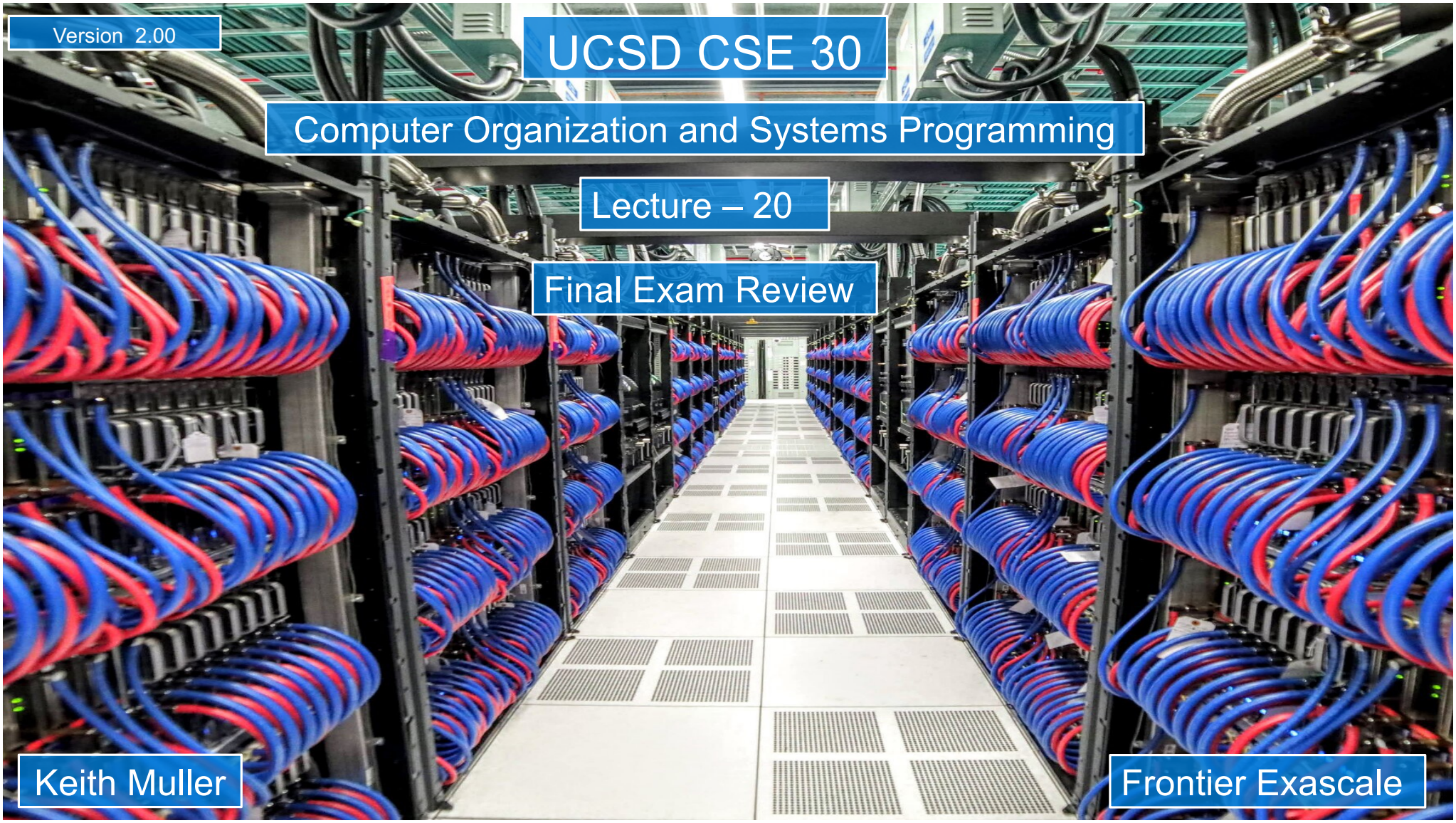

Version 2.00
UCSD CSE 30
Computer Organization and Systems Programming
Lecture – 20
Final Exam Review
Keith Muller
Frontier Exascale

CSE 30 Final

380 points total

Spring 2024

DO NOT LOOK AT YOUR EXAM UNTIL TOLD TO DO SO

Name _____

PID _____

"While taking this examination, I have not witnessed any wrongdoing, nor have I personally violated any conditions of this course's integrity policy." **[sign before turning in]**

If you can honestly attest to the statement above, **write *"I excel with Integrity"* below and sign**. If you do not write and sign, the instructor will contact you by e-mail to request you clarify/explain.

