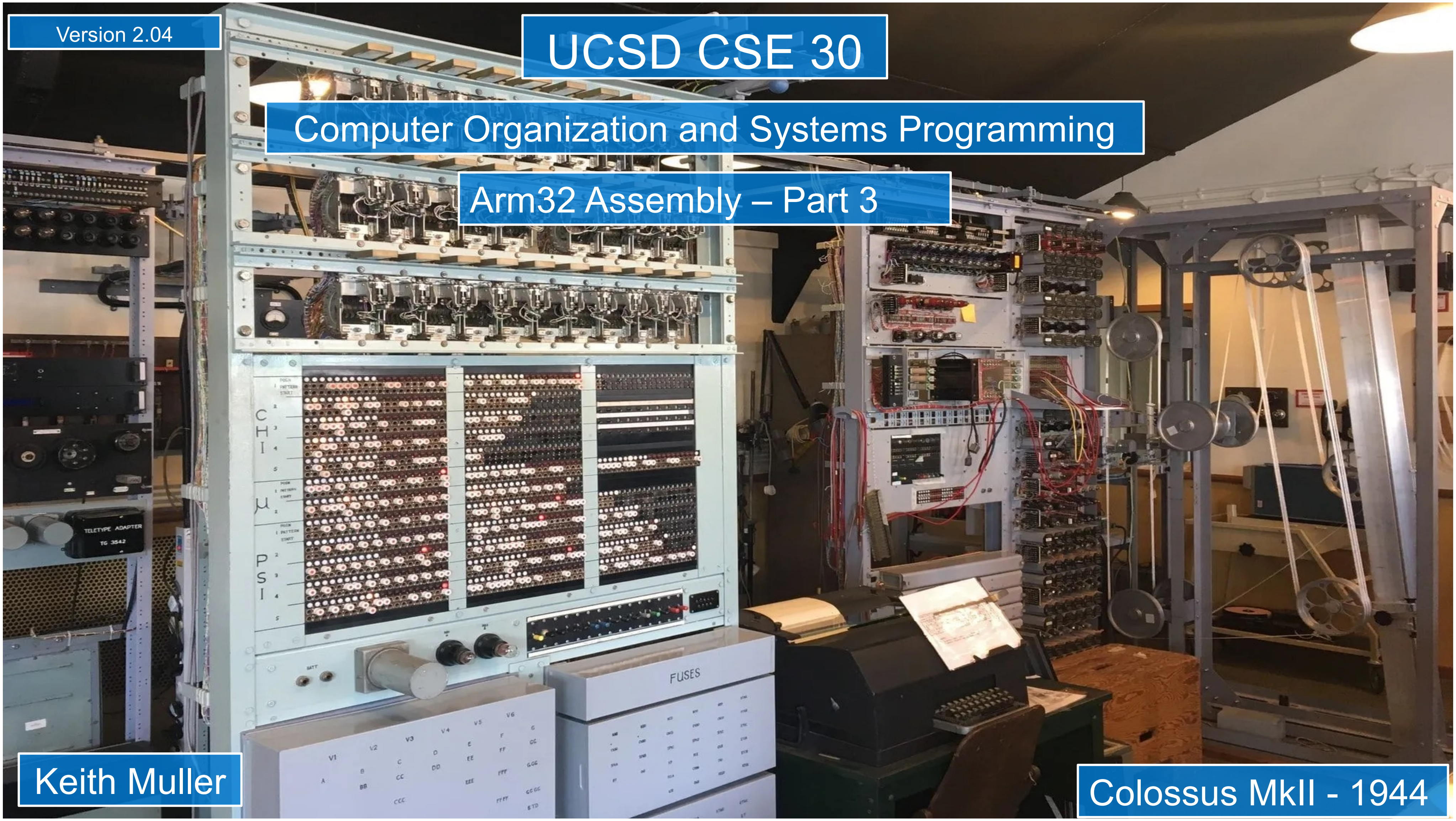
Version 2.04

UCSD CSE 30

Computer Organization and Systems Programming

Arm32 Assembly – Part 3



Keith Muller

Colossus MkII - 1944

Reference For PA7/8: C Stream Functions Opening Files

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

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

"r" Open for reading.

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

"w" Open for writing.

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

"a" Open for writing.

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

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

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

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Reference: C Stream Functions Closing Files and Usage

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

- Closes the specified stream, forcing output to complete (eventually)
  - returns EOF on failure (often ignored as no easy recovery other than a message)
- Usage template for **`fopen()`** and **`fclose()`**
  1. Open a file with **`fopen()`** **always** checking the return value
  2. do i/o – keep calling stdio io routines
  3. close the file with **`fclose()`** when done with that I/O stream

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C Stream Functions Array/block read/write

- These do not process contents they simply **transfer** a fixed number of bytes to and from a buffer passed to them
- `size_t fwrite(void *ptr, size_t size, size_t count, FILE *stream);`
  - Writes an array of *count **elements*** of ***size*** bytes from **stream**
  - *Updates the write file pointer forward by the number of bytes written*
  - returns number of elements written
  - error is short element count or 0
- `size_t fread(void *ptr, size_t size, size_t count, FILE *stream);`
  - Reads an array of ***count elements*** of ***size*** bytes from *stream*
  - *Updates the read file pointer forward by the number of bytes read*
  - returns number of elements read, EOF is a return of 0
  - error is short element count or 0
- **I almost always set size to 1 to return bytes read/written**

x

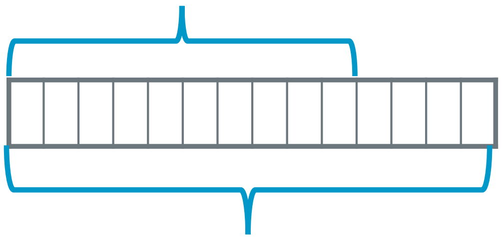
C fread() and fwrite()

element size of 1 with a char buffer is byte I/O
Capture bytes read so you know how many bytes to write

```c
#define BUFSZ   128

int copy(FILE *infp, FILE *outfp) {
    unsigned char buf[BUFSZ];
    size_t cnt;

    while ((cnt = fread(buf, 1, BUFSZ, infp)) > 0) {
        fprintf(stderr, "bytes: %u\n", cnt);

        if (fwrite(buf, 1, cnt, outfp) != cnt)
            return -1;
    }
    return 0;
}
```

unless the input file length is an exact multiple of BUFSIZ, last fread() will always read less than BUFSIZ which is why you write cnt

cnt



BUFSZ

Jargon: the last record is often called the "runt"

```
% ls -l a
4 -rw-r--r-- 1 kmuller 1104 May 15 09:45 a
% ./a.out a b
bytes: 128
bytes: 128
bytes: 128
bytes: 128
bytes: 128
bytes: 128
bytes: 128
bytes: 128
bytes: 80
```

128 * 8 + 80 = 1104

```
size_t
fread(void *ptr, size_t size, size_t count, FILE *stream)
```

- Reads an array of ***count elements*** of ***size*** bytes from *stream*

```
size_t
fwrite(void *ptr, size_t size, size_t count, FILE *stream
```

- Writes an array of ***count elements*** of ***size*** bytes to *stream*

Using fopen() and fclose()

```
int main(int argc, char **argv)
{
    FILE *infp;
    FILE *outfp;
    int reslt;

    if (argc != 3) {
        fprintf(stderr, "%s requires two args\n", argv[0]);
        return EXIT_FAILURE;
    }
    // Open the input file for read
    if ((infp = fopen(*(argv+1), "r")) == NULL) {
        fprintf(stderr,"fopen for read failed\n");
        return EXIT_FAILURE;
    }
    //  Open the output file for write
    if ((outfp = fopen(*(argv+2), "w")) == NULL) {
        fprintf(stderr, "fopen for write failed\n");
        fclose(infp);
        return EXIT_FAILURE;
    }
    reslt = copy(infp, outfp);
    fclose(infp);
    fclose(outfp);
    if (reslt != 0) {
        fprintf(stderr, "copy %s to %s failed\n", *(argv+1), *(argv+2));
        return EXIT_FAILURE;
    }
    return EXIT_SUCCESS;
}
```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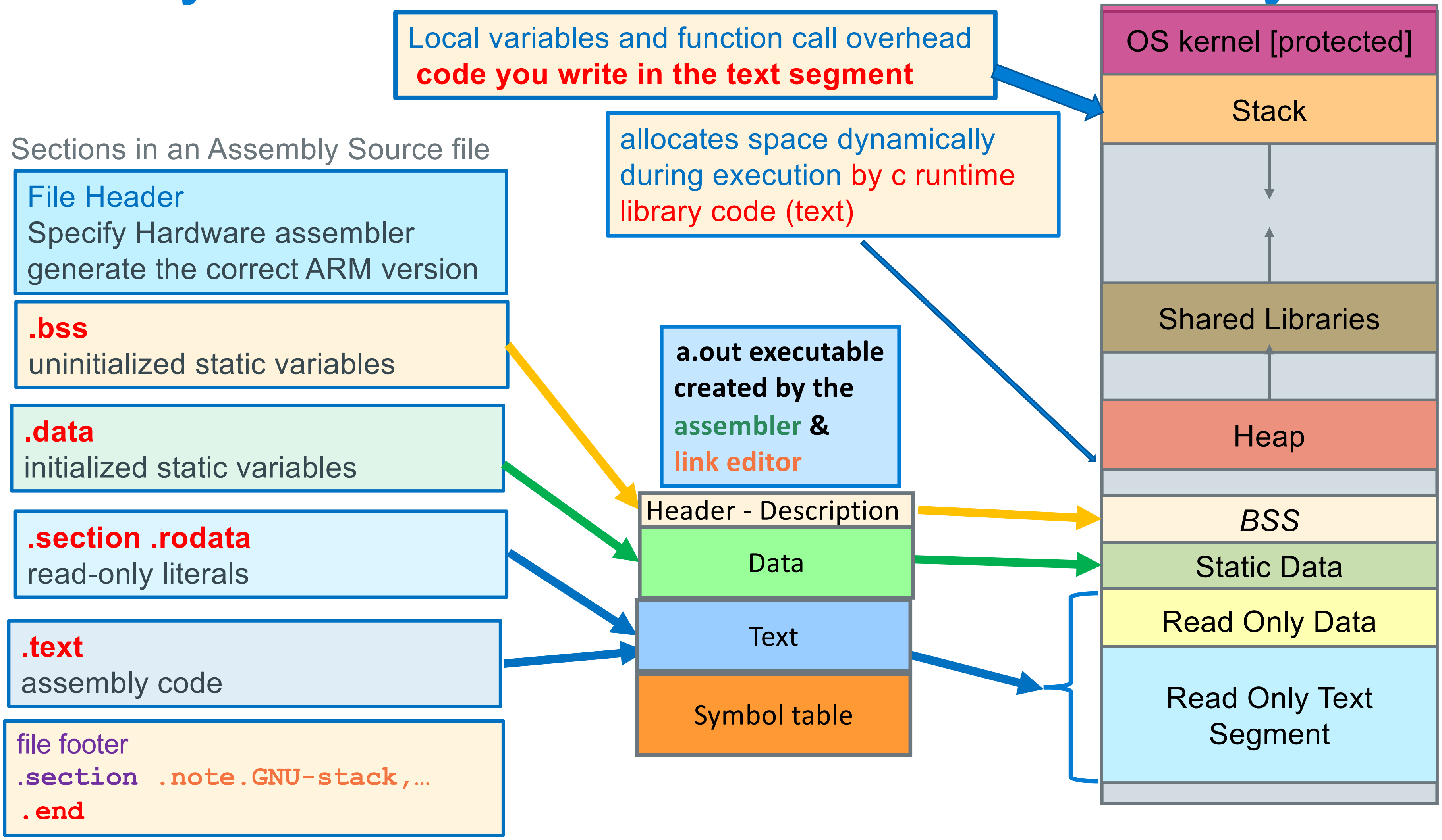
Assembly Source File to Executable to Linux Memory



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Creating Segments, Definitions In Assembly Source

- The following assembler directives indicate the ***start*** of a **memory segment specification**
  - **Remains in effect** until the next segment directive is seen

```
.bss
        // start uninitialized static segment variables definitions
        // does not consume any space in the executable file
.data
        // start initialized static segment variables definitions
.section .rodata
        // start read-only data segment variables definitions
.text
        // start read-only text segment (code)
```


x

```
// 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 uninitialized globals)
         .bss
// Data Segment (only when you have initialized 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`

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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

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

Example: Assembler Directive and Instructions

assembler directive .equ does not allocate any memory (NULL = 0)

Regular label main is associated with memory location 0x3000

Local label .Lloop is associated with memory location 0x3004

space.S

```
10                                  .equ    NULL, 0
11                             main:
12 3000 0310A0E1                    mov     r1, r3
13                             .Lloop:
14 3004 043083E2                    add     r3, r3, 4
15 3008 001093E5                    ldr     r1, [r3]
16 300c 000051E3                    cmp     r1, NULL
17 3010 FBFFFF1A                    bne     .Lloop
```

Memory Contents
Warning contents shown in *"reverse"* byte order: Lsb – Msb

```
output generated with
gcc -c -Wa,-ahlns space.S
partial output is shown
```

Instruction Memory Addresses (lowest 2-bits are always are 00)
Notice alignment and how addresses increase by 4 (32-bit instructions)

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

Function Template

```
        .text                           // start of the text segment

        .global myfunc                  // make myfunc global for linking
        .type   myfunc, %function       // define myfunc to be a function
        .equ    FP_OFF,  4              // fp offset in main stack frame

myfunc:

    push    {fp, lr}                    // push (save) fp and lr on stack
    add     fp, sp, FP_OFF              // set fp for this function

        // your code


    sub     sp, fp, FP_OFF
    pop     {fp, lr}                     // pop (retore) fp and lr from stack
    bx      lr                          // return to caller

        .size myfunc, (. - myfunc)
```

myfunc label is the address of the first instruction in myfunc (the push below)

Function header

Function Prologue creates stack frame

Function Epilogue removes stack frame

Function footer

x

Preview: Return Value and Passing Parameters to Functions

(Four parameters or less)

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

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

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Preview: Writing an ARM32 function

```c
#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;
}
```

```c
#ifndef SUM4_H
#define SUM4_H

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

#endif
```

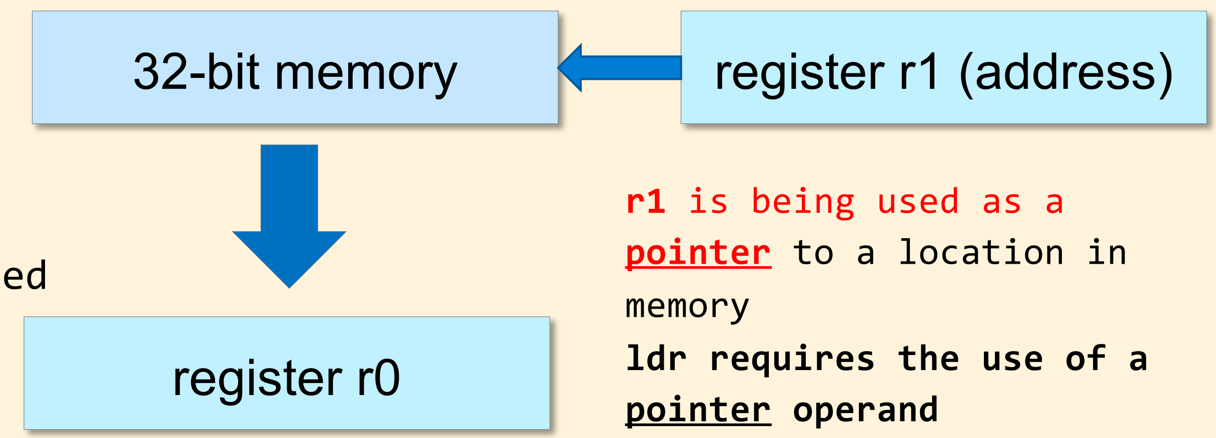
```
#include "sum4.h"
    .arch armv6
    .arm
    .fpu vfp
    .syntax unified
    .global sum4
    .type   sum4, %function
    .equ    FP_OFF, 28
    // r0 = sum4(r0, r1, r2, r3)
sum4:
    push    {r4-r9, fp, lr}
    add     fp, sp, FP_OFF

    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

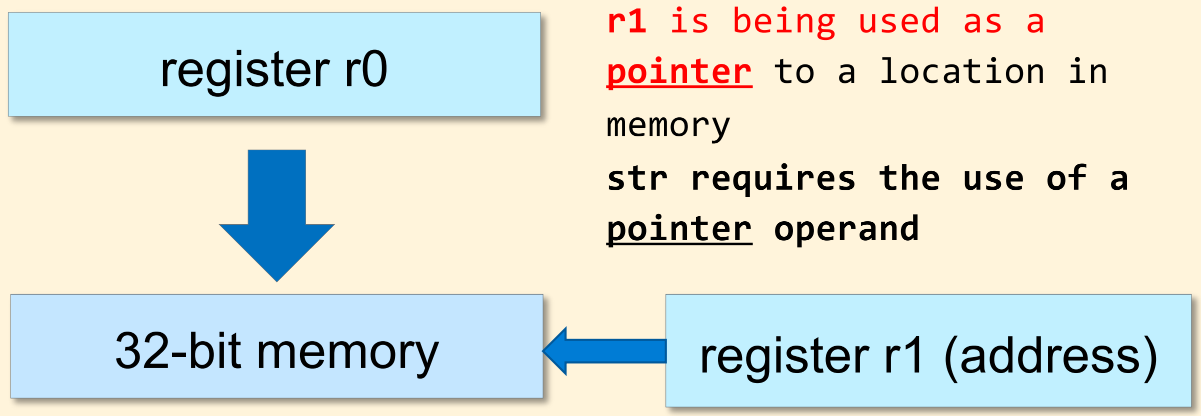


r1 is being used as a **pointer** to a location in memory

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

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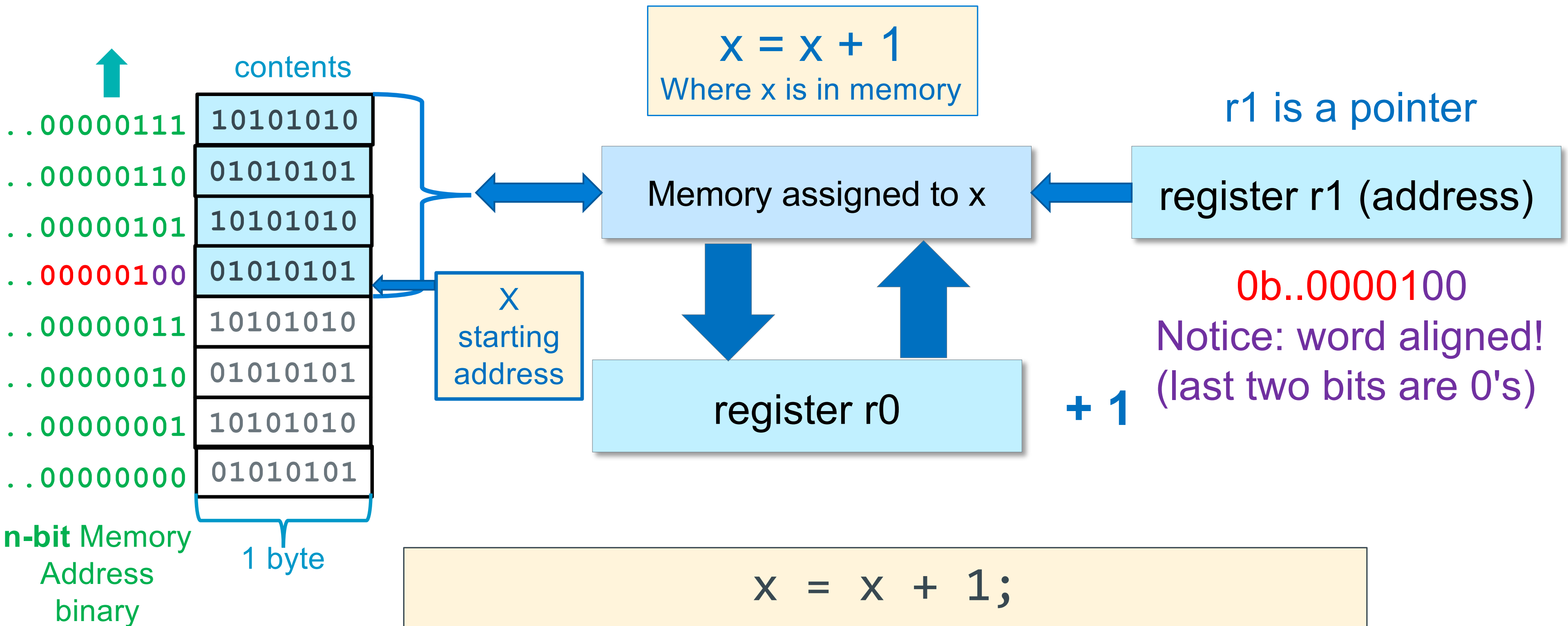
Example Base Register Addressing Load – Modify – Store



