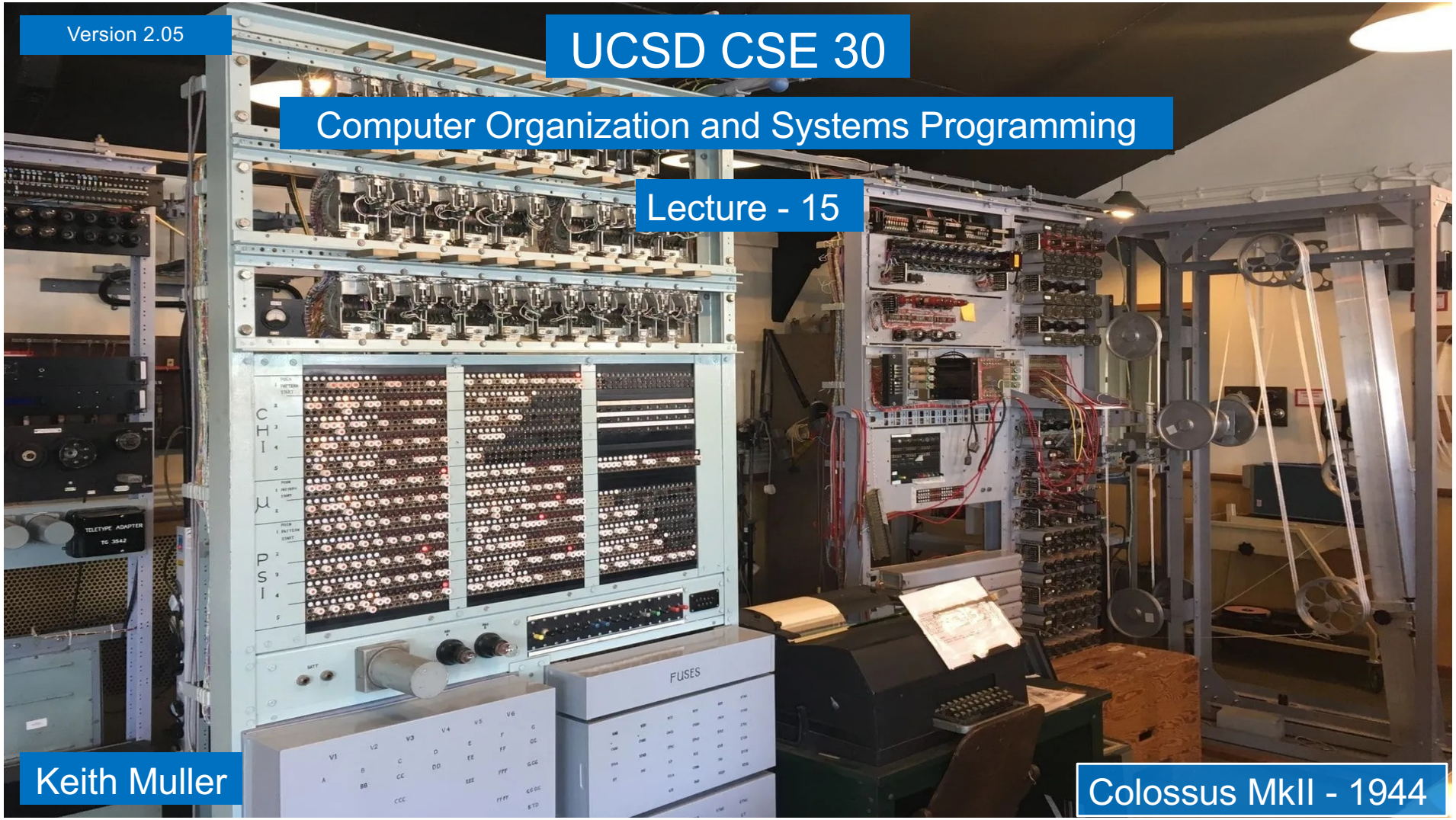
Version 2.05

UCSD CSE 30

Computer Organization and Systems Programming

Lecture - 15



Keith Muller

Colossus MkII - 1944

Masking Summary - 1

Select a field: Use `and` with a mask of one's surrounded by zeros to select the bits that have a 1 in the mask, all other bits will be set to zero

selects this field when used with and

0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 1 1 1 1 0 0

selection mask 0x3c

Clear a field: Use `and` with a mask of zero's surrounded by ones to select the bits that have a 1 in the mask, all other bits will be set to zero

clears this field when used with and

1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1	1 1 0 0 0 0 1 1

clear a field mask 0xffffffc3

Isolate a field: Use `lsr, lsl` to get a field surrounded by zeros

lsl this edge to bit 31 (left edge) then lsr to move back

lsr this edge to bit 0 (right edge) then lsl to move back

x

Masking Summary - 2

Isolate a field: Use `and` to get a field surrounded by zeros

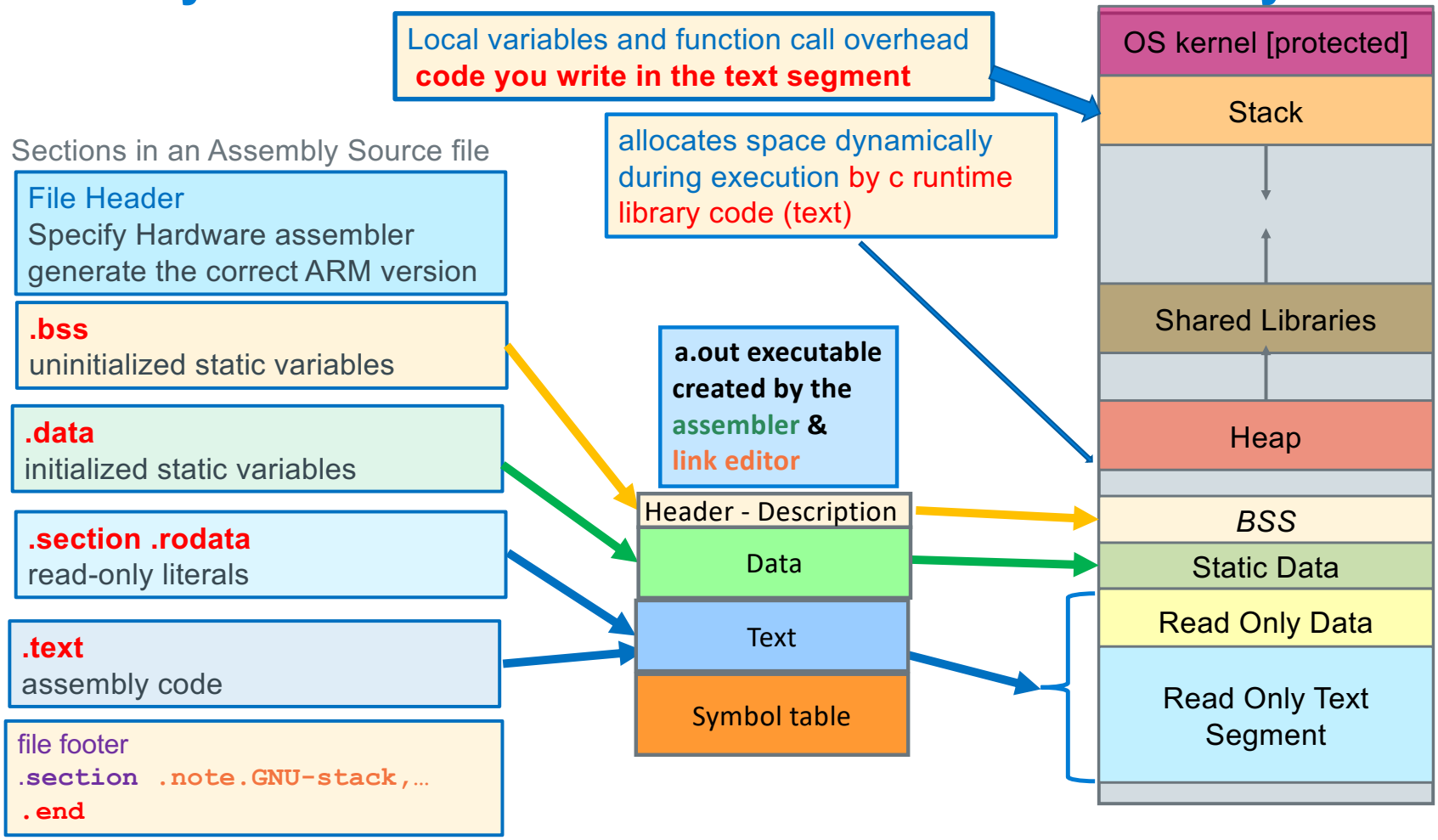

```
selection mask 0x00ff0000
```

rotate a field: Use `ror` to move a field without changing other bits

Insert a field: Use `orr` with fields surrounded by zeros

x

Assembly Source File to Executable to Linux Memory



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

// BSS Segment (only when you have initialized globals)
         .bss
// Data Segment (only when you have uninitialized globals)
         .data
// Read-Only Data (only when you have literals)
         .section .rodata
// Text Segment – your code
         .text

// Function Header
        .type   main, %function    // define main to be a function
        .global main               // export function name
main:
// function prologue               // stack frame setup
                  // your code for this function here
// function epilogue               //stack frame teardown

// function footer
         .size  main, (. - main)

// File Footer
          .section .note.GNU-stack,"",%progbits // stack/data non-exec
.end
```

Assembly Source File Template

- assembly programs end in .S
  - That is a **capital** .S
  - example: test.S
- Always use gcc to assemble
  - _start() and C runtime
- File has a complete program

  `gcc file.S`
- File has a partial program

  `gcc -c file.S`
- Link files together

  `gcc file.o cprog.o`

x

Assembler Directives: .equ and .equiv

```
        .equ    BLKSZ,  10240     // buffer size in bytes
        .equ    BUFCNT, 100*4     // buffer for 100 ints
        .equ    BLKSZ,  STRSZ * 4 // redefine BLKSZ from here
```

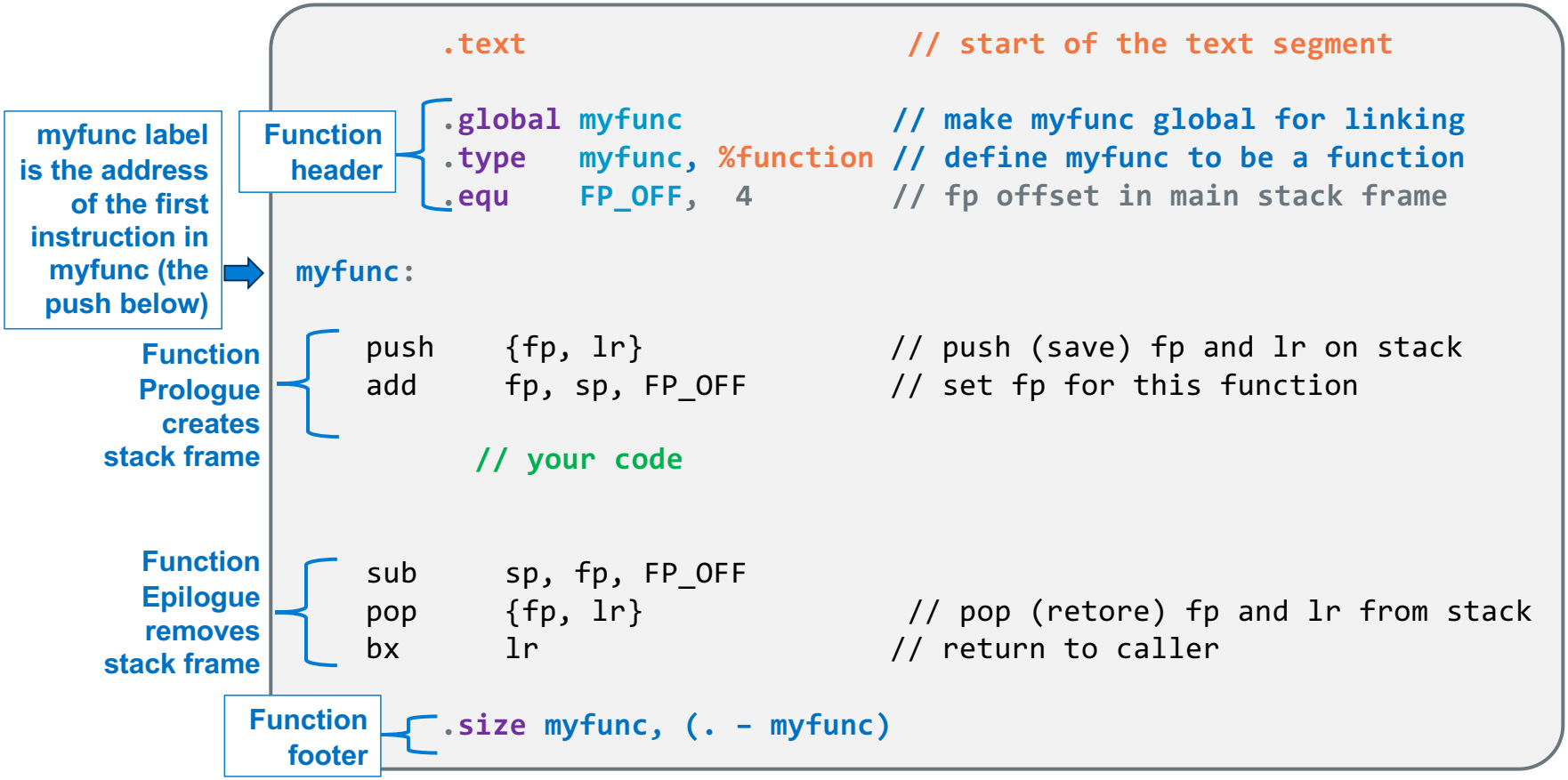
`.equ <symbol>, <expression>`

- Defines and sets the value of a symbol to the evaluation of the expression
- Used for specifying constants, like a `#define` in C
- You can (re)set a symbol many times in the file, last one seen applies

```
        .equ    BLKSZ,  10240       // buffer size in bytes
        // other lines
        .equ    BLKSZ,  1024        // buffer size in bytes
```


x

Function Template



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Preview: 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**
  - **In terms of C runtime support, these registers contain the copies given to the called function**
  - **C allows the copies to be changed in any way by the called function**

X

Preview: Writing an ARM32 function

```
#include <stdlib.h>
#include <stdio.h>
#include "sum4.h"
int main()
{
    int reslt;

    reslt = sum4(1,2,3,4);

    printf("%d\n", reslt);
    return EXIT_SUCCESS;
}
```

```
#ifndef SUM4_H
#define SUM4_H

#ifndef __ASSEMBLER__
int sum4(int, int, int, int);
#else
.extern sum4
#endif

#endif
```

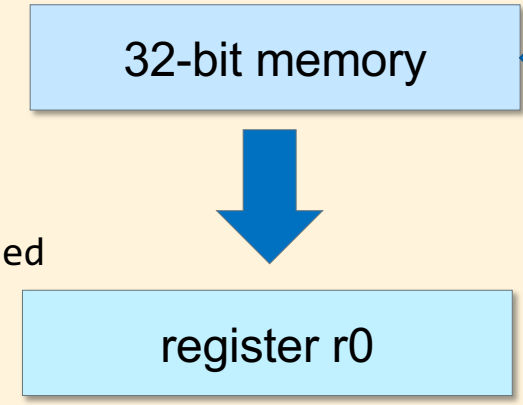
```
#include "sum4.h"
    .arch armv6
    .arm
    .fpu vfp
    .syntax unified
    .global sum4
    .type   sum4, %function
    .equ    FP_OFF, 28
    // r0 = sum4(r0, r1, r2, r3)
sum4:
    push    {r4-r9, fp, lr}
    add     fp, sp, FP_OFF

    add     r0, r0, r1
    add     r0, r0, r2
    add     r0, r0, r3

    sub     sp, fp, FP_OFF
    pop     {r4-r9, fp, lr}
    bx      lr
    .size sum4, (. - sum4)
    .section .note.GNU-stack,"",%progbits
.end
```

```
$ gcc -Wall -Wextra -c main.c
$ gcc -c sum4.S
$ gcc sum4.o main.o
$ ./a.out
10
```

Load/Store: Register Base Addressing

ldr r0, [r1]

Copies a 32-bit word from the memory location whose address is contained in r1 (r1 is a pointer) into register r0

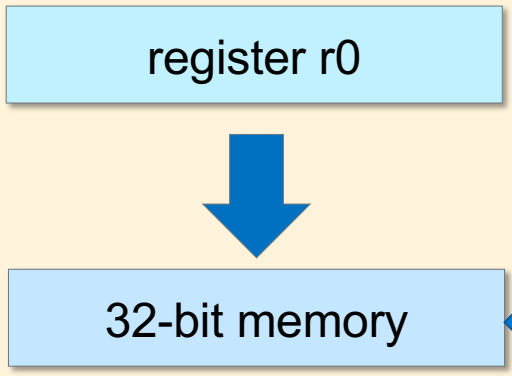


r1 is being used as a **pointer** to a location in memory

ldr requires the use of a pointer operand

str r0, [r1]

Copies all 32 bits of the value held in register r0 to the 32-bit memory location contained in register r1 (r1 pointer)

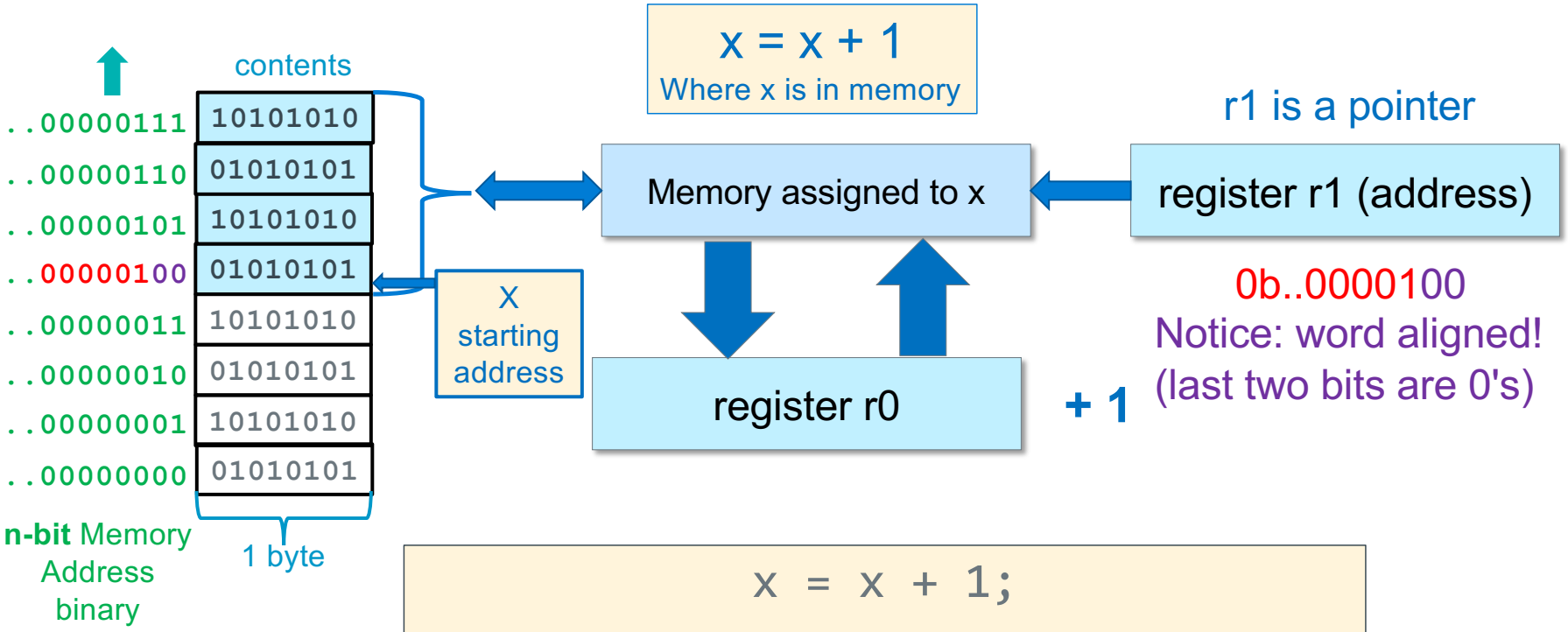


r1 is being used as a **pointer** to a location in memory

str requires the use of a pointer operand

x

Example Base Register Addressing Load – Modify – Store



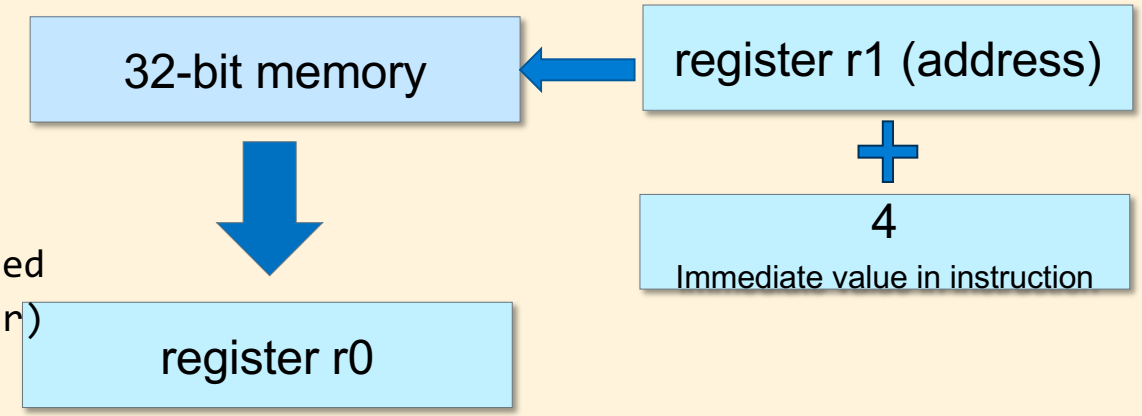

```
                x = x + 1;
ldr r0, [r1]          // r0 = *r1 (read x)
add r0, r0, 1         // r0 = r0 + 1 (x++)
str r0, [r1]          // *r1 = r0 write x
```


x

Load/Store: Register Base Addressing + Immediate

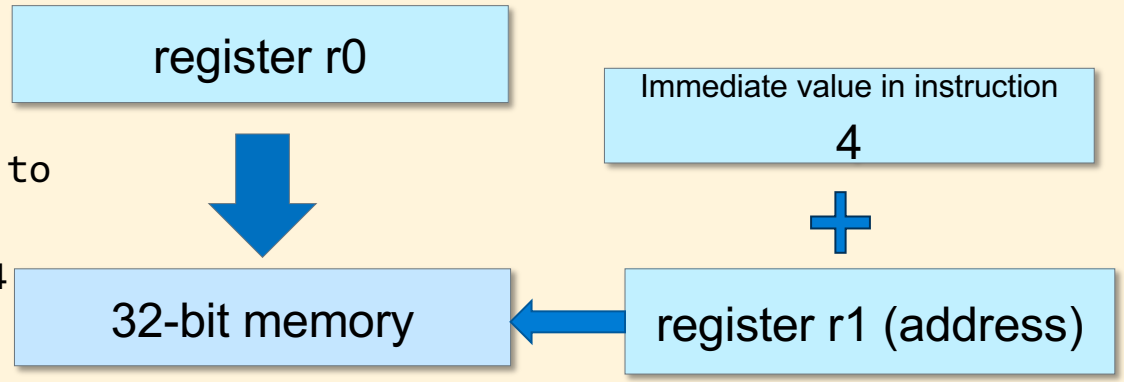
```
ldr r0, [r1, 4]
```

Copies a 32-bit word from the memory location whose address is contained in r1 +4 (r1 is a pointer) into register r0




