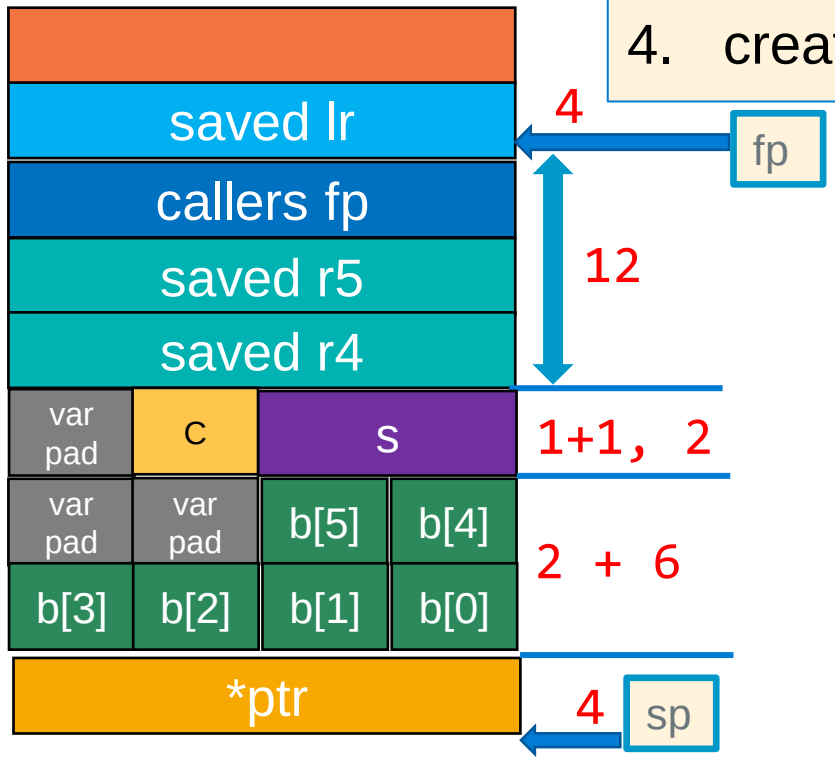
```
./a.out
-136572160 0 hi
```

Variable	distance from fp	Address on Stack	Read variable	Write Variable
int c	C	add r0, fp, -C	ldr r0, [fp, -C]	str r0, [fp, -C]
int count	COUNT	add r0, fp, -COUNT	ldr r0, [fp, -COUNT]	str r0, [fp, -COUNT]
char buf[0]	BUF	add r0, fp, -BUF	ldrb r0, [fp, -BUF]	strb r0, [fp, -BUF]
char buf[1]	BUF-1	add r0, fp, -BUF+1	ldrb r0, [fp, -BUF+1]	strb r0, [fp, -BUF+1]
char buf[2]	BUF-2	add r0, fp, -BUF+2	ldrb r0, [fp, -BUF+2]	strb r0, [fp, -BUF+2]

Frame Design Practice

1. Write the variables in C
2. Draw a picture of the stack frame
3. Write the code to generate the offsets
4. create the table to access the variables

```
void func(void)
{
  signed char c;
  signed short s;
  unsigned char b[] = "Stack";
  unsigned char *ptr = &bufl
    // rest of code
}
```

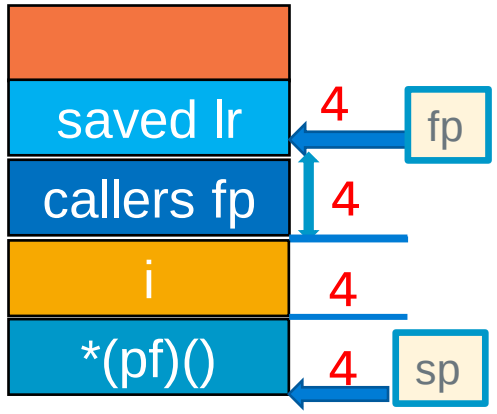



```
.equ    FP_OFF,     12
.equ    C,          2 + FP_OFF
.equ    S,          2 + C
.equ    B,          8 + S
.equ    PTR,        4 + BUF
.equ    PAD,        0 + PTR
.equ    FRMADD,     PAD - FP_OFF
// FRMADD =  28 - 12 = 8
```