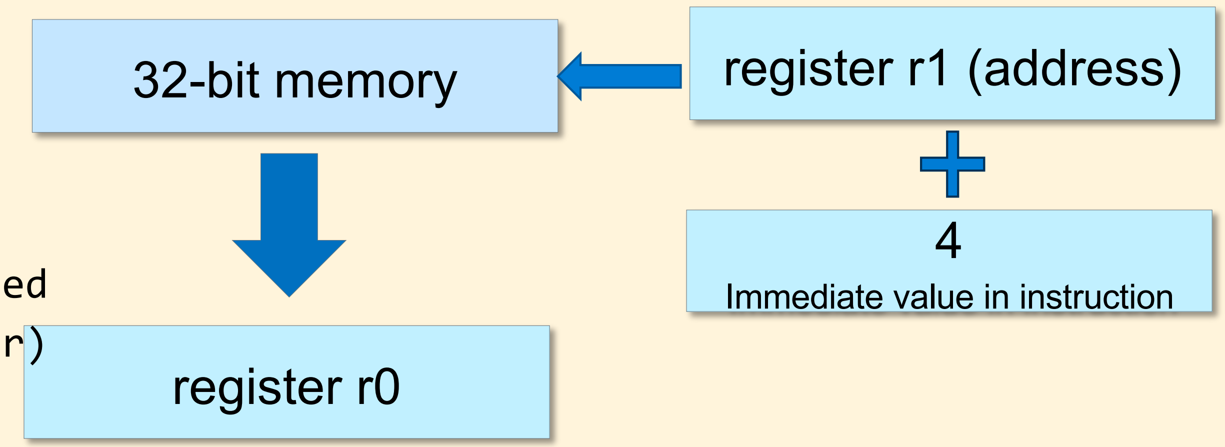

```
                x = x + 1;
ldr r0, [r1]          // r0 = *r1 (read x)
add r0, r0, 1         // r0 = r0 + 1 (x++)
str r0, [r1]          // *r1 = r0 write x
```


x

Load/Store: Register Base Addressing + Immediate

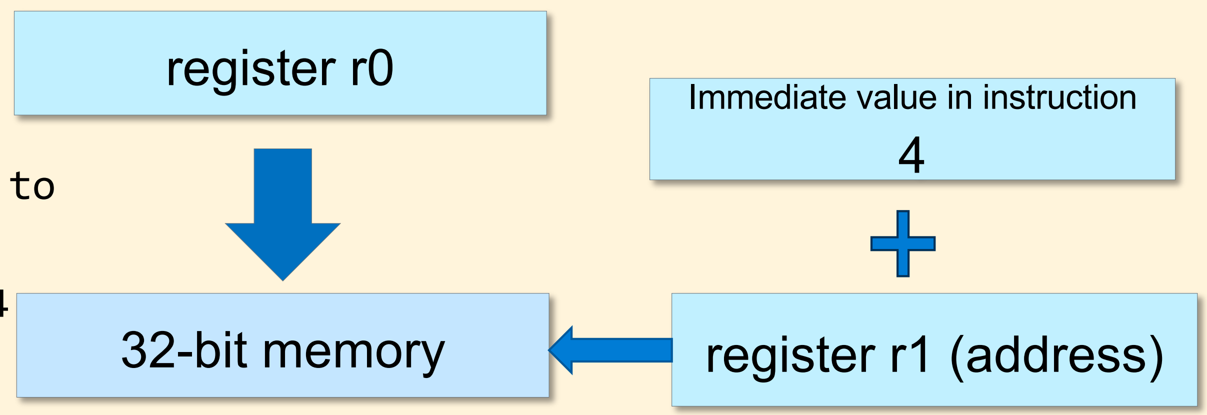
```
ldr r0, [r1, 4]
```

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

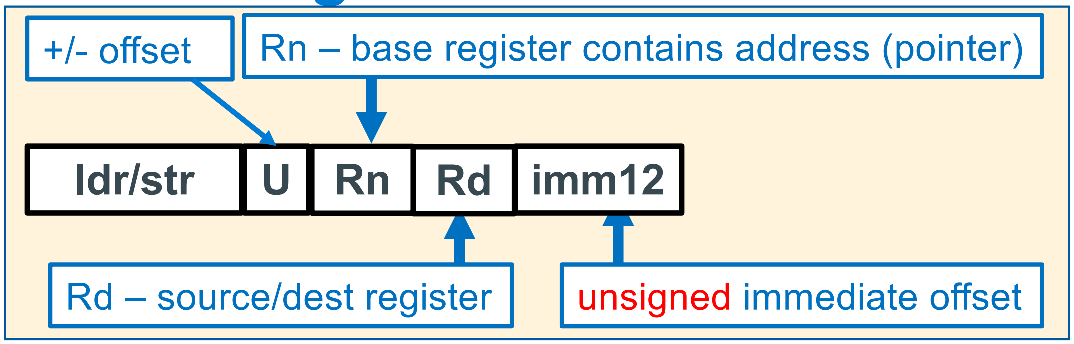



```
str  r0, [r1, 4]
```

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



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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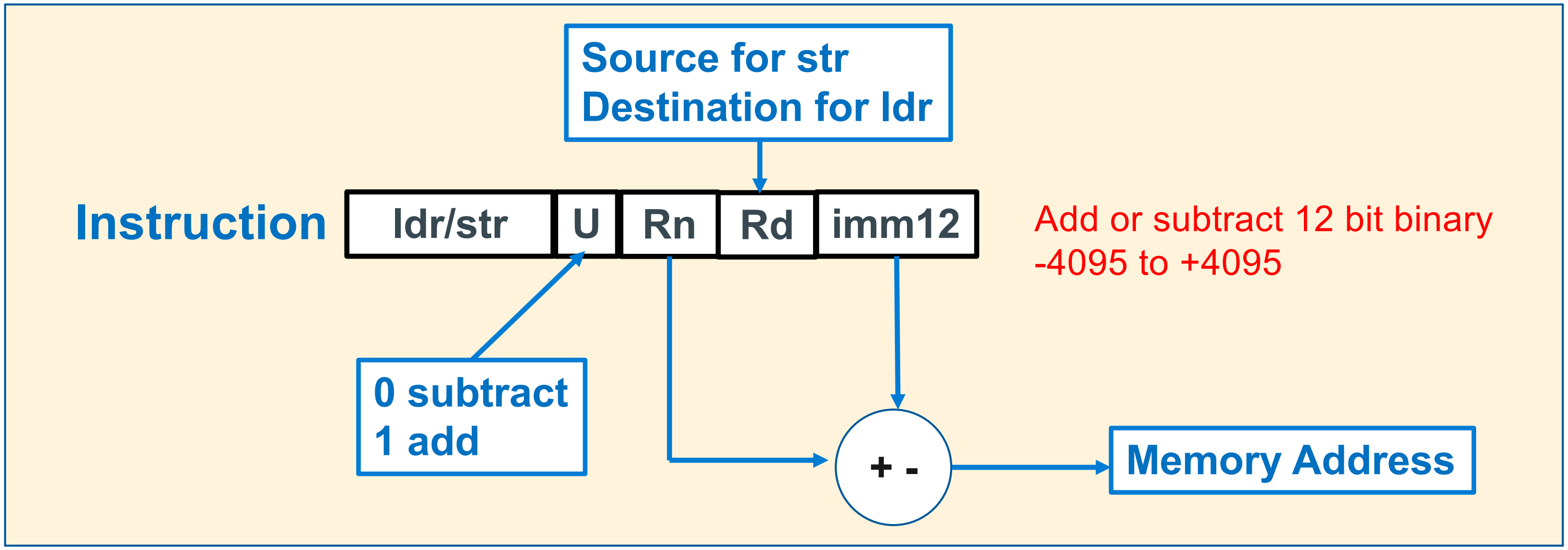
ldr/str Register Base + Immediate Offset Addressing



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)

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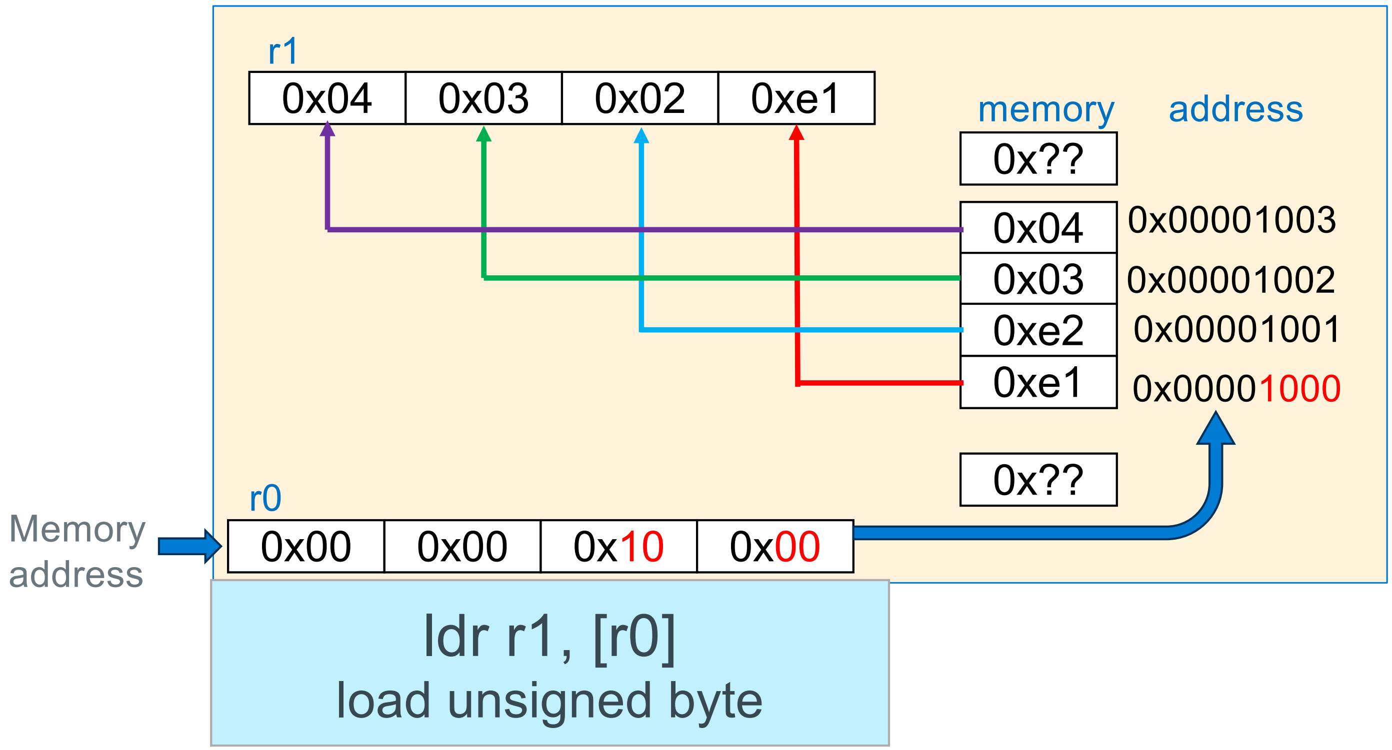
Loading 32-bit Registers From Memory, 32-bit



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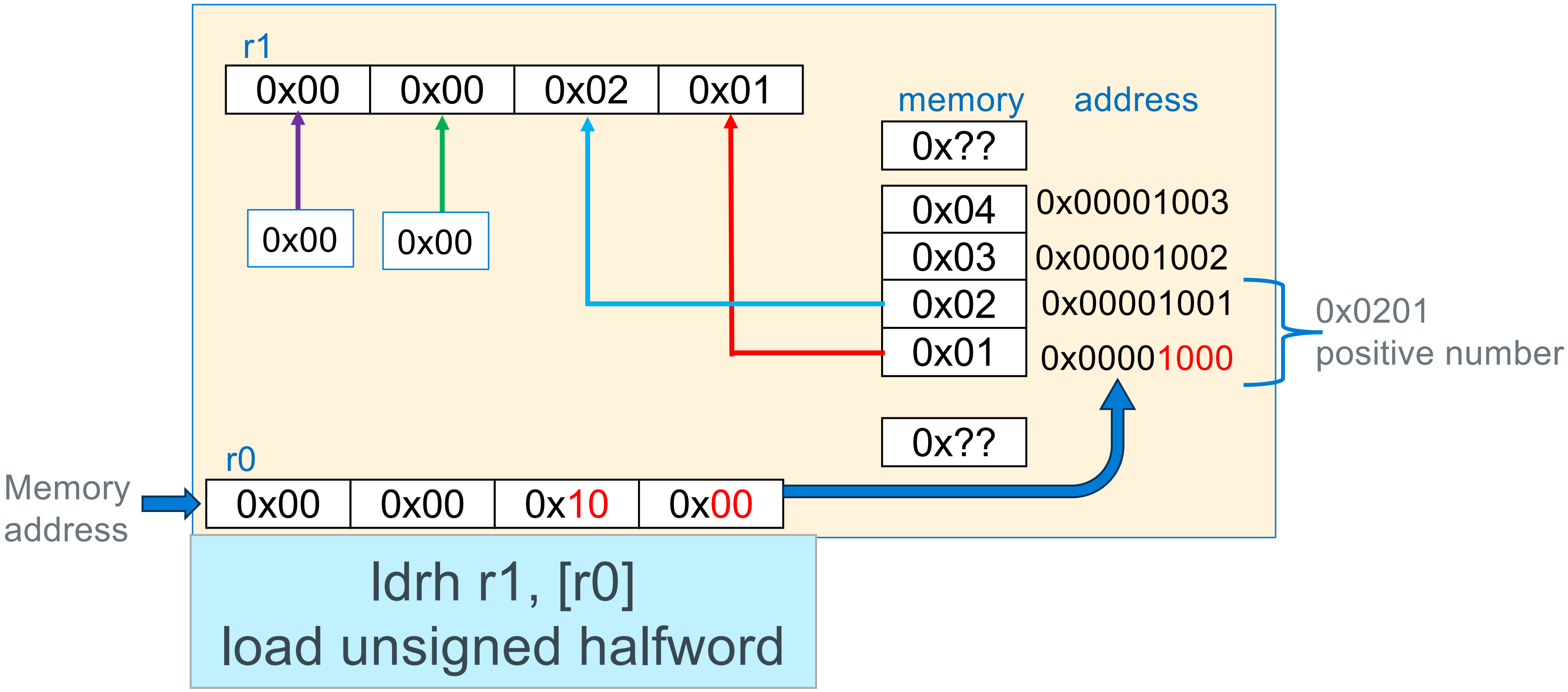
Loading 32-bit Registers From Memory, 16-bit



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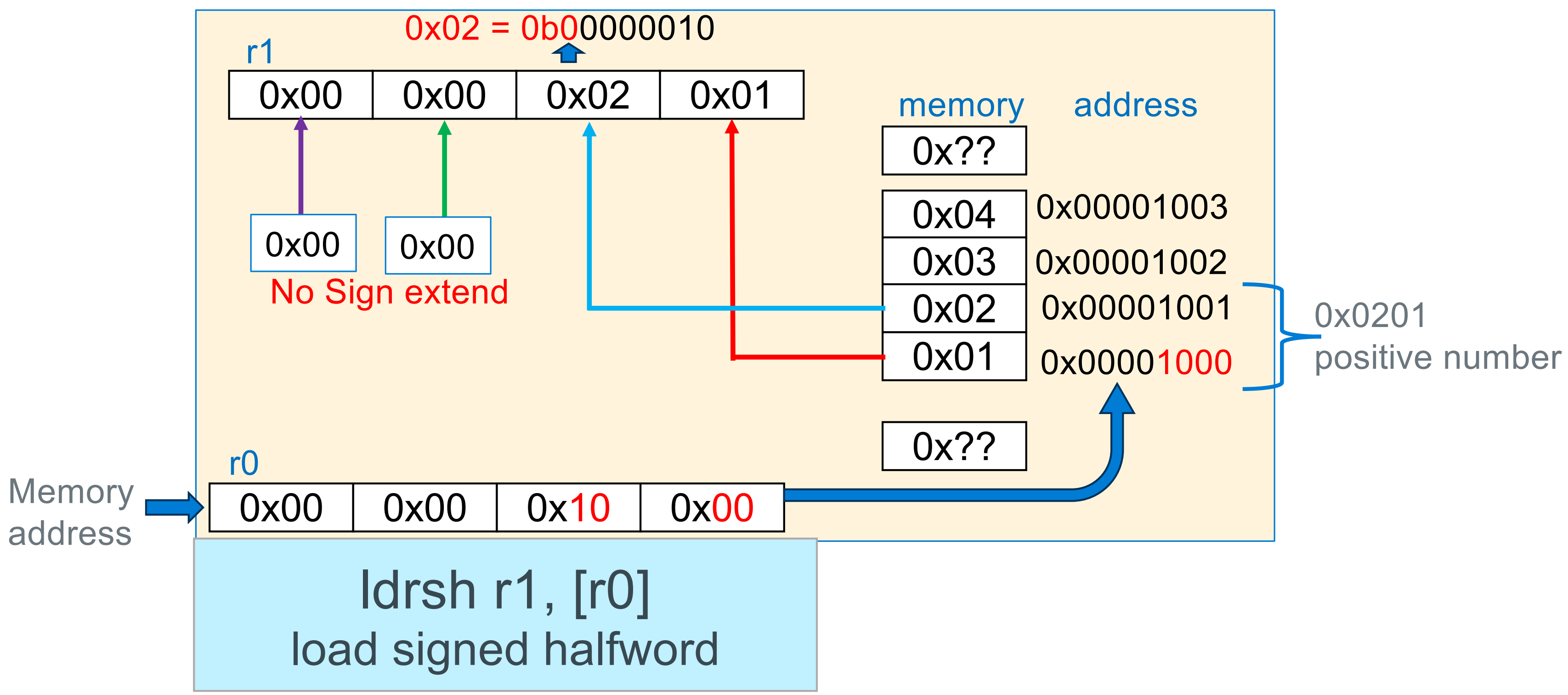
Loading 32-bit Registers From Memory, 16-bit



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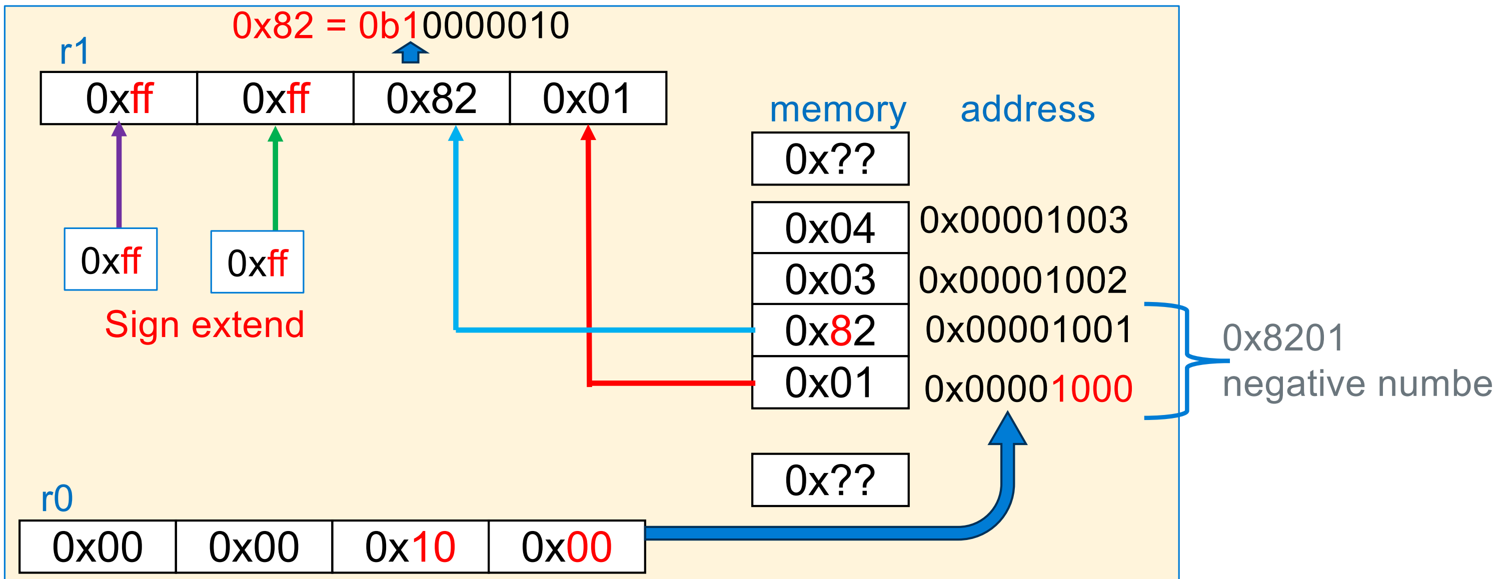
Loading 32-bit Registers From Memory, 16-bit Signed



ldrsh r1, [r0]
load signed halfword

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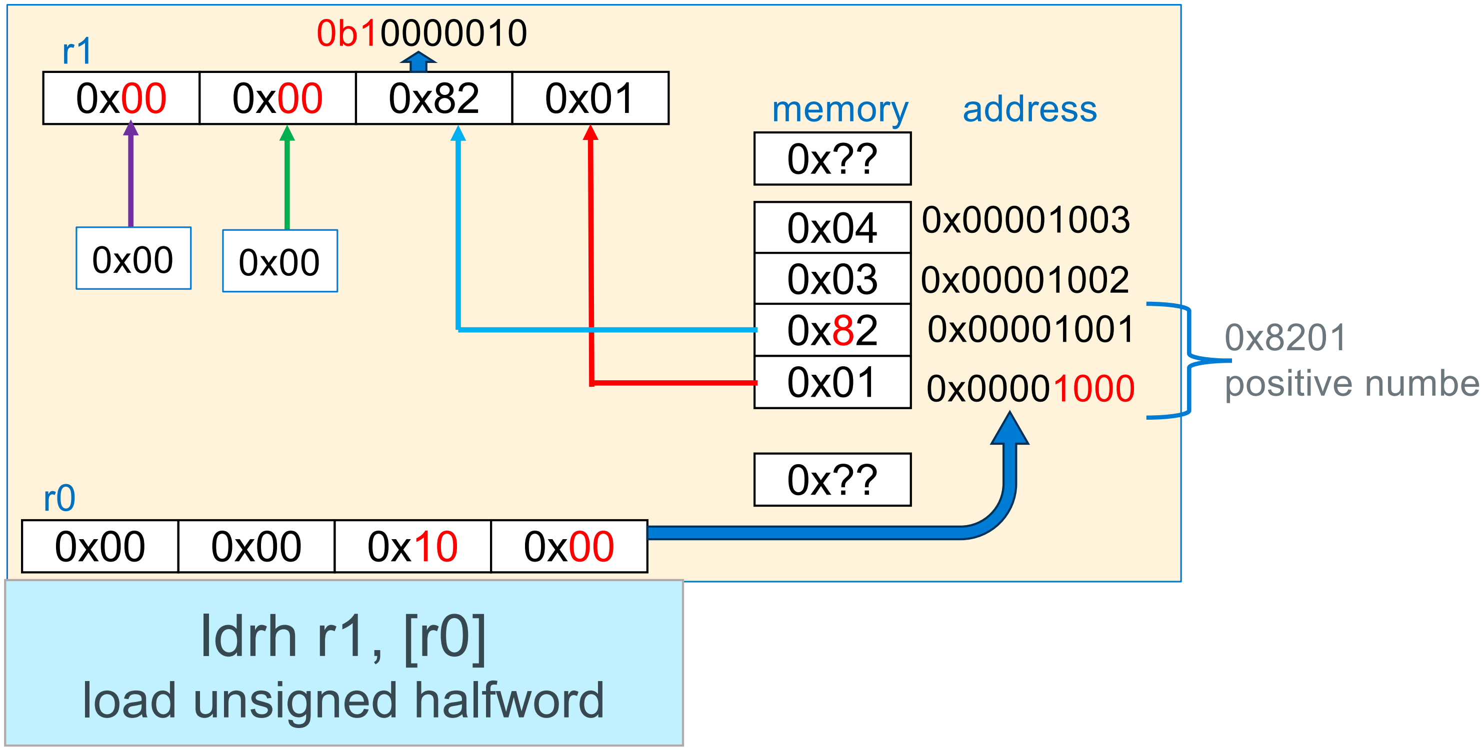
Loading 32-bit Registers From Memory, 16-bit Unsigned