```
str   r0, [r1, 4]
```

Copies all 32 bits of the value held in register r0 to the 32-bit memory location contained in register r1+4 (r1 pointer)



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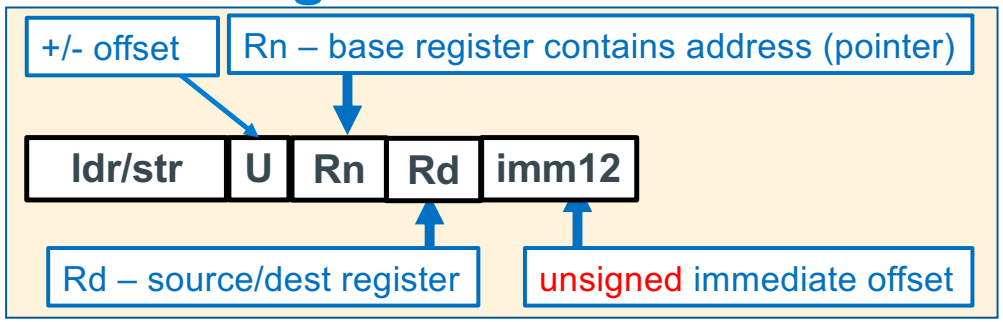
LDR/STR – Base Register + Immediate Offset Addressing



- **Register Base Addressing**:
  - Pointer Address: Rn; source/destination data: Rd
  - **Unsigned pointer address** in stored in the base register
- **Register Base + immediate offset Addressing:**
  - Pointer Address = register content + immediate offset `-4095 <= imm12 <= 4095 (bytes)`
  - Unsigned offset integer immediate value (bytes) is added or subtracted (U bit above says to add or subtract) from the pointer address in the base register
  - Often used to address struct members
    - Address of struct is address of the first member and subsequent members are a fixed offset from the first based on their size of the preceding members

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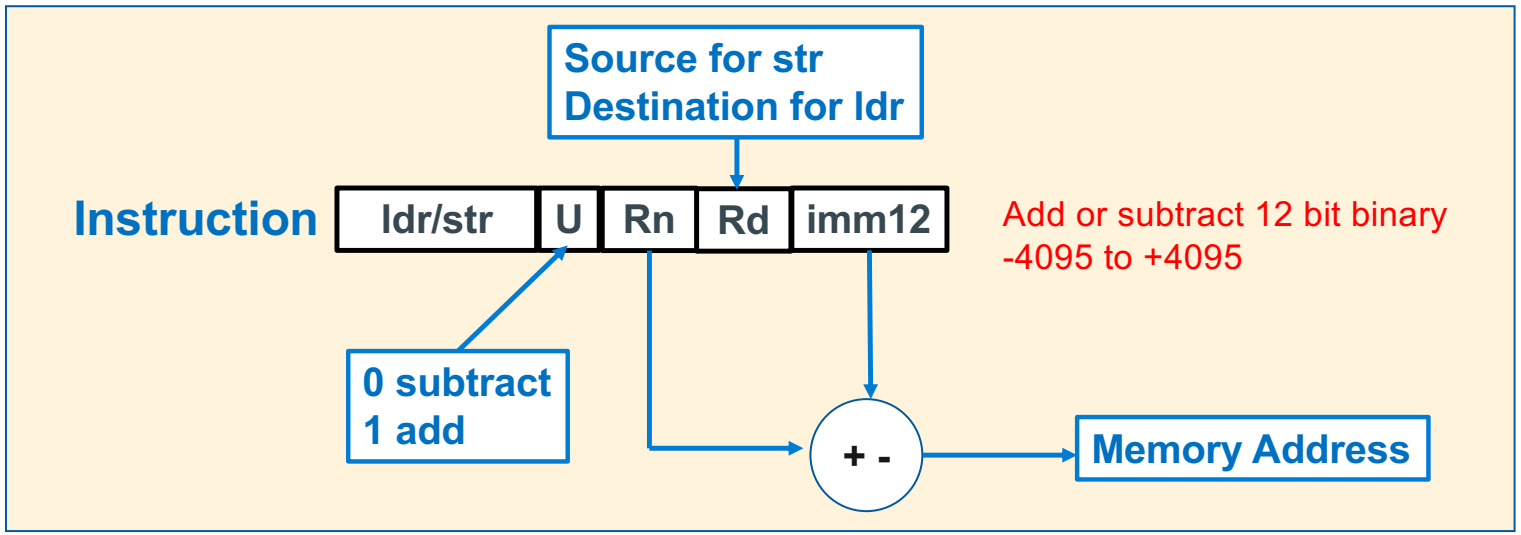
ldr/str Register Base + Immediate Offset Addressing



Syntax	Address	Examples
ldr/str Rd, [Rn, +/- constant] constant is in bytes ldr/str Rd, [Rn]	Rn + or – constant same →	ldr r0, [r5,100] str r1, [r5, 0] str r1, [r5]

x

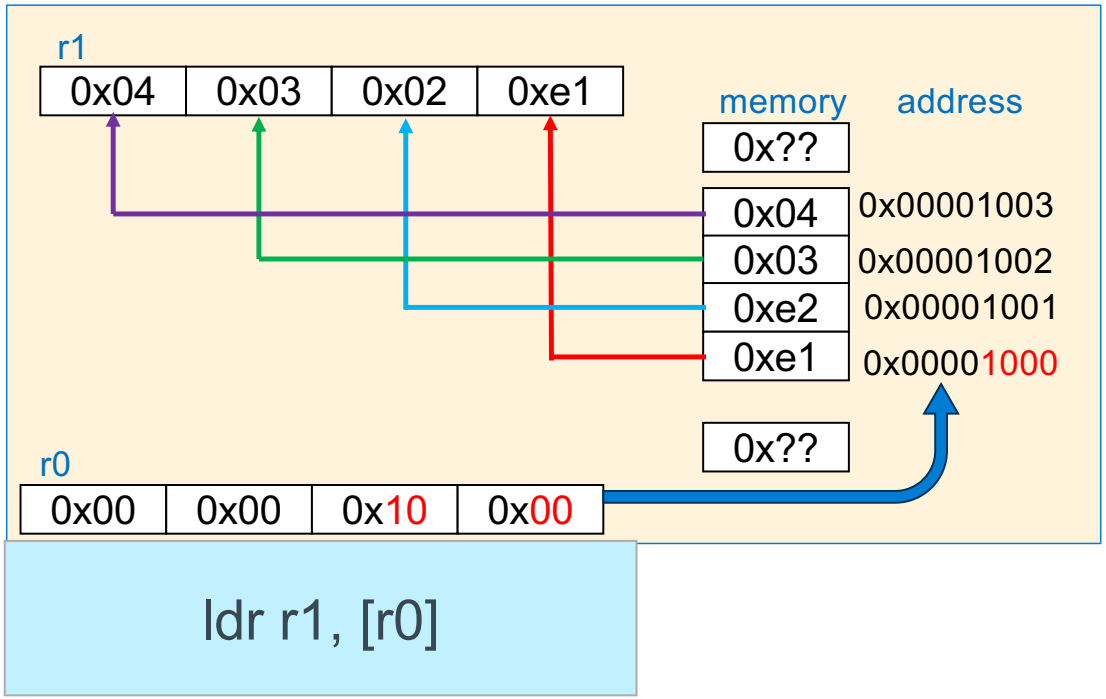
Loading and Storing: Variations List

- Load and store have variations that move 8-bits, 16-bits and 32-bits
- Load into a register with less than 32-bits will set the upper bits not filled from memory differently depending on which variation of the load instruction is used
- Store will only select the lower 8-bit, lower 16-bits or all 32-bits of the register to copy to memory, register contents are not altered

Instruction	Meaning	Sign Extension	Memory Address Requirement
`ldrsb`	load signed byte	sign extension	none (any byte)
`ldrb`	load unsigned byte	zero fill (extension)	none (any byte)
`ldrsh`	load signed halfword	sign extension	halfword (2-byte aligned)
`ldrh`	load unsigned halfword	zero fill (extension)	halfword (2-byte aligned)
`ldr`	load word	---	word (4-byte aligned)
`strb`	store low byte (bits 0-7)	---	none (any byte)
`strh`	store halfword (bits 0-15)	---	halfword (2-byte aligned)
`str`	store word (bits 0-31)	---	word (4-byte aligned)

x

Loading 32-bit Registers From Memory, 32-bit



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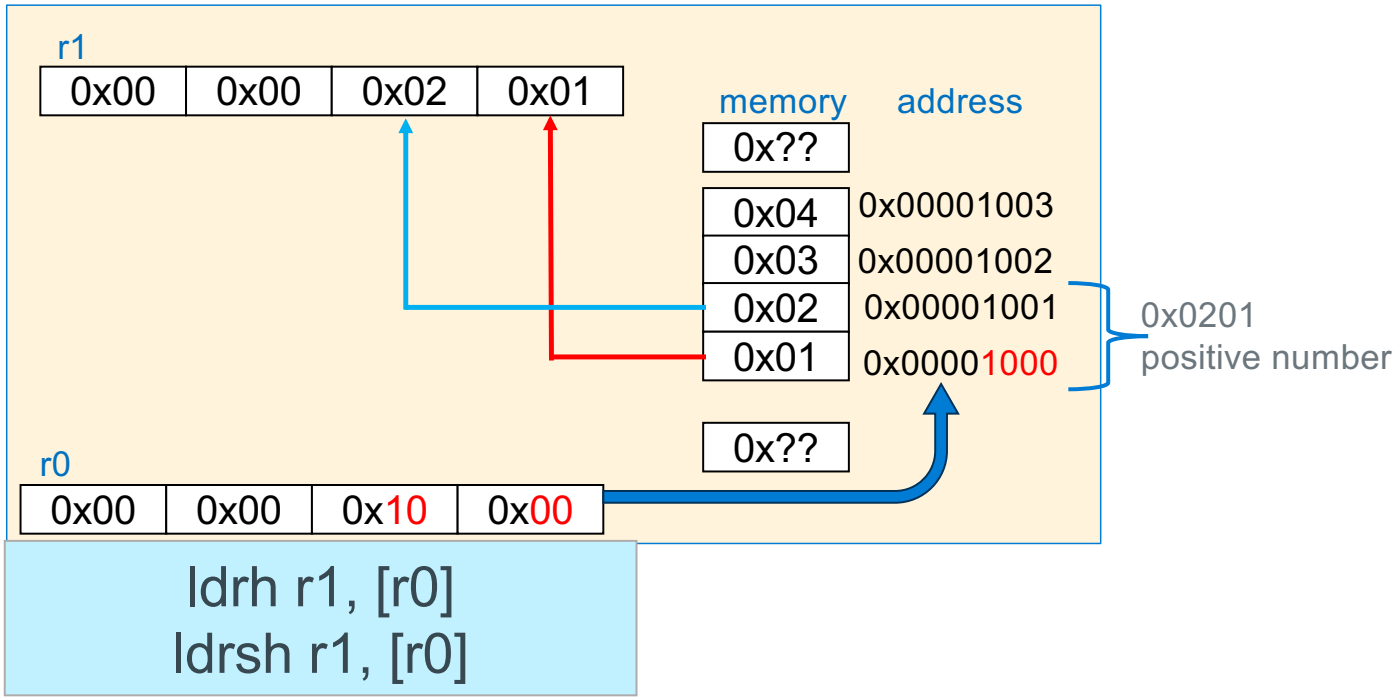
Loading 32-bit Registers From Memory, 16-bit



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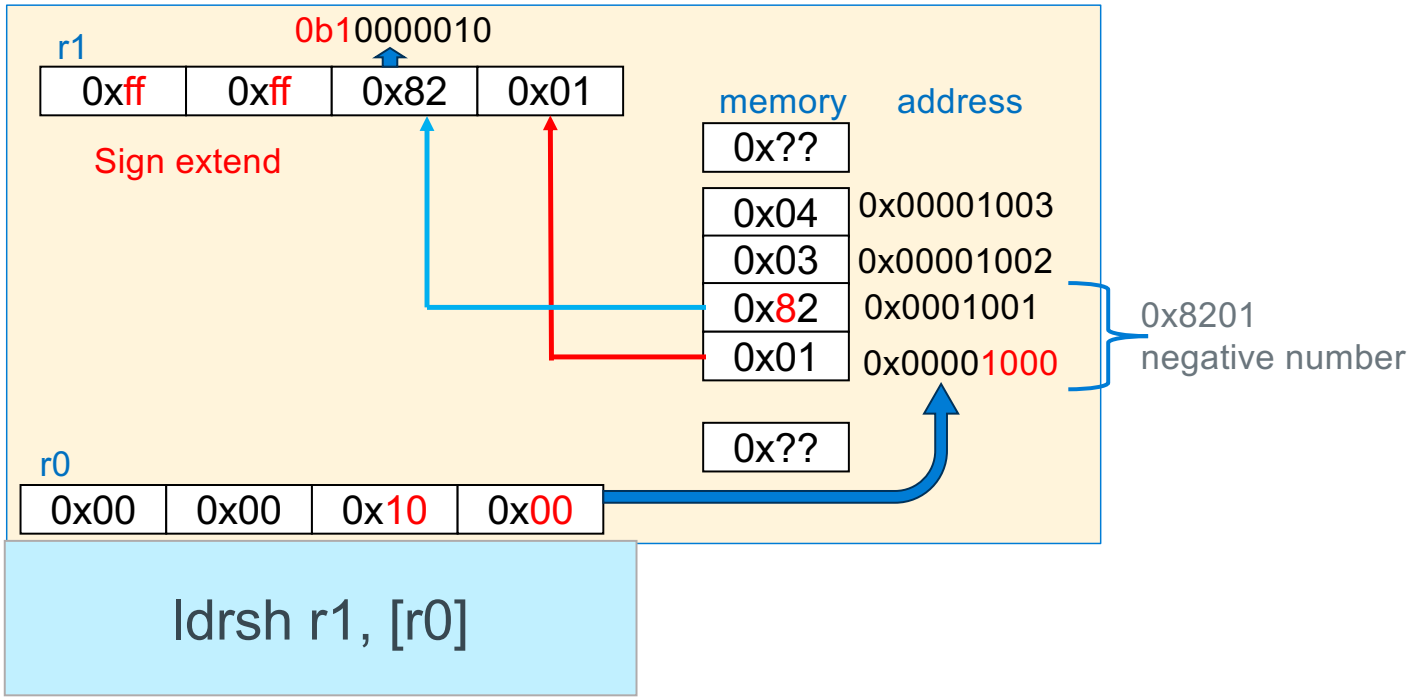
Loading 32-bit Registers From Memory, 16-bit Signed



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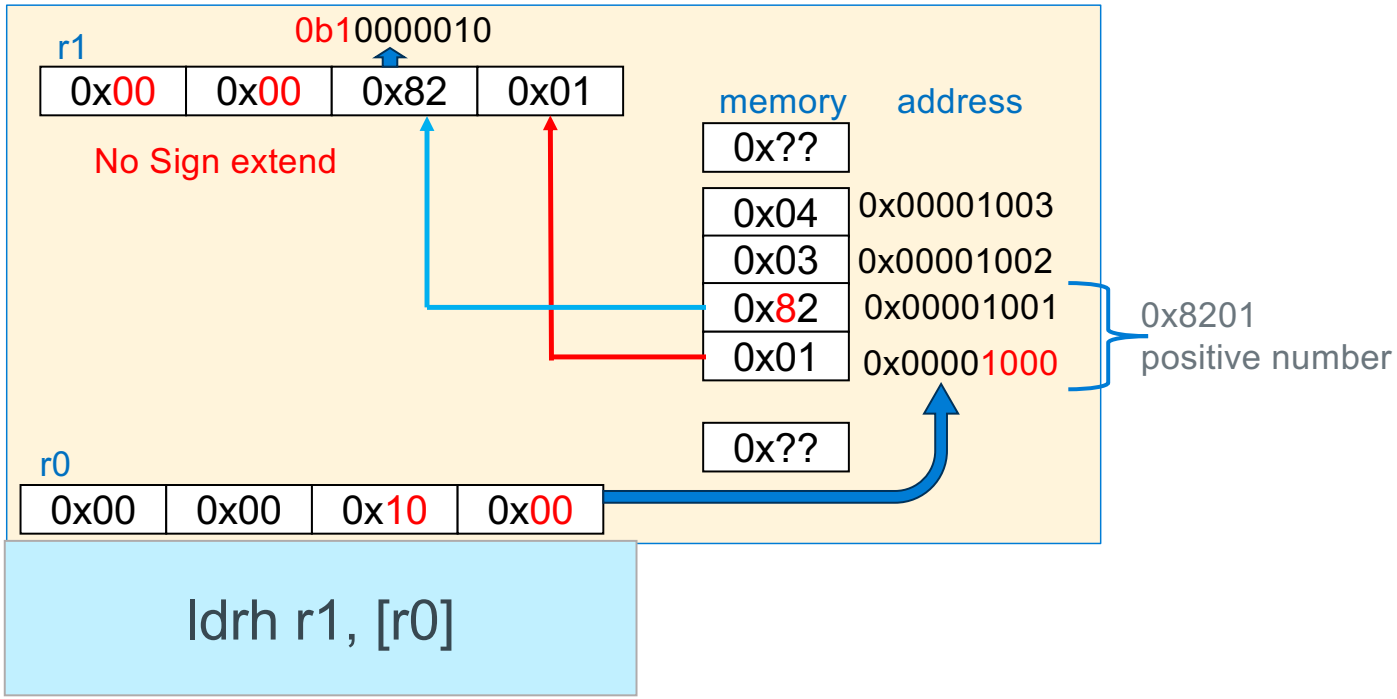
Loading 32-bit Registers From Memory, 16-bit Unsigned



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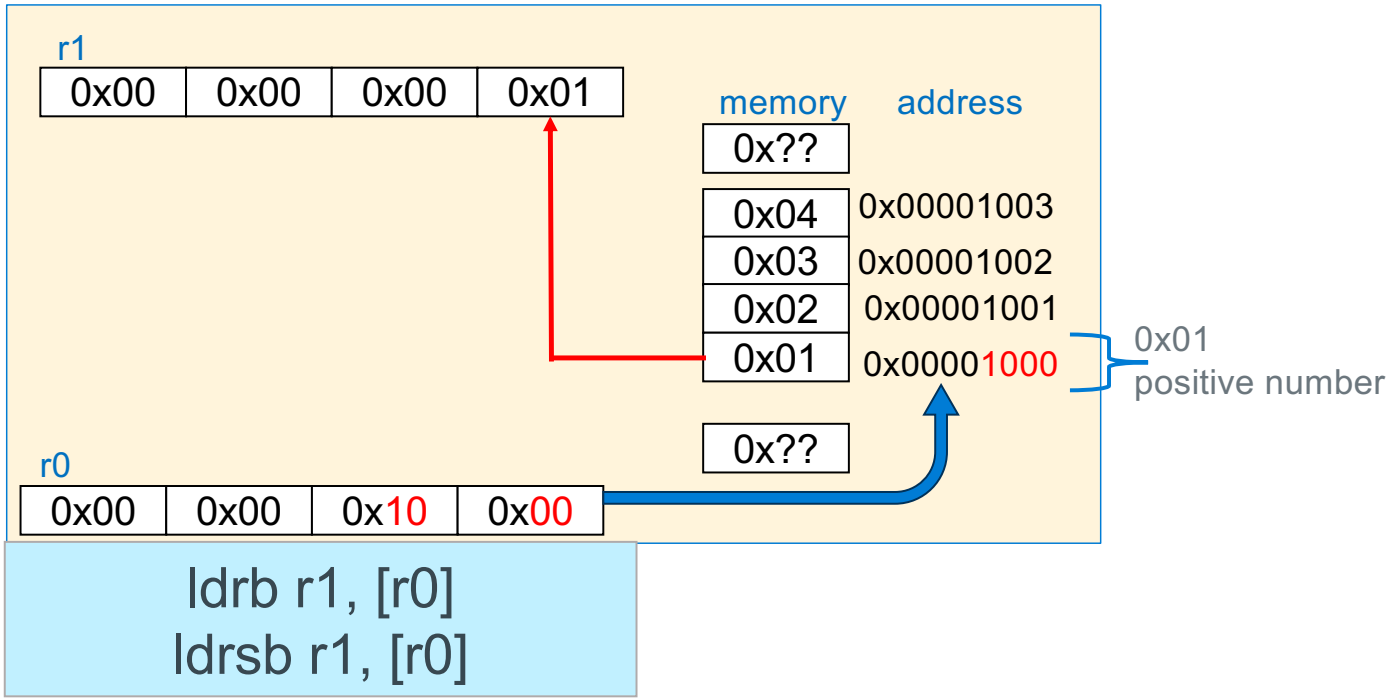
Loading 32-bit Registers From Memory, 8-bit



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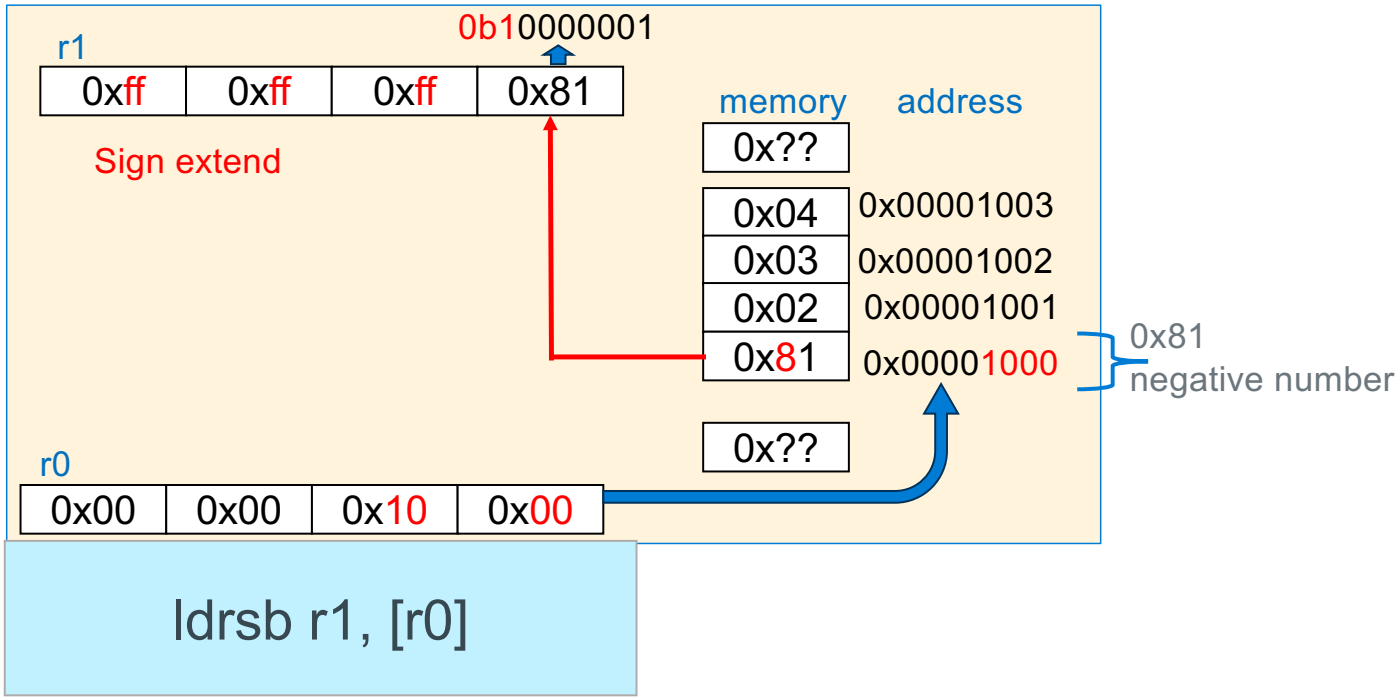
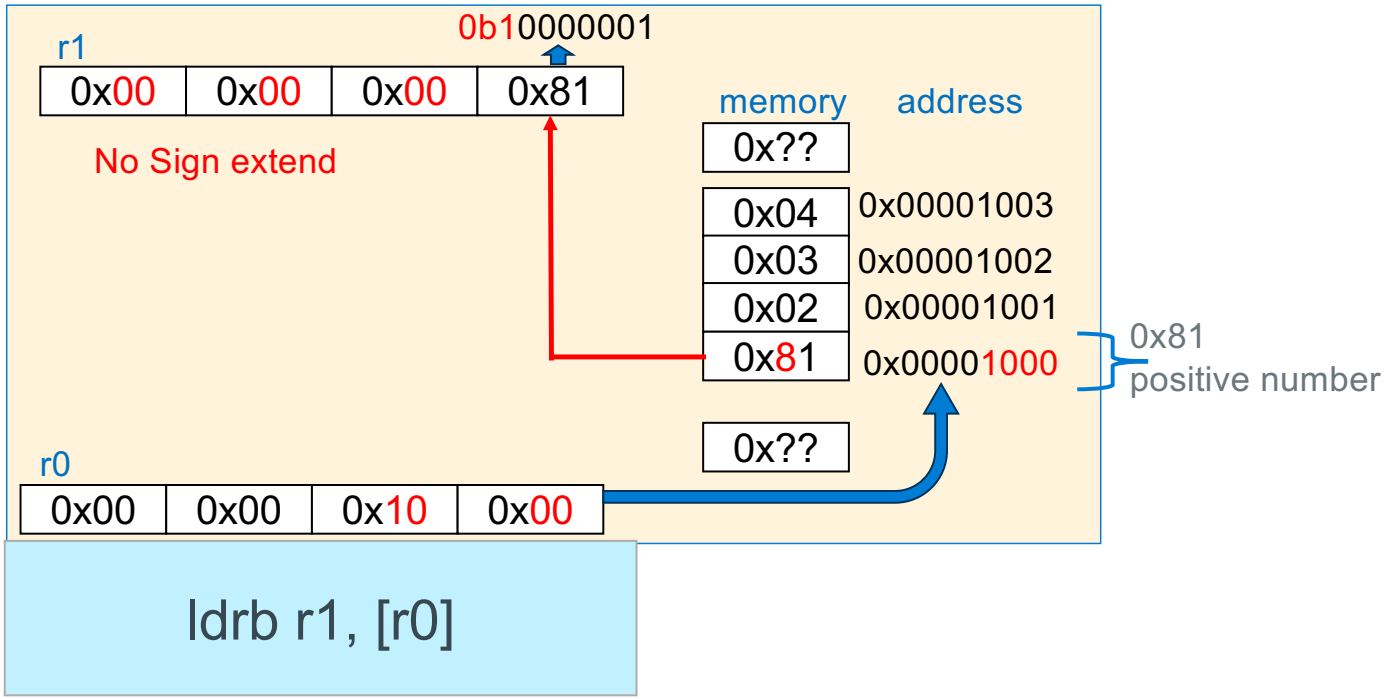
Loading 32-bit Registers From Memory, 8-bit Signed



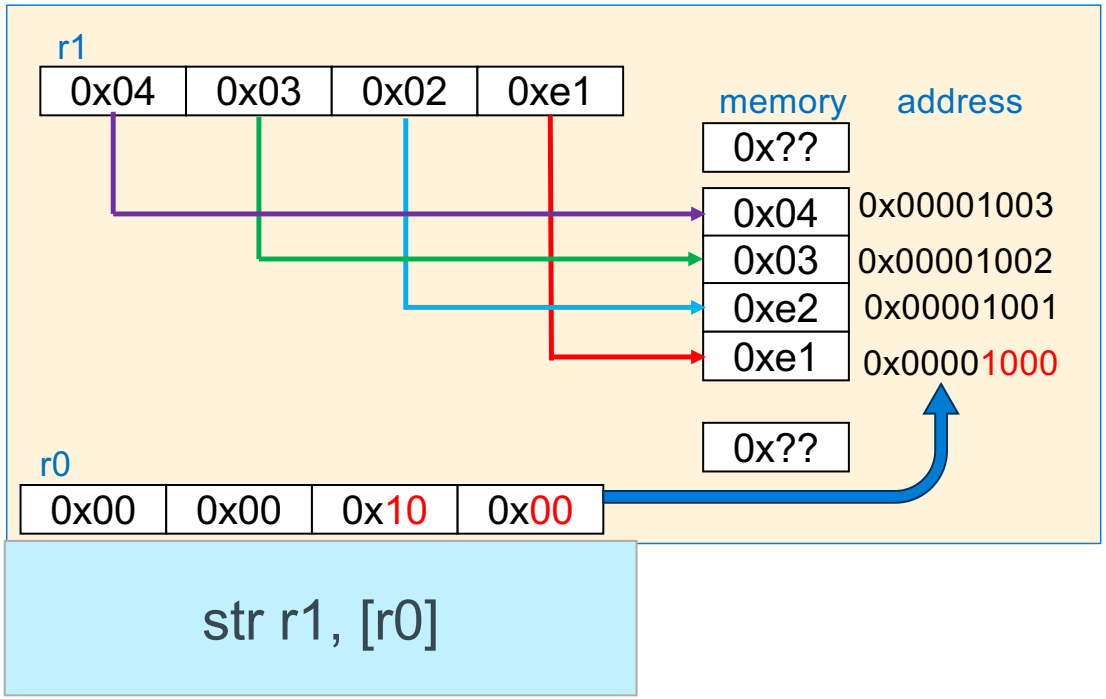
x

Loading 32-bit Registers From Memory, 8-bit Signed



x

Storing 32-bit Registers To Memory, 32-bit



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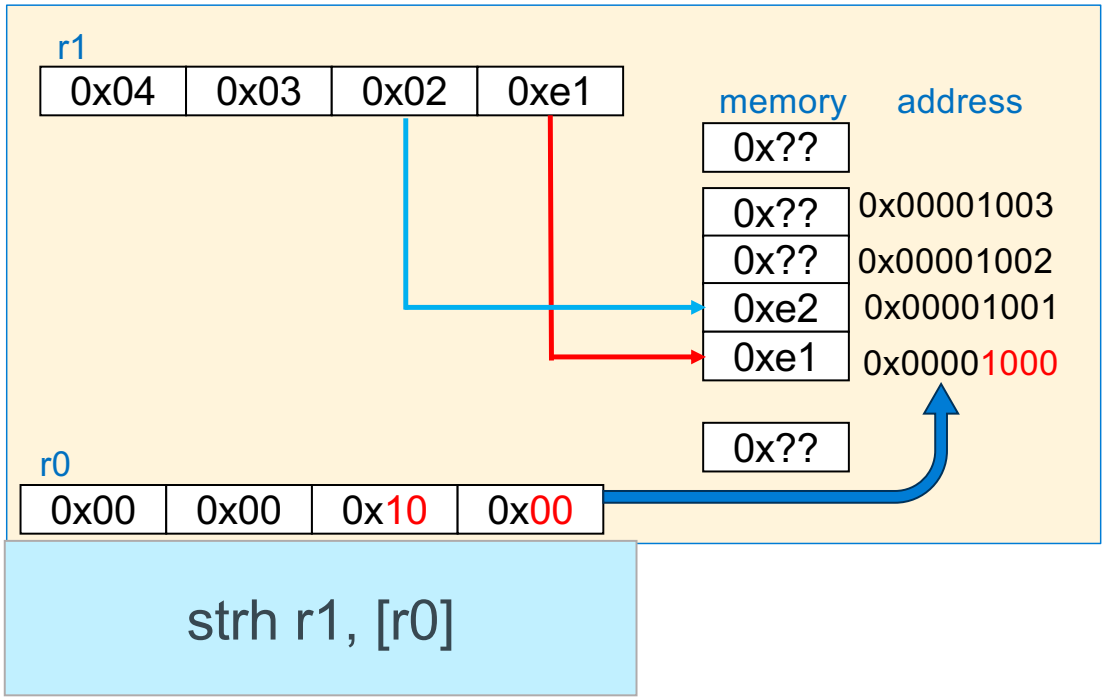
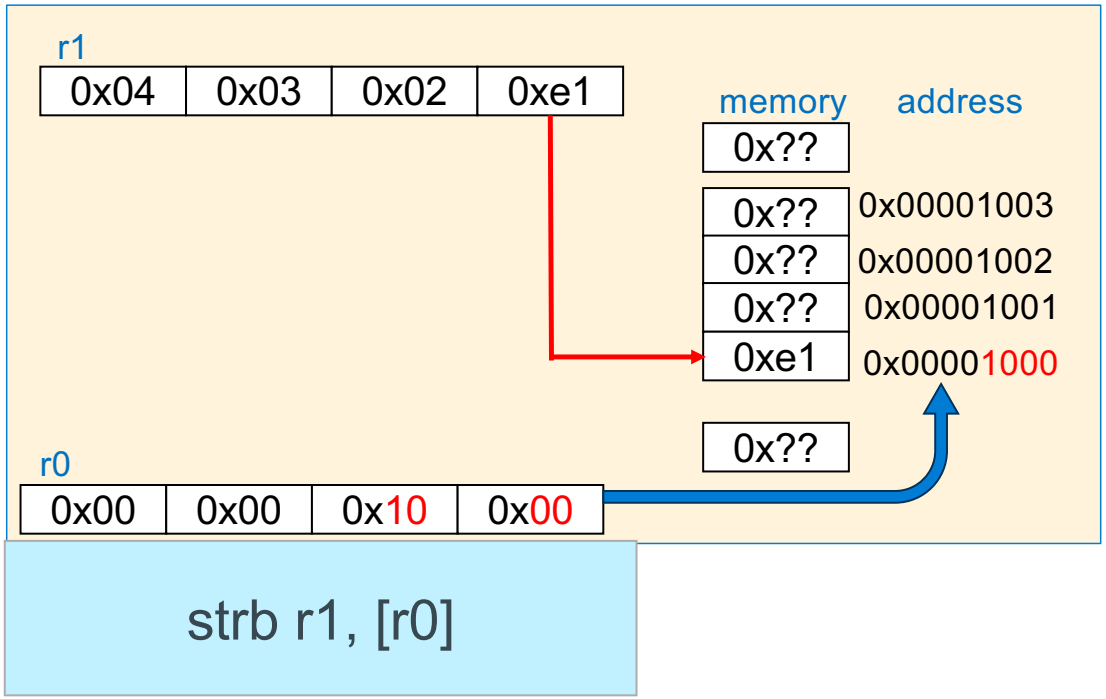
Storing 32-bit Registers To Memory, 16-bit



x

Storing 32-bit Registers To Memory, 8-bit



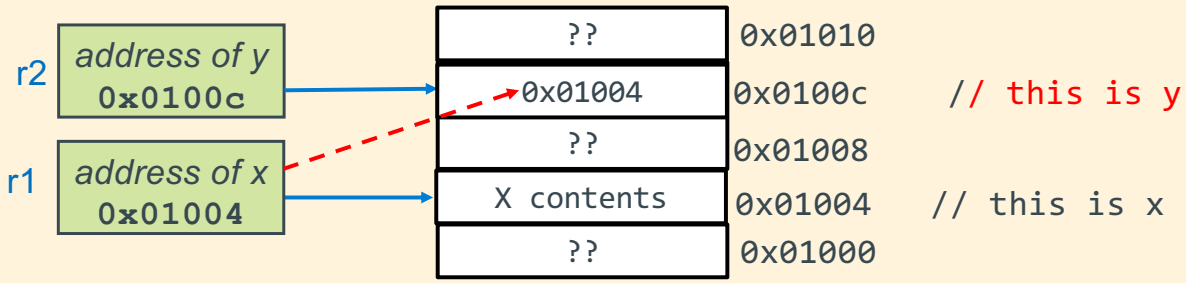
x

ldr/str practice - 1

r1 contains the Address of X (defined as int X) in memory; r1 points at X

r2 contains the Address of Y (defined as int *Y) in memory; r2 points at Y

write Y = &X;