Variable	distance from fp	Address on Stack	Read variable	Write Variable
signed char c	C	add r0, fp, -C	ldrsb r0, [fp, -C]	strsb r0, [fp, -C]
signed short s	S	add r0, fp, -S	ldrsh r0, [fp, -S]	strsh r0, [fp, -S]
unsigned char b[0]	BUF	add r0, fp, -B	ldrb r0, [fp, -B]	strb r0, [fp, -B]
unsigned char *ptr	PTR	add r0, fp, -PTR	ldr r0, [fp, -PTR]	str r0, [fp, -PTR]

Working with Pointers on the stack

```
int
sum(int j, int k)
{
   return j + k;
}
void
testp(int j, int k, int (*func)(), int *i)
{
   *i = func(j,k);
   return;
}
int
main()
{
   int i;
   int (*pf)() = add;

   testp(1, 2, pf, &i);
   printf("%d\n", i);
   return EXIT_SUCCESS;
}
```




```
   .section .rodata
.Lmess: .string "%d\n"
   .extern printf
   .text
   .global main
   .type   main, %function
   .equ    FP_OFF, 4
   .equ    I,     4 + FP_OFF
   .equ    PF,    4 + I
   .equ    PAD,   0 + PF
   .equ    FRMADD, PAD-FP_OFF
```

Variable	distance from fp	Address on Stack	Read variable	Write Variable
`int i`	I	`add r0, fp, -I`	`ldr r0, [fp, -I]`	`str r0, [fp, -I]`
`int (*pf)()`	PF	`add r0, fp, -PF`	`ldr r0, [fp, -PF]`	`str r0, [fp, -PF]`

Working with Pointers on the stack

```
int
sum(int j, int k)
{
   return j + k;
}

void
testp(int j, int k, int (*func)(), int *i)
{
   *i = func(j,k);
   return;
}

int
main()
{
   int i;
   int (*pf)() = add;

   testp(1, 2, pf, &i);
   printf("%d\n", i);
   return EXIT_SUCCESS;
}
```

```
   .global sum
   .type   sum, %function
add:
   push    {fp, lr}
   add     fp, sp, FP_OFF

   add     r0, r0, r1

   sub     sp, fp, FP_OFF
   pop     {fp, lr}
   bx      lr
.size sum, (. - sum)
```

r0,r1,r2 already set

```
   .global testp
   .type   testp, %function
   .equ    FP_OFF, 12
testp:
   push    {r4, r5, fp, lr}
   add     fp, sp, FP_OFF

   mov     r4, r3        // save i
   blx     r2            // r0=func(r0,r1)
   str     r0, [r4]      // *i =r0

   sub     sp, fp, FP_OFF
   pop     {r4, r5, fp, lr}
   bx      lr
.size testp, (. - testp)
```