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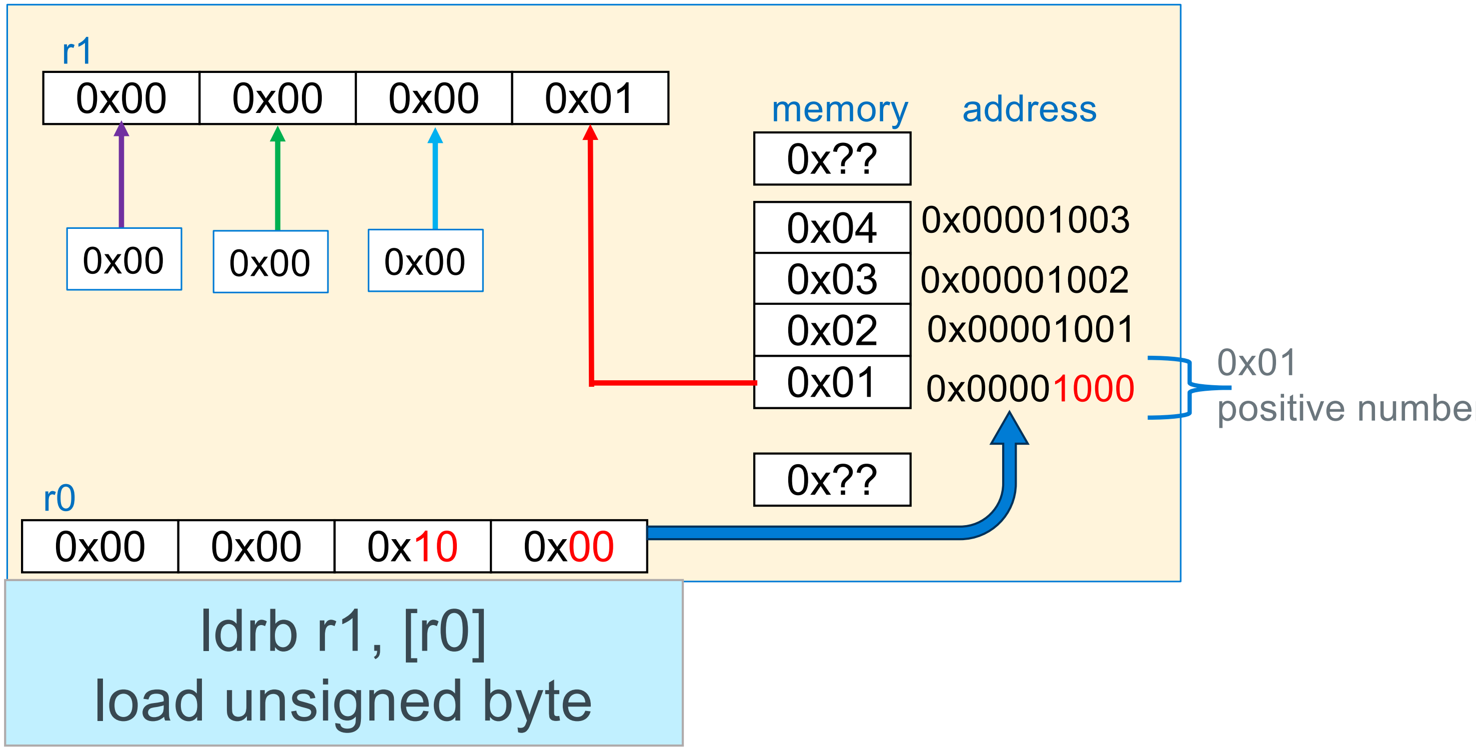
Loading 32-bit Registers From Memory, 8-bit



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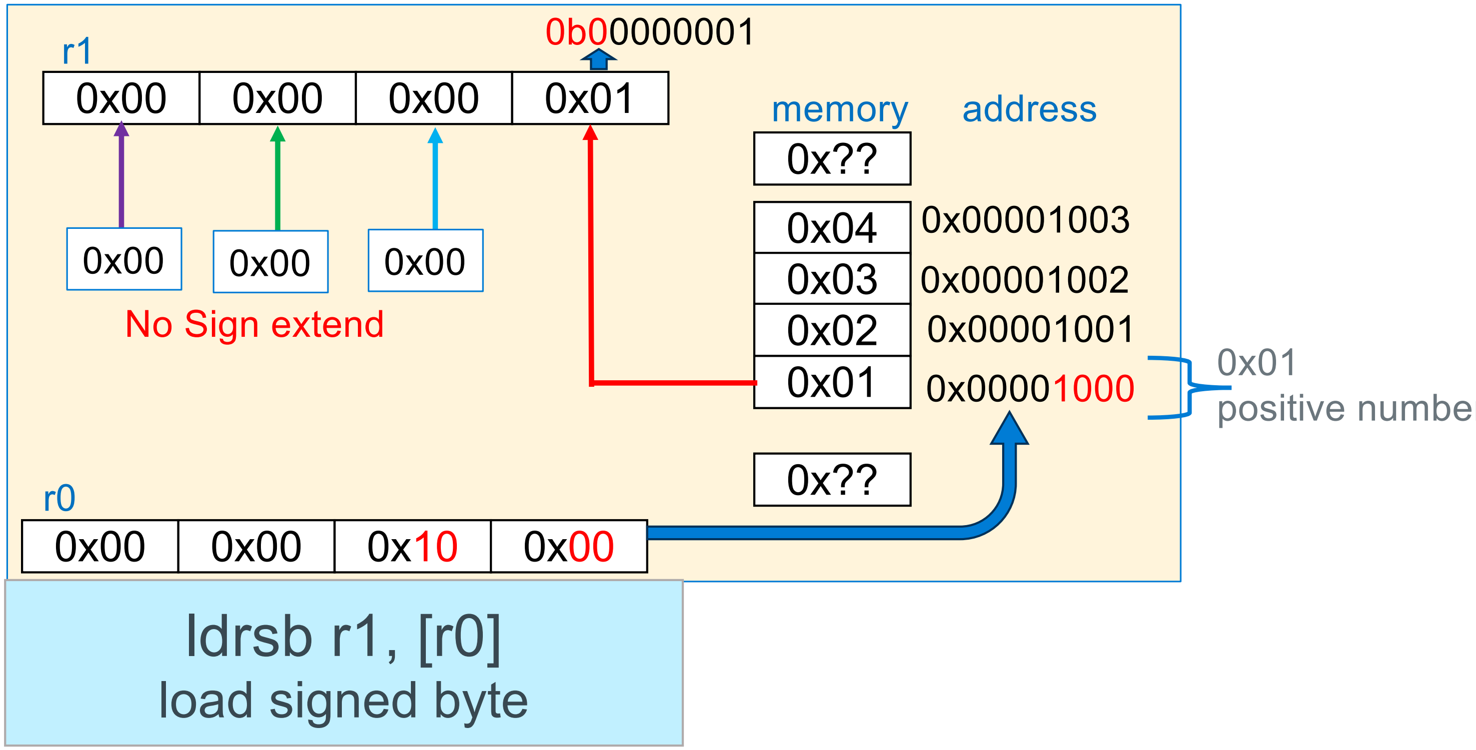
Loading 32-bit Registers From Memory, 8-bit



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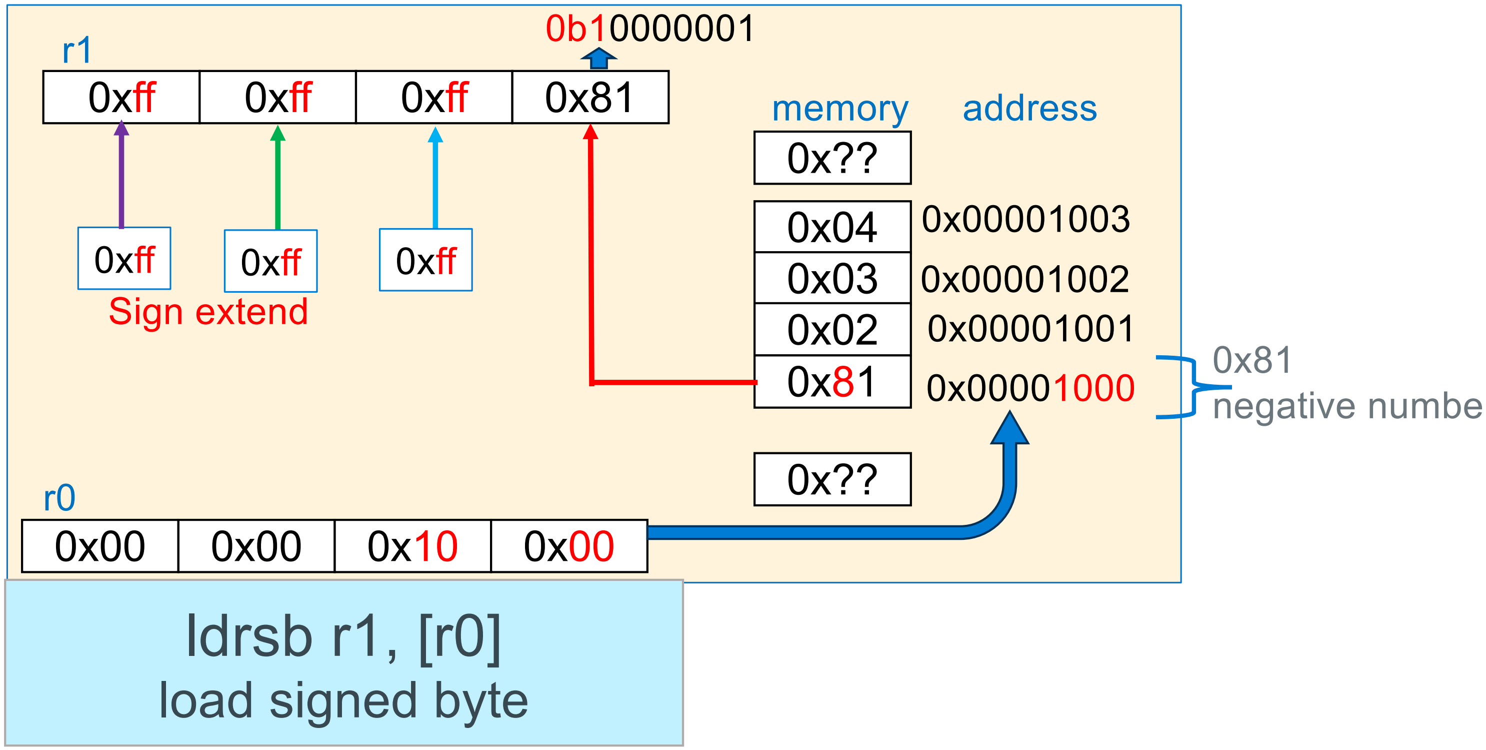
Loading 32-bit Registers From Memory, 8-bit Signed



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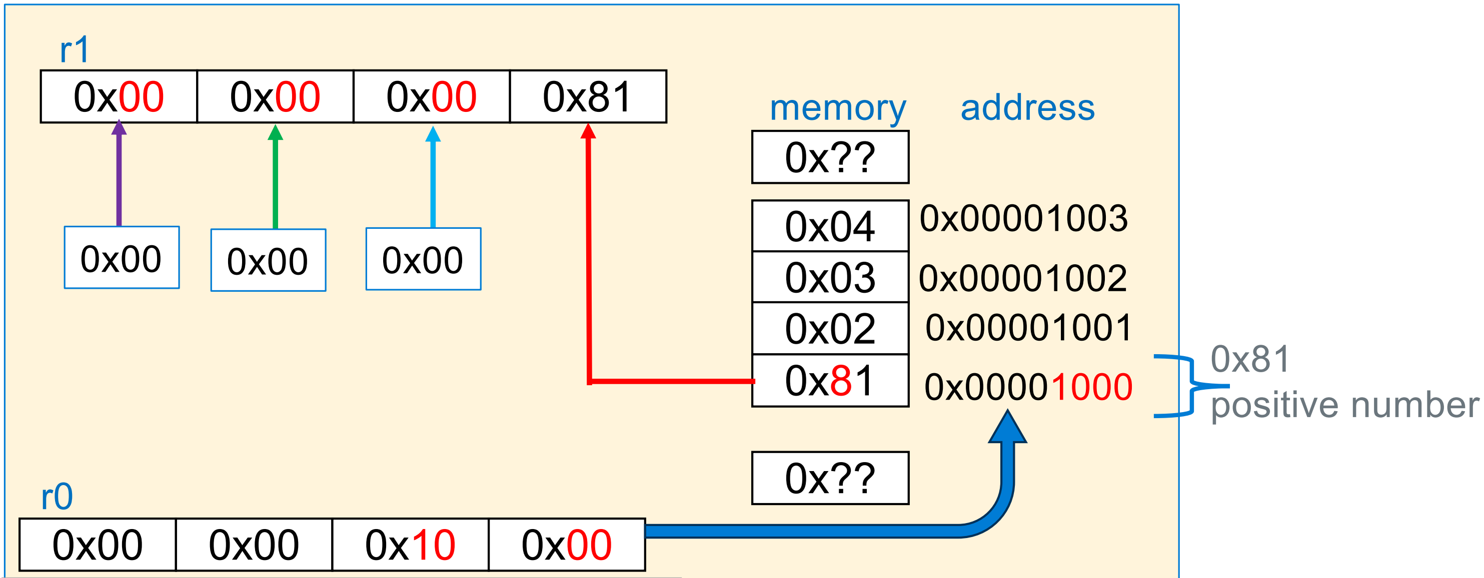
Loading 32-bit Registers From Memory, 8-bit Signed



ldrb r1, [r0]
load unsigned byte

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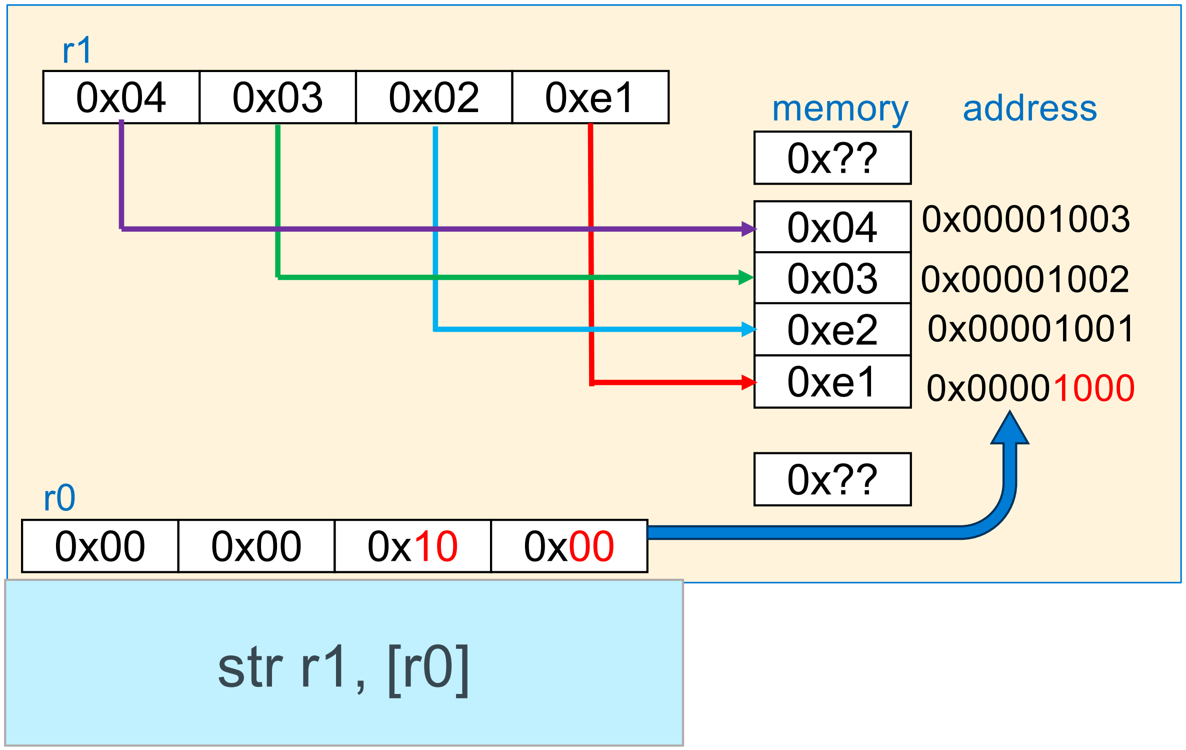
Storing 32-bit Registers To Memory, 32-bit



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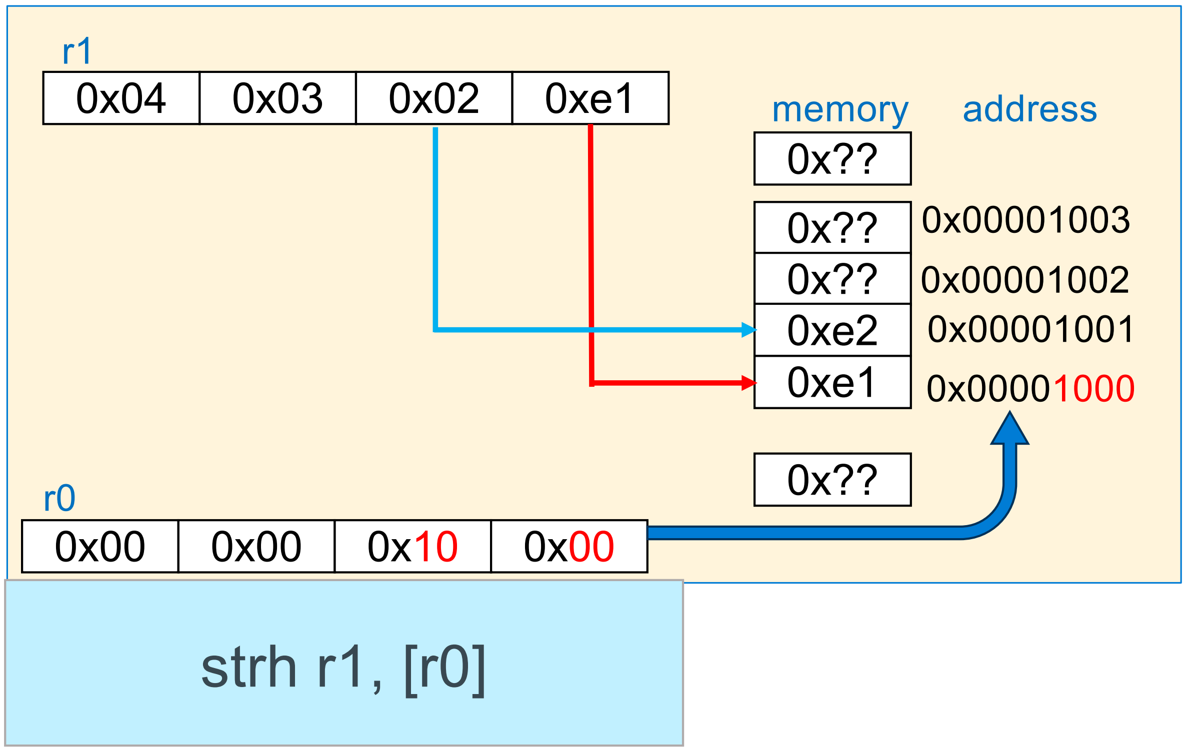
Storing 32-bit Registers To Memory, 16-bit



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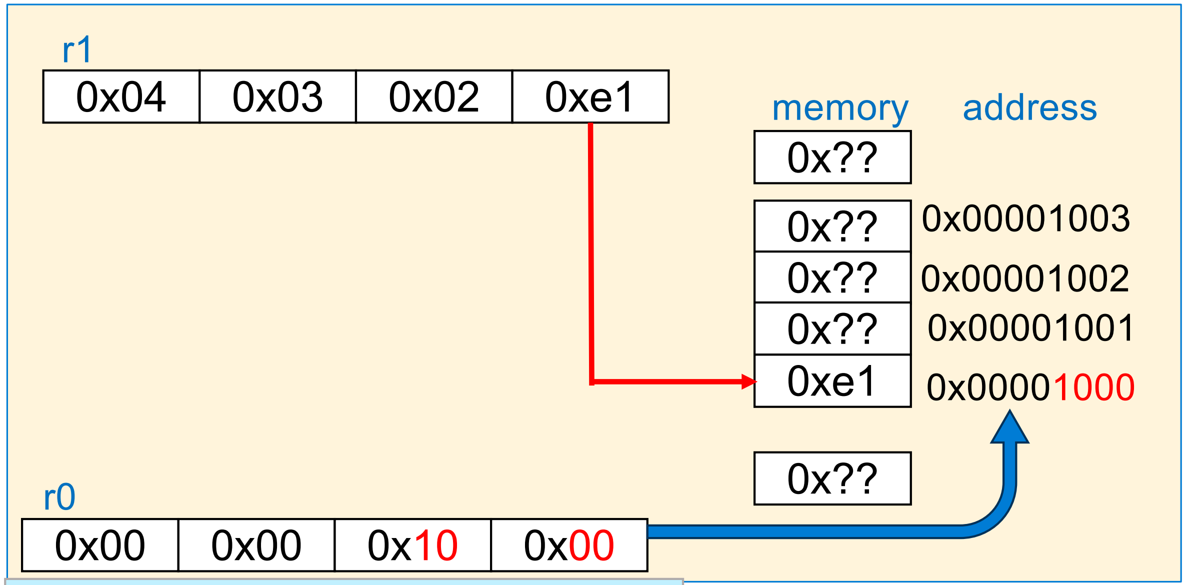
Storing 32-bit Registers To Memory, 8-bit

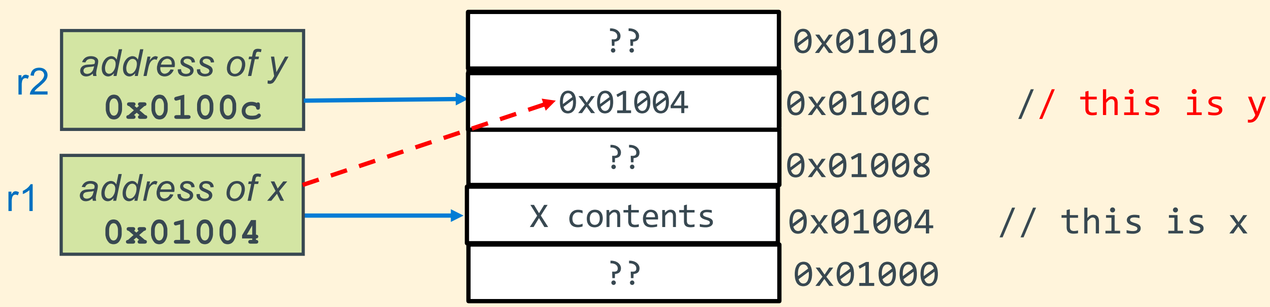


strb r1, [r0]