```
str    r1, [r2]        // y ← &x
```

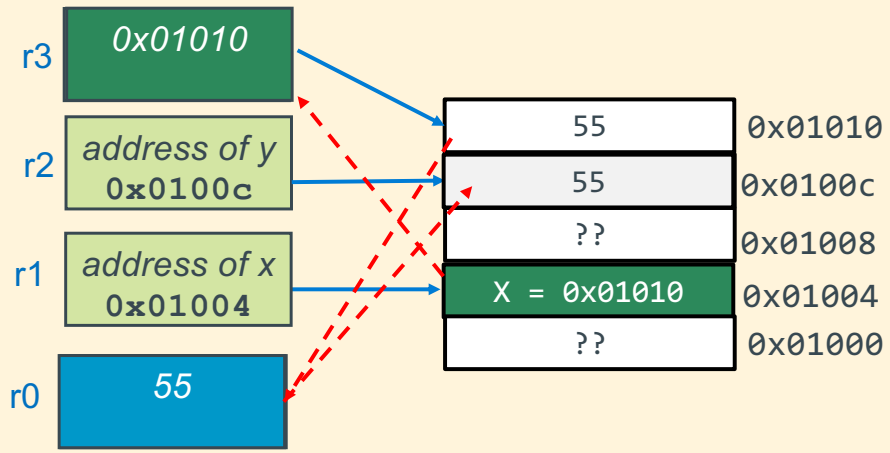

x

ldr/str practice - 2

r1 contains the Address of X (defined as int *X) in memory r1 points at X

r2 contains the Address of Y (defined as int Y) in memory; r2 points at Y

write Y = *X;




```
ldr   r3, [r1]  // r3 ← x (read 1)
ldr   r0, [r3]  // r0 ← *x (read 2)
str   r0, [r2]  // y ← *x
```


x

using ldr/str: array copy

```
#include <stdio.h>
#include <stdlib.h>
#define SZ 6

void icpy(int *, int *, int);

int main(void)
{
    int  src[SZ] = {1, 2, 3, 4, 5, 6};
    int  dst[SZ];

    icpy(src, dst, SZ);
    for (int i = 0; i < SZ; i++)
        printf("%d\n", *(dst + i));

    return EXIT_SUCCESS;
}
```

```
void icpy(int *src, int *dst, int cnt)
{
    for (int i = 0; i < cnt; i++)
        *dst++ = *src++;

    return;
}
```


x

Base Register version

```
    .arch armv6
    .arm
    .fpu vfp
    .syntax unified
    .text
    .global icpy
    .type   icpy, %function
    .equ    FP_OFF, 12

    // r0 contains int *src
    // r1 contains int *dst
    // r2 contains int cnt
    // r3 use as loop term pointer
    // r4 use as temp

icpy:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
// see right ->
    sub     sp, fp, FP_OFF
    pop     {r4, r5, fp, lr}
    bx      lr
    .size icpy, (. - icpy)
    .end
```

```
    cmp     r2, 0
    ble     .Ldone

    lsl     r2, r2, 2  //convert cnt to int size
    add     r3, r0, r2 // loop term pointer
.Ldo:
    ldr     r4, [r0]   // load from src
    str     r4, [r1]   // store to dest

    add     r0, r0, 4  // src++
    add     r1, r1, 4  // dst++

    cmp     r0, r3     // src < term pointer?
    blt     .Ldo

.Ldone:
```

pre loop guard

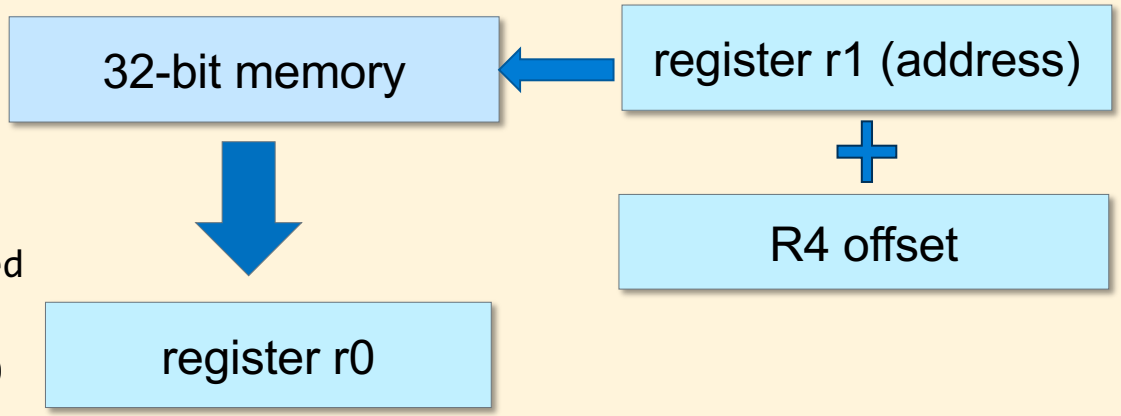
loop guard

x

Load/Store: Register Base Addressing + Register Offset

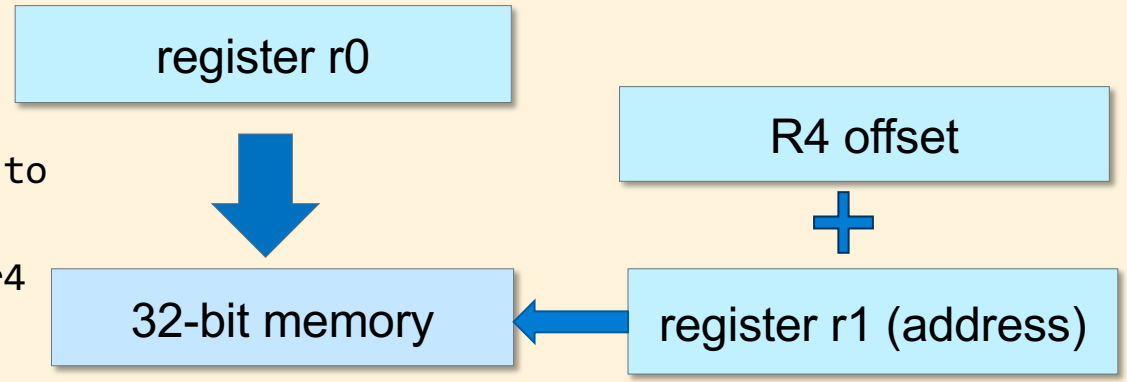
```
ldr r0, [r1, r4]
```

Copies a 32-bit word from the memory location whose address is contained in r1 + r4 (r1 is a pointer) into register r0




```
str   r0, [r1, r4]
```

Copies all 32 bits of the value held in register r0 to the 32-bit memory location contained in register r1+r4 (r1 pointer)



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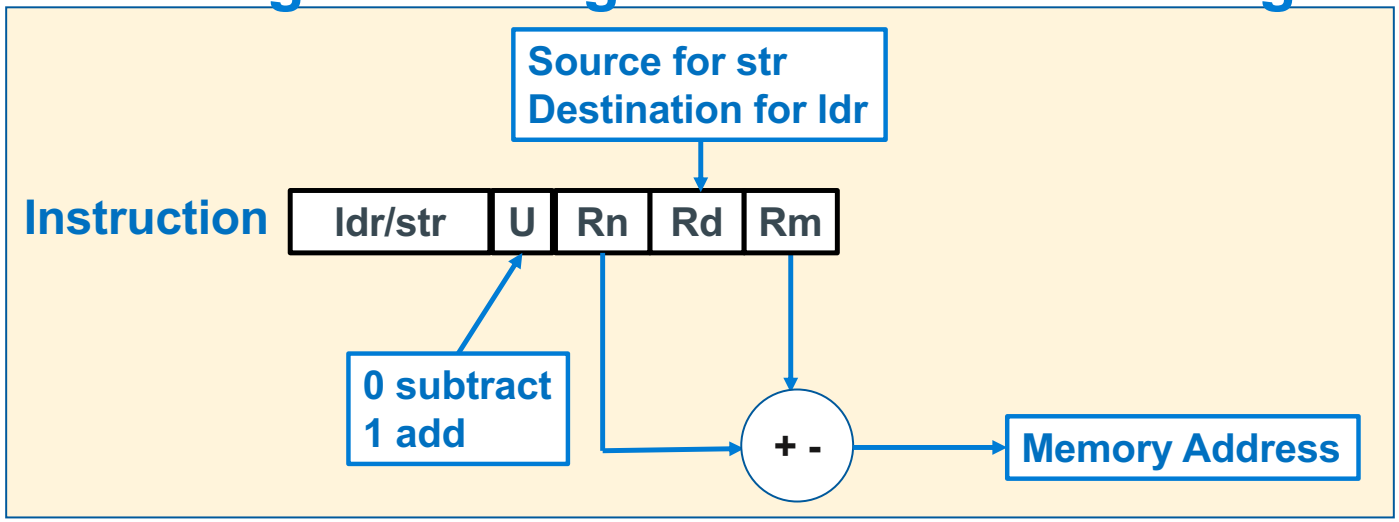
ldr/str Base Register + Register Offset Addressing



Pointer Address = Base Register + Register Offset

- **Unsigned** offset integer **in a register (bytes)** is either added/subtracted from the **pointer address** in the **base register**

Syntax	Address	Examples
`ldr/str Rd, [Rn +/- Rm ]`	`Rn + or – Rm`	`ldr r0, [r5, r4]` `str r1, [r5, r4]`

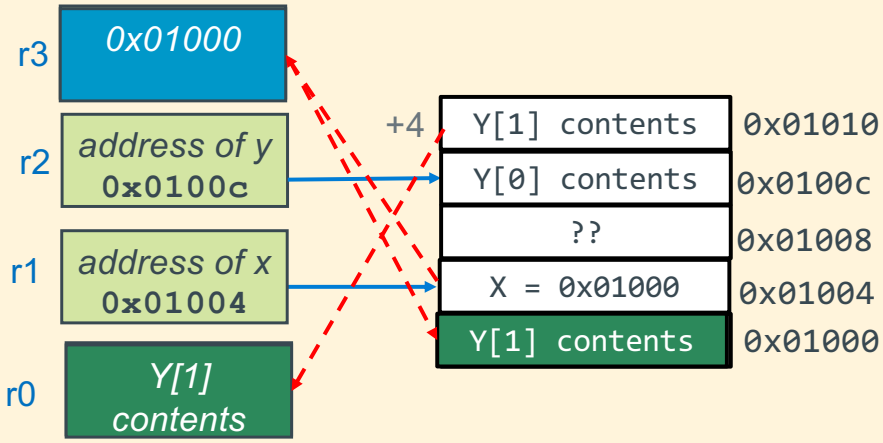
x

ldr/str practice - 3

r1 contains Address of X (defined as int *X) in memory; r1 points at X

r2 contains Address of Y (defined as int Y[2]) in memory; r2 points at &(Y[0])

write *X = Y[1];




```
ldr    r0, [r2, 4]        // r0 ← y[1]
ldr    r3, [r1]           // r3 ← x
str    r0, [r3]           // *x ← y[1]
```


x

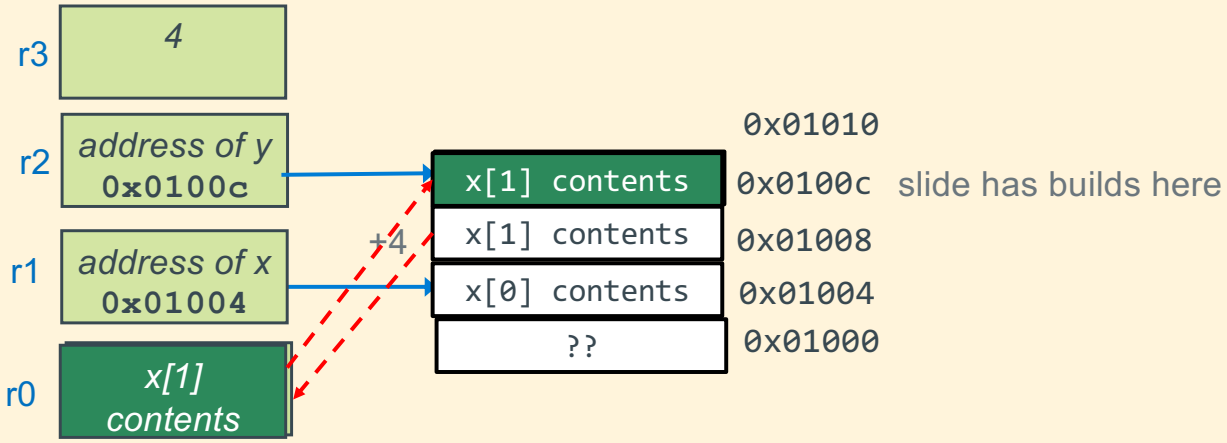
ldr/str practice - 4

r1 contains Address of X (defined as int X[2]) in memory; r1 points at &(x[0])

r2 contains Address of Y (defined as int Y) in memory; r2 points at Y

r3 contains a 4

write Y = X[1];



slide has builds here

```
ldr   r0, [r1, r3]  // r0 ← x[1]
str   r0, [r2]      // y ← x[1]
```


x

Base Register + Register Offset Version

```
    .arch armv6
    .arm
    .fpu vfp
    .syntax unified
    .text
    .global icpy
    .type   icpy, %function
    .equ    FP_OFF, 12
    // r0 contains int *src
    // r1 contains int *dst
    // r2 contains int cnt
    // r3 use as loop counter
    // r4 use as temp

icpy:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
// see right ->
    sub     sp, fp, FP_OFF
    pop     {r4, r5, fp, lr}
    bx      lr
    .size icpy, (. - cpy)
    .end
```

```
    cmp     r2, 0
    ble     .Ldone

    lsl     r2, r2, 2       //convert cnt to int size
    mov     r3, 0           // initialize counter
.Ldo:
    ldr     r4, [r0, r3]    // load from src
    str     r4, [r1, r3]    // store to dest
    add     r3, r3, 4       // counter++
    cmp     r3, r2          // count < r3
    blt     .Ldo

.Ldone:
```

pre loop guard

loop guard

one increment
covers both arrays

x

Base Register + Register Offset With chars

```
#include <stdio.h>
#include <stdlib.h>
#define SZ 6
void cpy(char *, char *, int);
int main(void)
{
    char src[SZ] =
       {'a', 'b', 'c', 'd', 'e', '\0'};
    char dst[SZ];


    cpy(src, dst, SZ);
    printf("%s\n", dst);
    return EXIT_SUCCESS;
}
```

```
    cmp     r2, 0
    ble     .Ldone

    mov     r3, 0           // initialize counter
.Ldo:
    ldrb     r4, [r0, r3]   // load from src
    strb     r4, [r1, r3]   // store to dest
    add     r3, r3, 1       // counter++
    cmp     r3, r2          // count < r3
    blt     .Ldo

.Ldone:
```


x

Reference: Addressing Mode Summary for use in CSE30

index Type	Example	Description
Pre-index immediate	ldr r1, [r0]	r1 ← memory[r0] r0 is unchanged
Pre-index immediate	ldr r1, [r0, 4]	r1 ← memory[r0 + 4] r0 is unchanged
Pre-index immediate	str r1, [r0]	memory[r0] ← r1 r0 is unchanged
Pre-index immediate	str r1, [r0, 4]	memory[r0 + 4] ← r1 r0 is unchanged
Pre-index register	ldr r1, [r0, +-r2]	r1 ← memory[r0 +- r2] r0 is unchanged
Pre-index register	str r1, [r0, +-r2]	memory[r0 +- r2] ← r1 r0 is unchanged

x

Variable Alignment In Memory and Performance

Accessing **address aligned** memory on many systems based on data type has the best performance (due to hardware implementation)

char

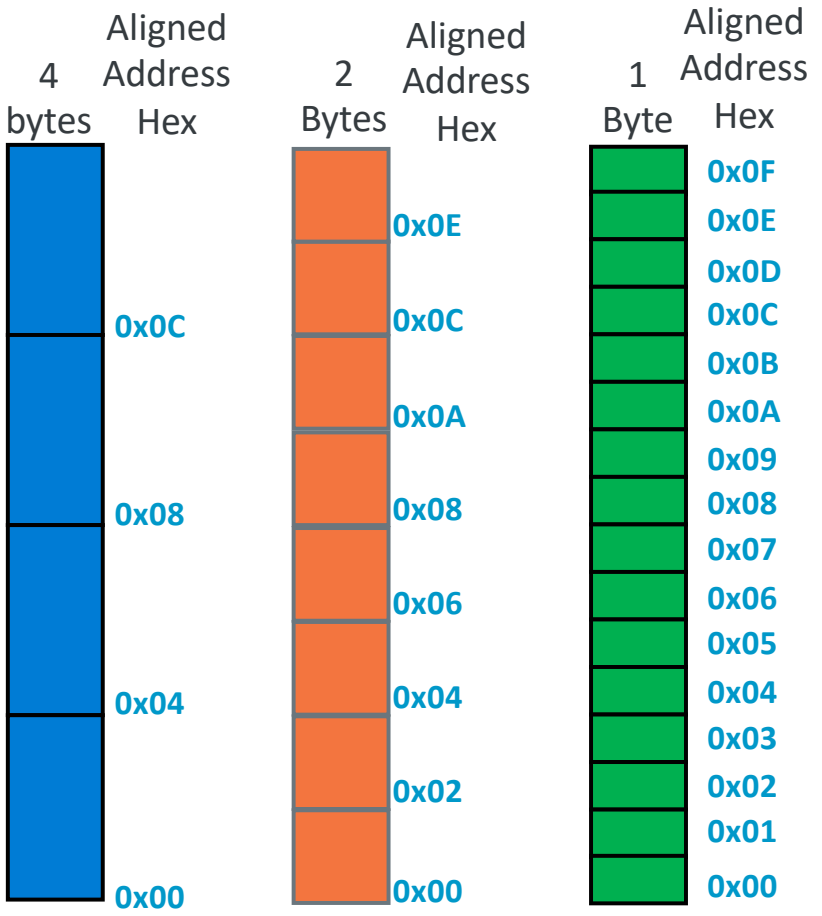
1 any address

short

2 bytes addresses that end in 0b0

integer

4 bytes addresses that end in 0b00



x

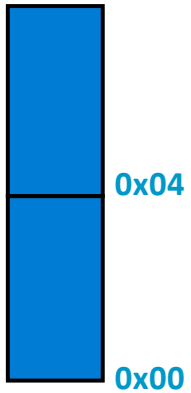
Defining Static Variables: Allocation and Initialization

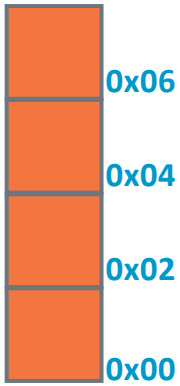
Variable SIZE	Directive	.align	C static variable Definition	Assembler static variable Definition
8-bit char (1 byte)	.byte		char chx = 'A' char string[] = {'A','B','C', 0};	chx: .byte 'A' string: .byte 'A','B',0x42,0
16-bit int (2 bytes)	.short	1	short length = 0x55aa;	length: .short 0x55aa

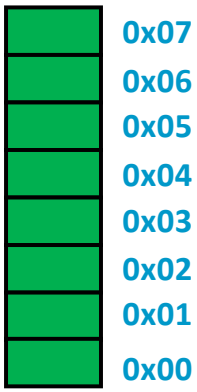
32-bit int
(4 bytes)
	.word
	.long
		2	int dist = 5;
			int *distptr = &dist;
			unsigned int mask = 0xaa55aa55;
			int array[] = {12,~0x1,0xCD,-1};
				dist: .word 5
				distptr: .word dist
				mask: .word 0xff
				array: .word 12,~0x1,0xCD,-3

string with '\0'	.string		char class[] = "cse30";	class: .string "cse30"

SIZE	Address ends in	Align
8-bit char -1 byte	0b..0 or 0b..1	
16-bit int -2 bytes	0b..0	.align 1
32-bit int -4 bytes and all arrays	0b..00	.align 2







x

Defining Static Variables: Allocation and Initialization