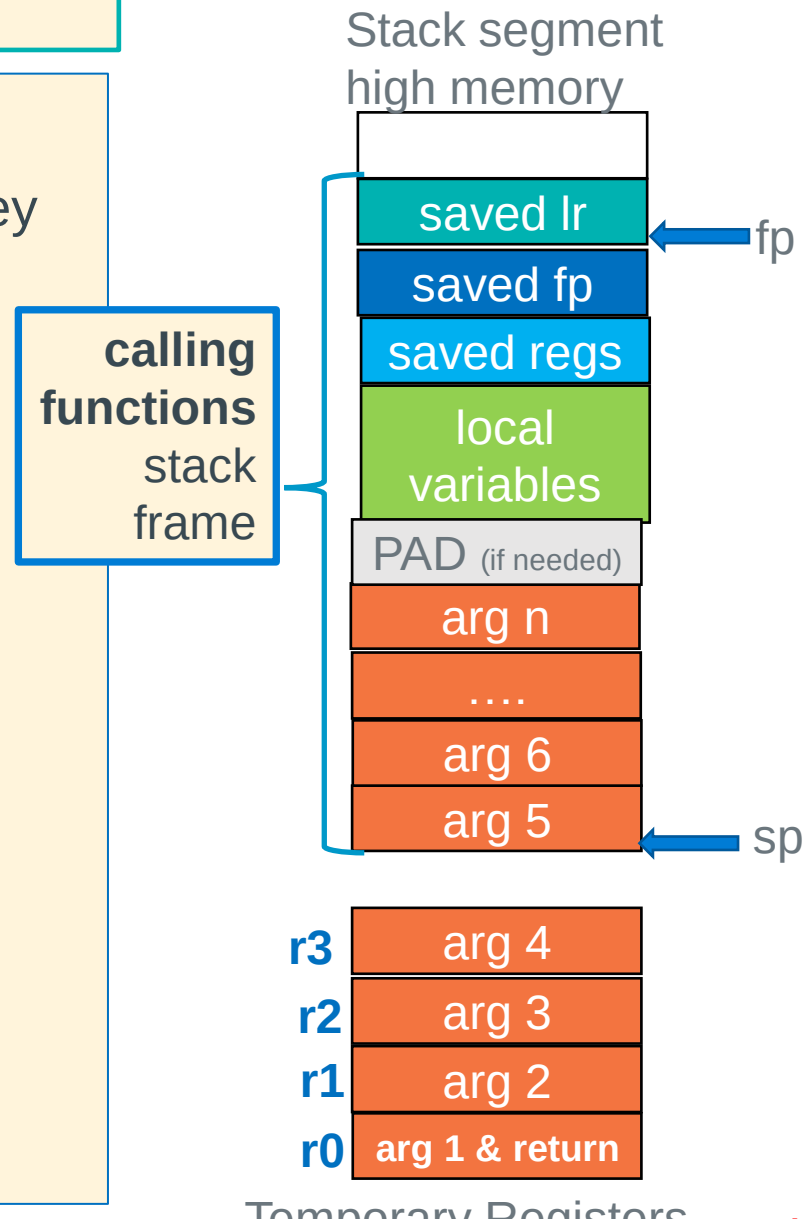
```
   .global main
   .type   main, %function
   .equ    FP_OFF, 4
   .equ    I,      4 + FP_OFF
   .equ    PF,     4 + I
   .equ    PAD,    0 + PF
   .equ    FRMADD, PAD-FP_OFF
main:
   push    {fp, lr}
   add     fp, sp, FP_OFF
   add     sp, sp,-FRMADD

   ldr     r2, =sum       // func address
   add     r1, fp, -PF    // PF address
   str     r2, [r1]       // store in pf

   mov     r0, 1          // arg 1: 1
   mov     r1, 2          // arg 2: 2
   ldr     r2, [fp, -PF]  // arg 3: (*pf)()
   add     r3, fp, -I     // arg 4: &I
   bl      testp

   ldr     r0, =.Lmess    // arg 1: "%d\n"
   ldr     r1, [fp, -I]   // arg 2: i
   bl      printf

   sub     sp, fp, FP_OFF
   pop     {fp, lr}
   bx      lr
.size main, (. - main)
```

Variable	distance from fp	Address on Stack	Read variable	Write Variable
`int i`	I	`add r0, fp, -I`	`ldr r0, [fp, -I]`	`str r0, [fp, -I]`
`int (*pf)()`	PF	`add r0, fp, -PF`	`ldr r0, [fp, -PF]`	`str r0, [fp, -PF]`