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
```

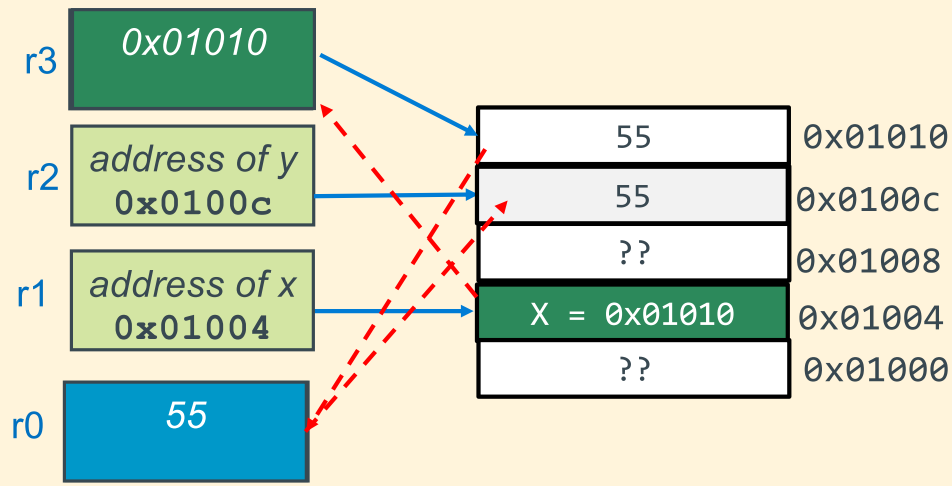

x

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)
{
    int *end = src + end;

    if (cnt <= 0)
        return;
    do {
        *dst++ = *src++;
    } while (src < end);
    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

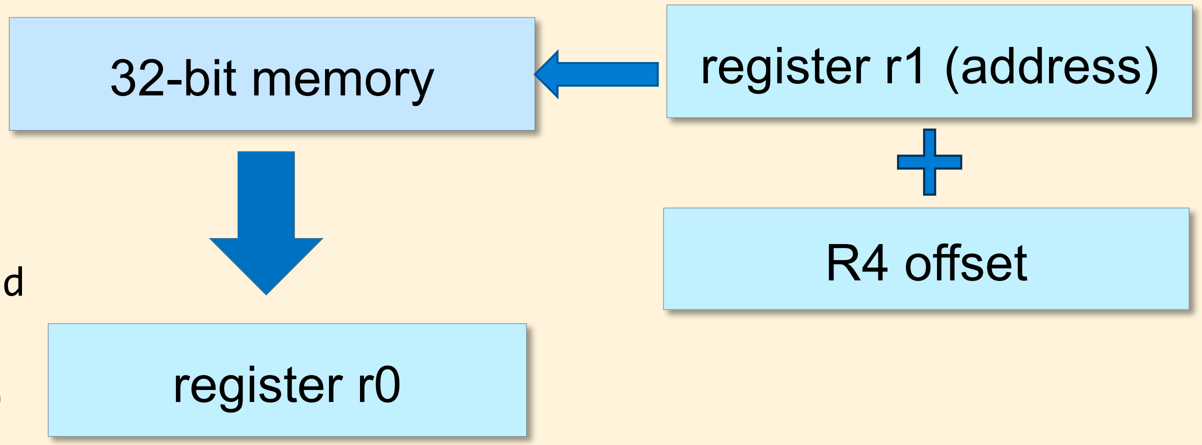
loop guard

x

Load/Store: Register Base Addressing + Register Offset

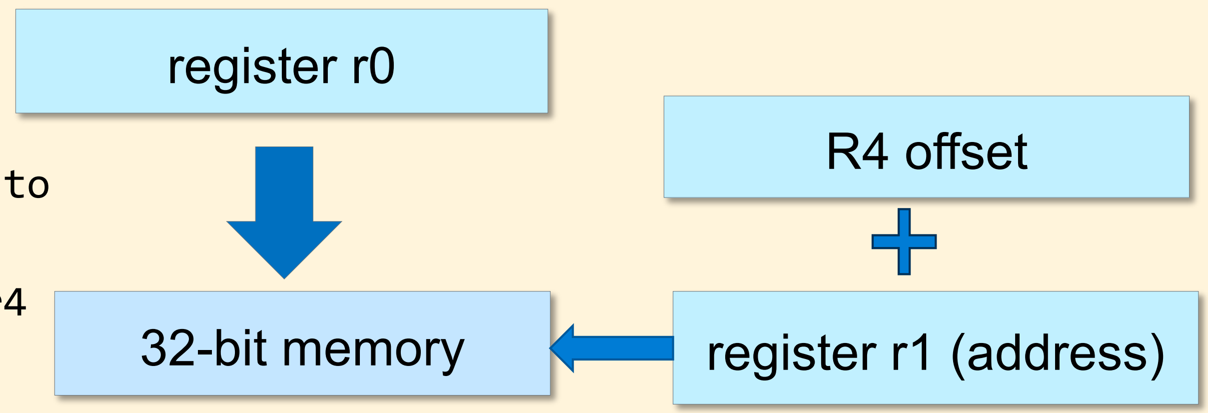
```
ldr r0, [r1, r4]
```

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

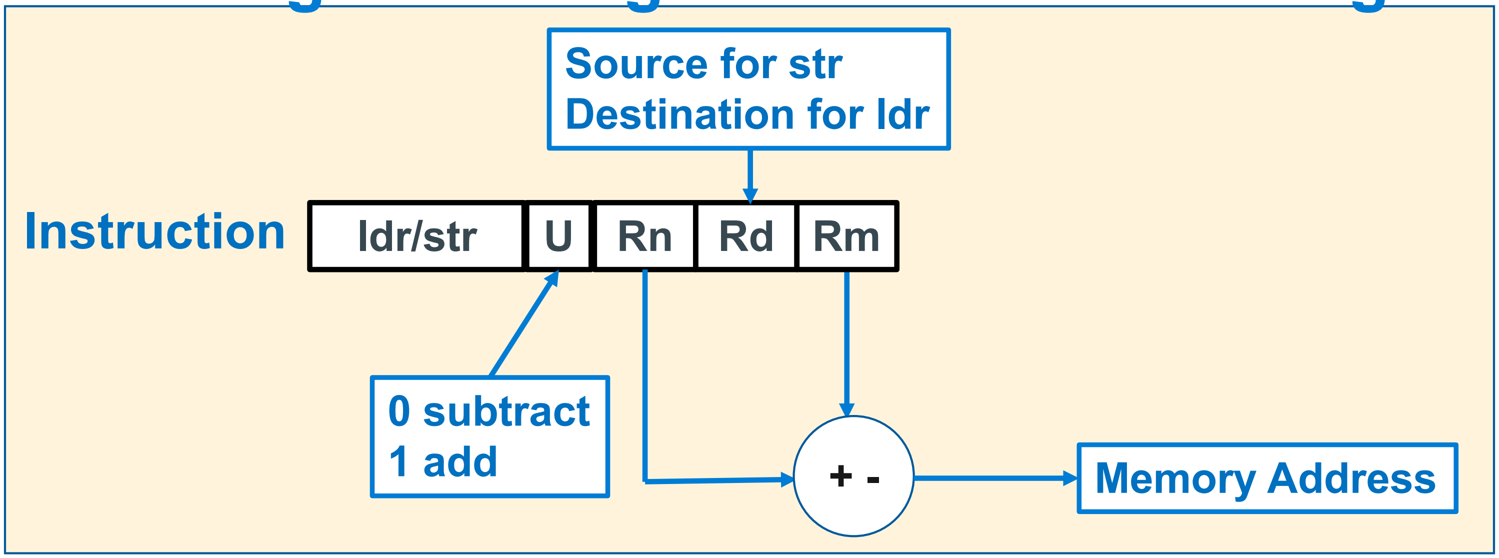



```
str  r0, [r1, r4]
```

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



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]`

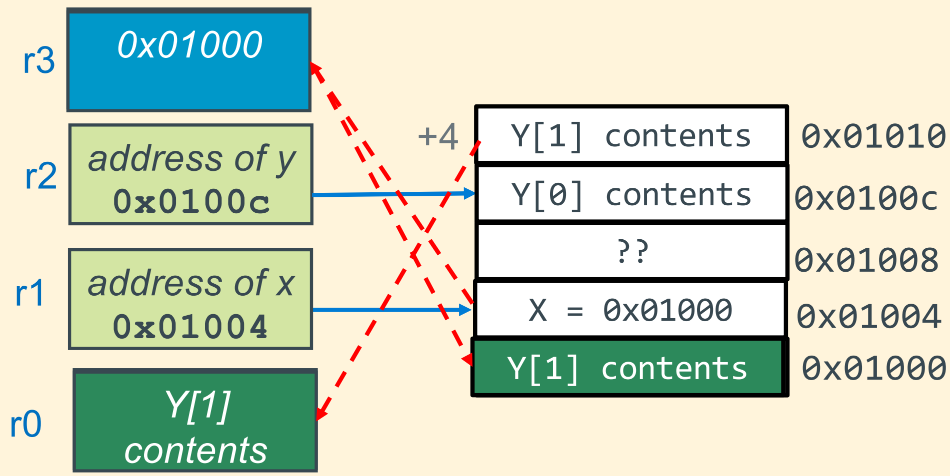
x

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];

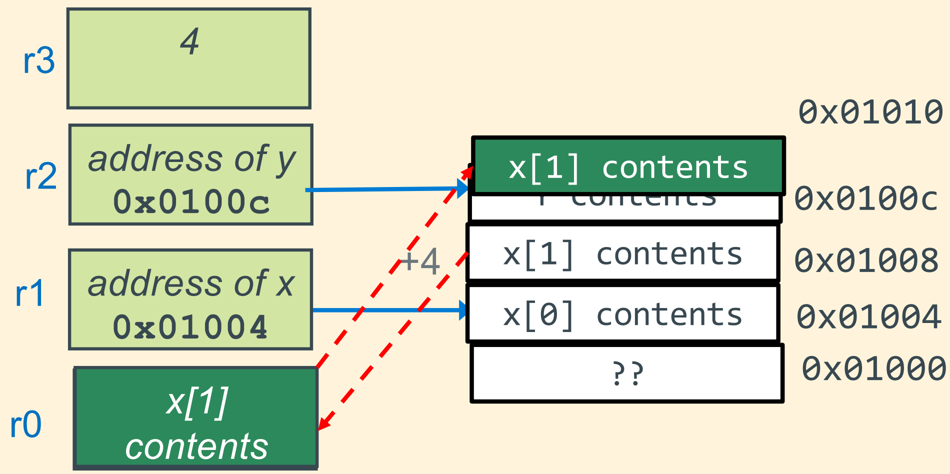



```
ldr    r0, [r2, 4]        // r0 ← y[1]
ldr    r3, [r1]           // r3 ← x
str    r0, [r3]           // *x ← y[1]
```


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];
```




```
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

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,…

```
count:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF

    mov     r2, 0
    cmp     r1, 0
    ble     .Ldone
    mov     r3, 0
.Lfor:
    cmp     r3, r1
    bge     .Ldone

    ldrb    r4, [r0, r3]
    cmp     r4, 'A'
    blt     .Lendif
    cmp     r4, 'Z'
    bgt     .Lendif
    add     r2, r2, 1

.Lendif:
    add     r3, r3, 1
    b       .Lfor

.Ldone:
    mov     r0, r2
```

loop guard

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

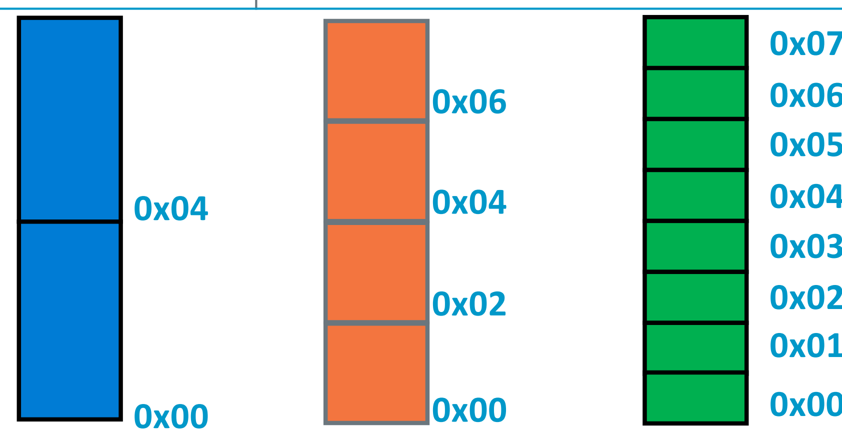
Variable SIZE	Directive	.align	C static variable Definition	Assembler static variable Definition
8-bit char (1 byte)	.byte		char chx = 'A' char string[] = {'A','B','C', 0};	chx: .byte 'A' string: .byte 'A','B',0x42,0
16-bit int (2 bytes)	.short	.align 1	short length = 0x55aa;	length: .short 0x55aa

32-bit int (4 bytes)	.word
	.long
		.align 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"

```
Rule: Place the align above the variable
      .align 1
len:  .short 0x55aa
```

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
```

See cnt is not word aligned

```
<chx>: 12028   00000041
<cnt>: 12029   00000004
```

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

See cnt is word aligned

```
<chx>: 12028   00000041
<cnt>: 1202c   00000004
```

Sets alignment for **next** variable

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

```
.bss
            .align 2
num:        .word 0
.data
            .align 2
ptr:        .word num
            .align 2
lit:        .word .Lmsg
            .align 2
msg:        .string "123"
.section .rodata
.Lmsg:      .string "456"
```

initializes a pointer

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 variablesinto 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?

mov	Rd	rot4	imm8

fails →
```
mov     r0, 1023
```
xxx.s:24: Error: invalid constant (3ff) after fixup

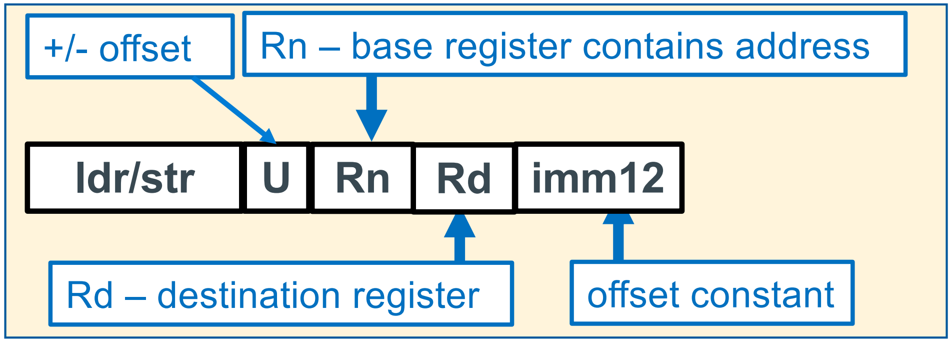
replacement →
```
ldr     r0, =1023
```

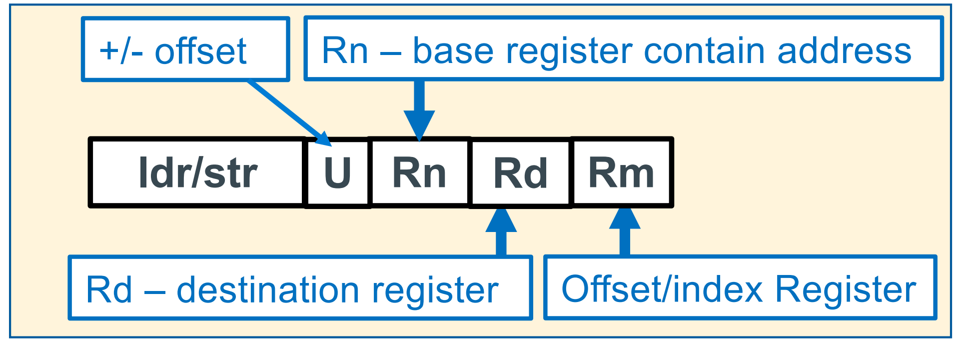
- Answer: use `ldr` instruction with the constant as an operand: **`=constant`**
- Assembler creates a **literal table entry** with the **constant**

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


x

Reference: LDR/STR – Register To/From Memory Copy





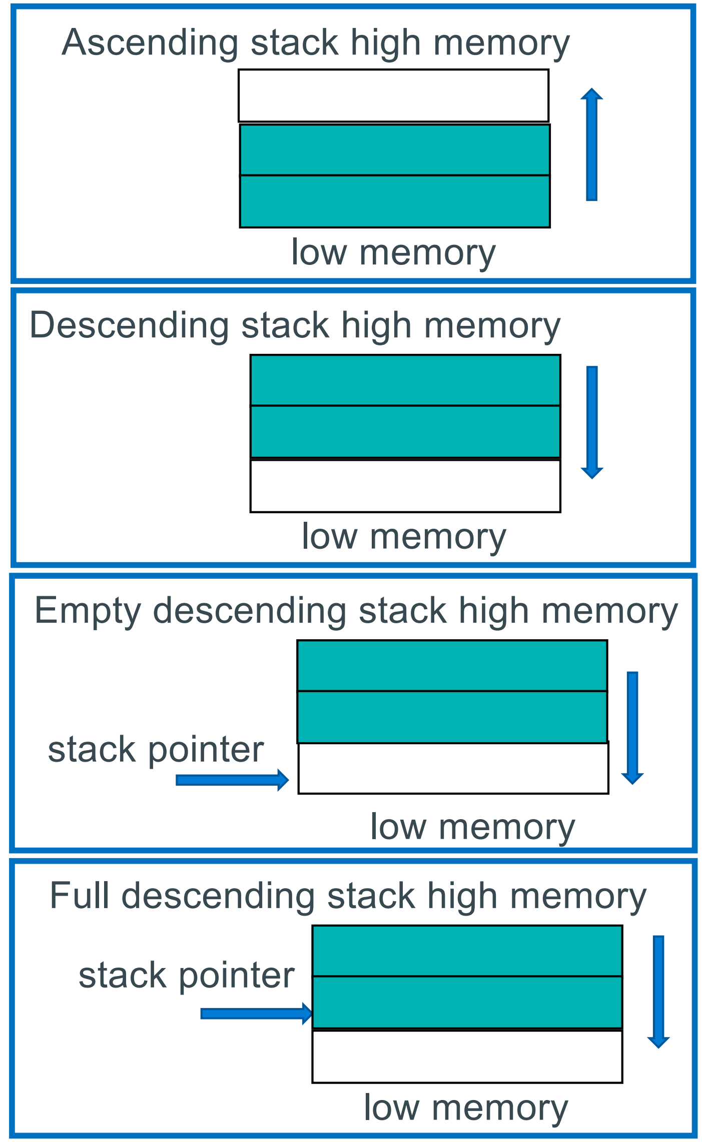

```
ldr/str  Rd,  [Rn, +- imm12] // base register pointer + offset  imm12 in bytes
                             -4095 <= imm12 <= 4095 (bytes)
ldr/str  Rd,  [Rn]           // base register pointer + 0 (imm12 is 0)
ldr/str  Rd,  [Rn, +- Rm]    // base register pointer +- offset register
```

```
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

Stack types

- A Stack Implements a **last-in first-out** (LIFO) protocol
- Each time a **function is called**, a **stack frame is activated**
  - space is allocated by moving the stack pointer
  - push adds space, pop removes space
- 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**



x

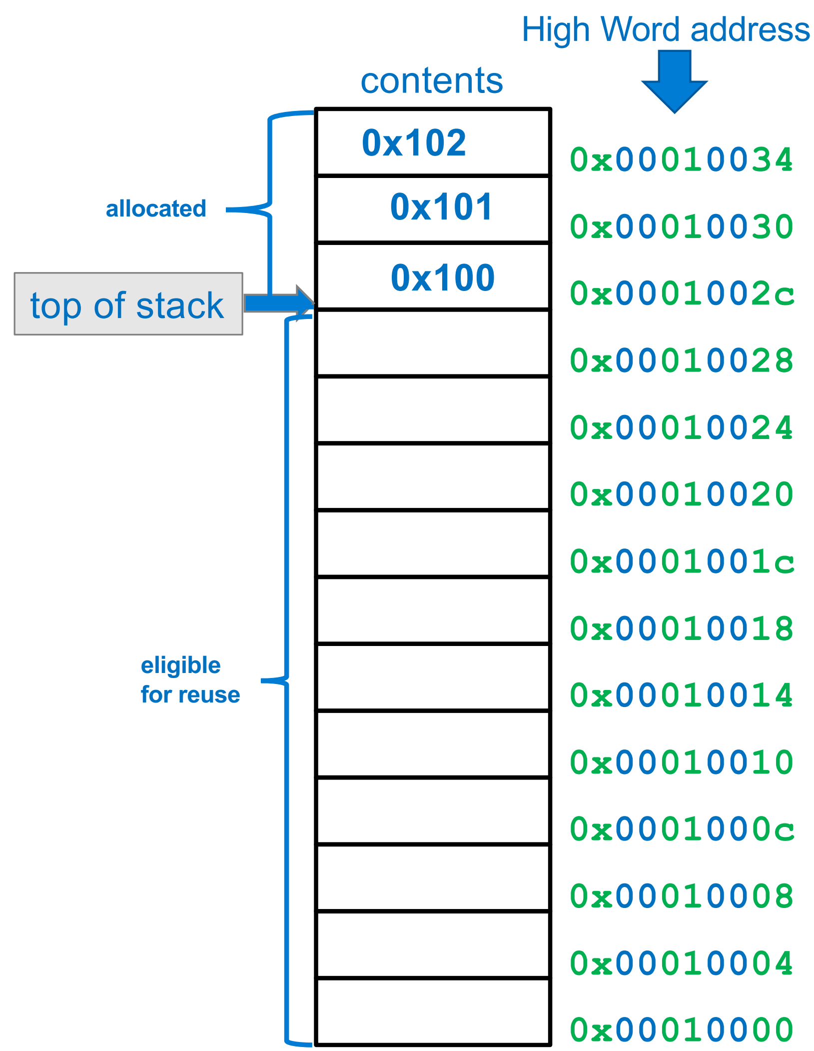
Arm: Stack Operation

- **Stack** is expandable and **grows downward** from high memory address towards low memory address
- **Stack pointer (sp)** **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)



Function Calls, Parameters and Locals: Requirements

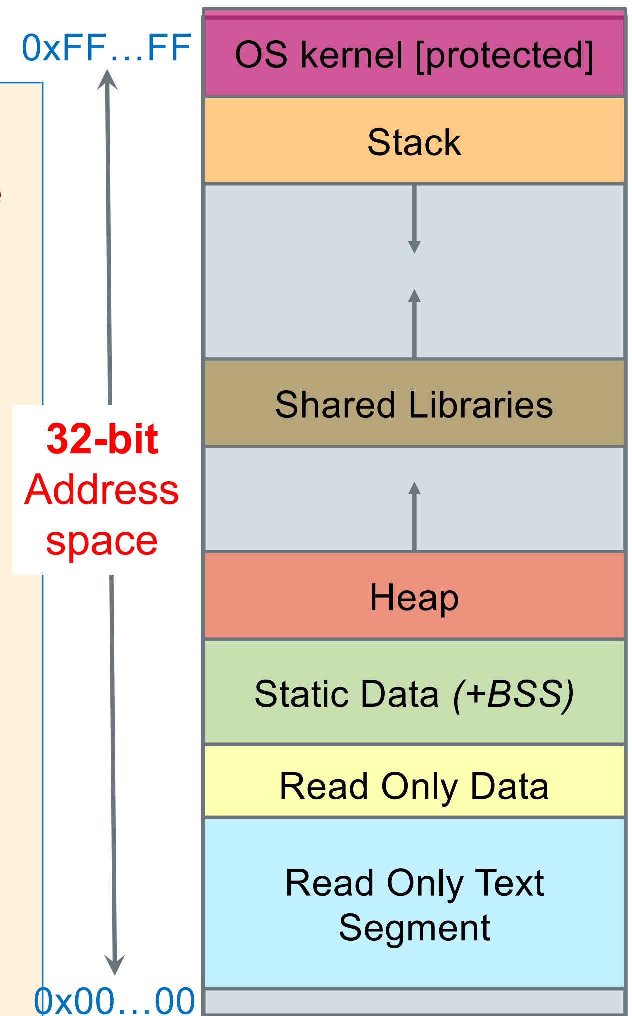
```
int
main(int argc, char *argv[])
{
    int x, z = 4;