```
    .data
chx:    .byte 'A'
cnt:    .word 4
```

```
00012028 <chx>:
  12028:  00000041

00012029 <cnt>:
  12029: 00000004
```

```
    .data
chx:    .byte 'A'
    .align 2
cnt:    .word 4
```

```
00012028 <chx>:
  12028:  00000041

0001202c <cnt>:
  1202c: 00000004
```

```
int num;            //4 bytes
int *ptr = &num;    //4 bytes
char *lit = "456";  //4 bytes,"456" string literal
char msg[] = "123"; //4 bytes – array
```

```
.bss

num:        .word 0

.data
            .align 2
ptr:        .word num
            .align 2
lit:        .word .Lmsg
            .align 2
msg:        .string "123"

.section .rodata
.Lmsg:      .string "456"
```

Optional

initializes a pointer

Sets alignment for **next** variable

read-only string literal

x

Defining Static Array Variables

```
Label:   .size_directive expression, … expression
```

```
In C:       int int_buf[100];
            int array[] = {1, 2, 3, 4, 5};
            char buffer[100];
```

```
.bss
int_buf:    .space 400    // convert 100 to 400 bytes
             .align 2
char_buf:   .space 100
.data
array:      .word 1, 2, 3, 4, 5
            .align 2
one_buf:    .space 100, 1      // 100 bytes each byte filled with 1
```

`.space size, fill`

- Allocates **`size`** bytes, each of which contain the value **`fill`**
- Both **`size`** and **`fill`** are absolute expressions
- If the comma and **`fill`** are **omitted**, **`fill`** is assumed to be **zero**
- **`.bss section:`** Must be used **without a specified fill**

x

Loading Static variable address and contents into a register

- Tell the assembler load the address (Lvalue) of a label into a register:

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

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

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

```
        .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
…
```

x

Loading large Constants into a register:

Error: invalid constant (3ff) after fixup

- In data processing instructions, the field **imm8 + rotate 4 bits** is too small to store store the immediate value, how do you get larger immediate values into a register?

fails ➡ `mov r0, 1023`

xxx.s:24: Error: invalid constant (3ff) after fixup

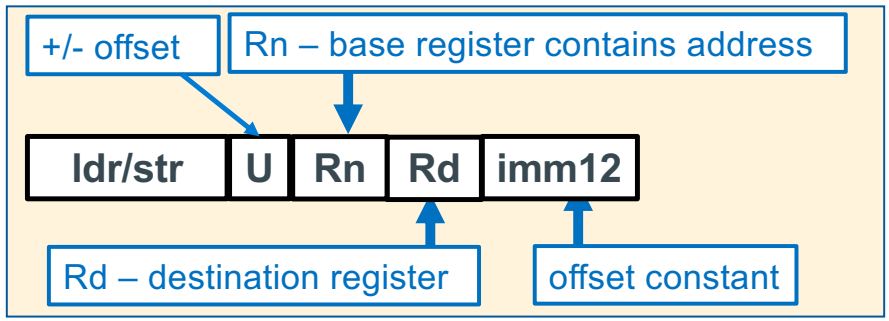
replacement ➡ `ldr r0, =1023`

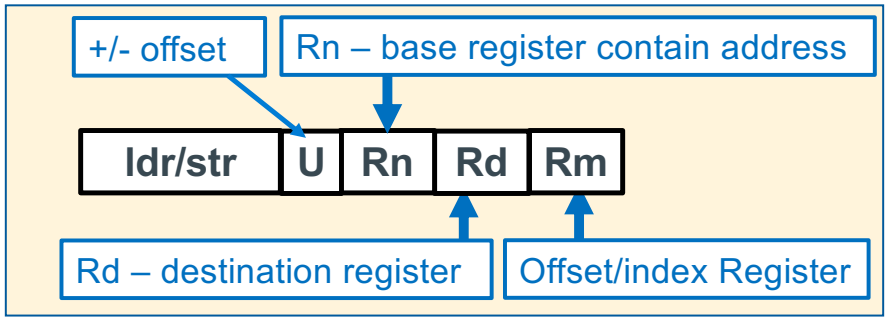
- Answer: use **`ldr`** instruction with the constant as an operand: **`=constant`**
- Assembler creates a **literal table entry** with the **constant**

```
ldr  Rd, =constant       // =constant
ldr  r1, =0x2468abcd     // loads the constant 0x246abcd into r1
```


x

LDR/STR – Register To/From Memory Copy






```
ldr/str  Rd,  [Rn, +- imm12] // base register pointer + offset  imm12 in bytes
                             -4095 <= imm12 <= 4095 (bytes)
ldr/str  Rd,  [Rn]           // base register pointer + 0 (imm12 is 0)
ldr/str  Rd,  [Rn, +- Rm]    // base register pointer +- offset register
```

```
ldr         r1, =var_x          // r1 = &var_x
str         r1, =mylabel+4      // *(mylabel+4) = r1
ldr         r1, =0x246abcd      // load an immediate into r1
ldr         r1, [r3]           // y = *r3 (4 bytes)
str         r1, [r0]           // *r0 = r1
ldr         r1, [r3, -4]       // y = *(r3 – 4) (4 bytes)
str         r1, [r0, r2]       // *(r0 + r2) = r1
```


x

Function Calls, Parameters and Locals: Requirements

```
int
main(int argc, char *argv[])
{
    int x, z = 4;

    x = a(z);
    z = b(z);
    return EXIT_SUCCESS;
}

int
a(int n)
{
    int i = 0;
    if (n == 1)
        i = b(n);
    return i;
}

int
b(int m)
{
    return m+1;
/* the return cannot be done with a
   branch */
}
```

- Since b() is called both by main and a() how does the **return m+1 statement in b() know where to return to? (Obviously, it cannot be a branch)**
- Where are the parameters (args) to a function stored so the function has a copy that it can alter?
- Where is the return value from a function call stored?
- How are Automatic variables *lifetime* and *scope* **implemented**?
  - When you enter a variables scope: memory is allocated for the variables
  - When you leave a variable scope: memory lifetime is ended (memory can be reused -- deallocated) – contents are **no longer valid**

x

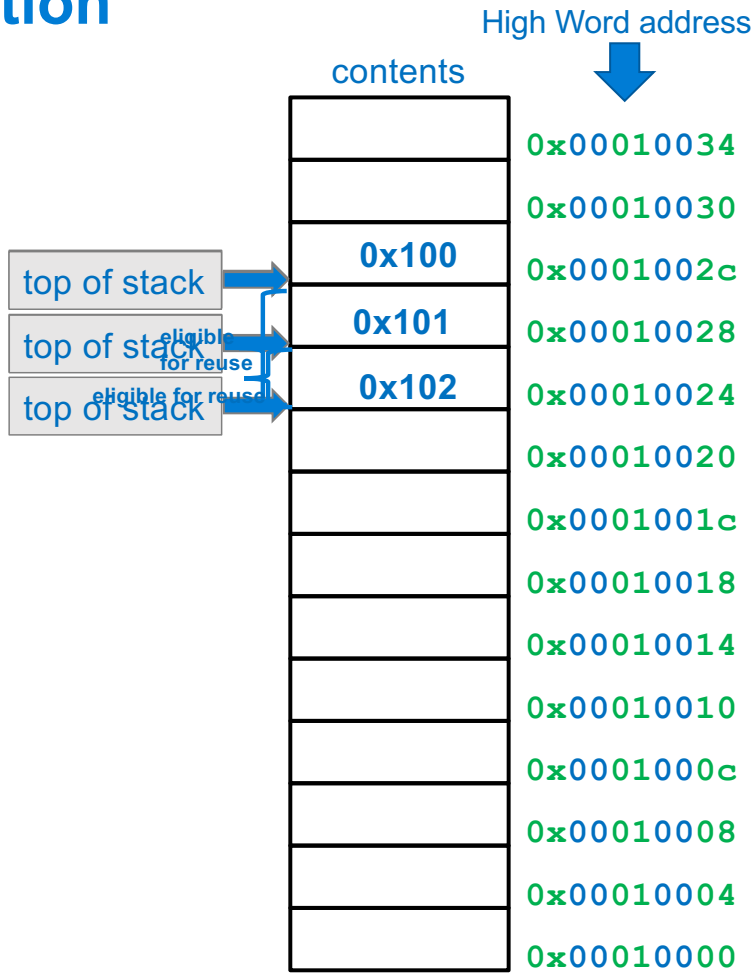
Data Structure Review: Stack Operation

- A Stack Implements a **last-in first-out** (LIFO) protocol
- **Stacks** are expandable and **grow downward** from high memory address towards low memory address
- **Stack pointer always** points at the **top of stack**
  - contains the **starting address** of the **top element**
- New items are pushed (*added*) onto the **top of the stack** by subtracting from the stack pointer the size of the element and then writing the element

  push (sp - element size) & write

- Existing items are popped (*removed*) from the top of the stack by adding to the stack pointer the size of the element (leaving the ***old contents unchanged***)

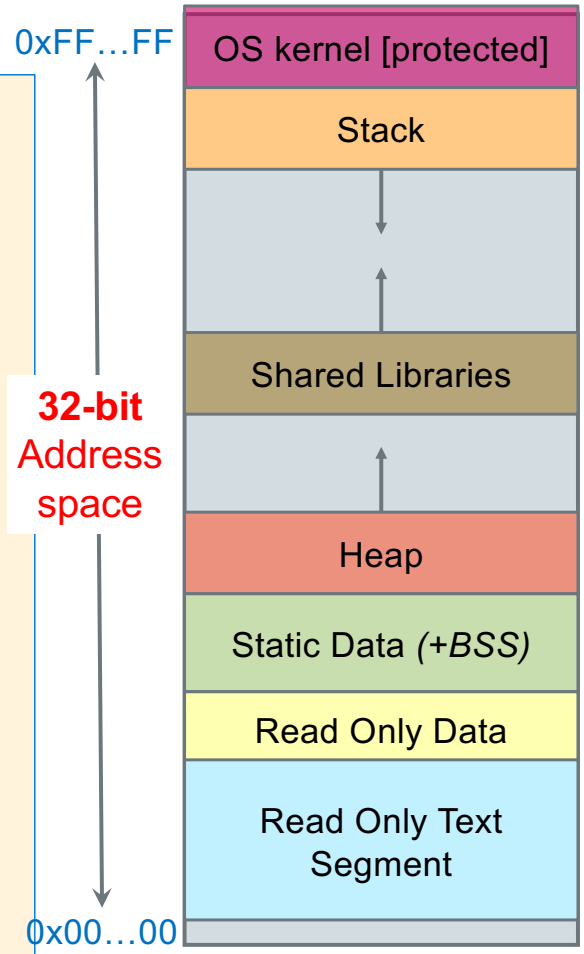
  pop (sp + element size)



x

Stack Segment: Support of Functions

- The stack consists of a series of *"stack frames"* or *"activation frames"*, one is created each time a function is called at runtime
- Each frame represents a function that is currently being executed and has not yet completed (why activation frame)
- A function's stack "frame" goes away when the function returns
- Specifically, a new stack frame is
  - allocated (**pushed** on the stack) for each function call (contents are not implicitly zeroed)
  - deallocated (**popped** from the stack) on function return
- Stack frame contains:
  - Local variables, parameters of function called
  - Where to return to which caller when the function completes (the return address)

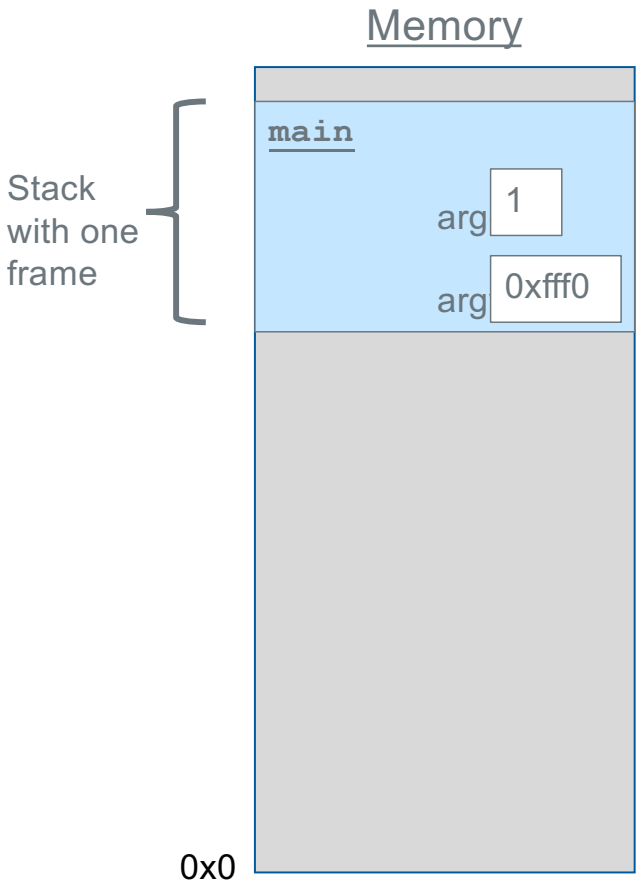


The Stack

```
void func2() {
    int d = 0;
}

void func1() {
    int c = 99;
    func2();
}

int main(int argc, char *argv[]) {
    int a = 42;
    int b = 17;
    func1();
    printf("Done.");
    return 0;
}
```



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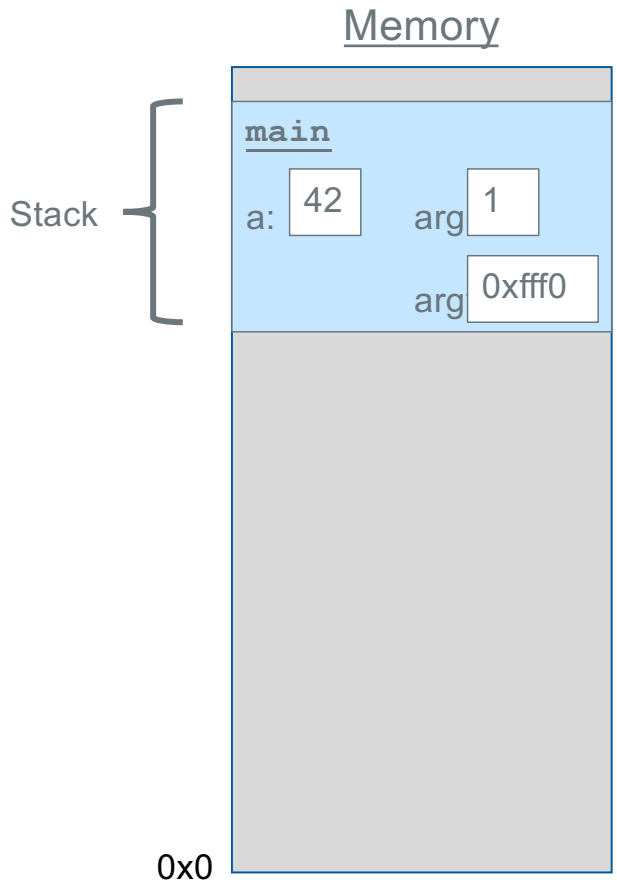

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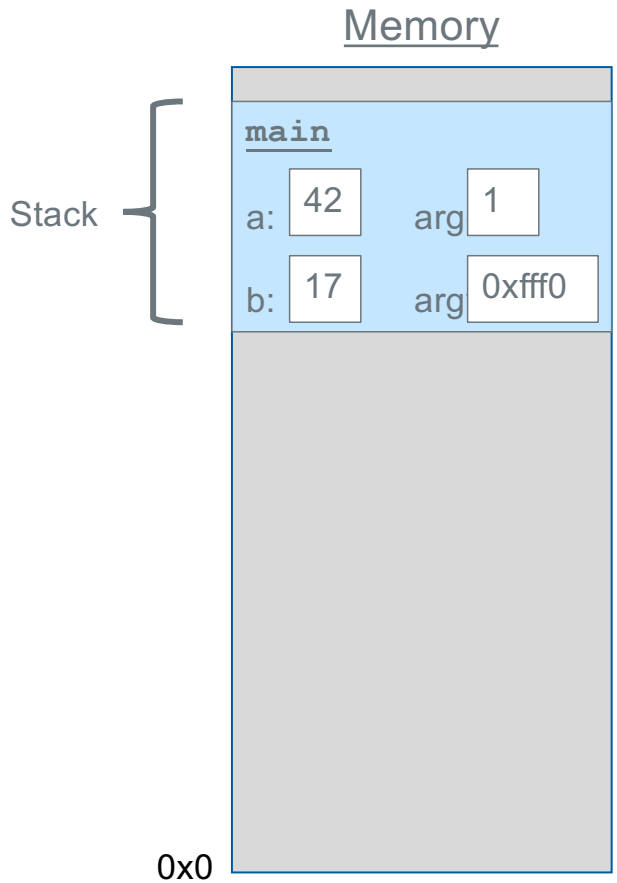

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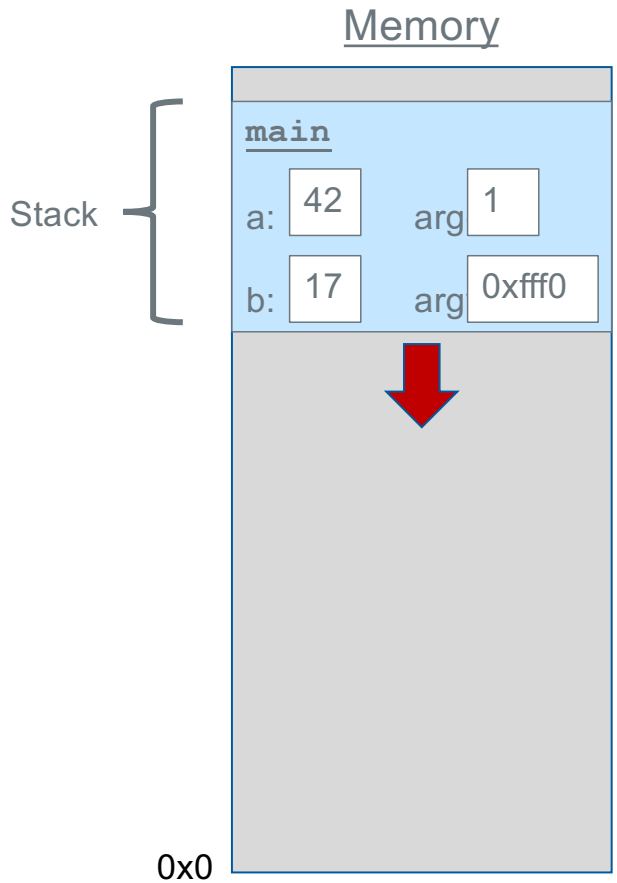

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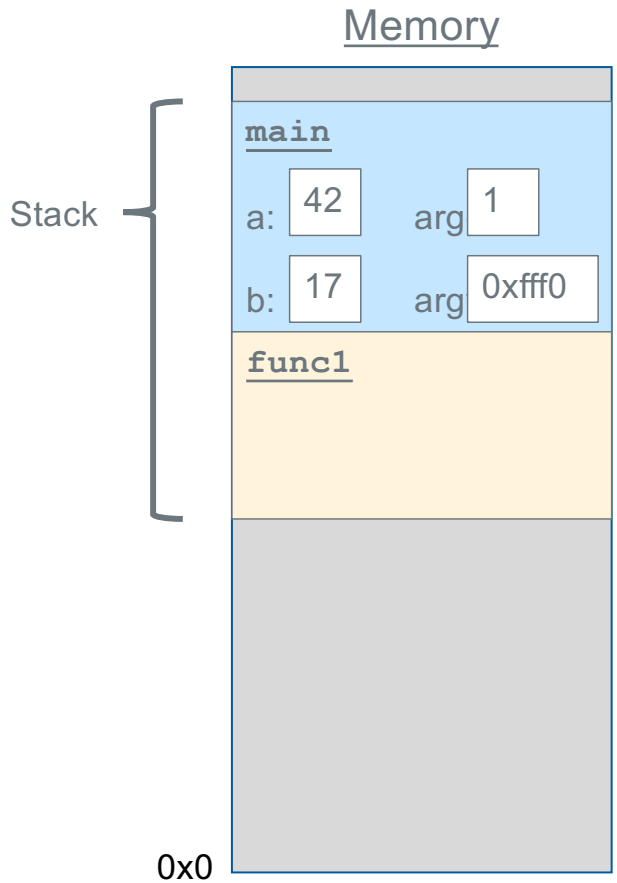

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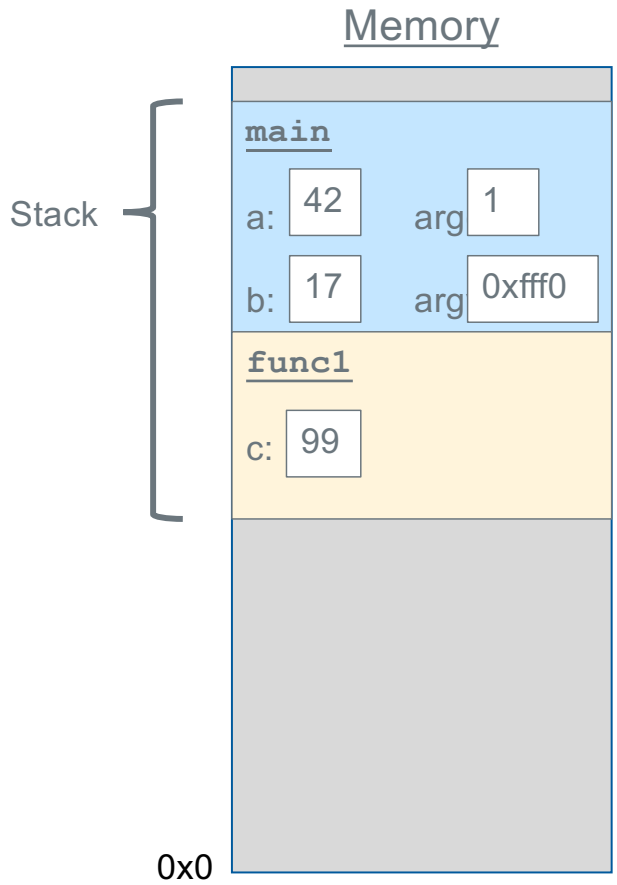

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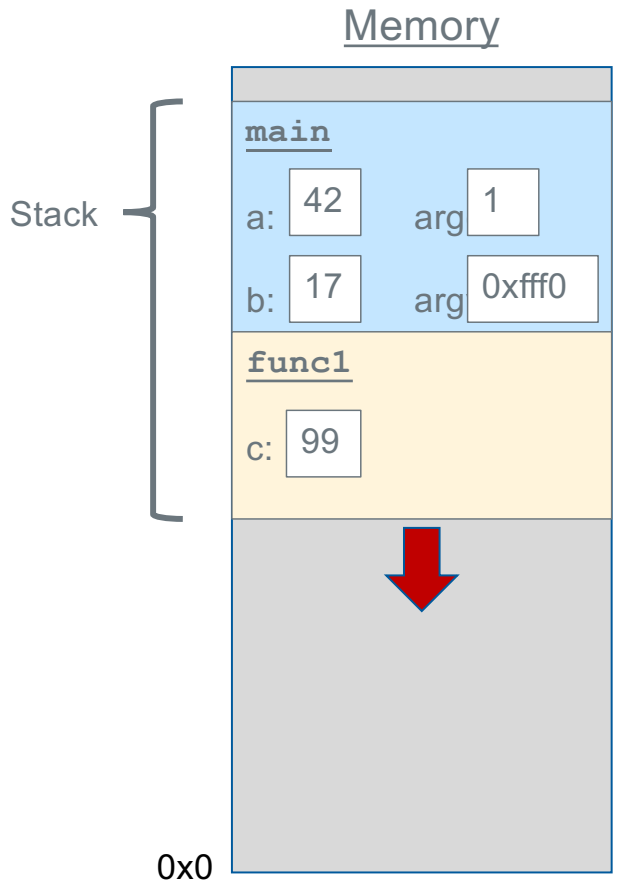

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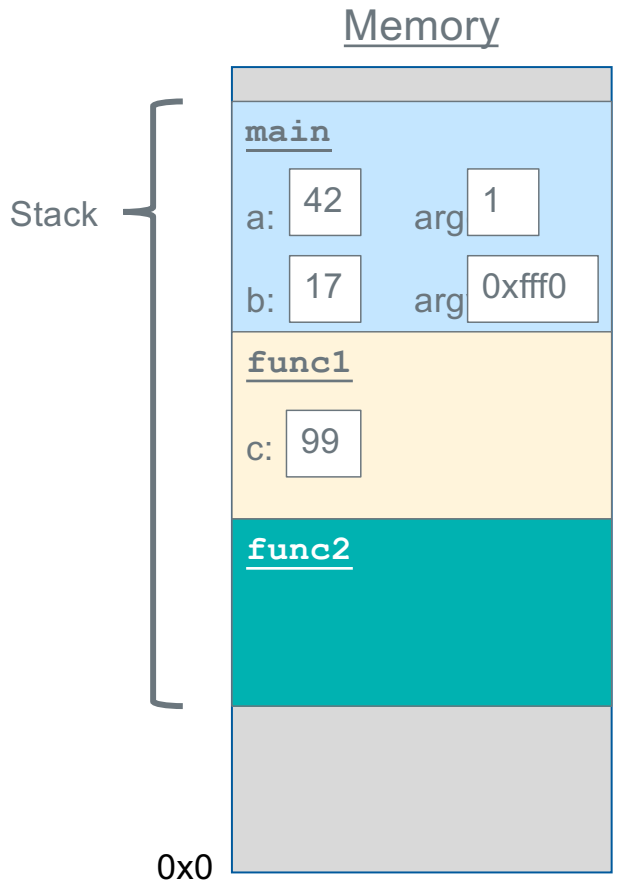

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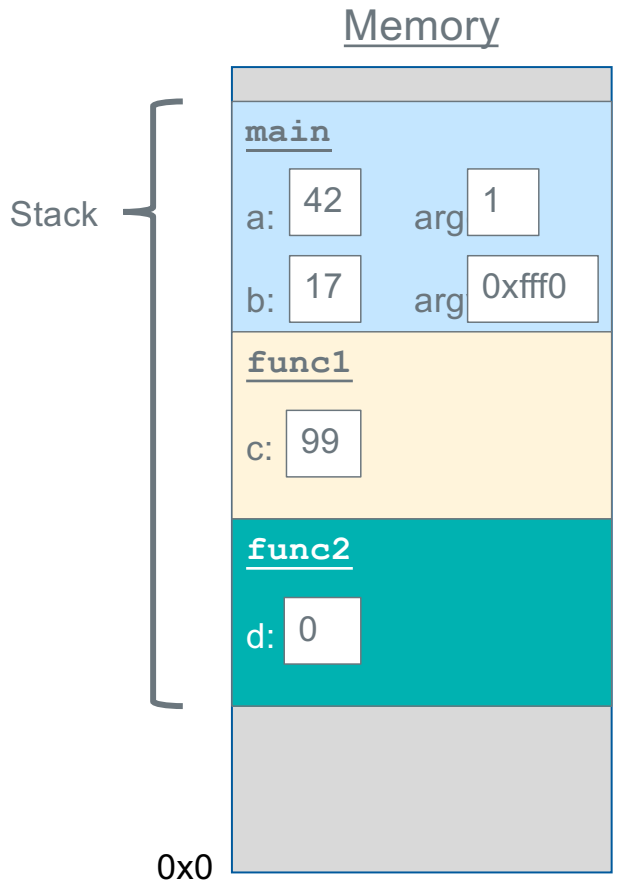

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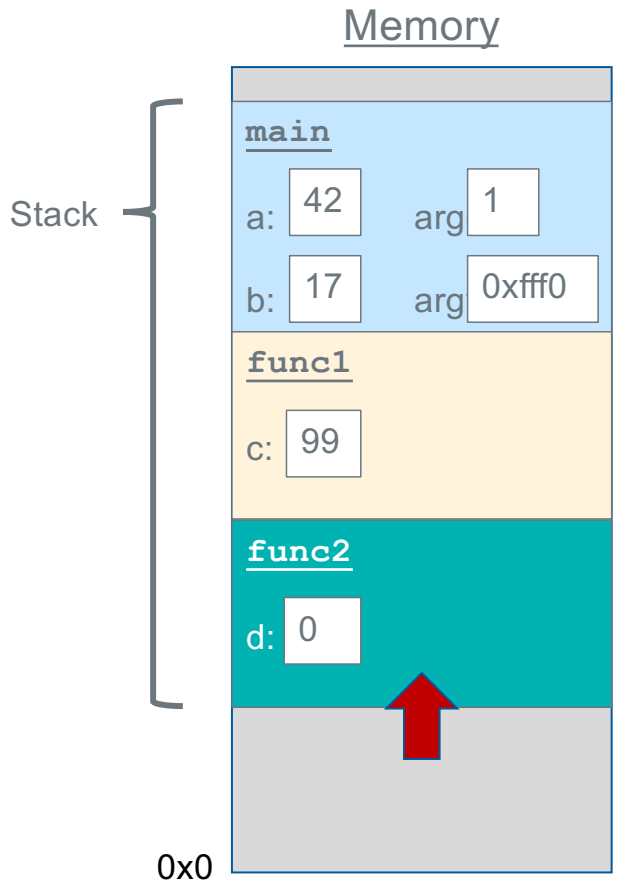

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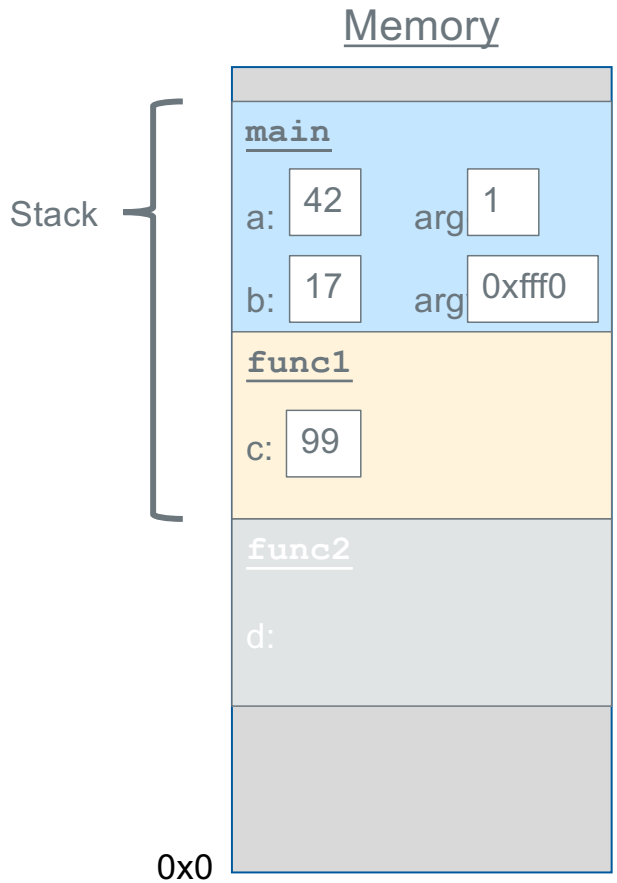
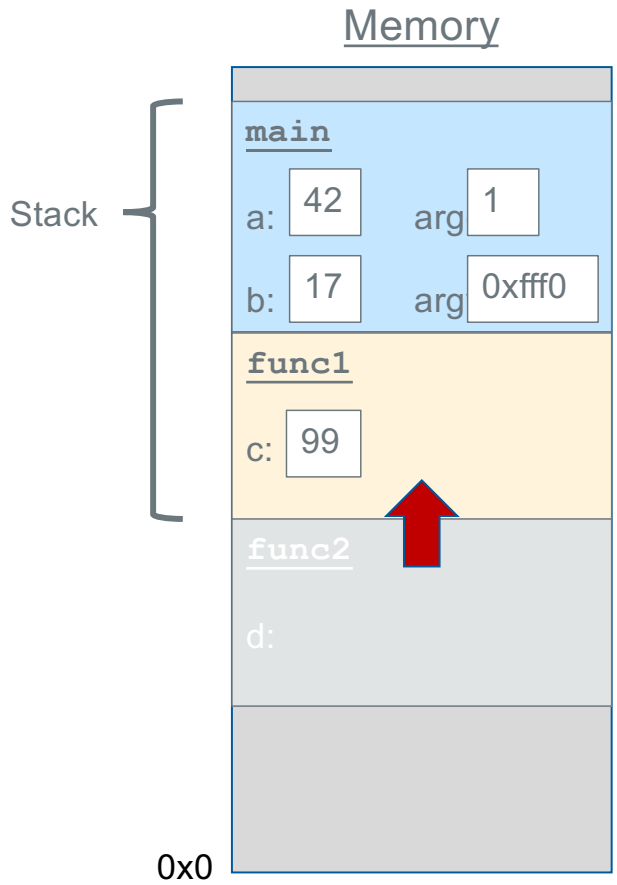


The Stack