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



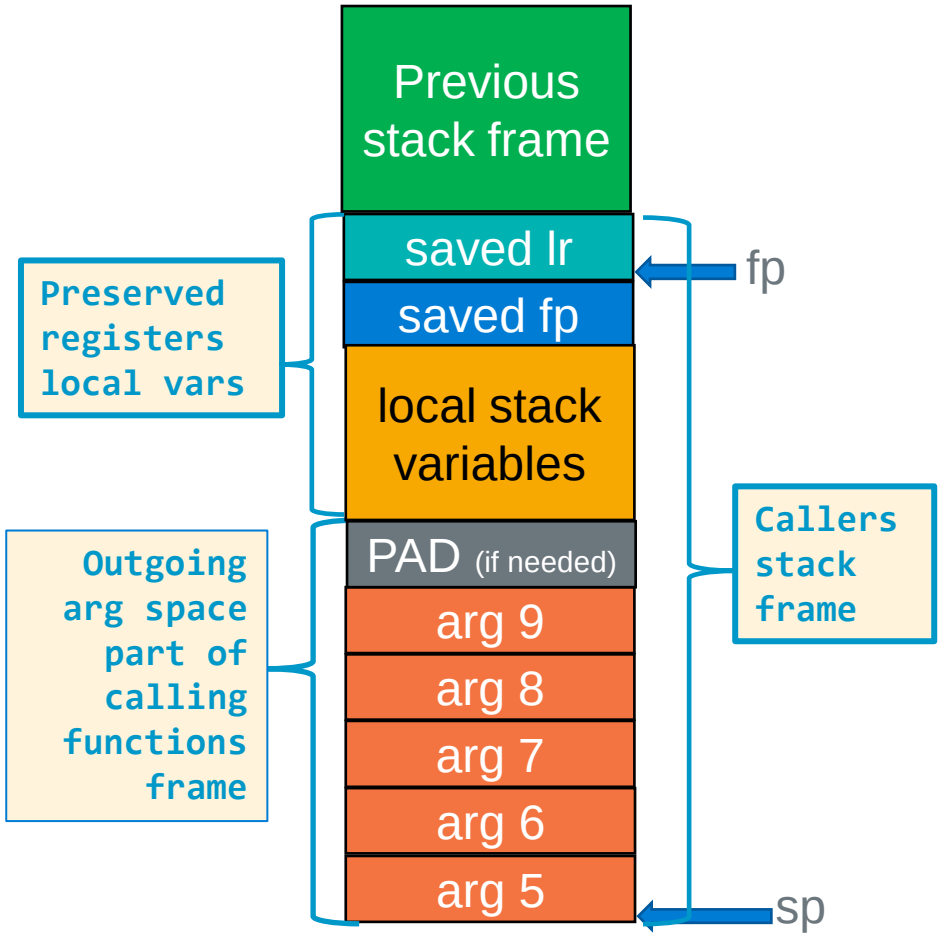
Calling Function: Allocating Stack Parameter Space

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

1. sp must point at arg5
2. sp and therefore arg5 **must be at an 8-byte boundary**,
   a) **padding** to force arg5 alignment if needed 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



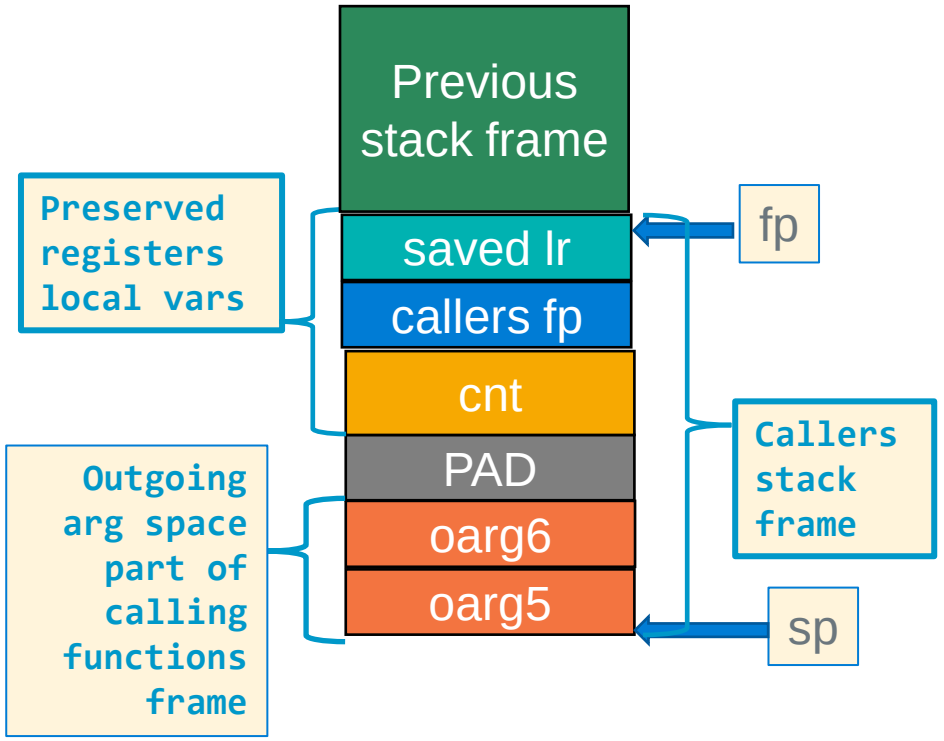
Rules: At point of call

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

x

Calling Function: Pass ARG 5 and higher

```
.equ    FP_OFF,4
.equ    CNT,            4 + FP_OFF      // int cnt
.equ    PAD,            4 + CNT         // added as needed
.equ    OARG6,          4 + PAD         // int a
.equ    OARG5,          4 + OARG6       // int b
.equ    FRMADD          OARG5 - FP_OFF
```