    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

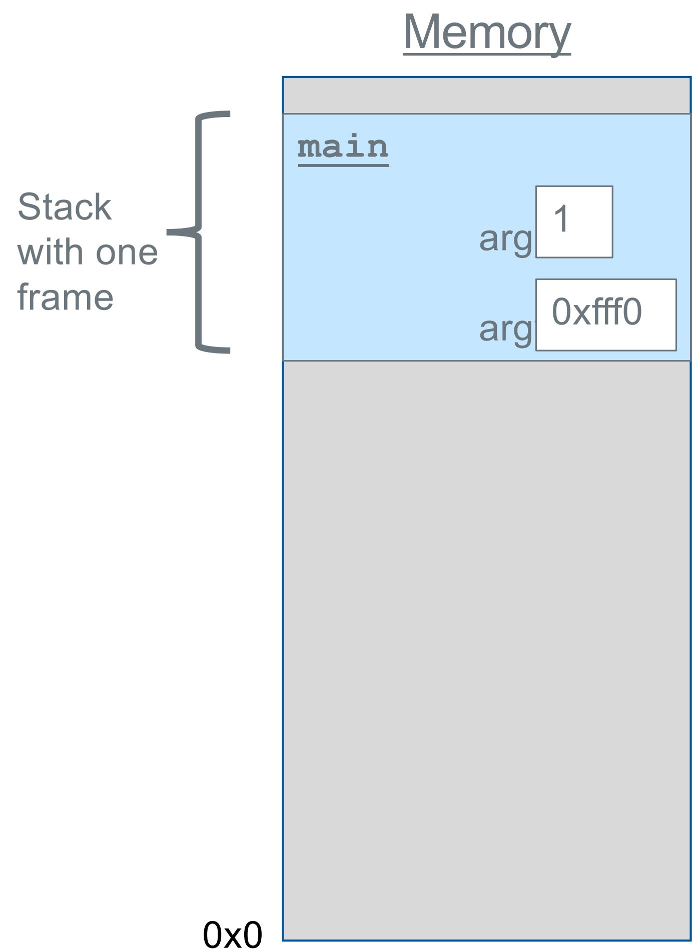
Stack Segment: Support of Functions

- 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)



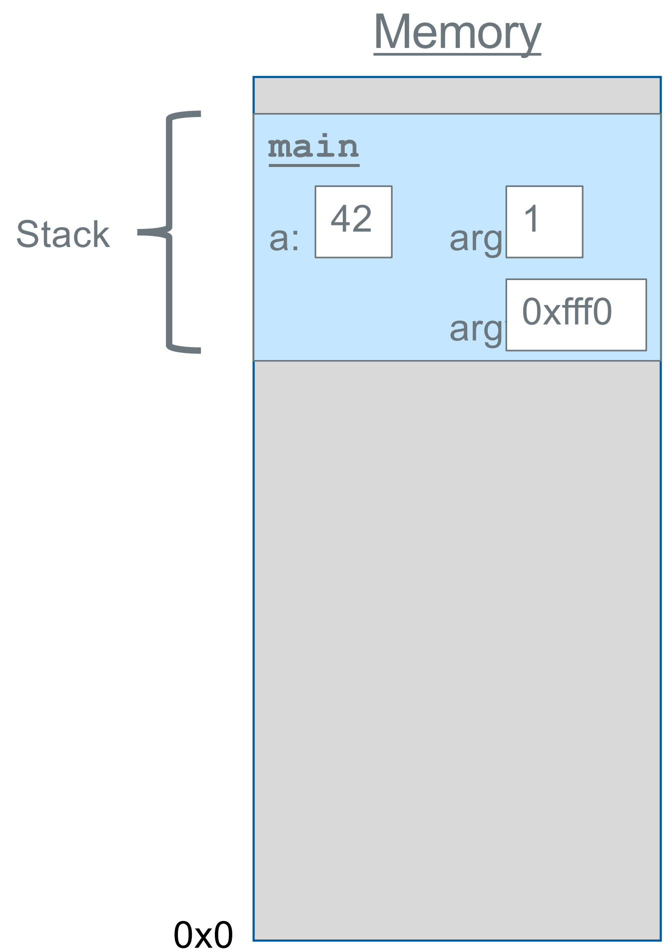
The Stack

```
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;
}
```



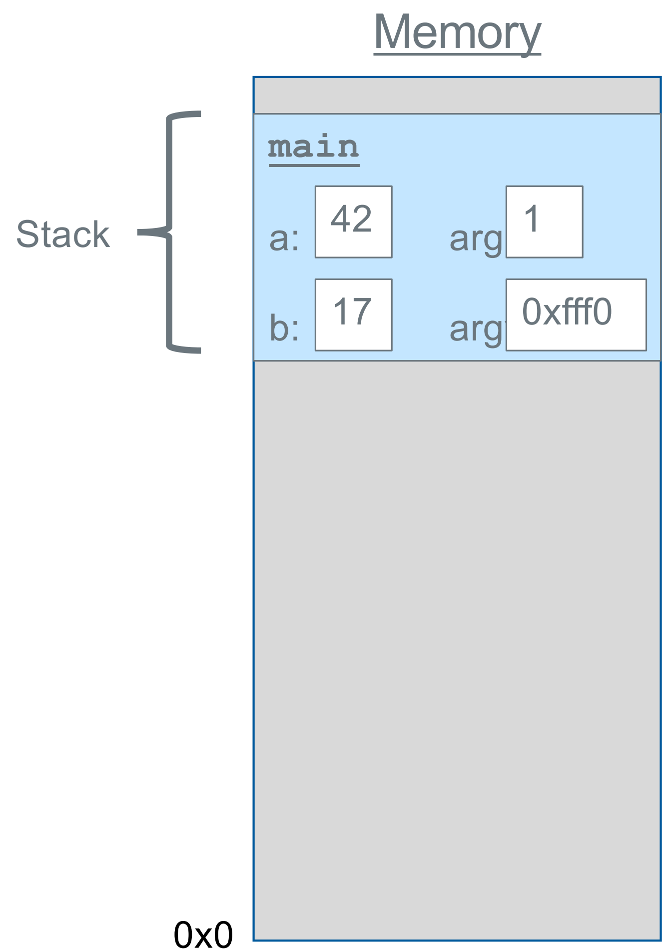
The Stack

```
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;
}
```



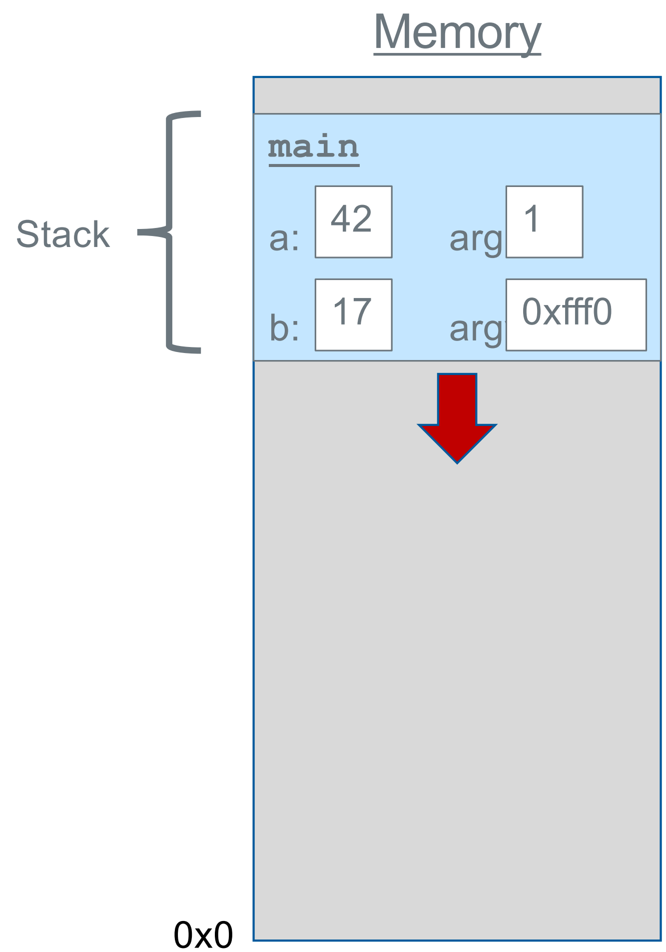
The Stack

```
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;
}
```



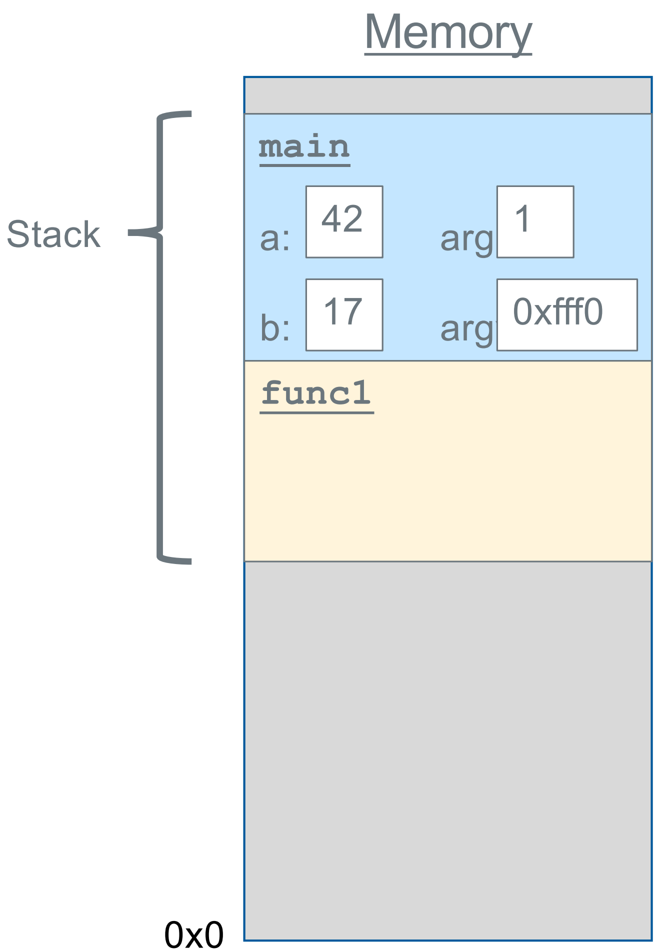
The Stack

```
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;
}
```



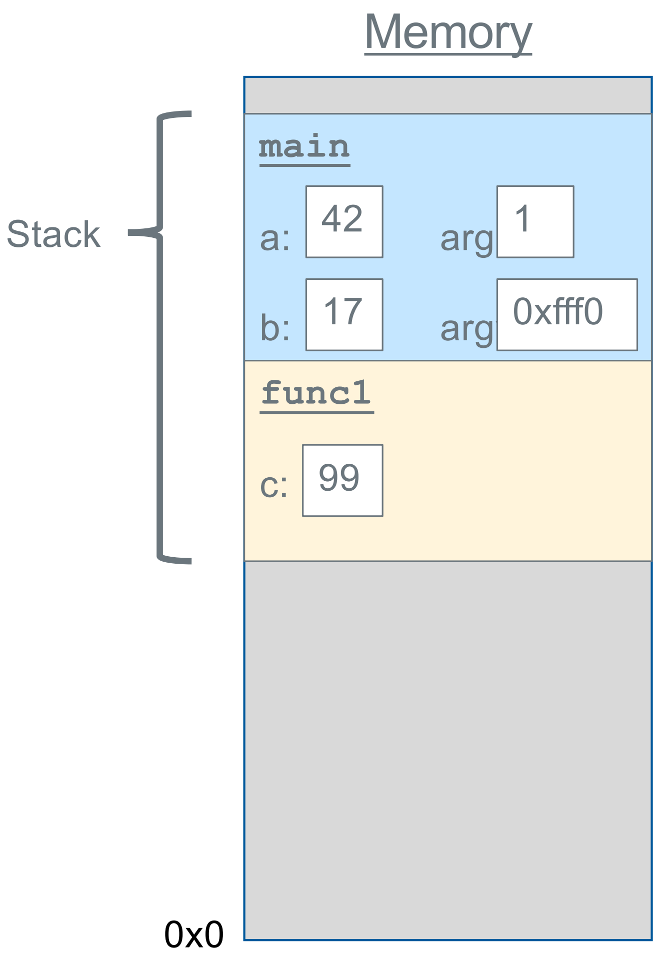
The Stack

```
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;
}
```



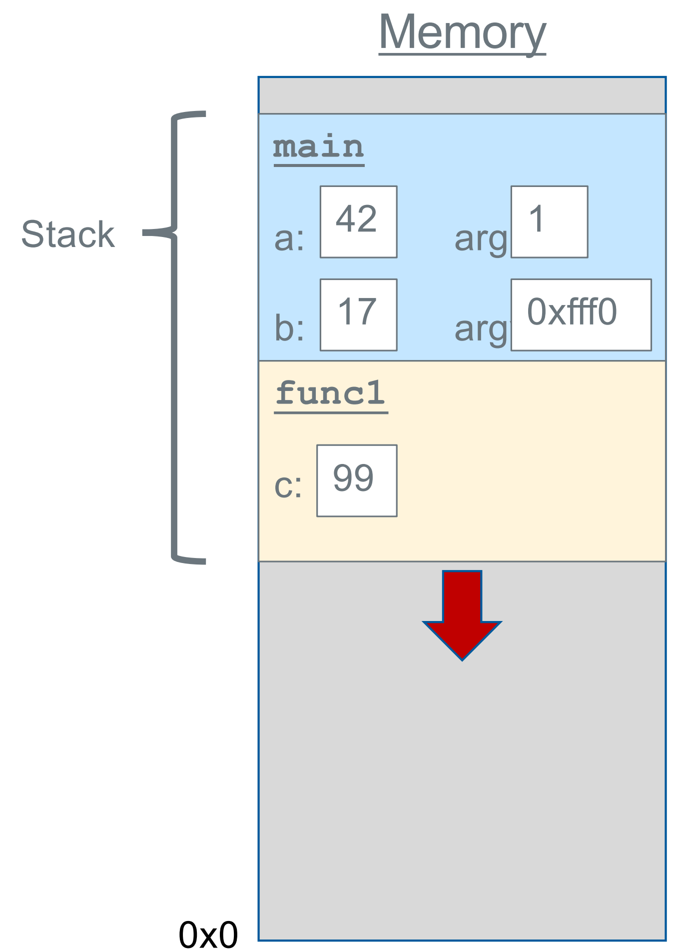
The Stack

```
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;
}
```



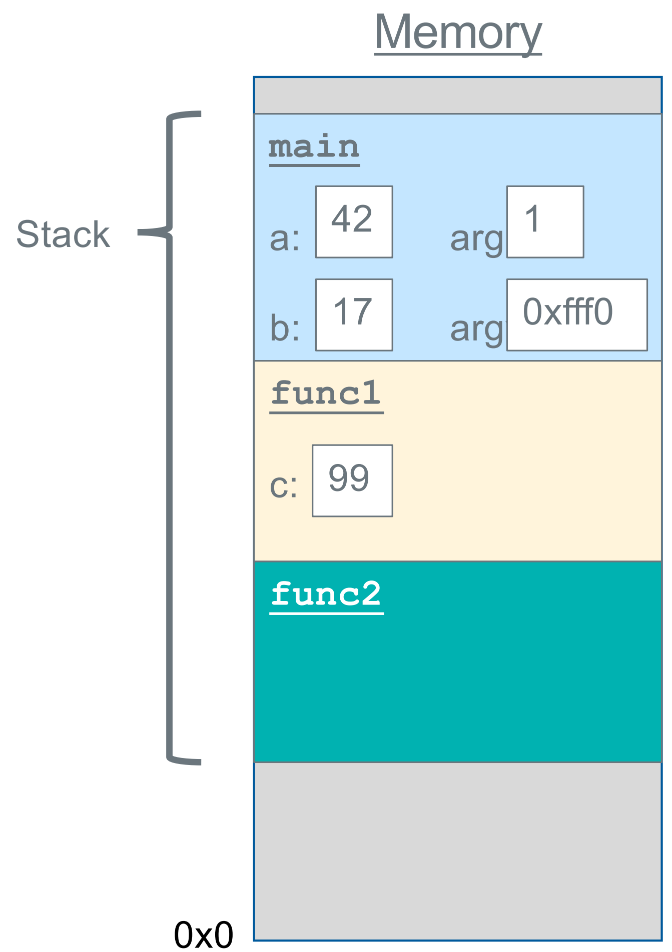
The Stack

```c
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;
}
```



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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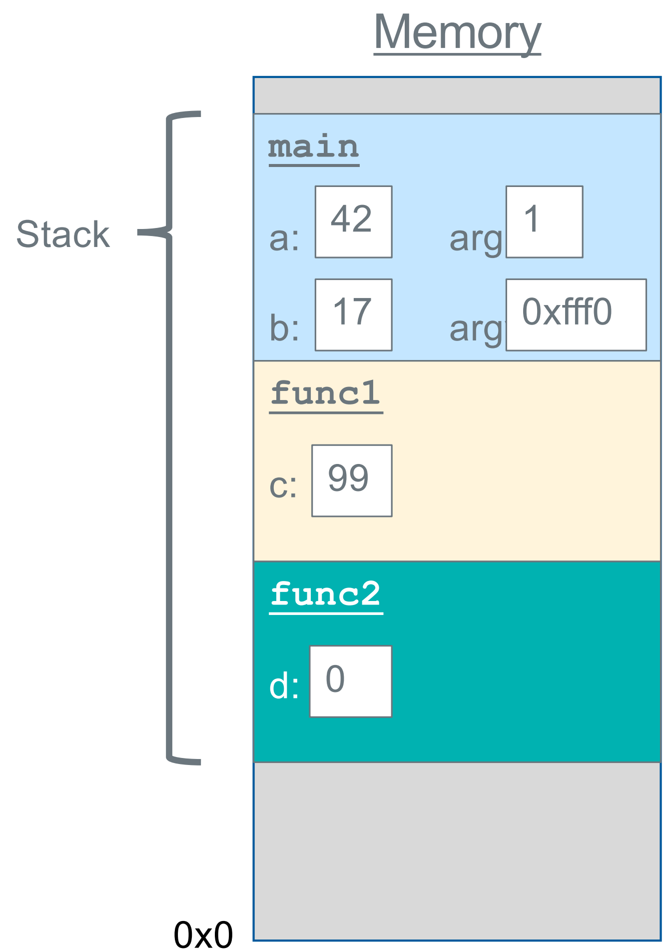

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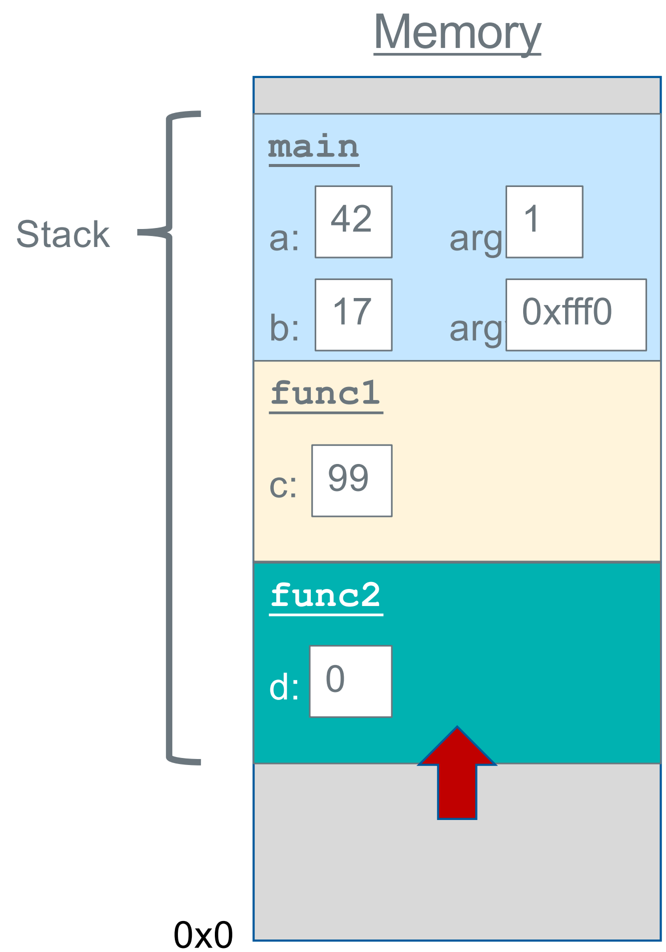

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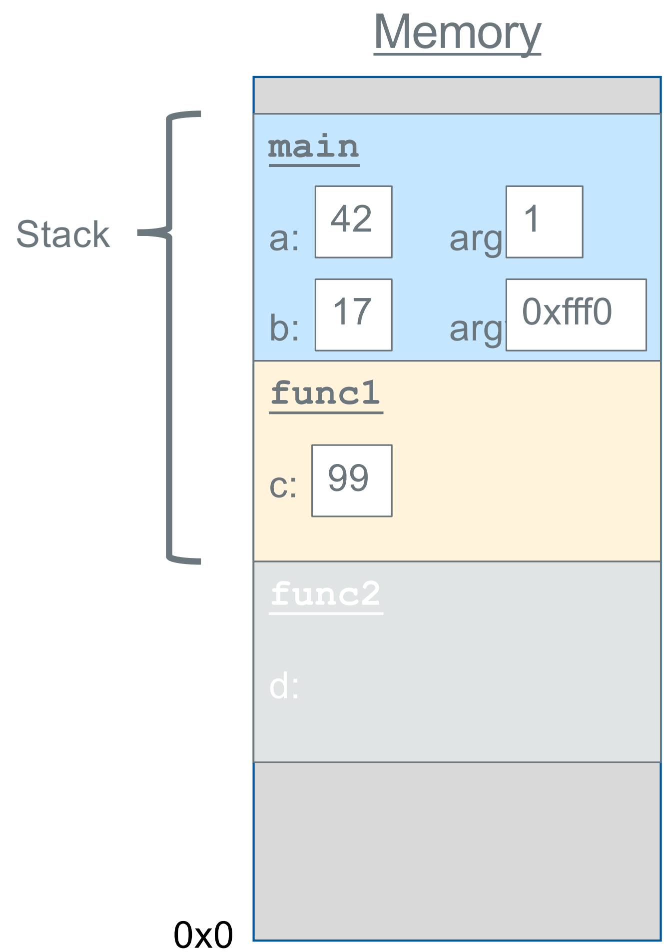

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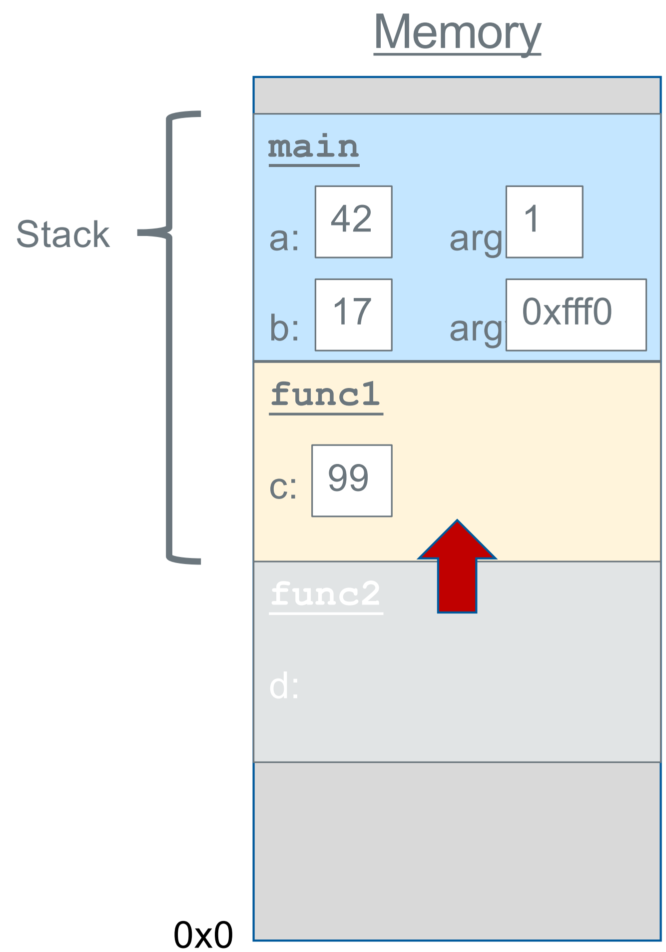