```
void func2() {
    int d = 0;
}

void func1() {
    int c = 99;
    func2();
}

int main(int argc, char *argv[]) {
    int a = 42;
    int b = 17;
    func1();
    printf("Done.");
    return 0;
}
```



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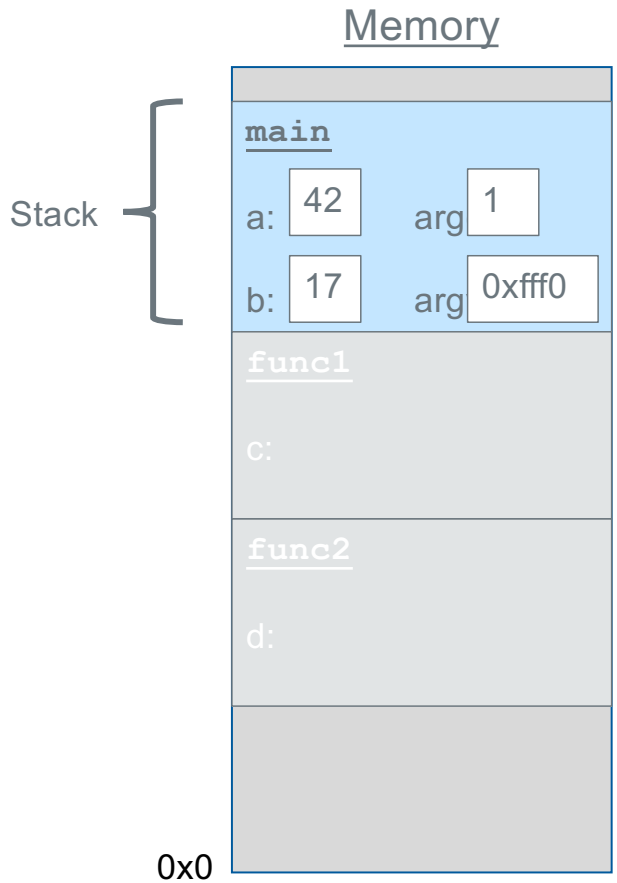

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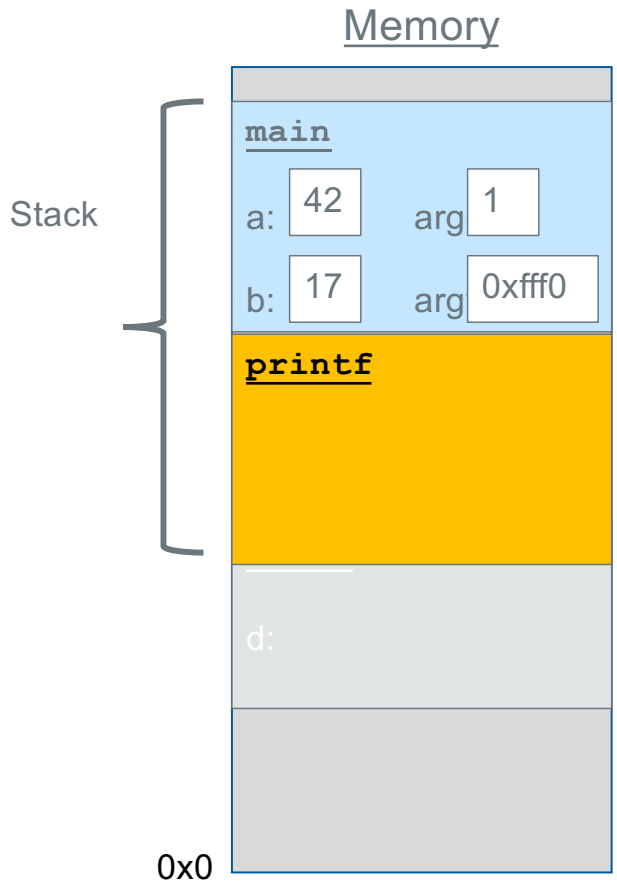

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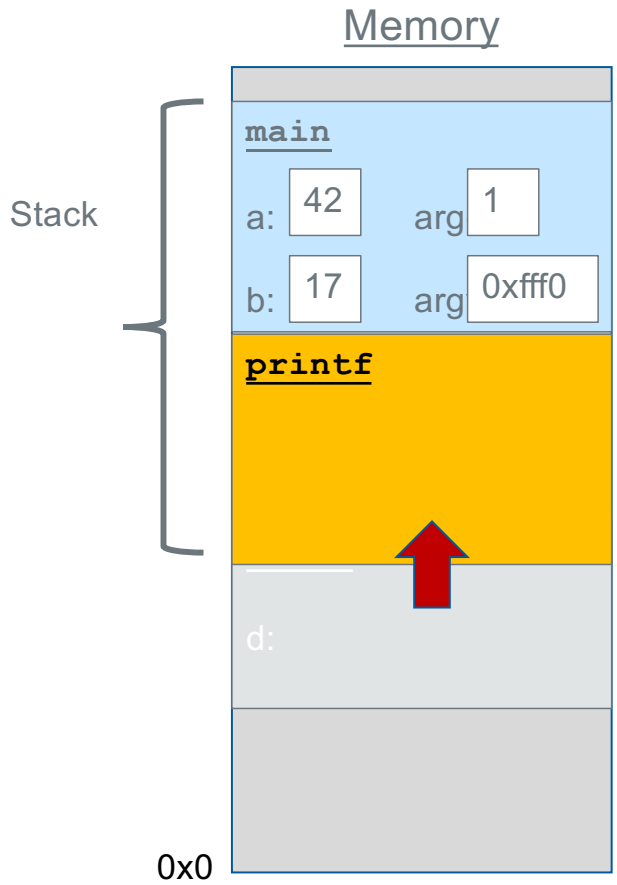

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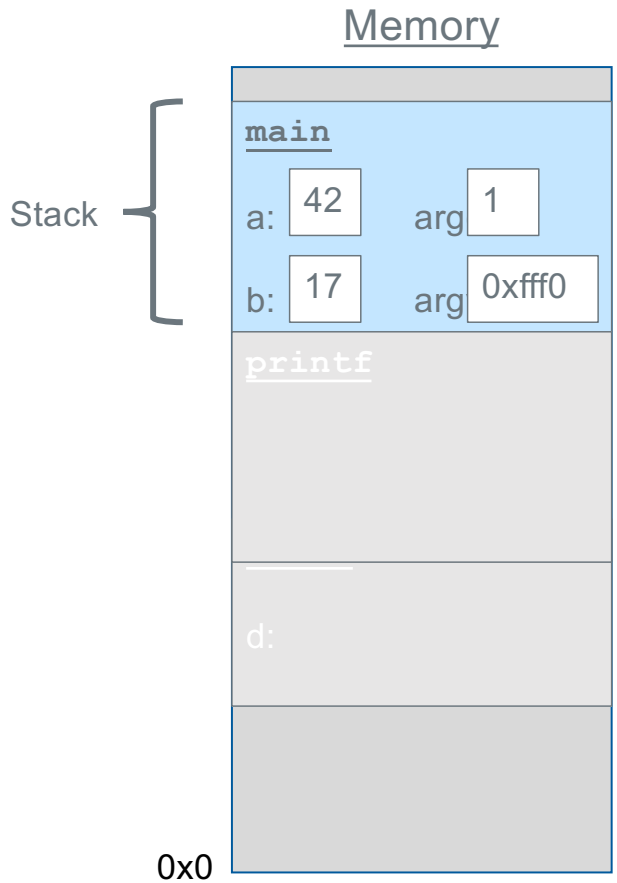

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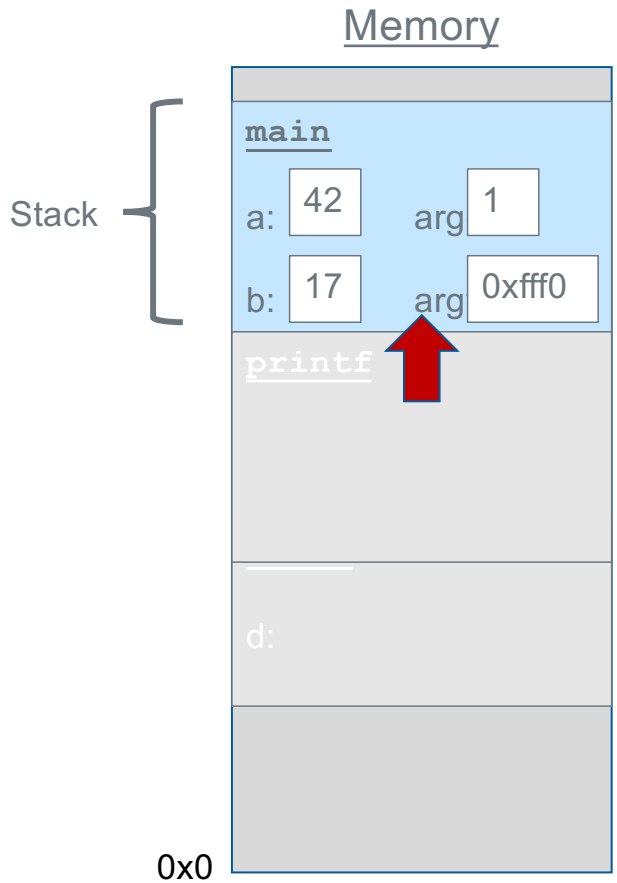

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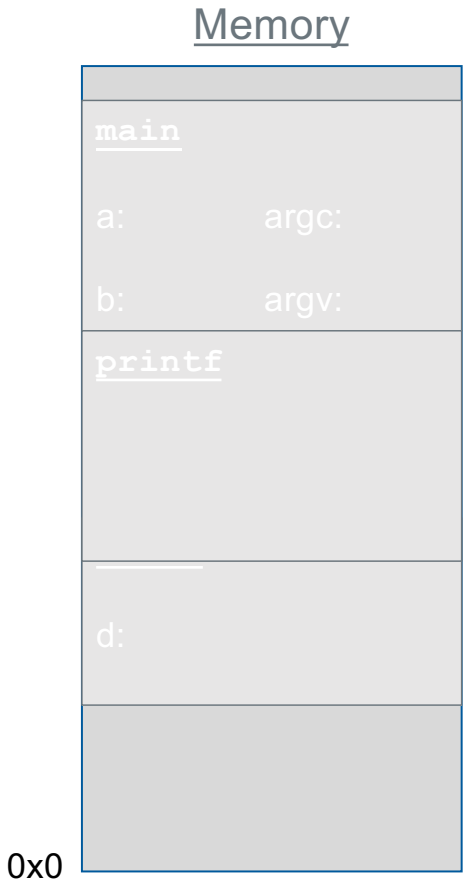
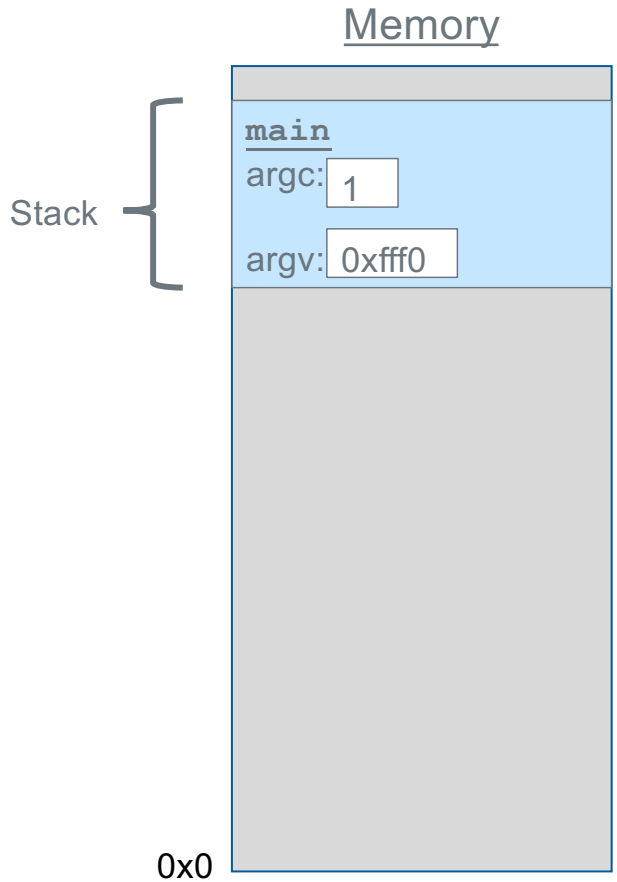


The Stack - Recursion

Each function **call** has its own *stack frame* for its own copy of variables

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

int main(int argc, char *argv[]) {
    printf("%d", factorial(4));
    return 0;
}
```



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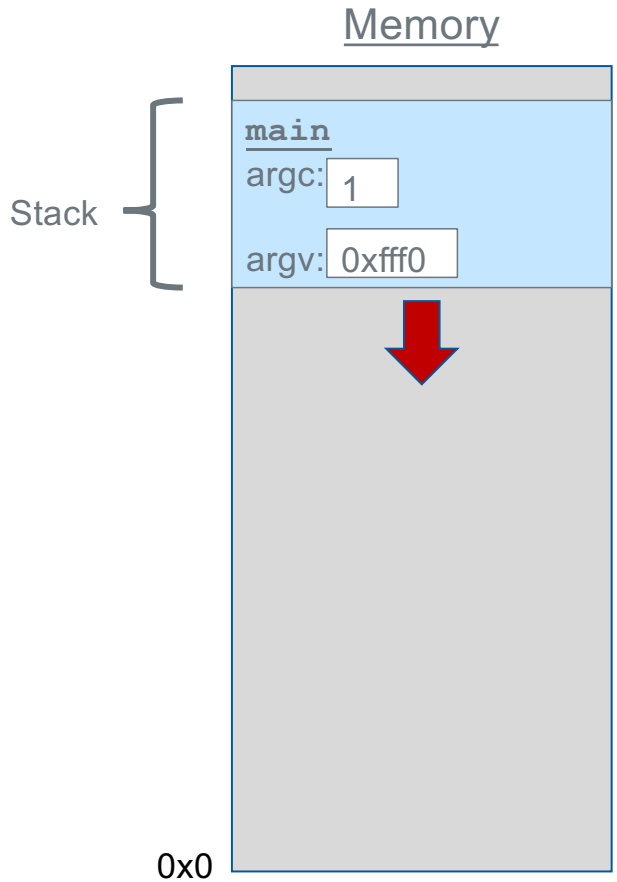

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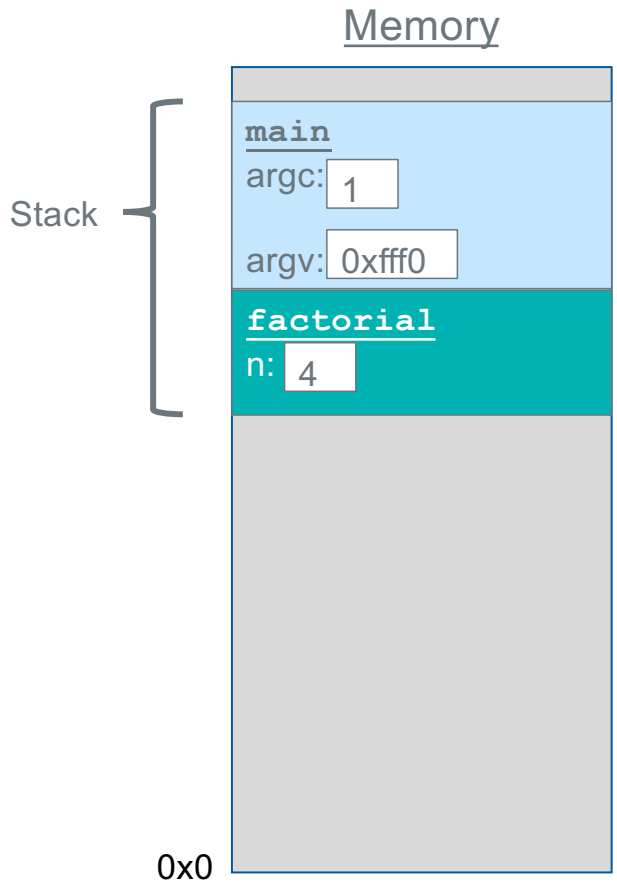

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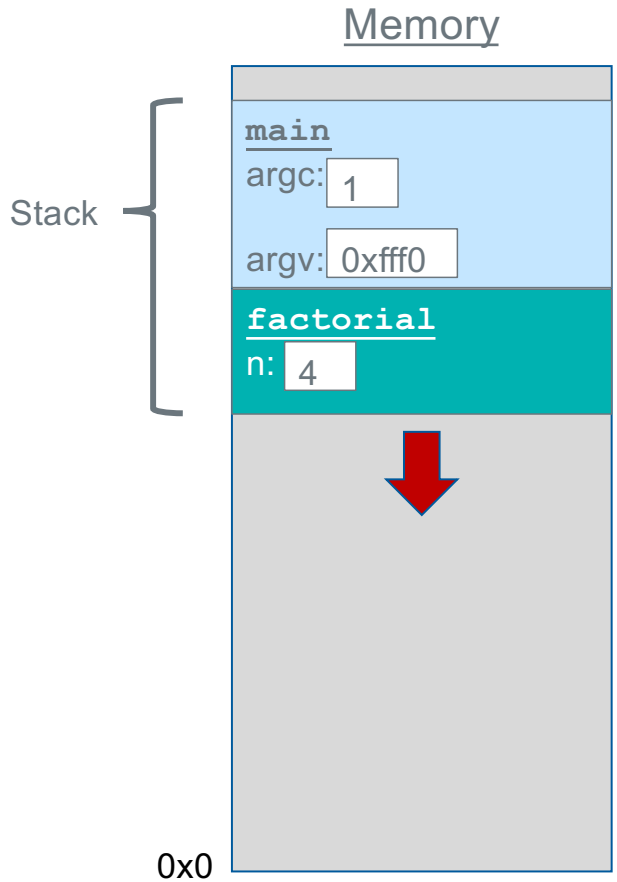

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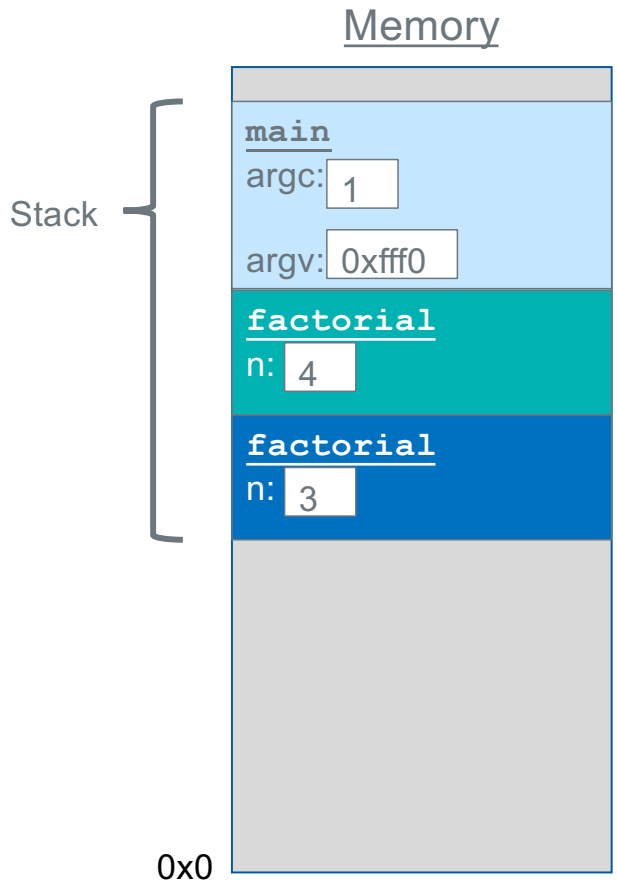