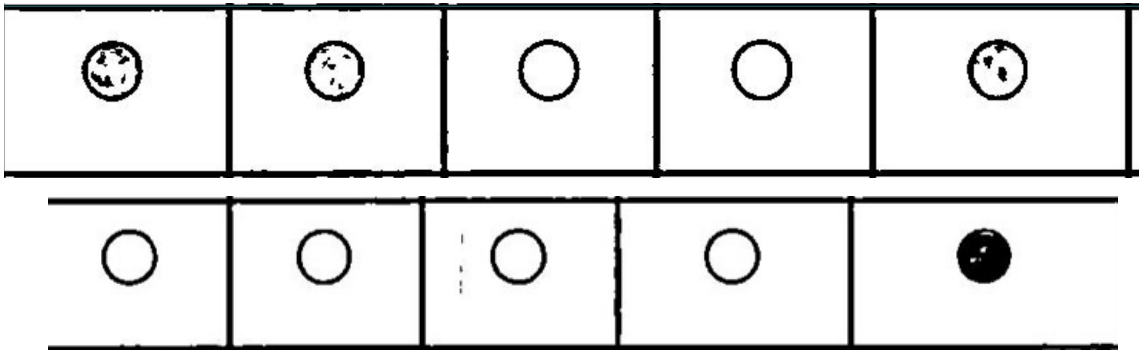
_____
Written Statement

_____
Signature

LOOK!! There are references/notes for your use at the end of the exam

0. It is suggested you use a pencil and have a good eraser for taking this exam.

1. **Place your PID at the top of each page.**
2. **FILL IN THE BUBBLES COMPLETELY.** Bubbles that have just dots or distinct lines will not qualify for any points!
3. For fill-in the box questions, **your answers must be within the box provided.** Answers placed outside the box will not qualify for any points!
4. **No calculators or other electronic devices allowed.**
5. **Three (3) pages of 8.5" x 11"** notes (both sides) allowed
6. **Be as neat as possible.** It's your responsibility to make your answers legible. If we cannot read it, **we will not give you credit for your answer**.
7. **Read each question *carefully*, start working on it, and then reread it.** A large number of mistakes occur from not carefully reading the question.
8. Be sure to place all your answers on the exam in the spaces provided. **We will not look at scratch paper for answers.**
9. All questions refer to the **pi-cluster (32-bit ARM v6 and Linux) environment** and the **version of C presented in lecture (unless stated otherwise).**



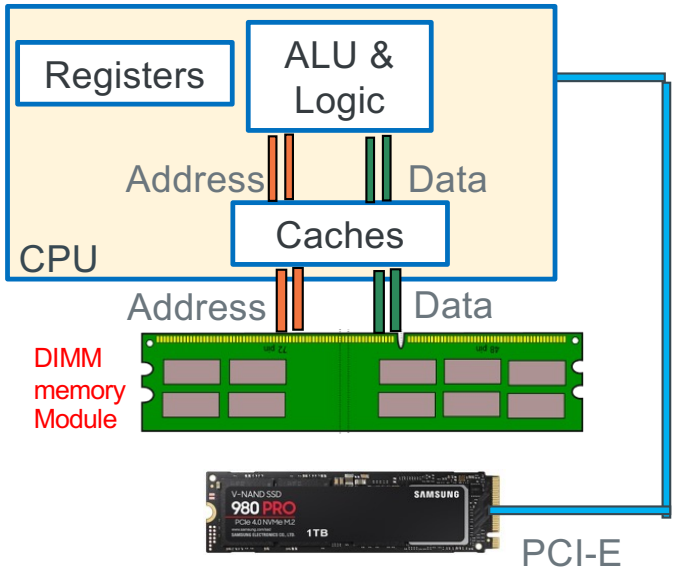
Asking me to Count the most dots…
WILL NOT Get Credit