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}
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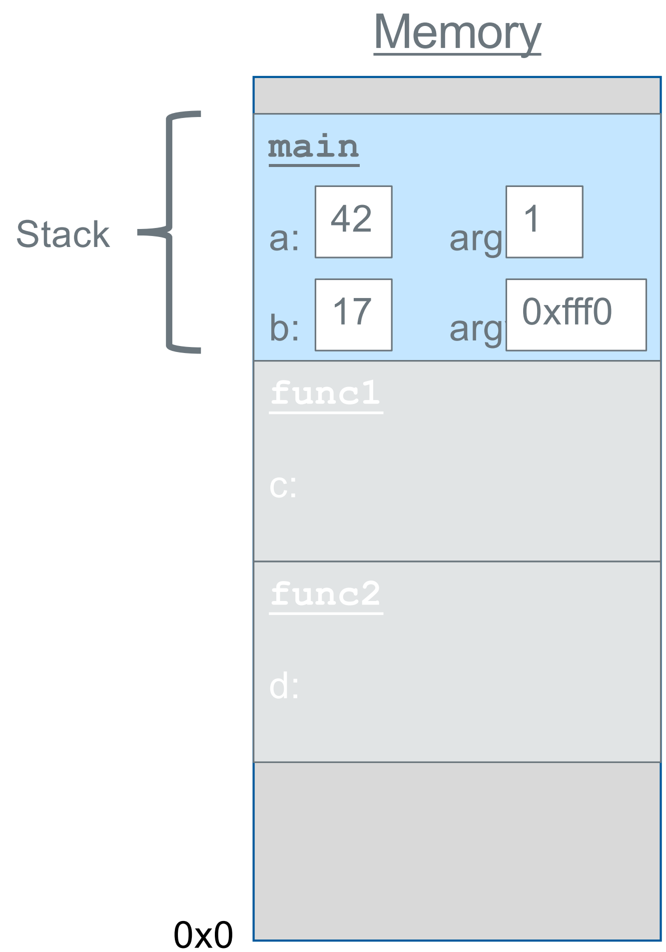

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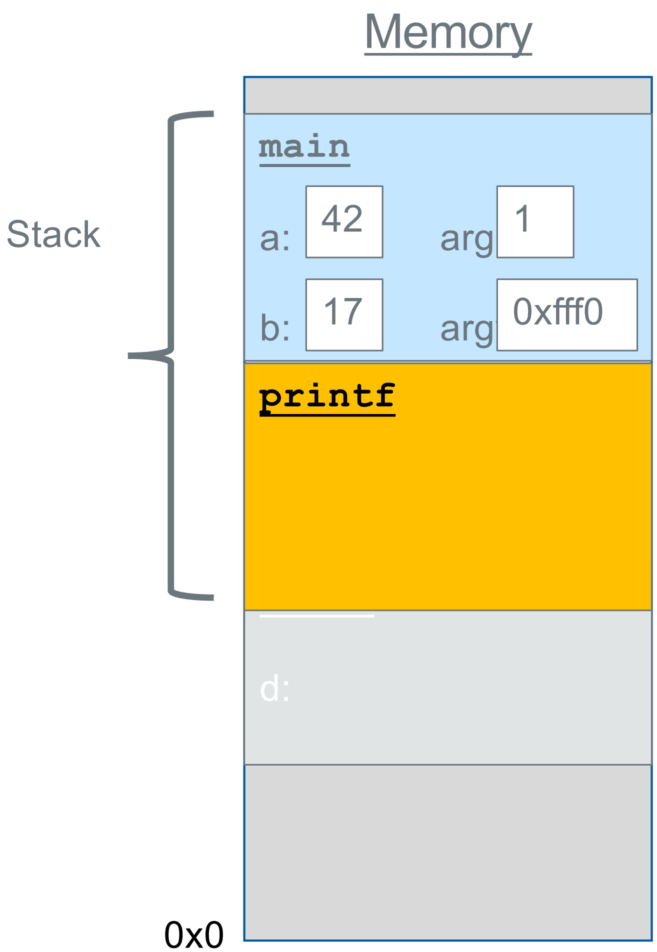

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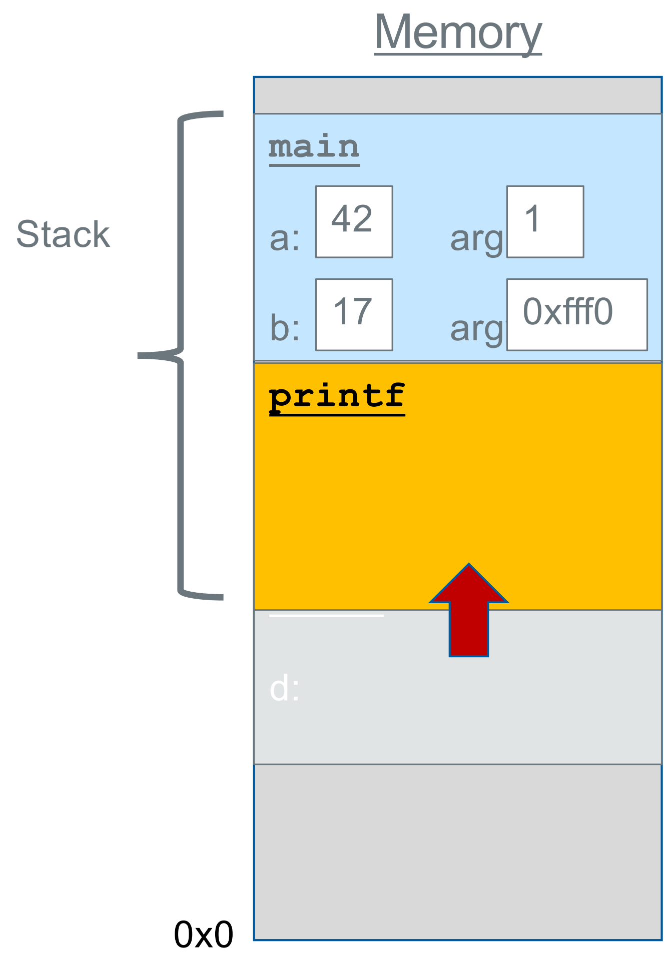

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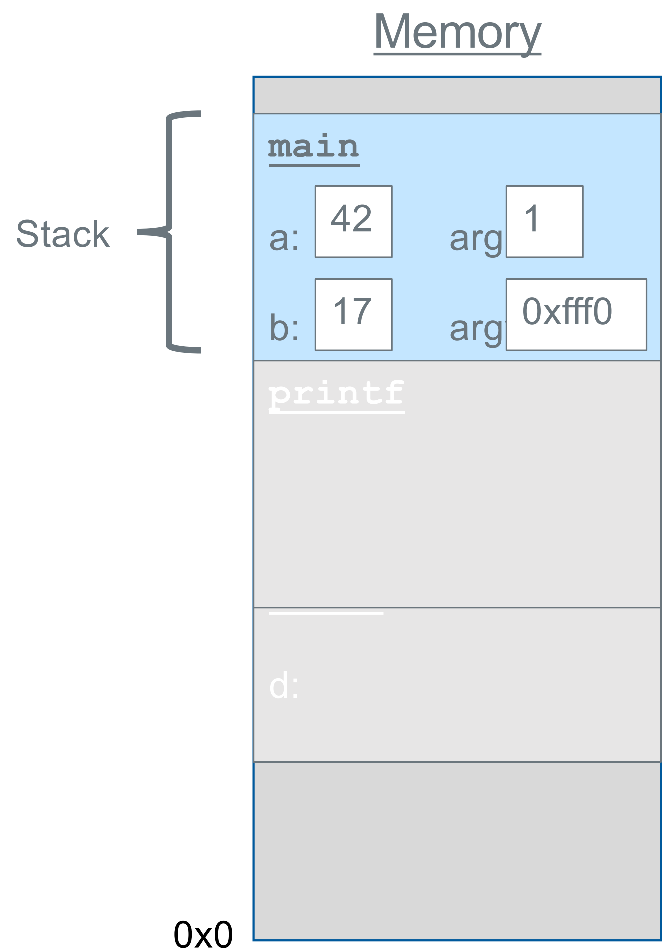

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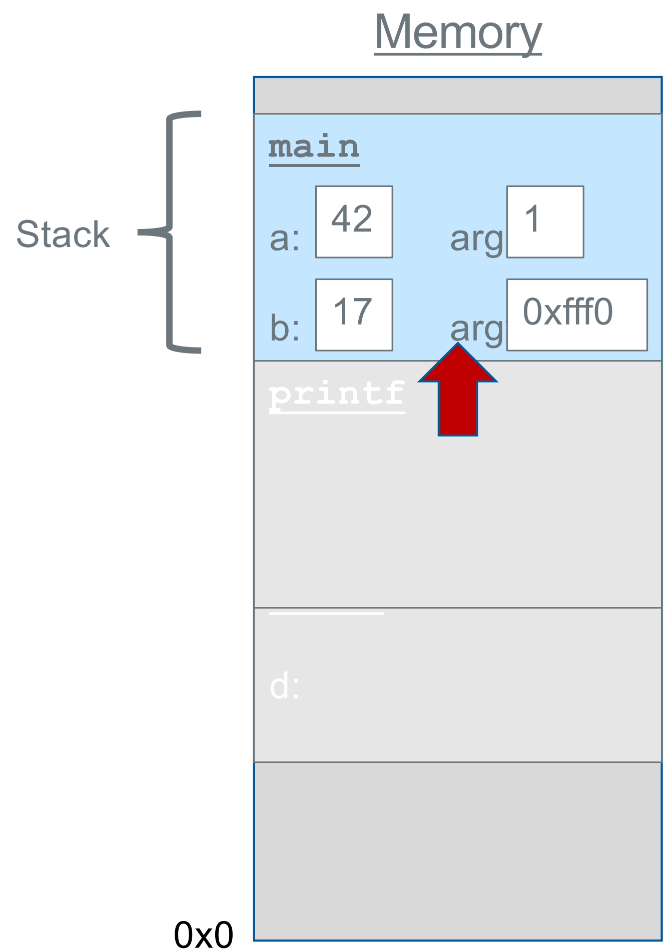

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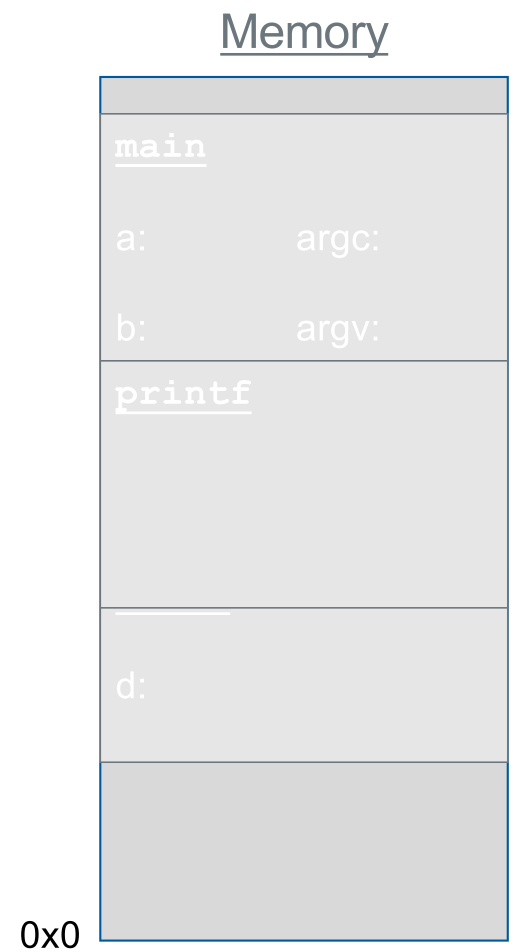
```

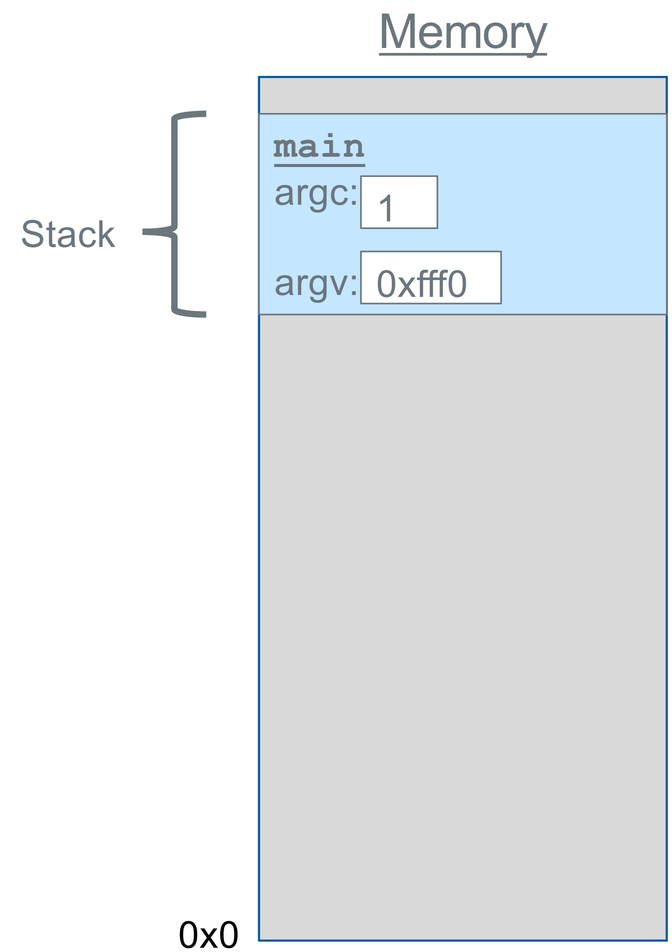


The Stack - Recursion

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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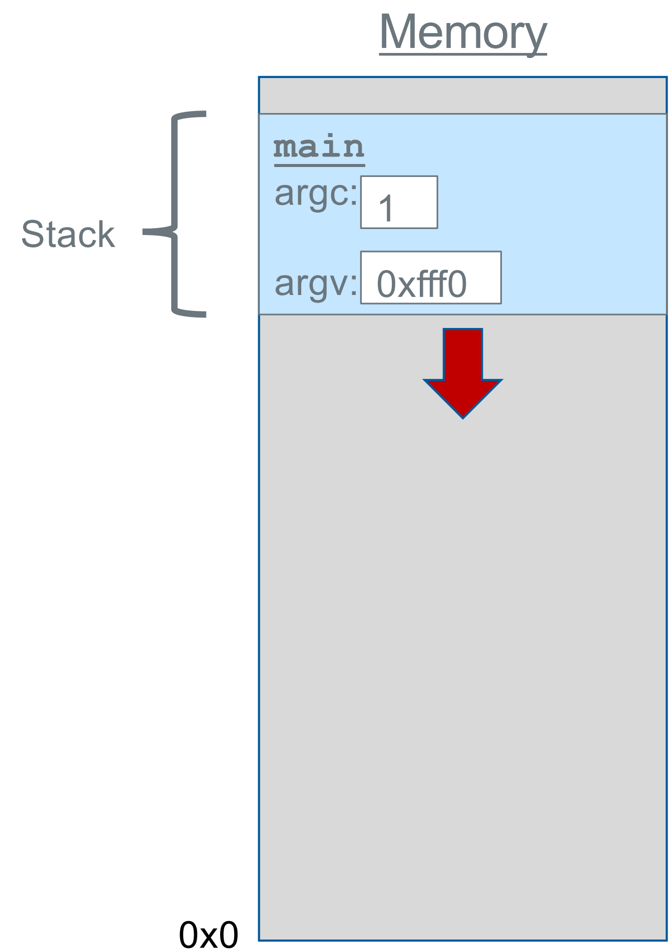

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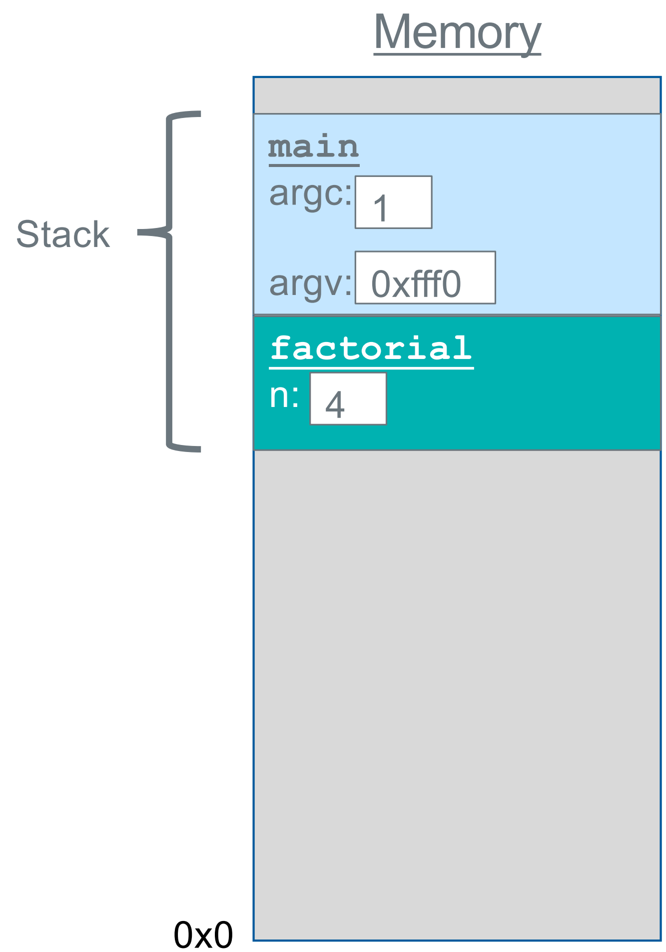

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}

int main(int argc, char *argv[]) {
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}
```

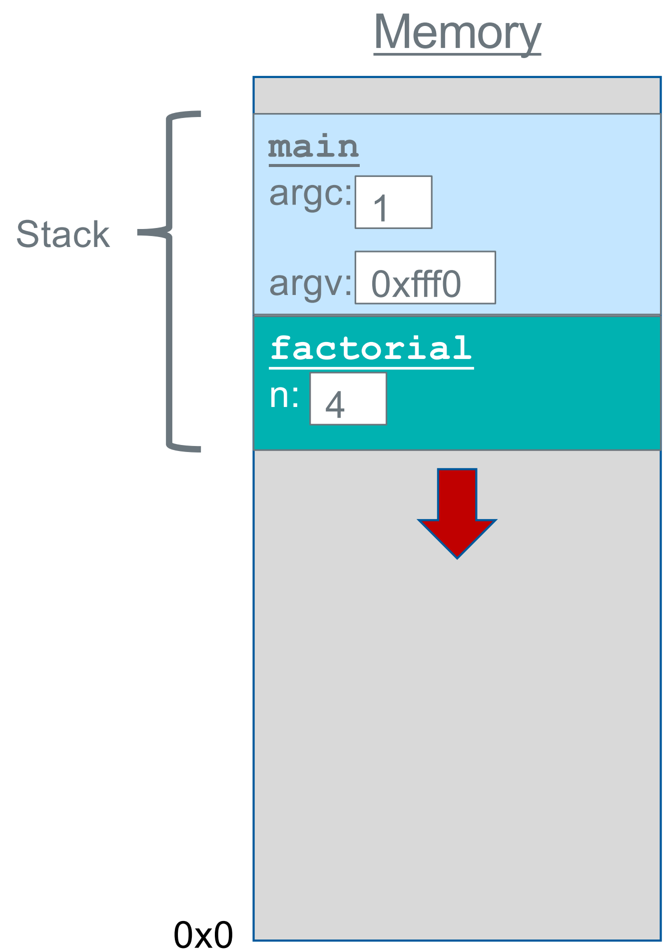

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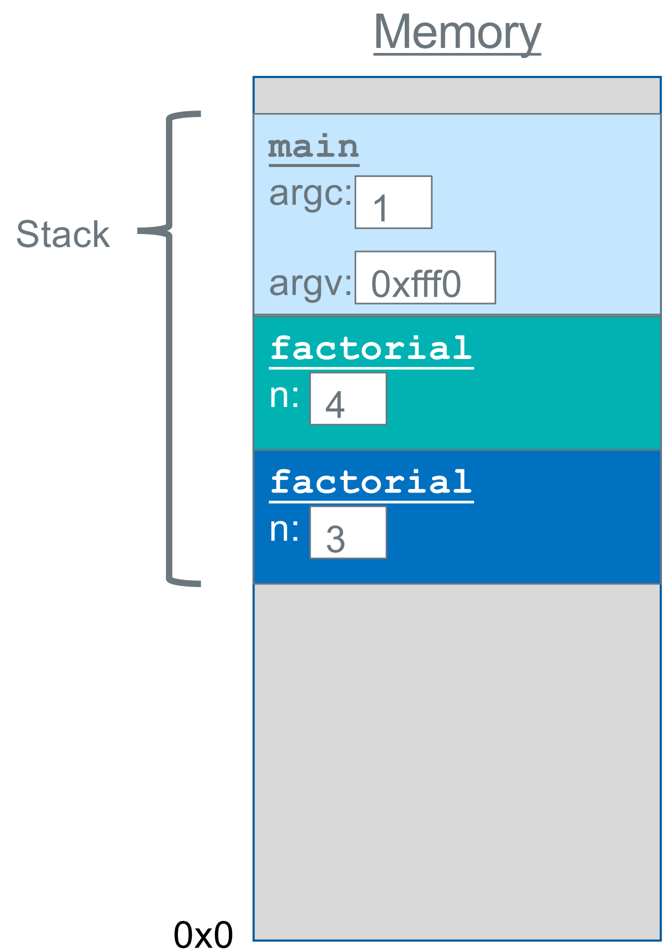

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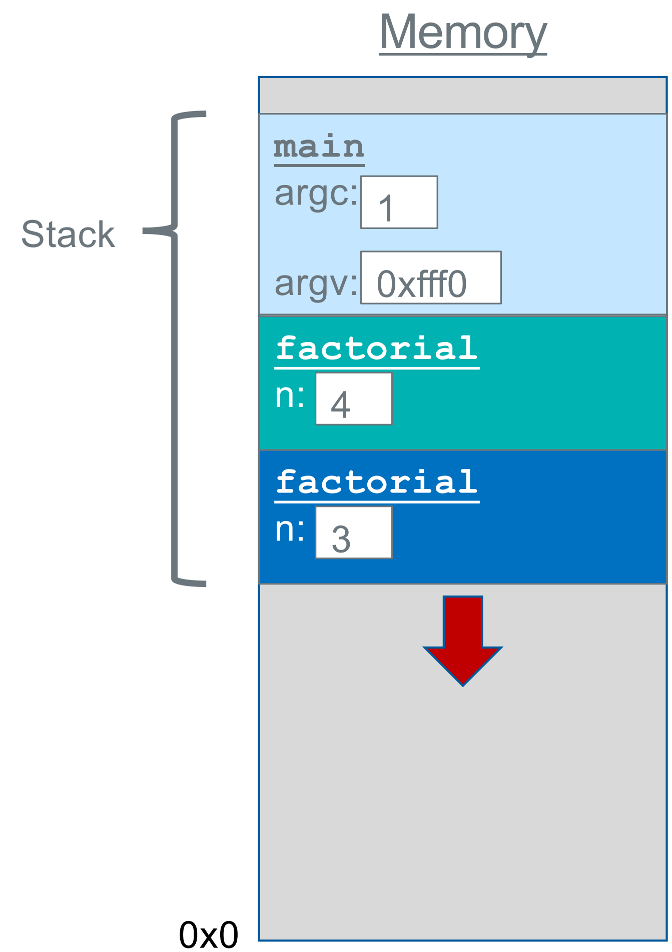