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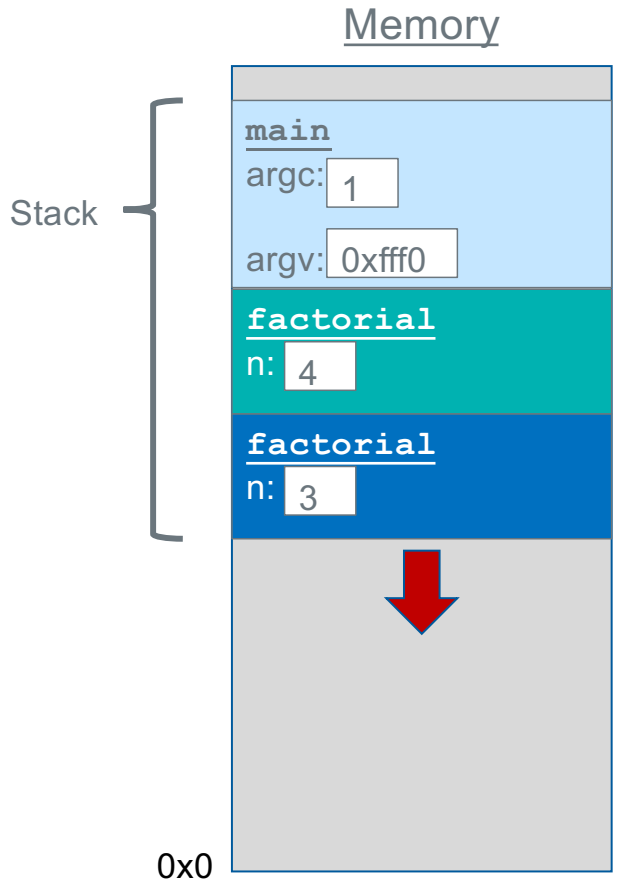

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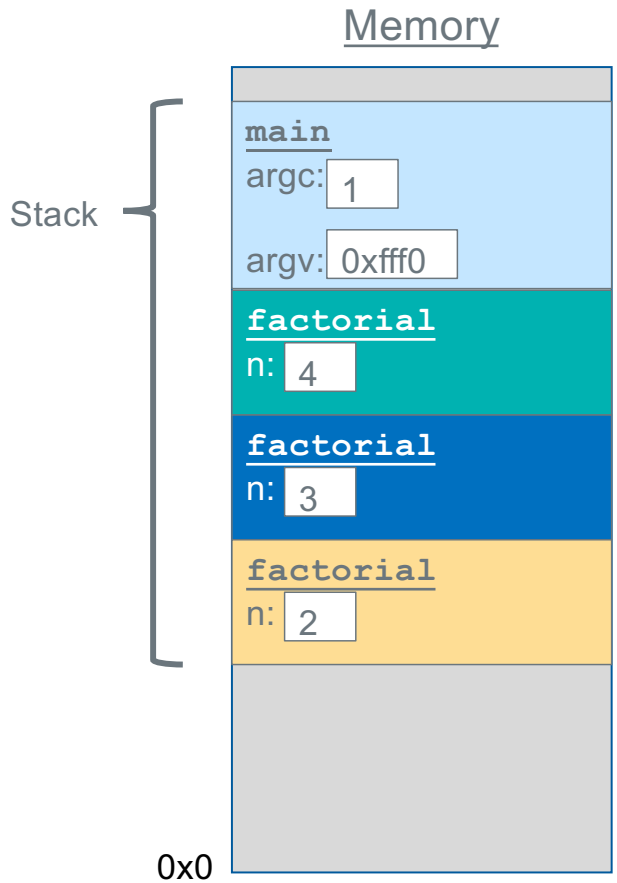

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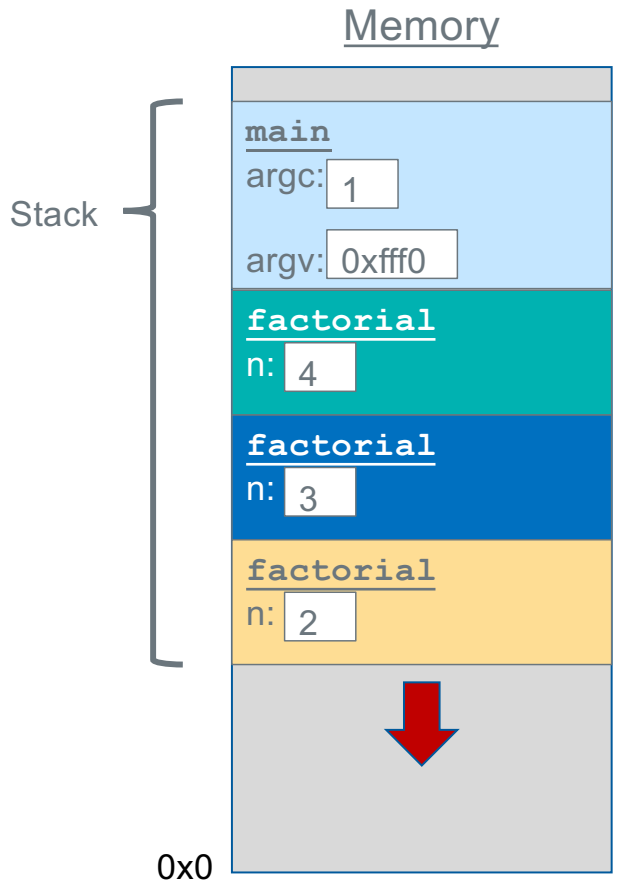

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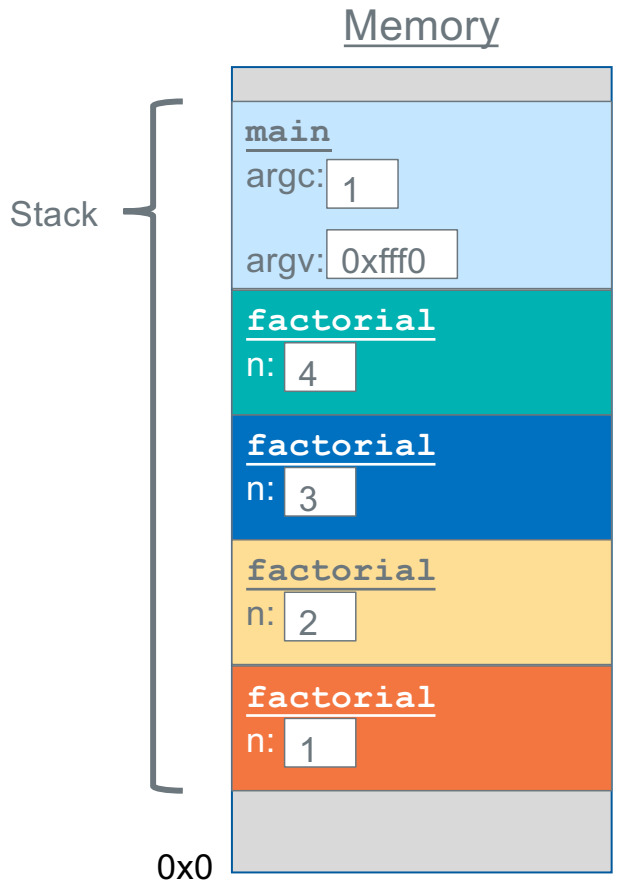

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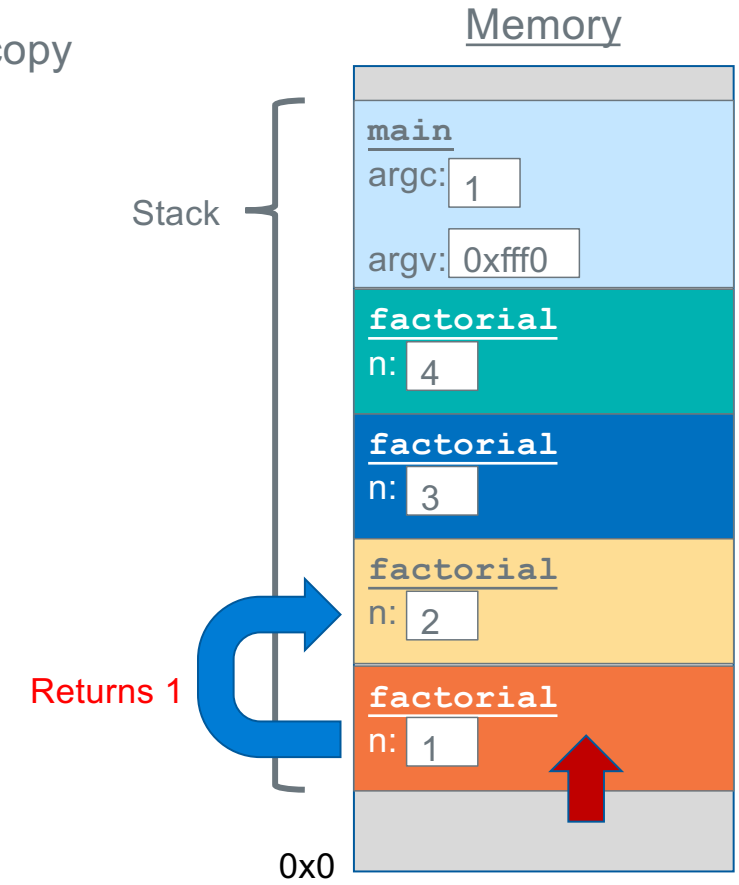

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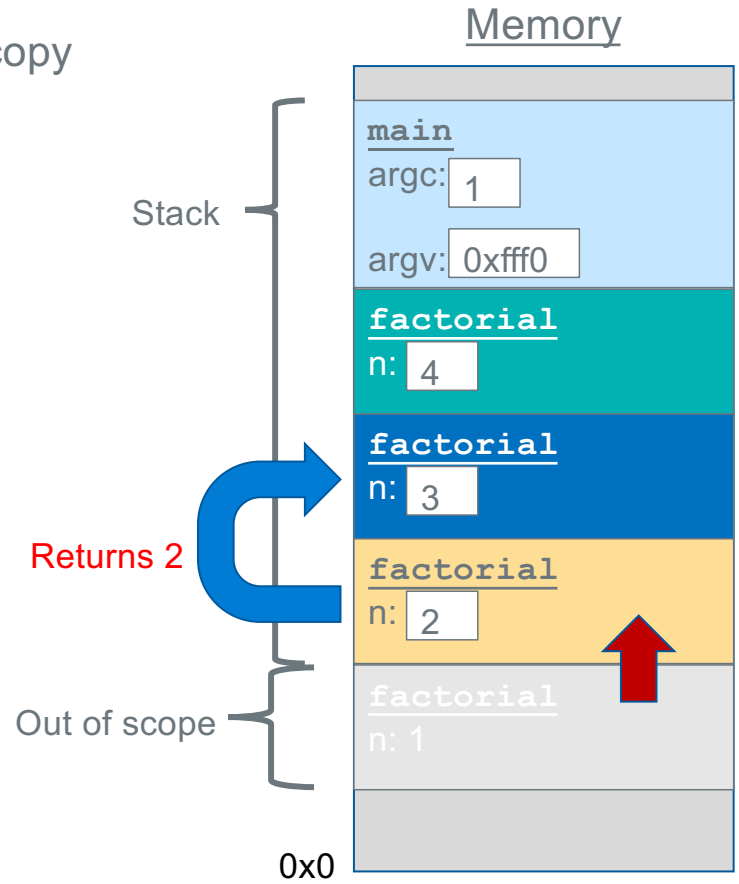

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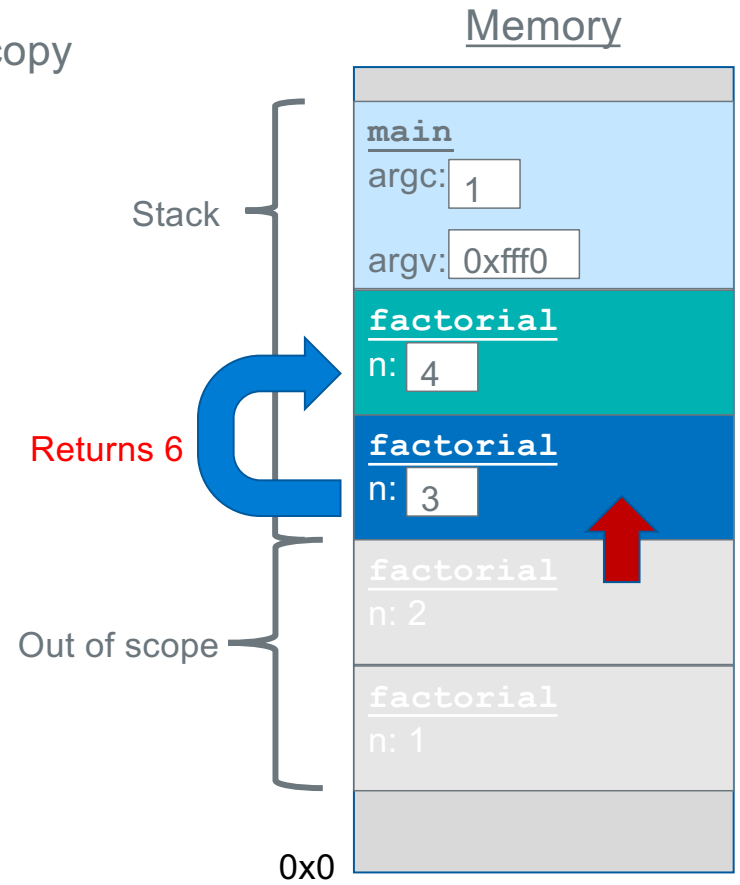

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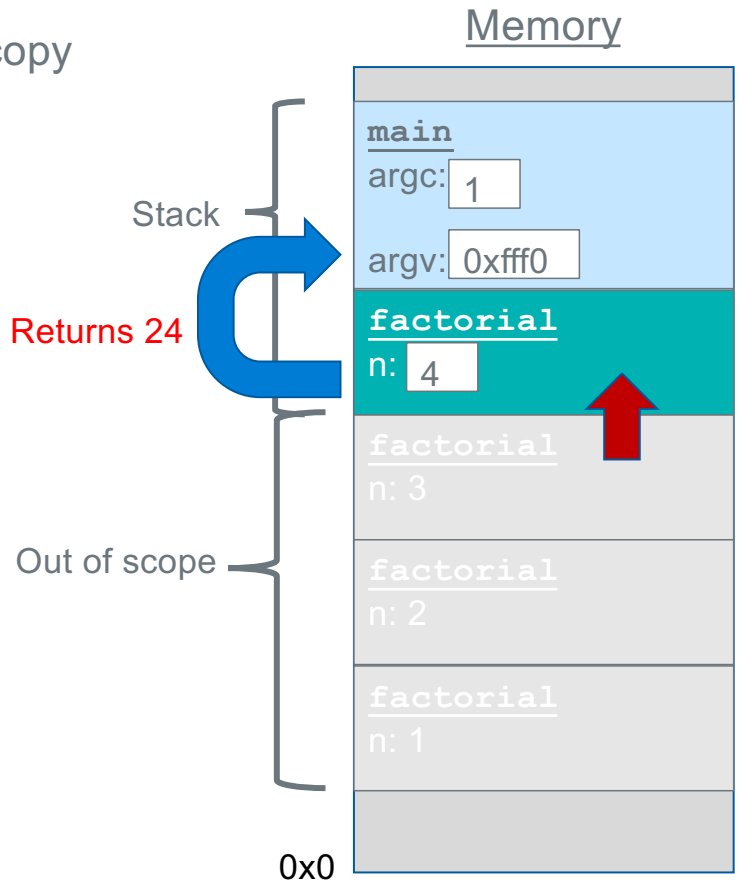

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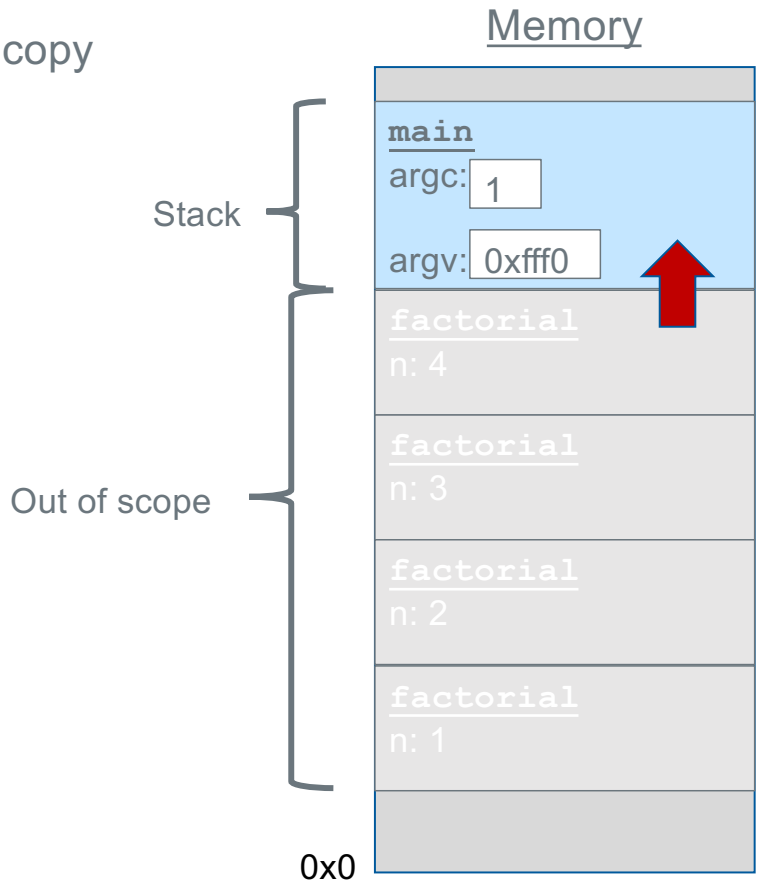

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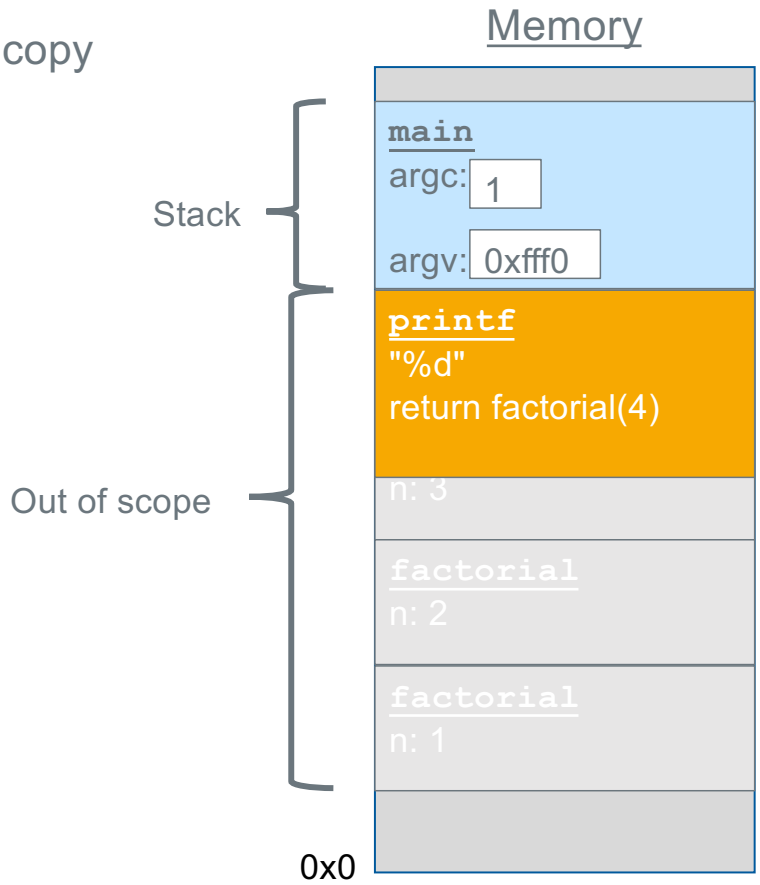


Function Calls

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

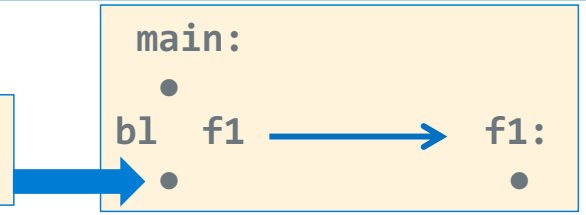
Branch with Link Indirect (function call) instruction

```
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



x

Function Call Return

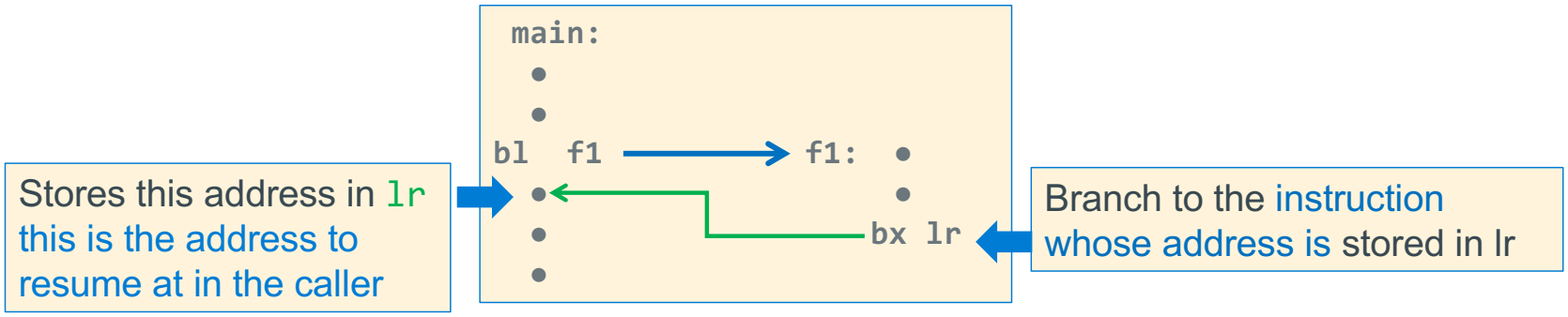
Branch & exchange (function return) instruction

```
bx lr
```

bx	Rn

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

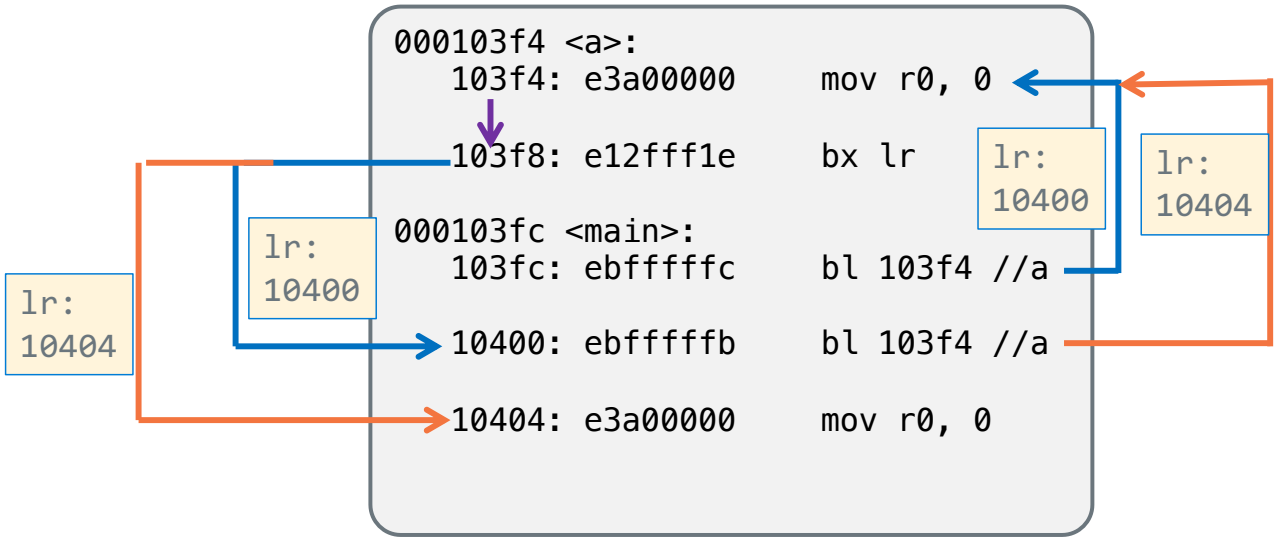
- Causes a branch to the instruction **whose address is stored** in register <`lr`>
  - It copies `lr` to the PC
- This is often used to implement a return from a function call (exactly like a C return) when the function is called using either `bl label, or blx Rm`



x

bl and bx operation working not together

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

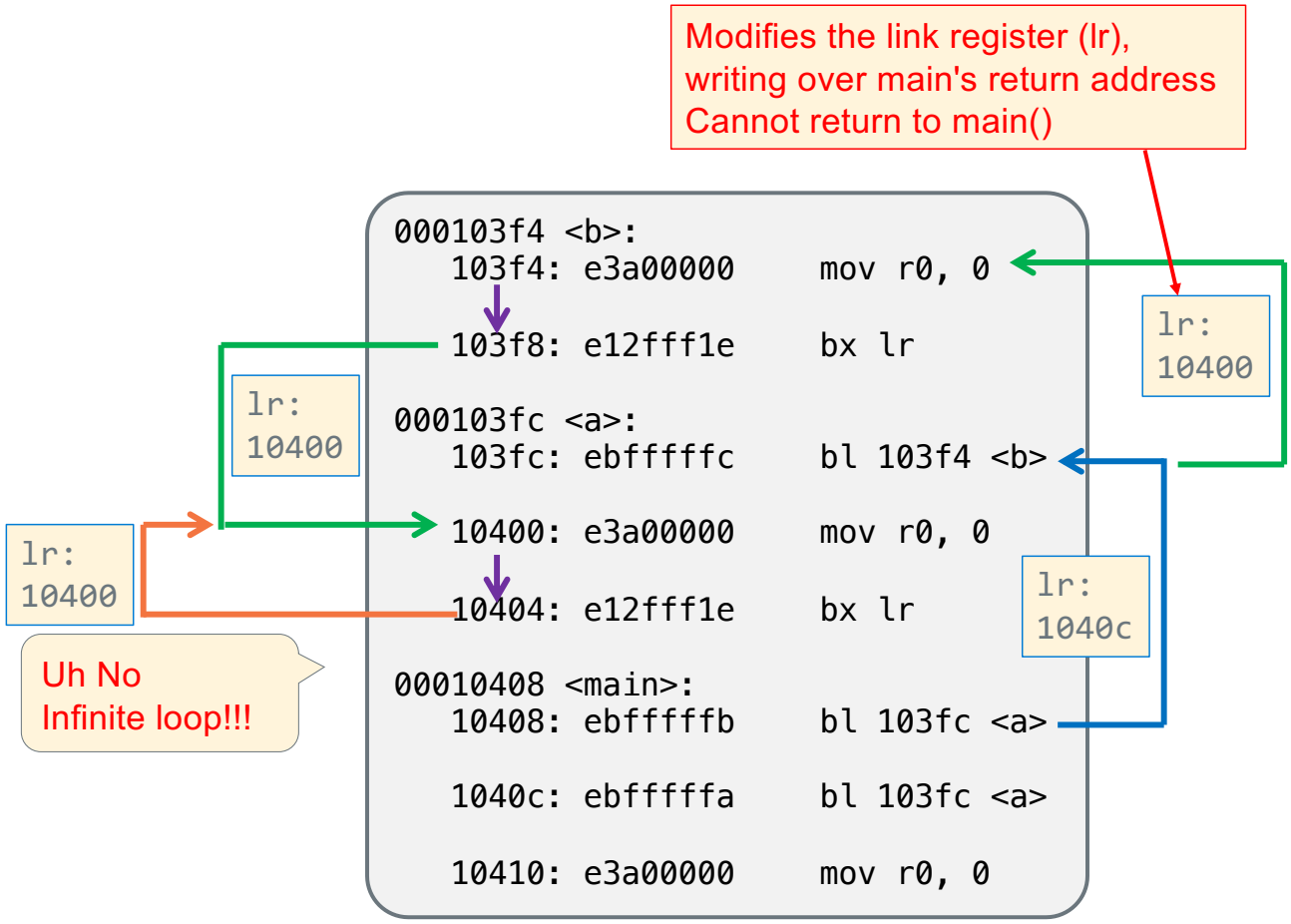


But there is a problem we must address here – next slide

x

bl and bx operation working together

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



We need to preserve the lr!

x

bl and blx operation not working together