Rules: At point of call

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

r0 = func(r0, r1, r2, r3, OARG5, OARG6);

Variable	distance from fp	Address on Stack	Read variable	Write Variable
int cnt	CNT	add r0, fp, -CNT	ldr r0, [fp, -CNT]	str r0, [fp, -CNT]
int oarg6	OARG6	add r0, fp, -OARG6	ldr r0, [fp, -OARG6]	str r0, [fp, -OARG6]
int oarg5	OARG5	add r0, fp, -OARG5	ldr r0, [fp, -OARG5]	str r0, [fp, -OARG5]

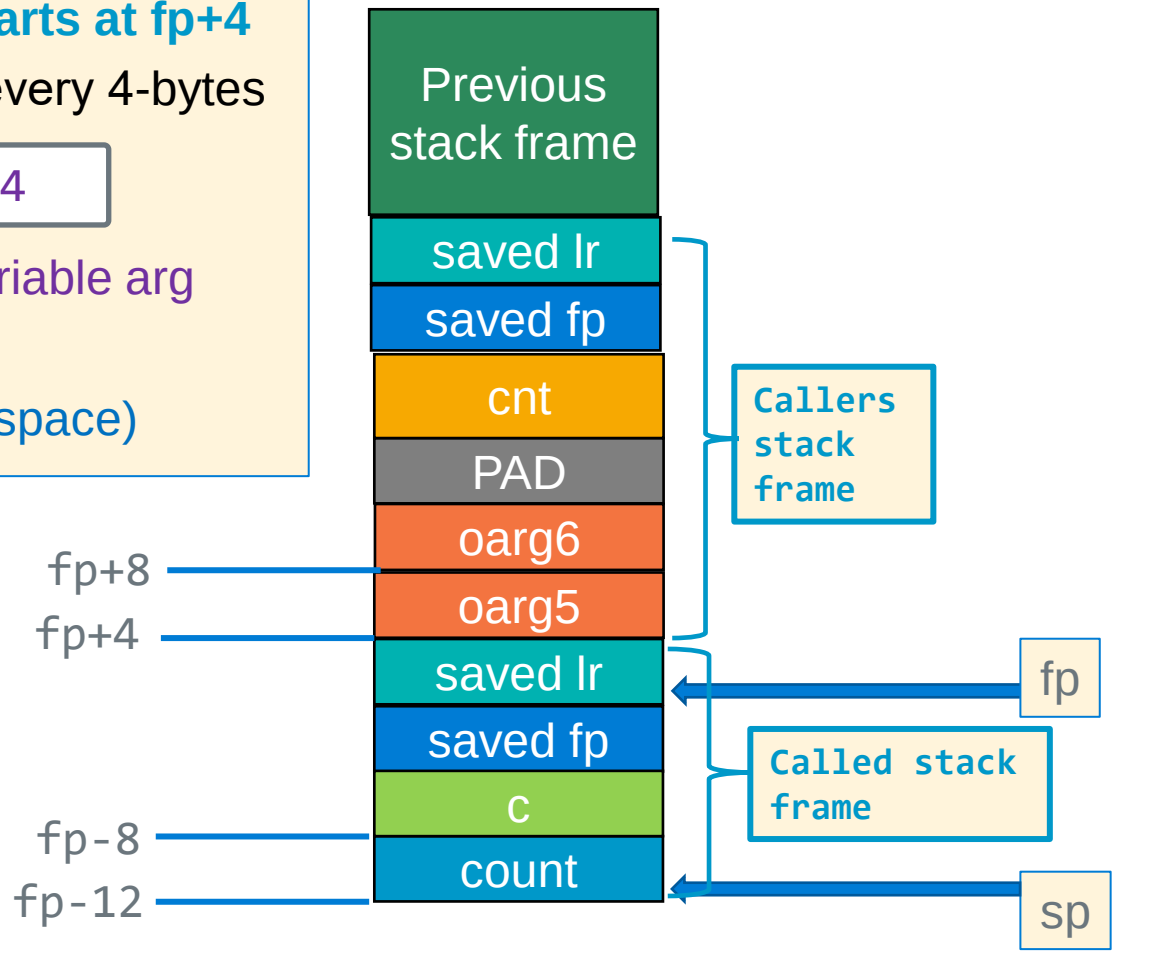
X

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

```
.equ ARGN,  (N-4)*4  // where n must be > 4
```