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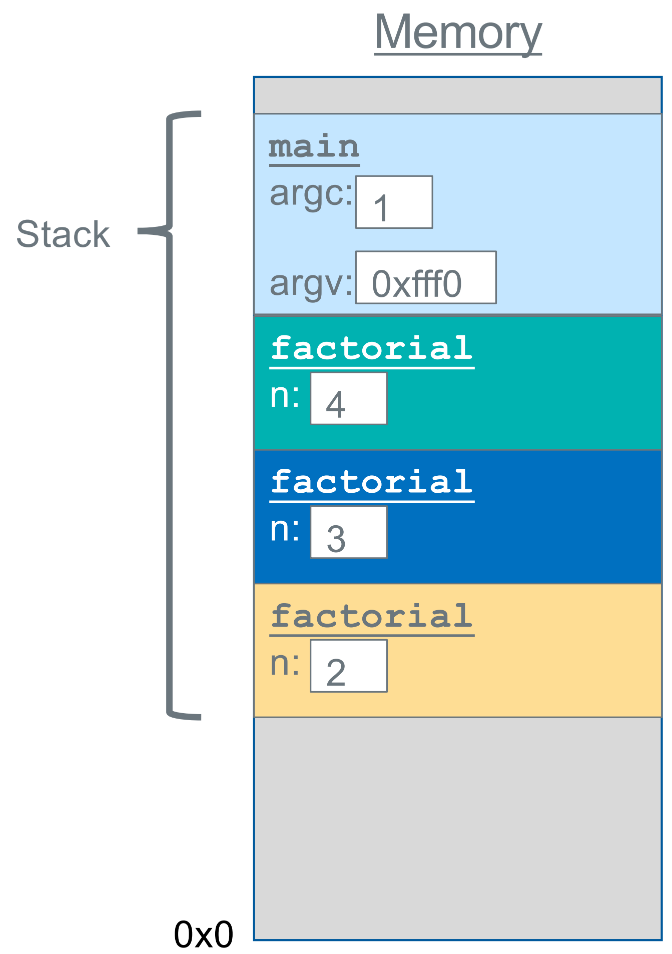

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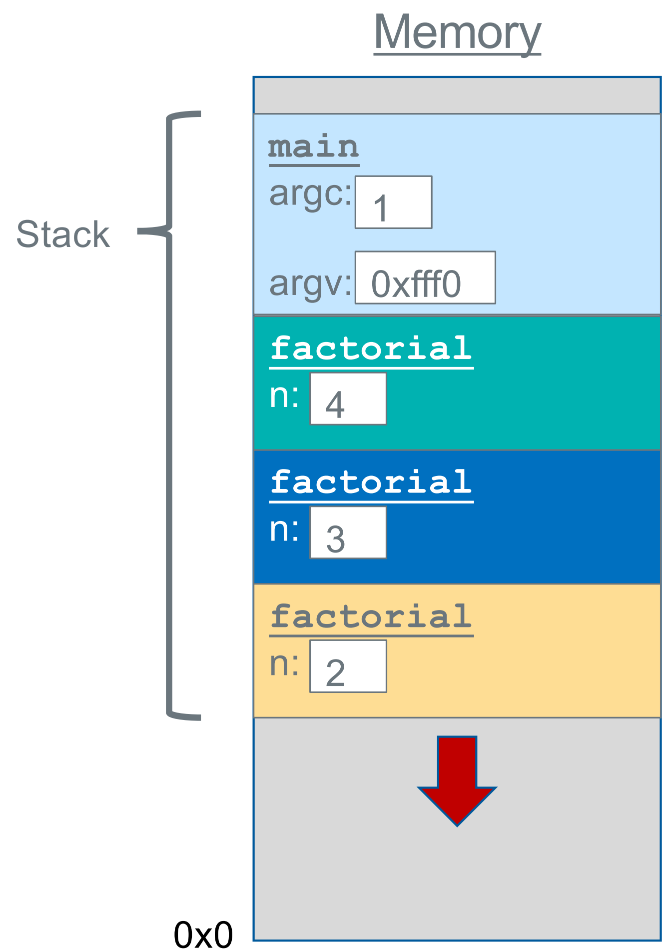

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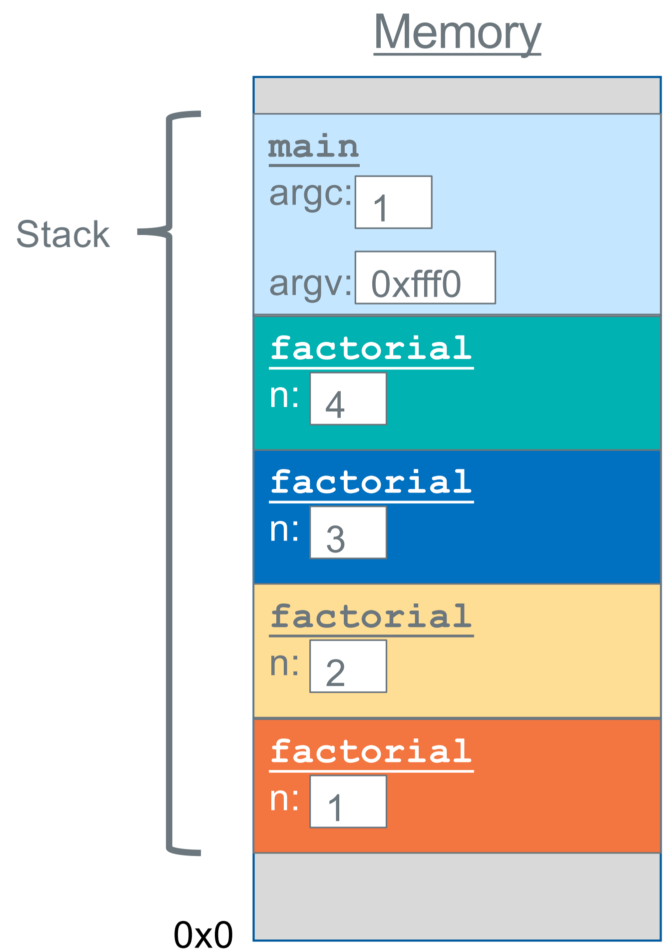

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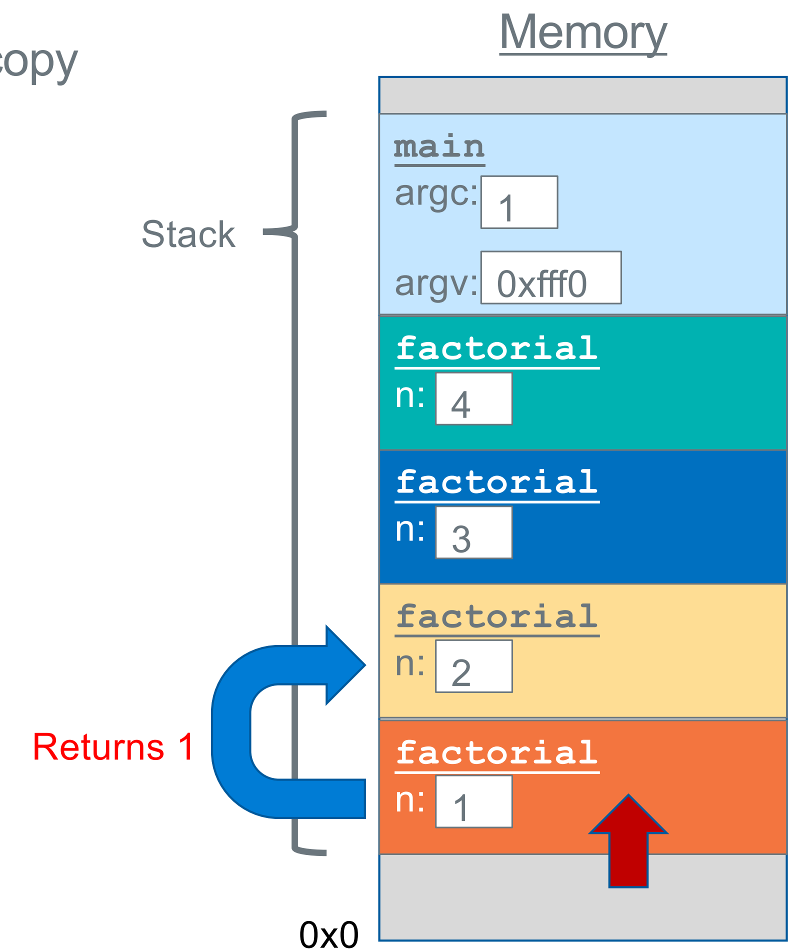

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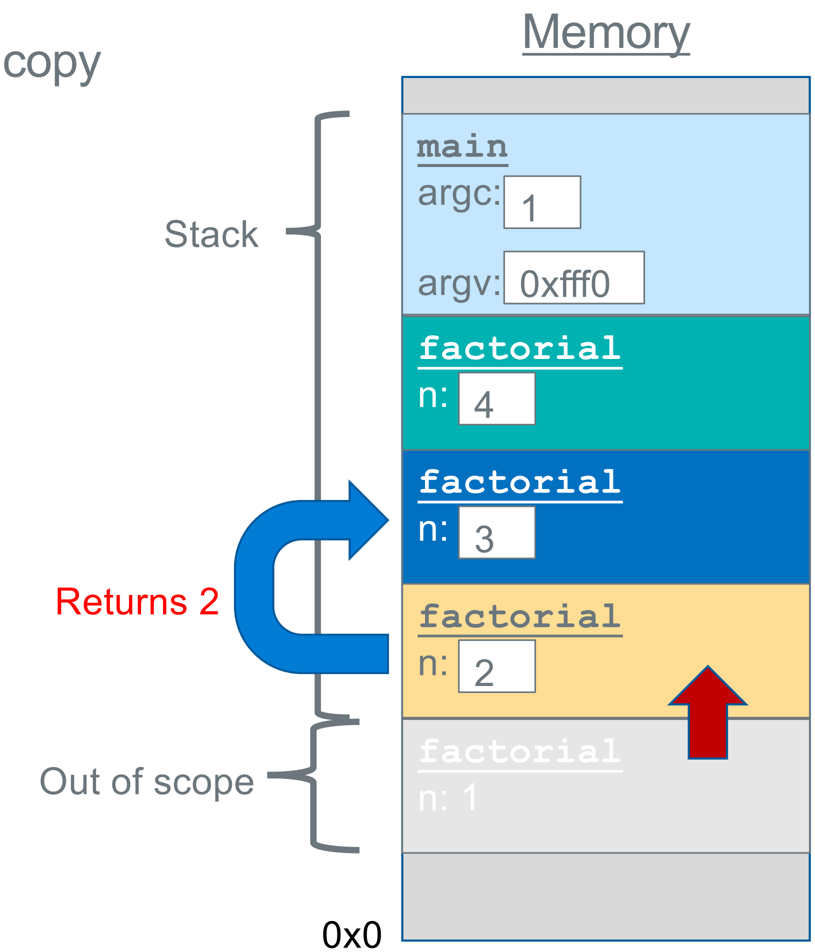

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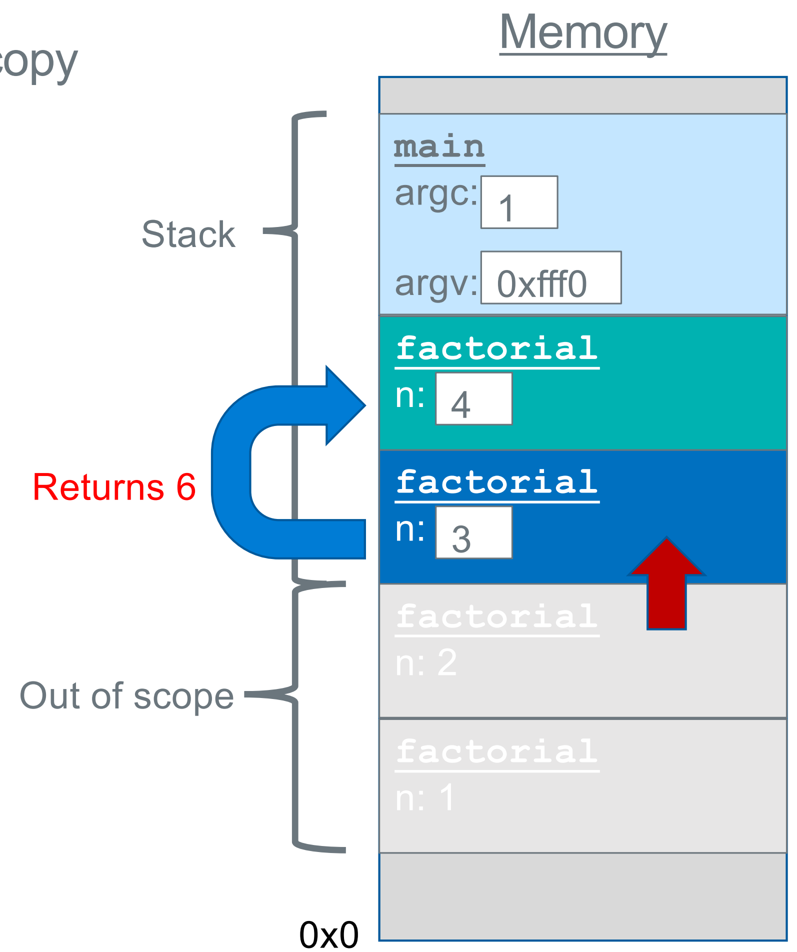

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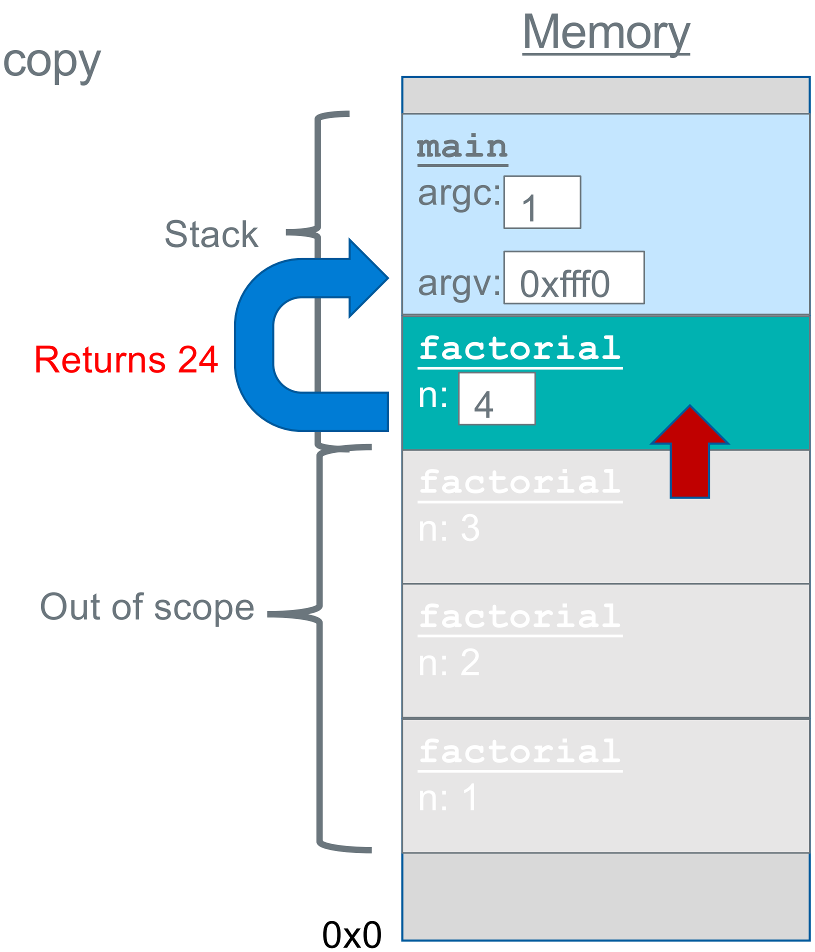

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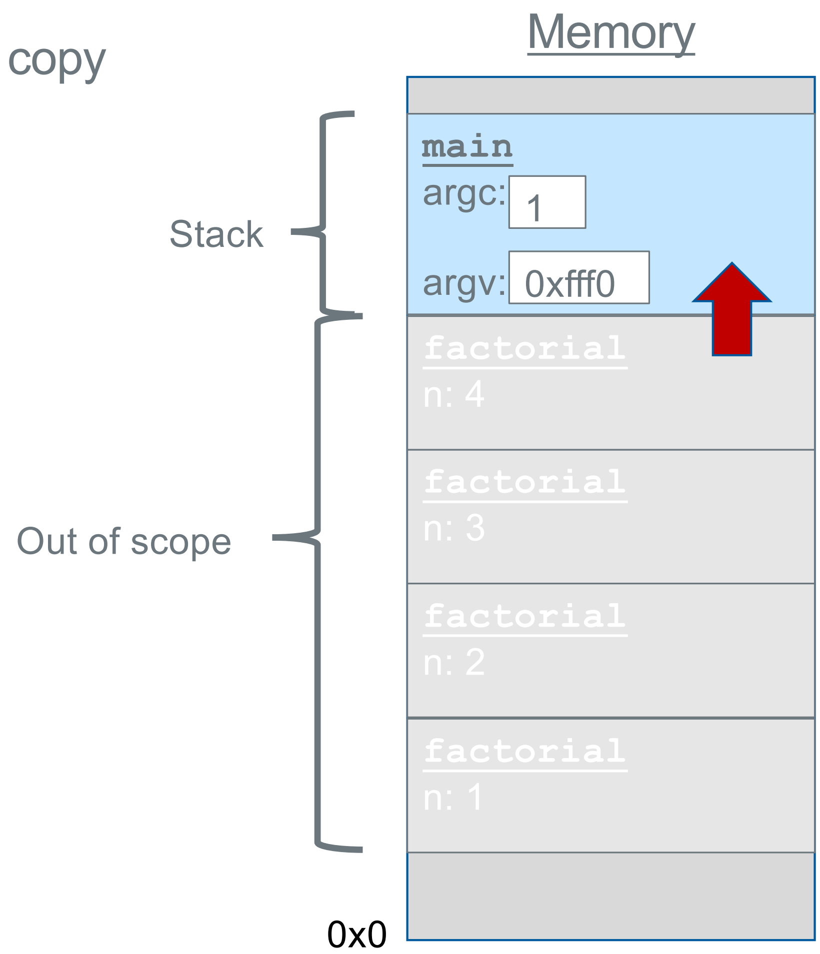

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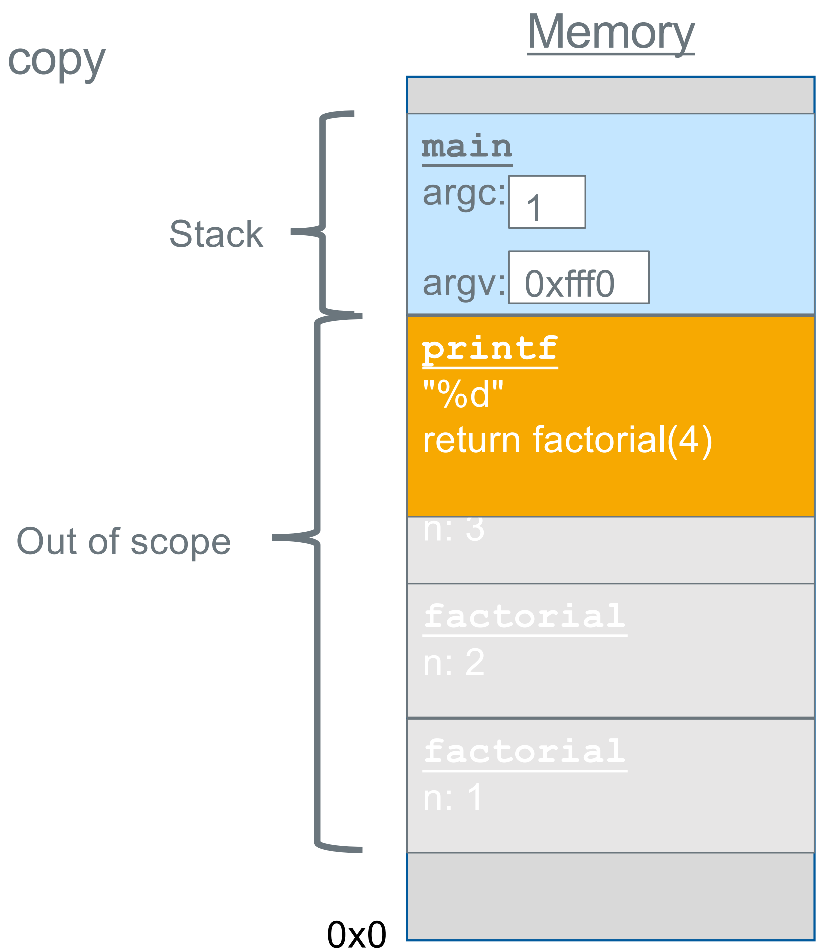


Extra Slides

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
```

```c
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;
}
```

Data Segment Variable Alignment

```
.data
ch:      .byte 'A','B','C','D','E'
str:     .string "HIT"
ary:     .hword 0, 1
a:       .byte 'A'
b:       .byte 'B'
xx:      .word 2
```

```
% gcc -c -Wa,-ahlns al1.S
  1                .data
  2 0000 41424344 ch:      .byte 'A','B','C','D','E'
  2      45
  3 0005 48495400 str:     .string "HIT"
  4 0009 00000100 ary:     .hword 0, 1
  5 000d 41       a:       .byte 'A'
  6 000e 42       b:       .byte 'B'
  8 000f 02000000 xx:      .word 2
```

address contents

- Output on the right side is generated by:
- `%gcc -c -Wa,-ahlns al1.S`

```
.data
xx:      .word 2
ch:      .byte 'A','B','C','D','E'
         .align 2
str:     .string "HI"
         .align 1
ary:     .hword 0, 1
a:       .byte 'A'
b:       .byte 'B'
```