```
int a(void)
{
     return 0;
}
int (*func)() = a;
int main(void)
{
     (*func)();
     // not shown
```

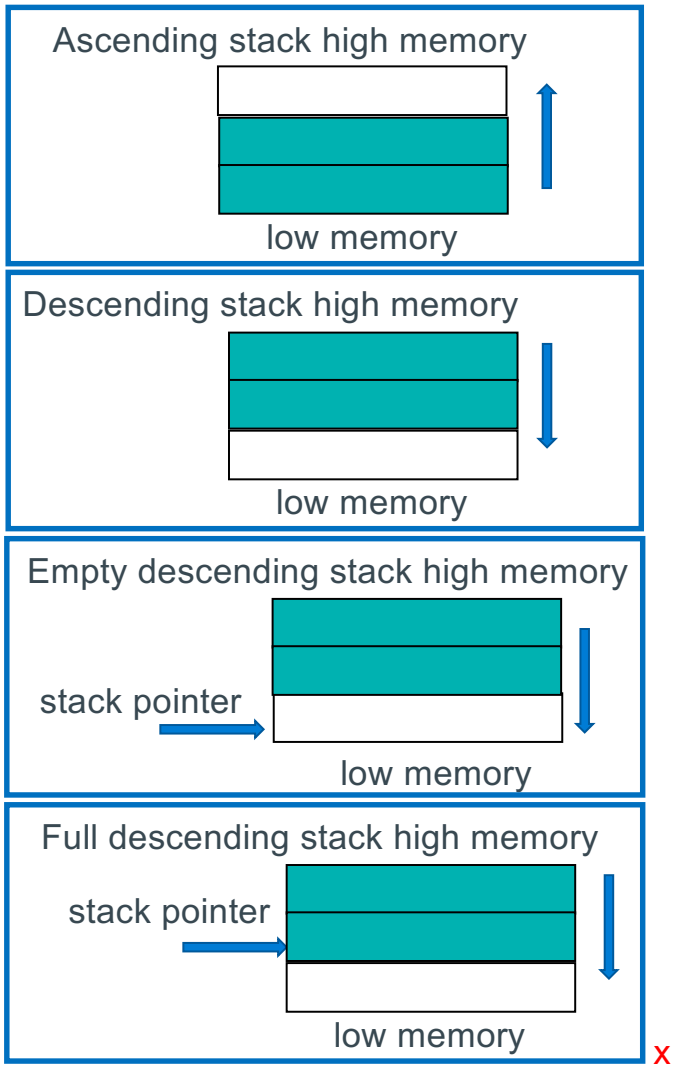
```
     .data
func:   .word a // func initialized with address of a()

    .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!
```

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

x

Review: Stack types

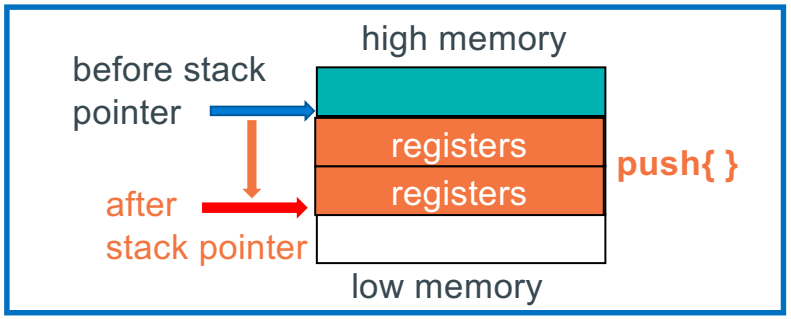
- Each time a **function is called**, a **stack frame is activated**
  - space is allocated by moving the stack pointer
- Stack growth direction
  - **Ascending stack:** grows from low memory towards high memory (adding to the sp to allocate memory)
  - **Descending stack:** grows from high memory towards low memory (subtracting from the sp to allocate memory)
- Full versus empty stacks
  - **Empty stack: stack pointer (**sp) points at the **next word address** after the last item pushed on the stack
  - **Full stack: stack pointer** (sp) points at the **last item pushed on the stack**
- ARM on Linux uses a **full descending stack**



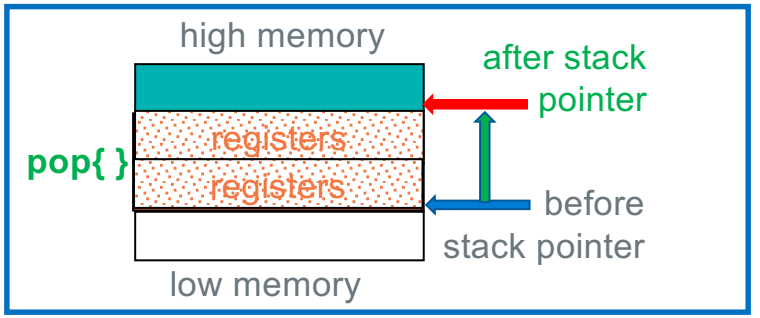
Preserving and Restoring Registers on the stack - 1

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)



x

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

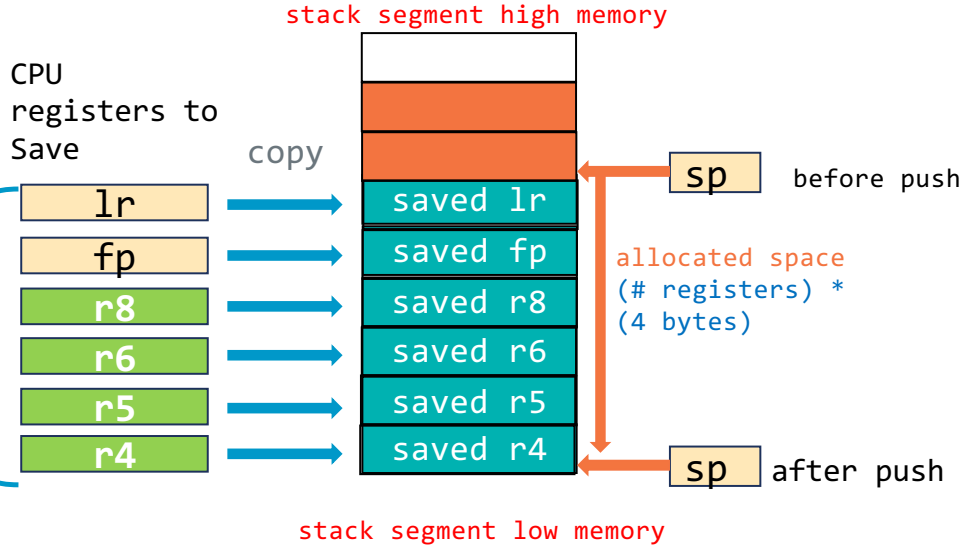
x

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 slides) then always push an **EVEN** number of registers!



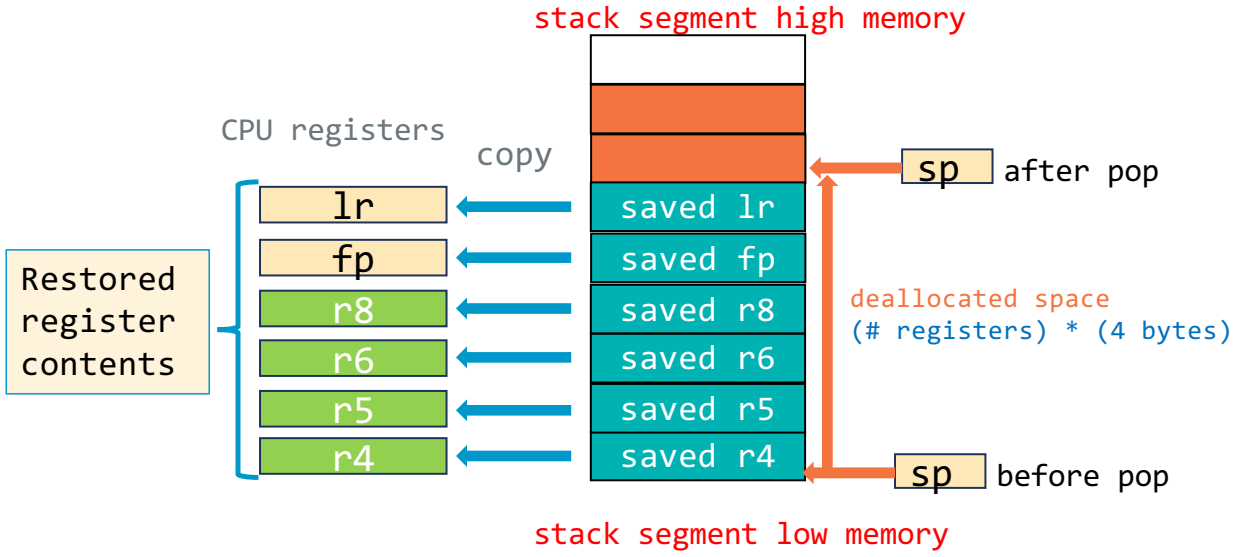
- **push** copies the contents of the **{reg list}** to stack segment memory
- **push** subtracts (# of registers saved) * (4 bytes) from the **sp** to ***allocate*** space on the stack
  - sp = sp – (# registers_saved * 4)
- **this must always be true: sp % 8 == 0**

x

pop: Multiple Register Restore (ldr from stack)

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

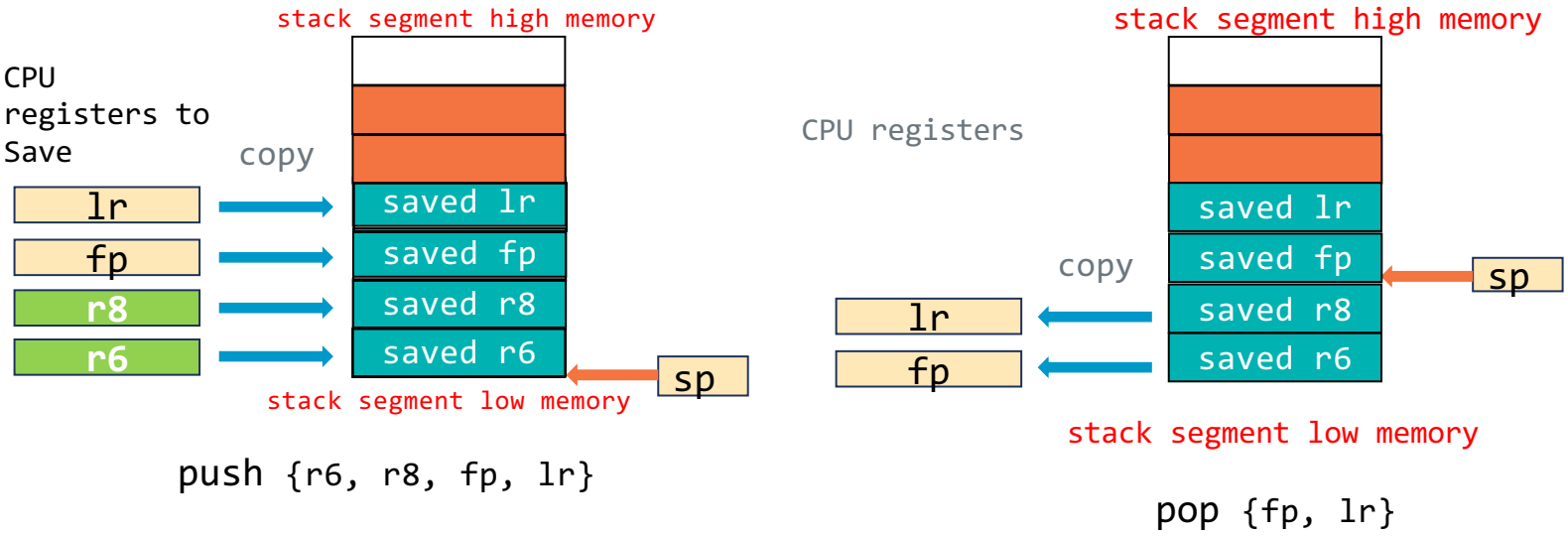
Registers are **pop'd** from the stack *in order* **left (low memory) to right (high memory)**



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

x

push and pop inconsistences

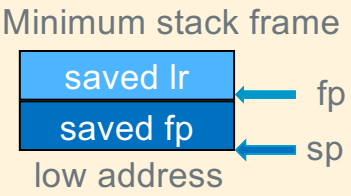


- lr gets an address on the stack, likely segmentation fault

x

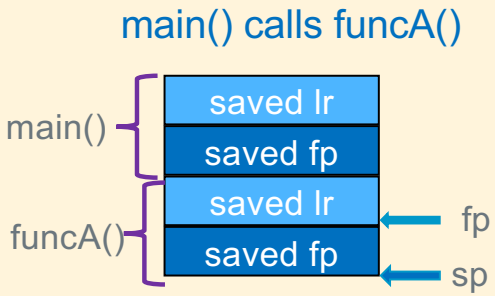
Minimum Stack Frame (Arm Arch32 Procedure Call Standards)

- **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 saved `lr` copy stored in the current stack frame
  - 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`)



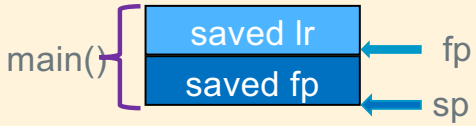
- Function entry (Function **Prologue**):
  1. create (activate) frame
  2. save preserved registers
  3. allocate space for locals

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



- Function return (Function **Epilogue**):
  1. deallocate space for locals
  2. restores preserved registers
  3. removes the frame

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



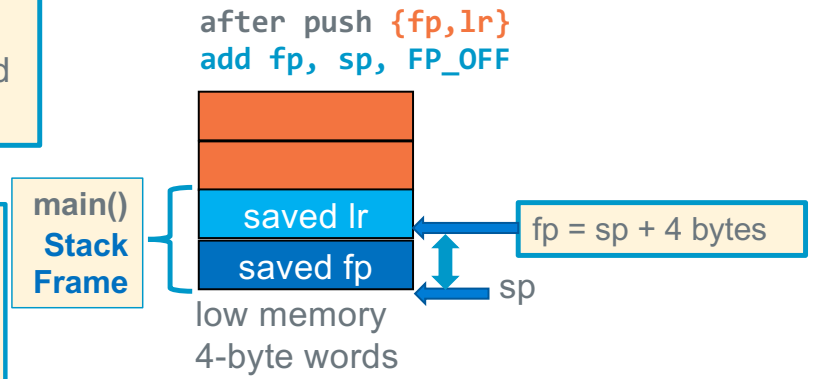
x

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

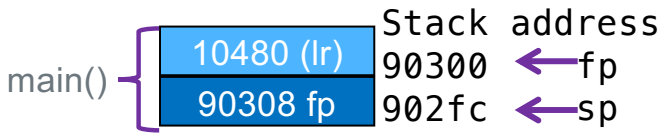


IMPORTANT: FP_OFF has **two** uses:
1. Where to set fp after prologue push (remember sp position)
2. Restore sp (deallocate locals) right before epilogue pop

x

Using Minimal Stack Frames

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

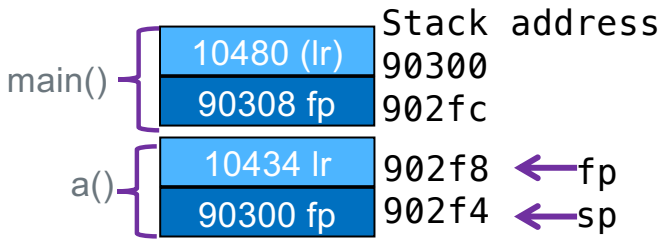



```
000103f4 <b>:
   103f4: e92d4800     push {fp, lr}
   103f8: e28db004     add fp, sp, 4
   103fc: e3a00000     mov r0, 0
   10400: e24bd004     sub sp, fp, 4
   10404: e8bd4800     pop {fp, lr}
   10408: e12fff1e     bx lr


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

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   1040c: e92d4800     push {fp, lr}
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   10418: e3a00000     mov r0, 0
   1041c: e24bd004     sub sp, fp, 4
   10420: e8bd4800     pop {fp, lr}
   10424: e12fff1e     bx lr
                                    lr:
                                    10434

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

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

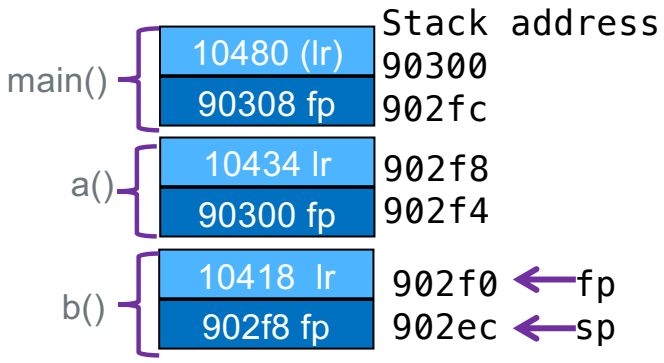


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   1042c: e28db004     add fp, sp, 4
   10430: ebffffff5    bl 1040c <a>
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// not shown
```

lr: 10418

lr: 10434

x

Using Minimal Stack Frames

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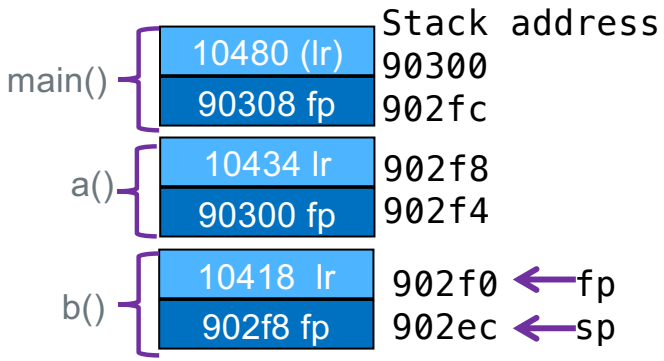
}
int a(void)
{
    b();
    return 0;
}
int main(void)
{
     a();
     a();
```

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   1041c: e24bd004     sub sp, fp, 4
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00010428 <main>:
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   1042c: e28db004     add fp, sp, 4
   10430: ebfffff5     bl 1040c <a>
   10434: ebfffff4     bl 1040c <a>
// not shown
```

lr: 10418

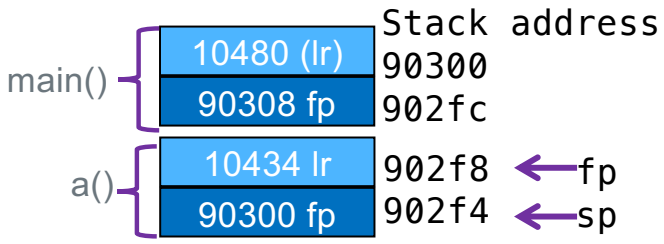
lr: 10418

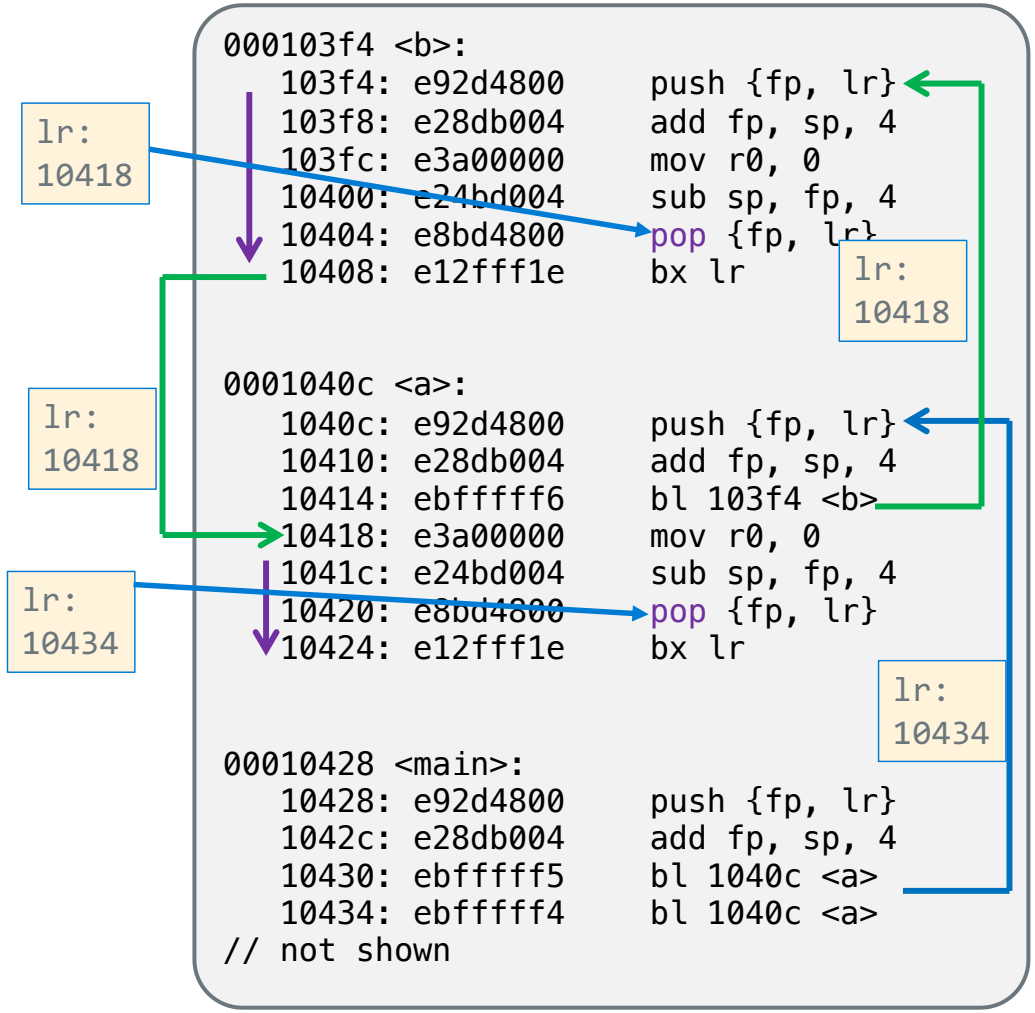
lr: 10434

x

Using Minimal Stack Frames

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





x

Using Minimal Stack Frames

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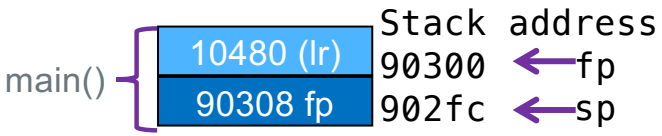
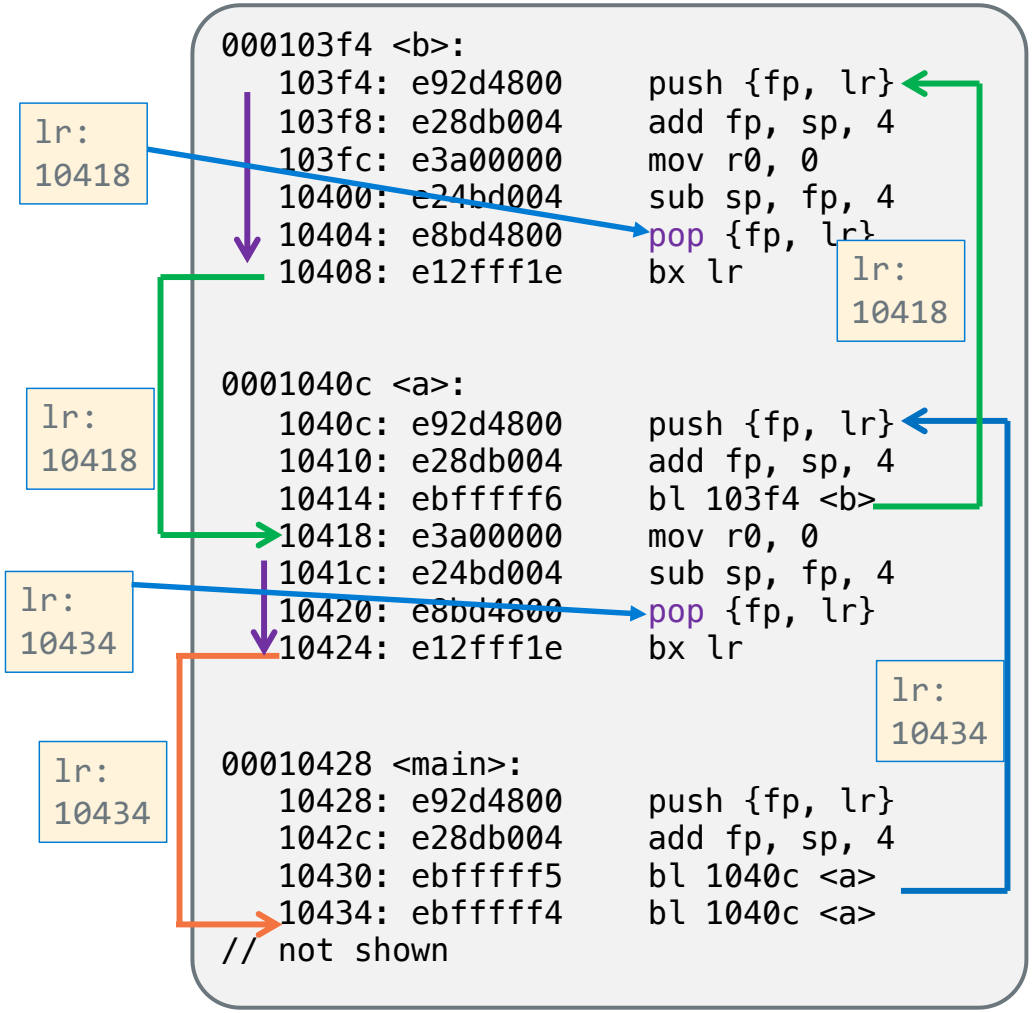





x

Ghost of Stack Frames Past…..

same stack frame
variable layout