- This "algorithm" for finding args was designed to enable variable arg count functions like printf("conversion list", arg0, … argn);
- No limit to the number of args (except running out of stack space)



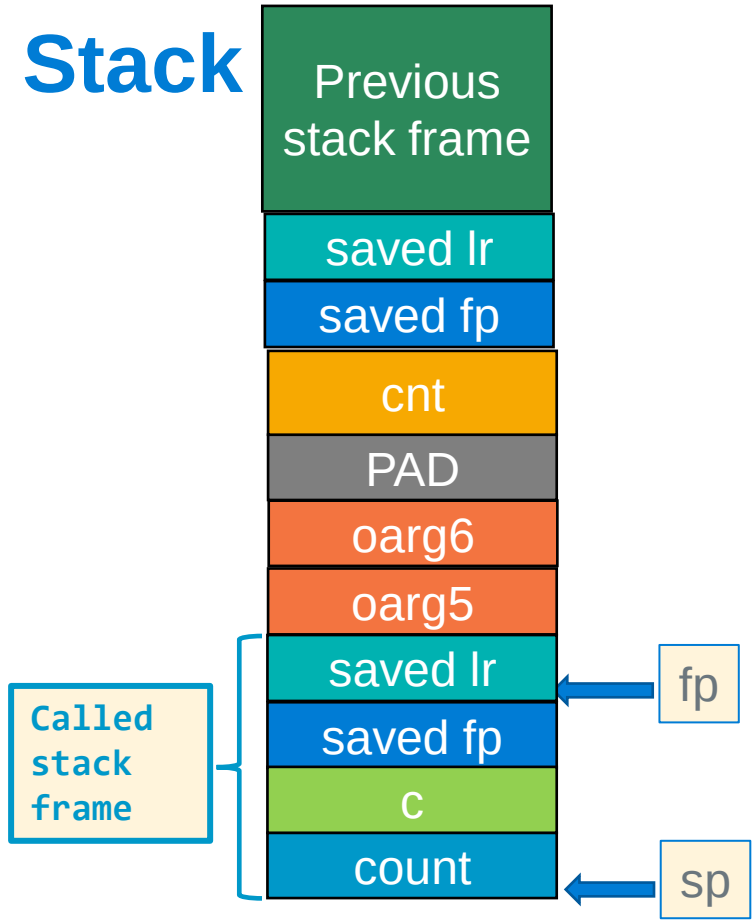
Rule:
Called functions always access stack parameters using a **positive offset to the fp**

```
r0 = func(r0, r1, r2, r3, r4, ARG5, ARG6);
```

Called Function: Retrieving Args From the Stack

```
.equ    FP_OFF,     4
.equ    C,          4 + FP_OFF
.equ    COUNT,      4 + C
.equ    PAD,        4 + COUNT
.equ    FRMADD,     PAD - FP_OFF
.equ    ARG6,       8
.equ    ARG5,       4
```

```
r0 = func(r0, r1, r2, r3, r4, ARG5, ARG6);
```



Rule:

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

Variable	distance from fp	Address on Stack	Read variable	Write Variable
int arg6	ARG6	add r0, fp, ARG6	ldr r0, [fp, ARG6]	str r0, [fp, ARG6]
int arg5	ARG5	add r0, fp, ARG5	ldr r0, [fp, ARG5]	str r0, [fp, ARG5]
int c	C	add r0, fp, -C	ldr r0, [fp, -C]	str r0, [fp, -C]
int count	COUNT	add r0, fp, -COUNT	ldr r0, [fp, -COUNT]	str r0, [fp, -COUNT]

Passing 6 Args Example

REWRITE EVERYTHING AFTER THIS SLIDE

Determining Size of 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

Structs and pointers

- not sure on this….