```
gcc -c -Wa,-ahlns al1.S
  1                .data
  2 0000 02000000 xx:      .word 2
  3 0004 41424344 ch:      .byte 'A','B','C','D','E'
  3      45
  4 0009 000000            .align 2
  5 000c 484900   str:     .string "HI"
  6 000f 00                .align 1
  7 0010 00000100 ary:     .hword 0, 1
  8 0014 41       a:       .byte 'A'
  9 0015 42       b:       .byte 'B'
```


X

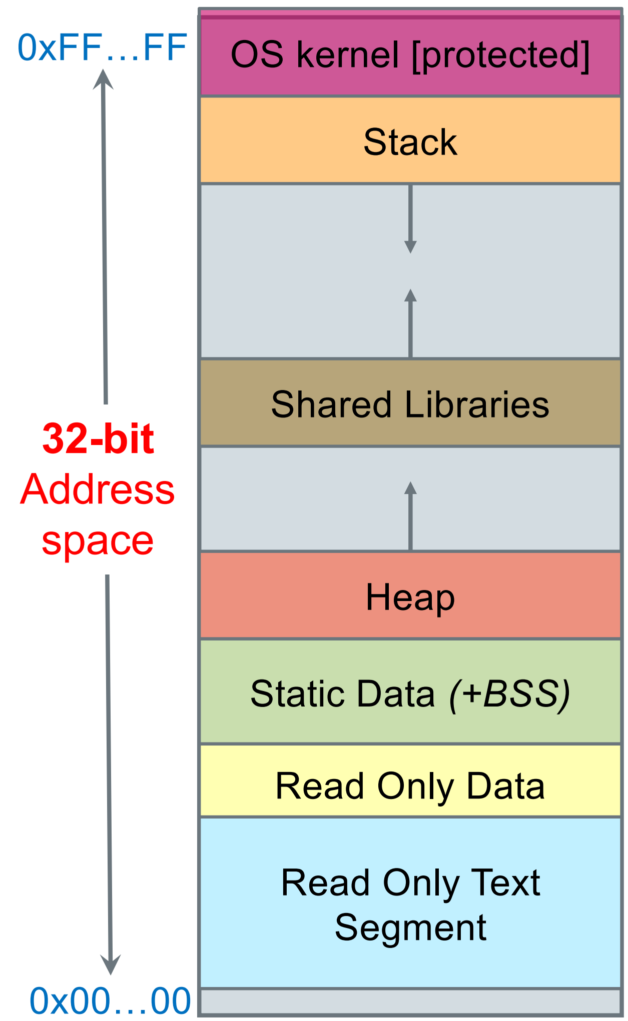
How to get an address into a register?

- Assembler **creates a table of pointers** in the **text segment** called the **literal table**
- For each variable in one of the data segments you reference in a special form of the `ldr` instruction (next slide), the assembler makes an entry (it does this while assembling, so it is not seen in your source code) for that variable whose contents is the 32-bit Label address

```
      .bss
y:    .space 40
```

```
       .data
x:    .word 200
```

```
       .text
       // your code
       // last line of your code
       // below is added by the assembler
     .word  y      // contents: 32-bit address of y
     .word  x      // contents: 32-bit address of x
```



x

Literal Table (Array) each entry is a pointer to a different Label

- **Assembler automatically inserts into the text** segment an array (table) of pointers
- Each entry contains a 32-bit address of one of the labels
- Uses r15 (PC) as base register to load the entry into a reg

displacement (bytes) - 8

The assembler creates this table before generating the .o file

```
        .bss
y:      .space 4
        .data
x:      .word 200
        .section .rodata
.Lmsg: .string "Hello World"
        .text
main:

(address)ldr r0, [PC, displacement]  // replaces:  ldr r0, =y

     <last line of your assembly, typically a function return>

    .word   y       // entry #1 32-bit address for y
    .word   x       // entry #2 32-bit address for x
    .word   .Lmesg  // entry #3 32-bit address for .Lmesg
```


x

Literal Table (Array) each entry is a pointer to a different Label

The **displacement is different** for each use.
As the PC is different at each instruction

```
        .bss
y:      .space 4
        .data
x:      .word 200
        .section .rodata
.Lmsg: .string "Hello World"
        .text
main:
(address) ldr r0, [PC, displacement1]  // replaces:  ldr r0, =y


(address) ldr r0, [PC, displacement2]  // replaces:  ldr r0, =y

        <last line of your assembly, typically a function return>

        .word  y       // entry #1 32-bit address for y
        .word  x       // entry #2 32-bit address for x
        .word  .Lmesg  // entry #3 32-bit address for .Lmesg
```

displacement1 - 8

displacement2 - 8

X

ARM Assembly Source File: Header

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)
```

`.arch <architecture>`

- Specifies the target architecture to generate machine code
- Typically specify oldest ARM arch you want the code to run on – most arm CPUs are backwards compatible

`.arm`

- Use the 32-bit ARM instructions, There is an alternative 16-bit instruction set called thumb that we will not be using

`.fpu <version>`

- Specify which floating point co-processor instructions to use (OPTIONAL we will not be using floating point)

x

putchar/getchar
Setting up and Usage

```c
#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;
}
```

r0 r1

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

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

Putchar/getchar:
The while loop

initialize count

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

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

did getchar() return EOF if not loop

saw EOF, print count

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

```
#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;
}
```

File header and footers are not shown

x

printing error messages in assembly

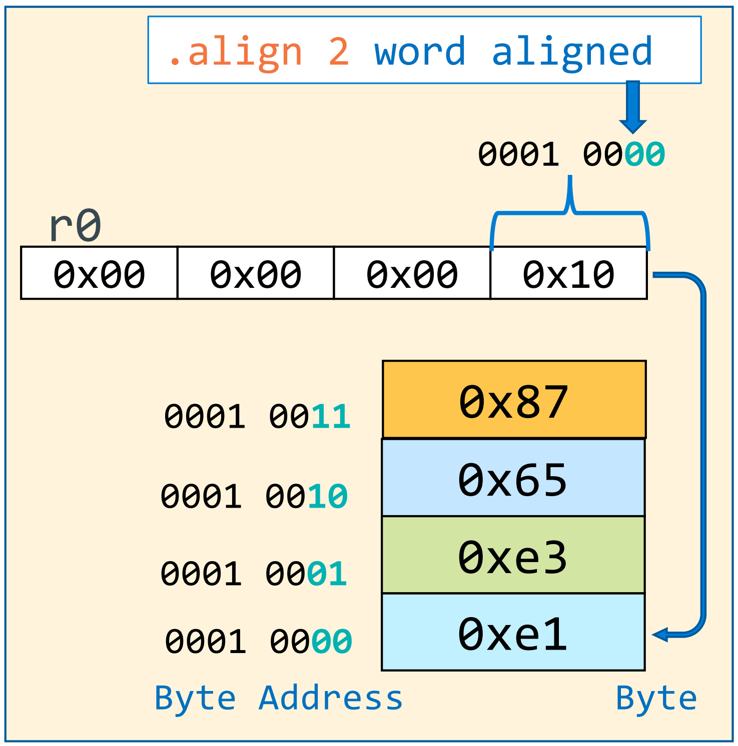
```
.Lmsg0: .string "Read failed\n"
        ldr     r0, =.Lmsg0                     // read failed print error
        bl      errmsg
```

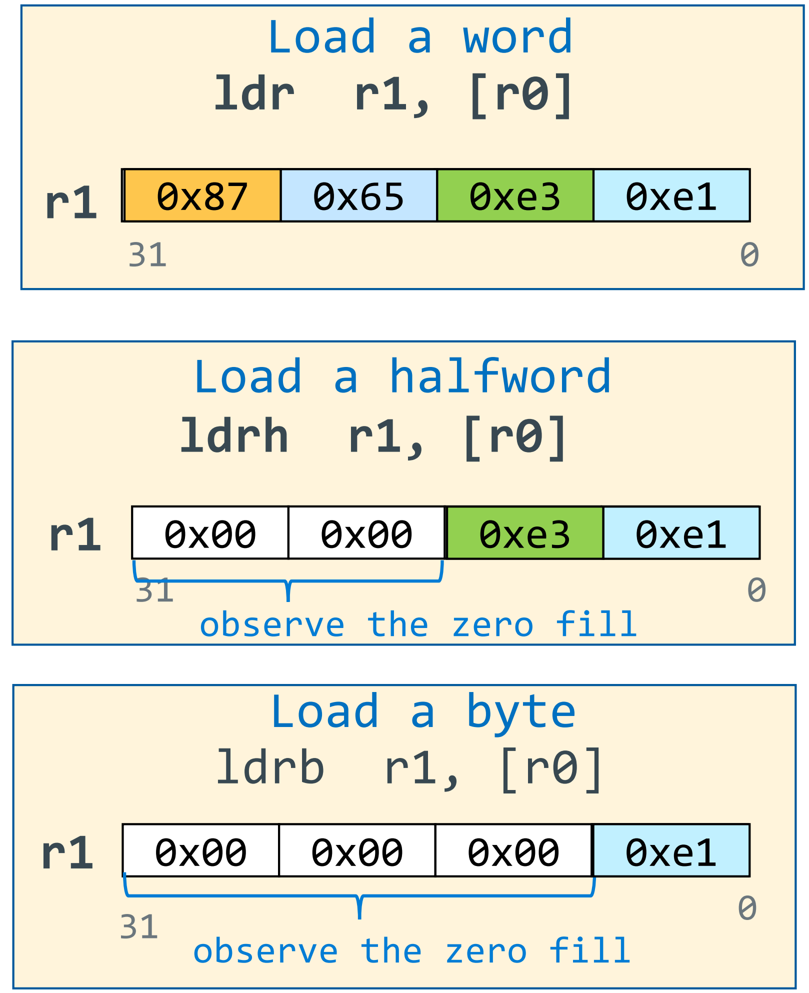
```
        // int errmsg(char *errormsg)
        // writes error messages to stderr
        .type   errmsg, %function               // define to be a function
        .equ    FP_OFF,         4               // fp offset in stack frame
errmsg:
        push    {fp, lr}                        // stack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

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

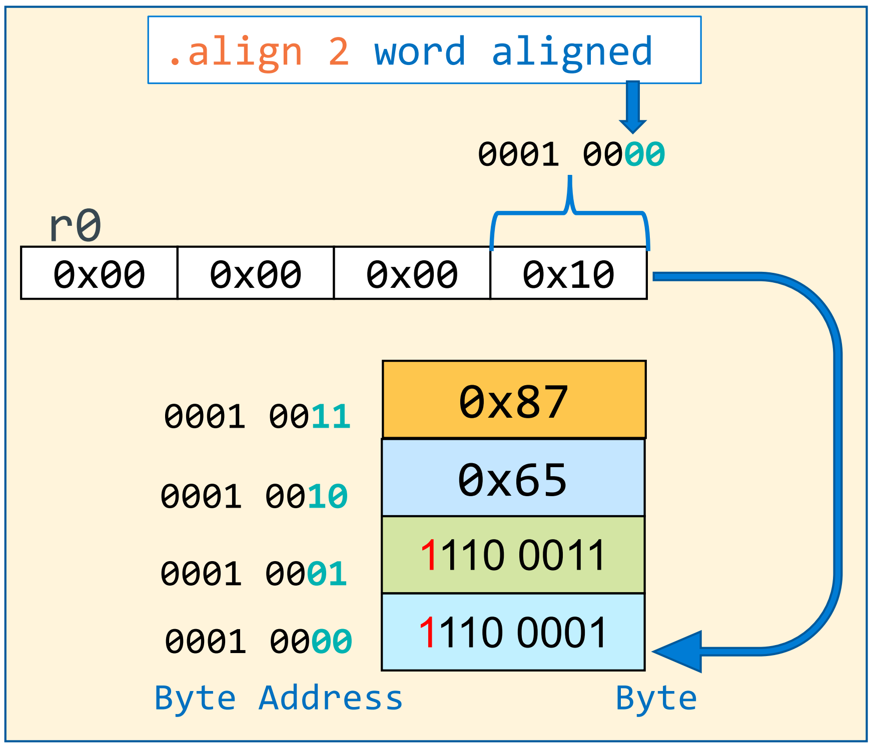

x

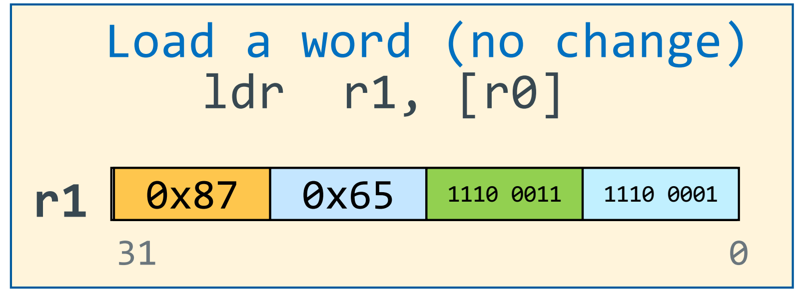
Load a Byte, Half-word, Word

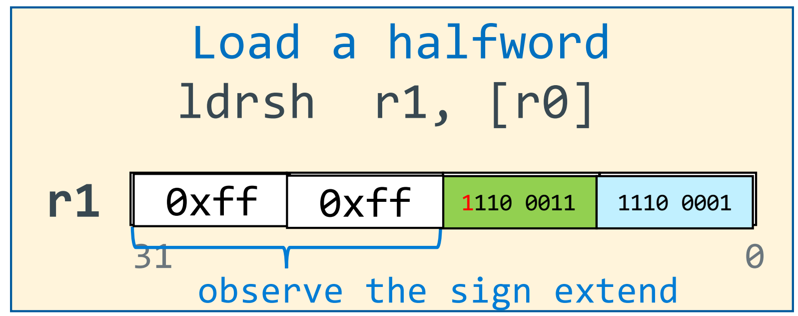


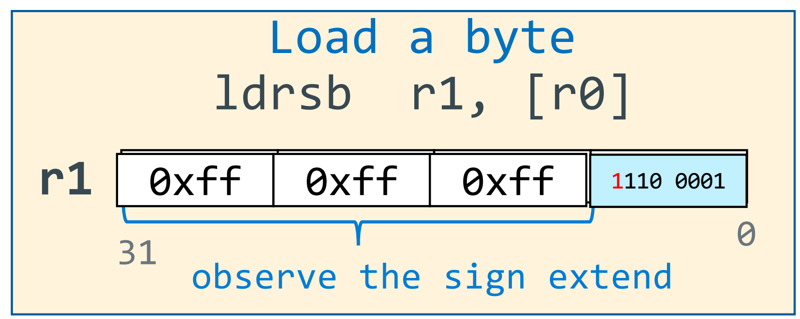


Signed Load a Byte, Half-word, Word

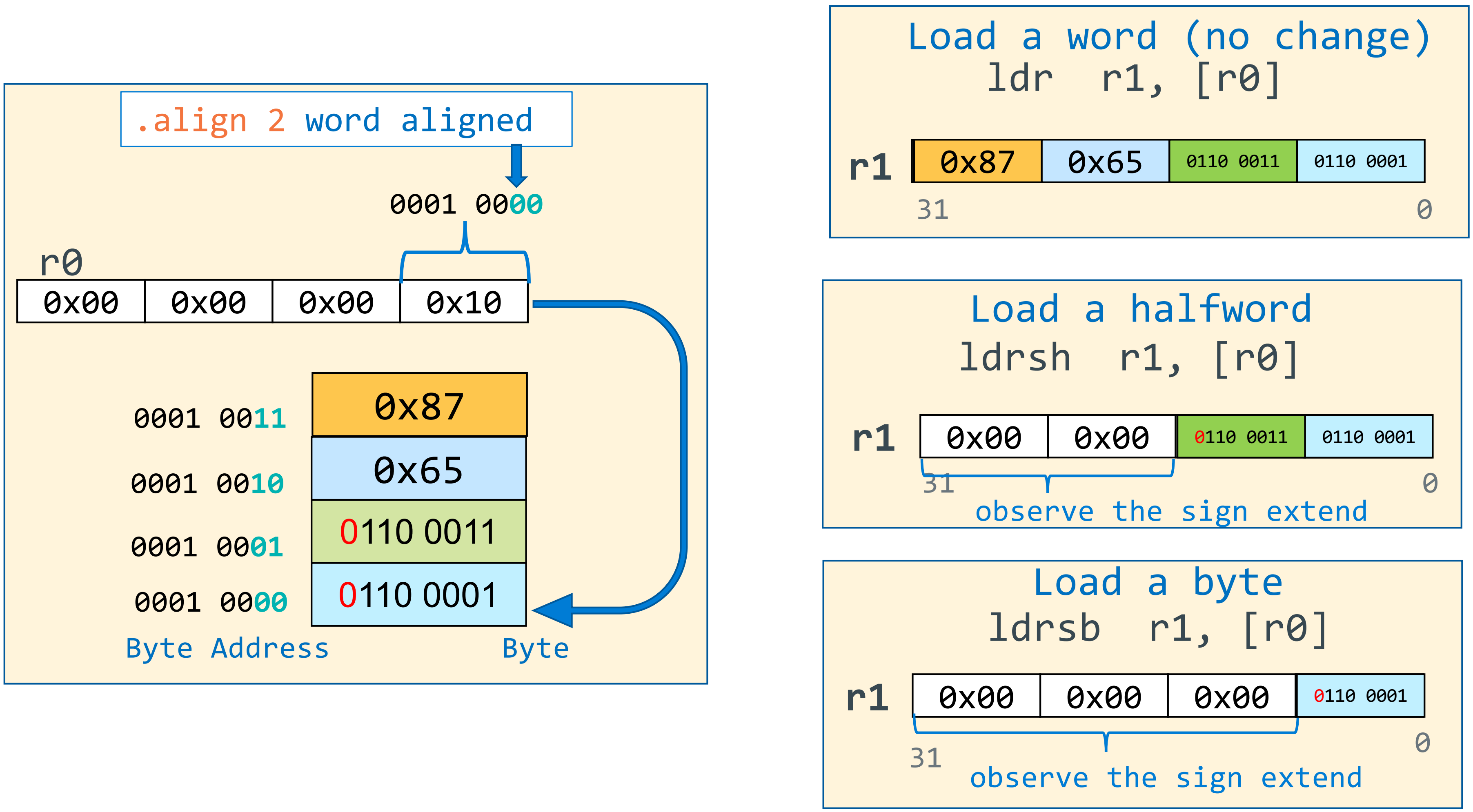




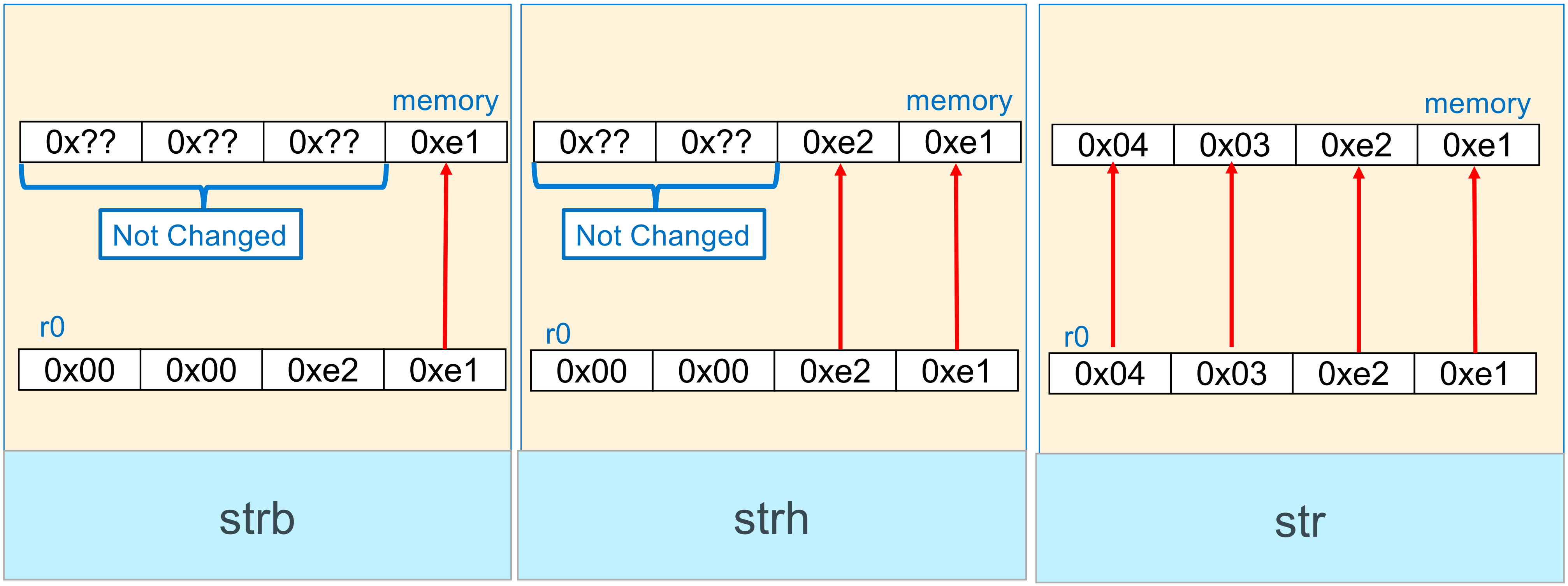




Signed Load a Byte, Half-word, Word



Storing 32-bit Registers To Memory 8-bit, 16-bit, 32-bit



x

Store a Byte, Half-word, Word

initial value in r0

0x20	0x00	0x00	0x00

Store a byte

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

	31			0
r1	0x87	0x65	0xe3	0xe1

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

observe other bytes NOT altered

Store a halfword

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

	31			0
r1	0x87	0x65	0xe3	0xe1

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

Store a word

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

	31			0
r1	0x87	0x65	0xe3	0xe1

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

x

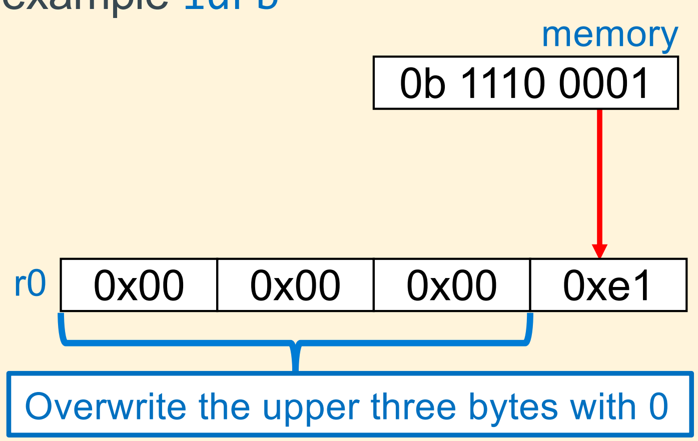
Loading 32-bit Registers From Memory Variables < 32-Bits Wide

Unsigned	Signed (2's complement)

Unsigned

Zero-Extend: Add leading 0's

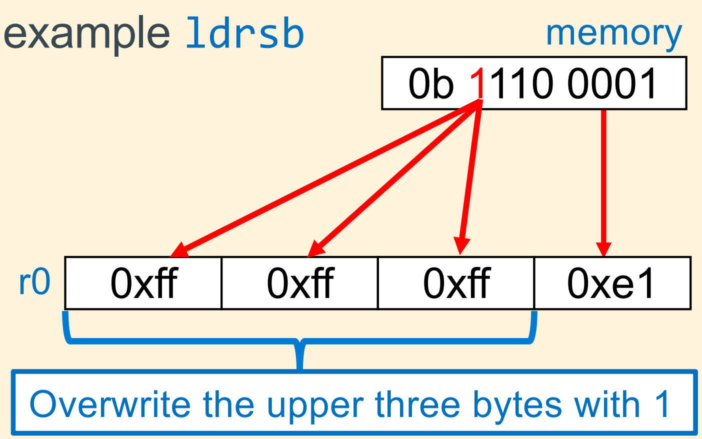
example `ldrb`



Signed (2's complement)

Sign-Extend: Replicate sign bit

example `ldrsb`



Instructions that zero-extend:
ldrb, ldrh

Instructions that sign-extend:
ldrsb, ldrsh

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,…

```
count:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF

    mov     r2, 0
    cmp     r1, 0
    ble     .Ldone
    mov     r3, 0
.Lfor:
    cmp     r3, r1
    bge     .Ldone

    ldrb    r4, [r0, r3]
    cmp     r4, 'A'
    blt     .Lendif
    cmp     r4, 'Z'
    bgt     .Lendif
    add     r2, r2, 1

.Lendif:
    add     r3, r3, 1
    b       .Lfor

.Ldone:
    mov     r0, r2
```

loop guard

x