```
% ./a.out
before ghost: 0 66328
after ghost: 30 300
wraith: 30 300
%

See how wraith has the
old values left over
from the prior call to
ghost
```

```
void ghost(int n)
{
    int x;
    int y;

    printf("before ghost: %d %d\n", x, y);
    x = 10*n;
    y = 100*n;
    printf("after ghost: %d %d\n", x, y);
    return;
}

void wraith (void)
{
    int a;
    int b;

    printf("wraith: %d %d\n", a, b);
    return;
}

int main(void)
{
    ghost(3);
    wraith();
    return EXIT_SUCCESS;
}
```

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

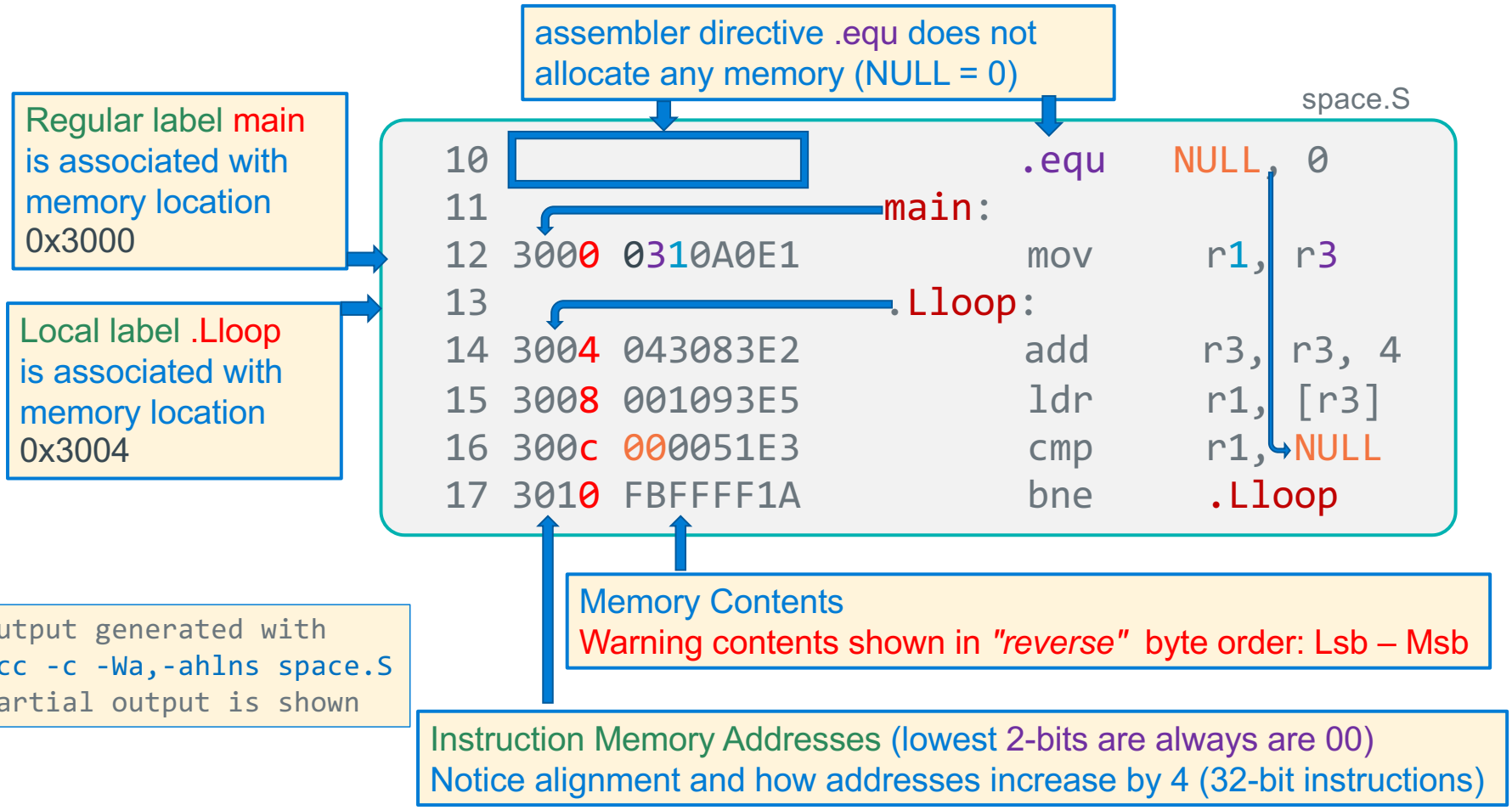
`.size name, bytes`

- 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)**

```
.size name, (. - name)
```


x

Example: Assembler Directive and Instructions



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Preview: 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**
  - **In terms of C runtime support, these registers contain the copies given to the called function**
  - **C allows the copies to be changed in any way by the called function**

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 **local to the file** from the point where they are defined

x

Variable Alignment In Memory and Performance

Accessing **address aligned** memory on many systems based on data type has the best performance (due to hardware implementation)

char

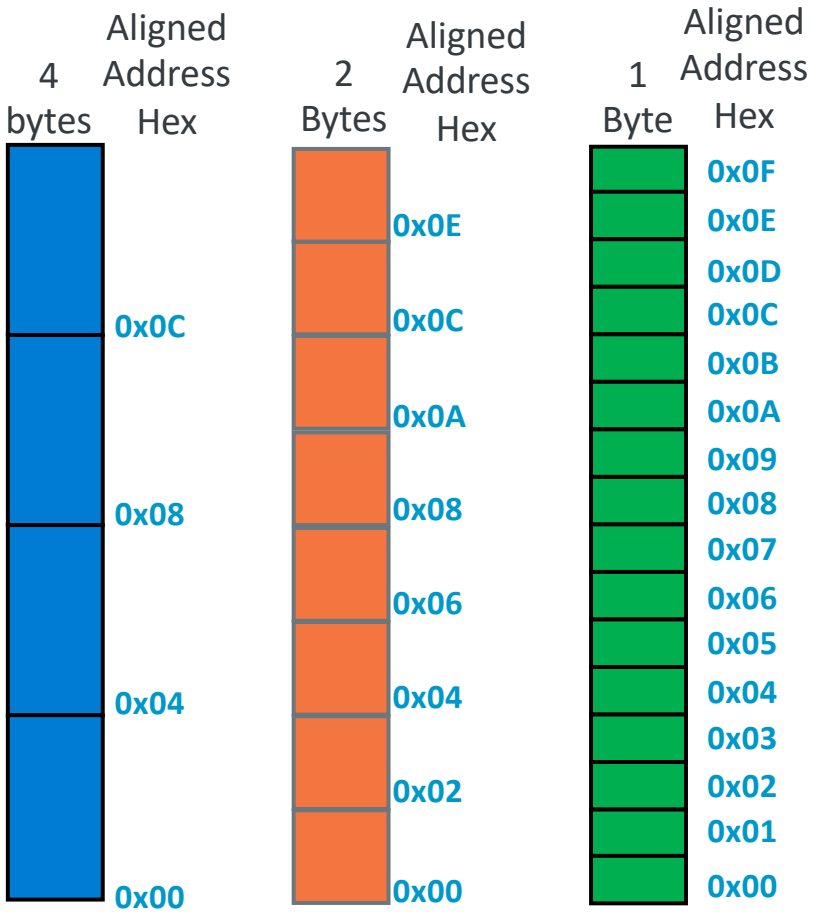
1 any address

short

2 bytes addresses that end in 0b0

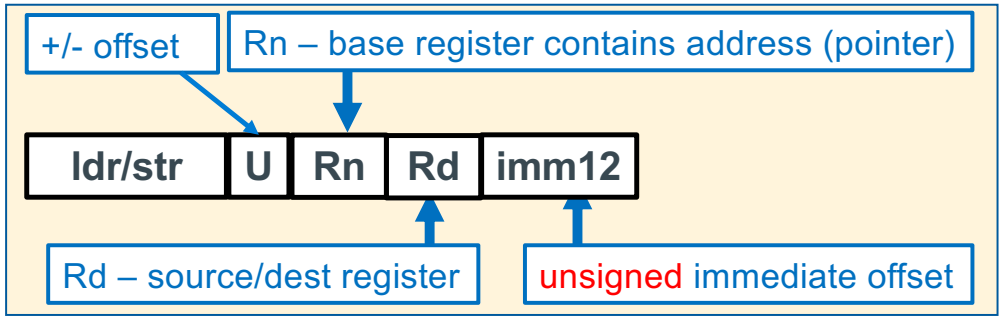
integer

4 bytes addresses that end in 0b00



x

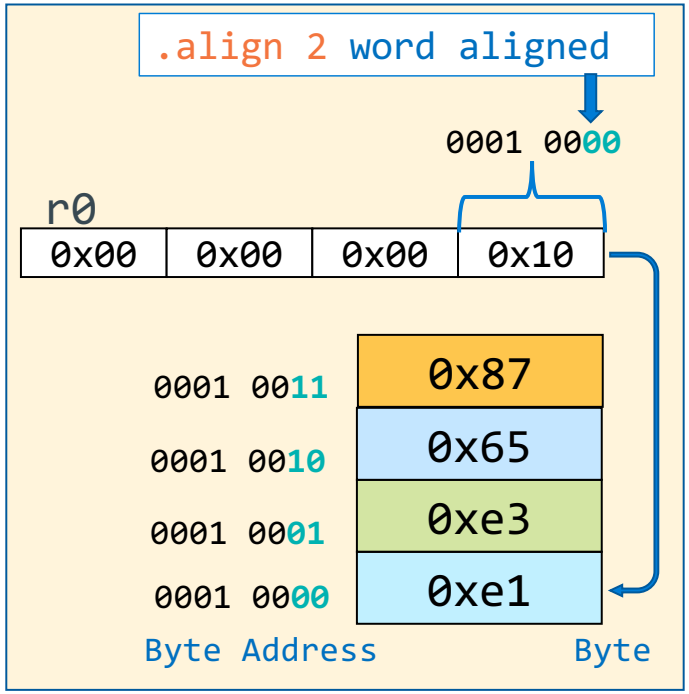
LDR/STR – Base Register + Immediate Offset Addressing

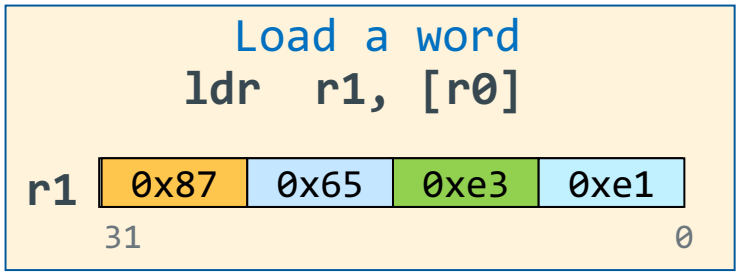


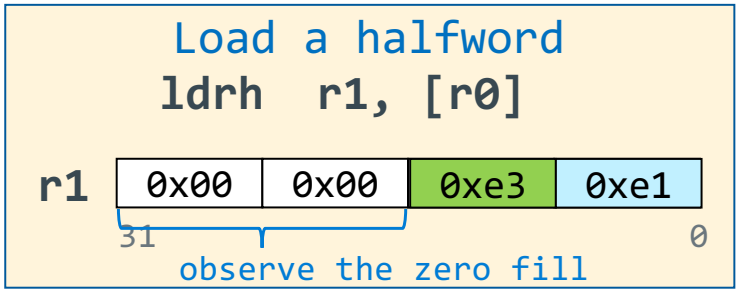
- **Register Base Addressing**:
  - Pointer Address: Rn; source/destination data: Rd
  - **Unsigned pointer address** in stored in the base register
- **Register Base + immediate offset Addressing:**
  - Pointer Address = register content + immediate offset `-4095 <= imm12 <= 4095 (bytes)`
  - Unsigned offset integer immediate value (bytes) is added or subtracted (U bit above says to add or subtract) from the pointer address in the base register

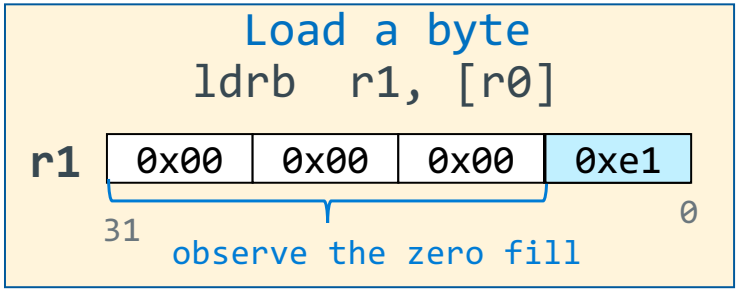
x

Load a Byte, Half-word, Word



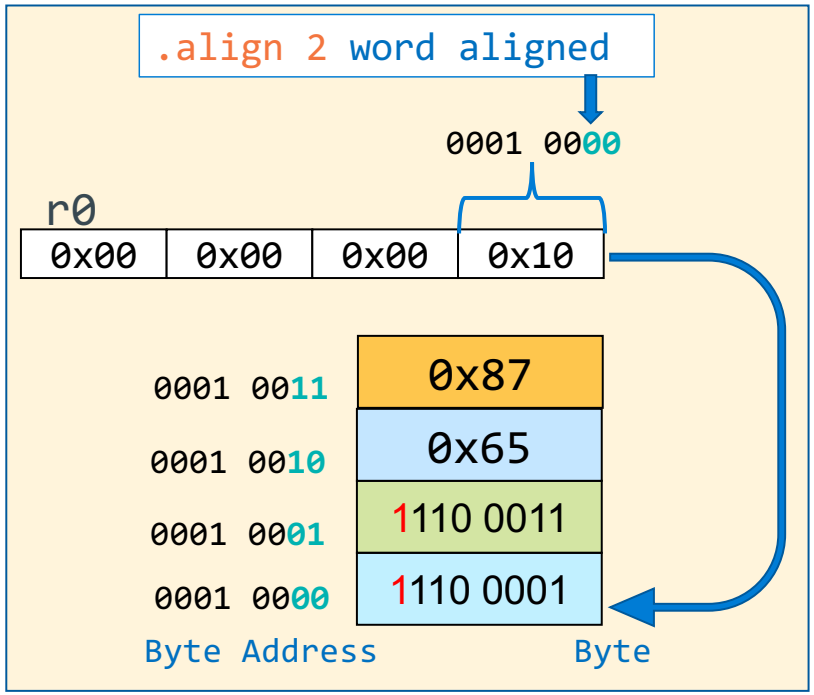


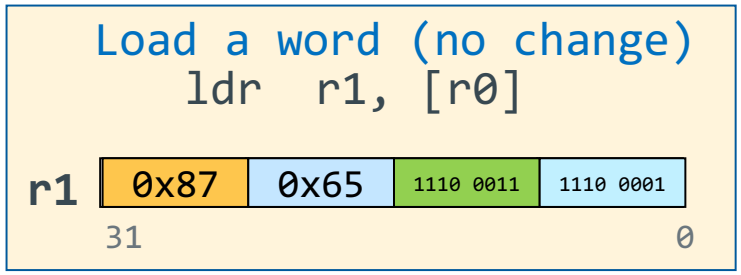


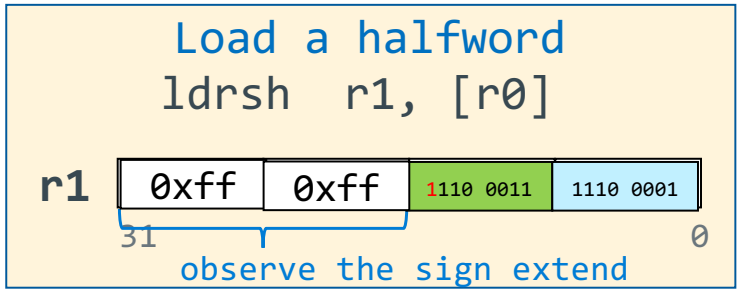


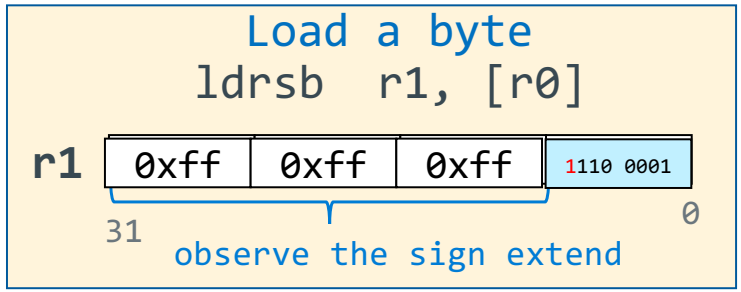
x

Signed Load a Byte, Half-word, Word



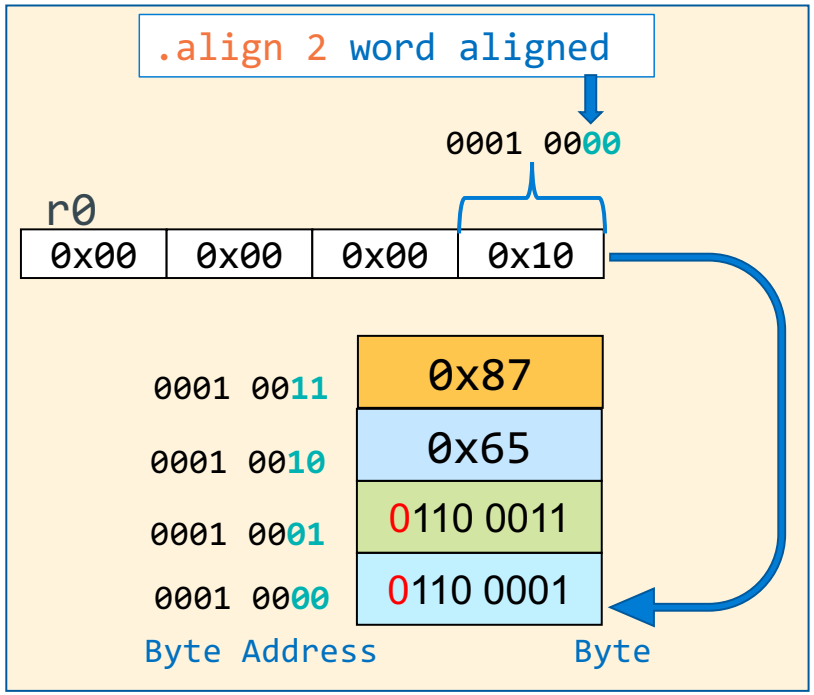






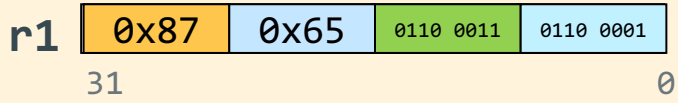
x

Signed Load a Byte, Half-word, Word



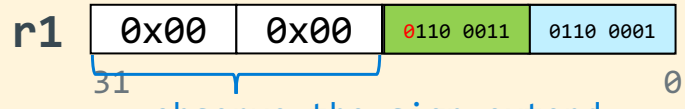
Load a word (no change)

```
ldr  r1, [r0]
```



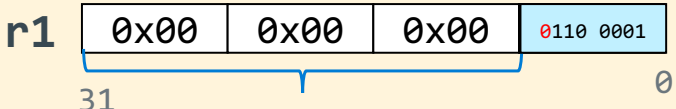
Load a halfword

```
ldrsh  r1, [r0]
```



Load a byte

```
ldrsb  r1, [r0]
```



x

Store a Byte, Half-word, Word

initial value in r0

0x20	0x00	0x00	0x00

Store a byte

```
strb  r1, [r0]
```

r1 | 0x87 | 0x65 | 0xe3 | 0xe1 |

31 ... 0

Byte Address	Byte
0x20000003	0x33
0x20000002	0x22
0x20000001	0x11
0x20000000	0xe1

observe other bytes NOT altered

Store a halfword

```
strh r1, [r0]
```

r1 | 0x87 | 0x65 | 0xe3 | 0xe1 |

31 ... 0

Byte Address	Byte
0x20000003	0x33
0x20000002	0x22
0x20000001	0xe3
0x20000000	0xe1

Store a word

```
str  r1, [r0]
```

r1 | 0x87 | 0x65 | 0xe3 | 0xe1 |

31 ... 0

Byte Address	Byte
0x20000003	0x87
0x20000002	0x65
0x20000001	0xe3
0x20000000	0xe1

x

Base Register Addressing + Offset register

```
#include <stdio.h>
#include <stdlib.h>
int count(char *, int);
int main(void)
{
    char msg[] ="Hello CSE30! We Are CountinG UpPER cASe letters!";

    printf("%d\n", count(msg, sizeof(msg)/sizeof(*msg)));
    return EXIT_SUCCESS;
}
```

```
int count(char *ptr, int len)
{
    int cnt = 0;
    int i;

    for (i = 0; i < len; i++) {
        if ((ptr[i] >= 'A') && (ptr[i] <= 'Z'))
            cnt++;
   }
    return cnt;
}
```

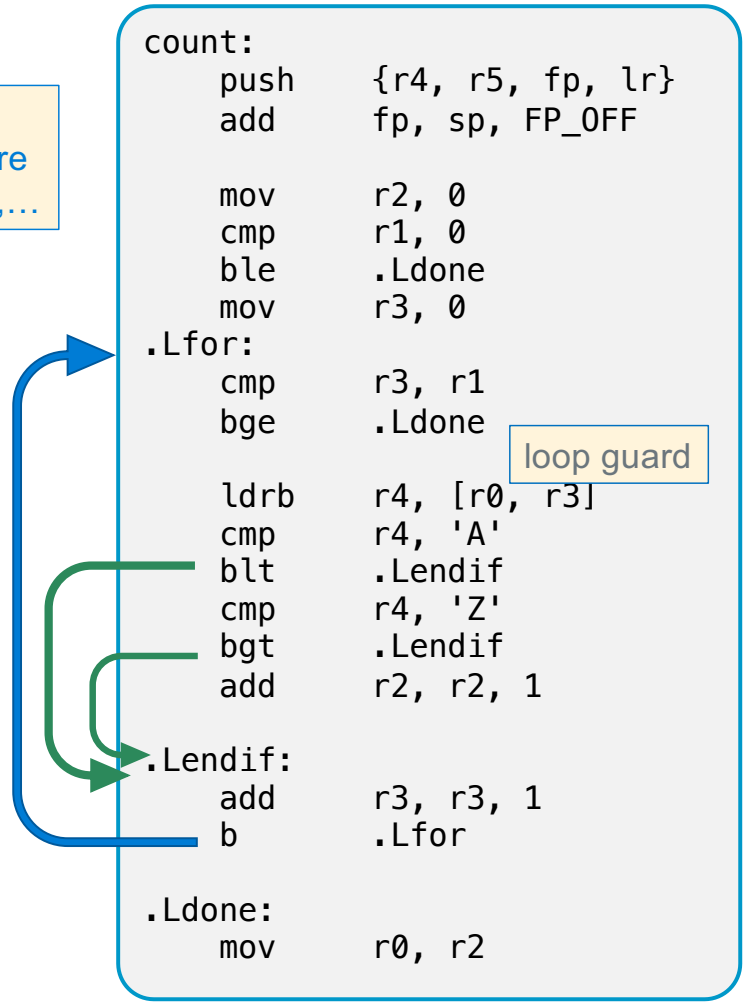

x

Base Register + Offset register

```
    .arch armv6
    .arm
    .fpu vfp
    .syntax unified
    .text
    .global count
    .type   count, %function
    .equ    FP_OFF, 12
    // r0 contains char *ptr
    // r1 contains int len
    // r2 contains int cnt
    // r3 contains int i
    // r4 contains char

count:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
// see right ->
    sub     sp, fp, FP_OFF
    pop     {r4, r5, fp, lr}
    bx      lr
    .size count, (. - count)
    .end
```

byte array
Also use ldrb here
offsets are 0,1,2,…



x