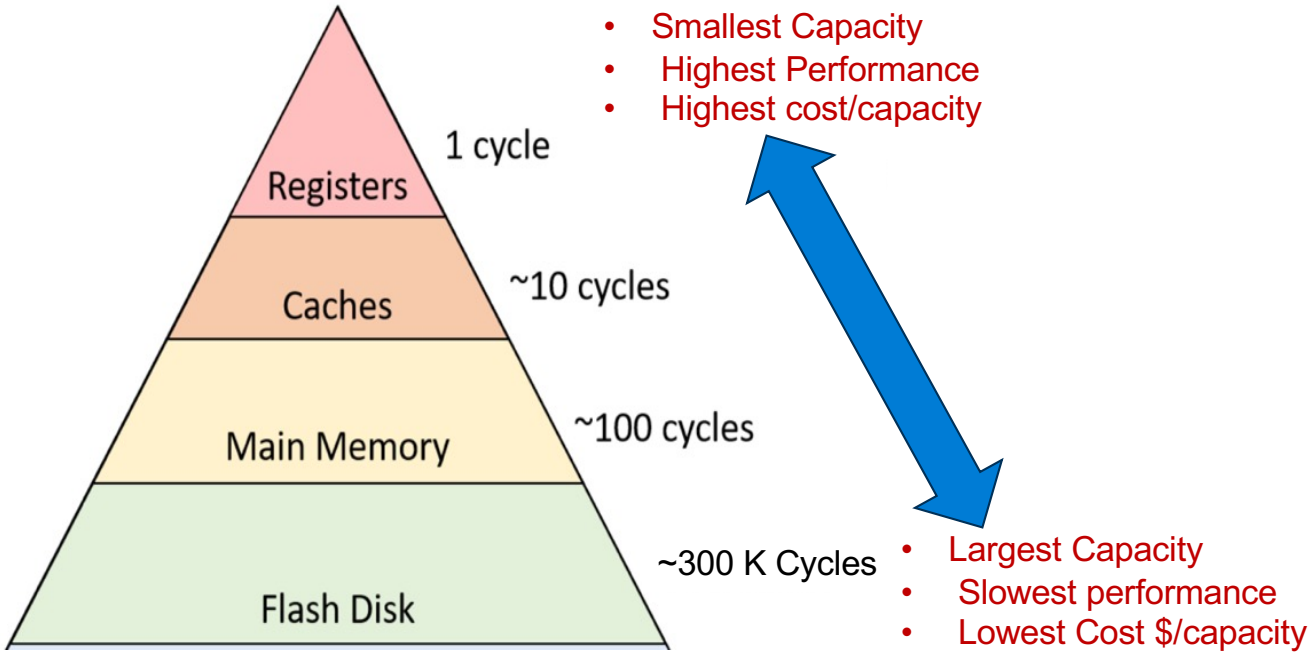
Nice Job, Will get Credit

Memory Triangle: Hardware Cost/Performance/Capacity Tiers

Assume each instruction takes 1 clock cycle

Clock cycle =~ time to access; larger is slower





Design Goal: best performance at the lowest (or specific) cost
Other goals: performance/energy (operating cost), expandability, high margin (price/cost)

x

Variables in C

- **Global variables**
  - **Defined at file scope** (outside of a block)
  - have static storage duration
  - global variables defined without an initial value default to 0 (set prior to program execution start)
  - global variables defined with an initial value are set at program start
- **Local (block scope, or automatic) variables** (including function parameter variables)
  - **Defined at block scope** (inside of a block)
  - have automatic storage duration, **with one exception (see below)**
  - block scope variables defined without an initial value have an **unspecified** initial value
  - block scope variables defined with an initial are set each time by code when the block is entered
  - All block scope variables become **unspecified** at block exit
- **Variable definitions preceded by the keyword** *static* always have static storage duration including variables defined with block scope (when used global variables it restricts scope – later slides)

```
int global;             // global with static storage duration, initial value = 0
int foo(void)
{
    static int s;       // "local" with static storage duration, initial value = 0
    int x;              // "local" with automatic storage duration
}
```


x

Example:
Block scope (local) static storage duration variables

```
#include <stdio.h>
#include <stdlib.h>
#define MAX 5

int foo(void)
{
    static int s;  //static storage duration, set to 0 at program start
    return s += 1;
}

int main(void)
{
    for (int i = 0; i < MAX; i++)
        printf("%d ", foo());
    printf("\n");
    return EXIT_SUCCESS;
}
```

```
% ./a.out
1 2 3 4 5
%
```


x

Conditional Statements (`if, while, do...while, for`)

- **C conditional test expressions**: **0 (NULL) is FALSE**, **any non-0 value is TRUE**
- **C comparison operators (==, !=, >, etc.) evaluate to either 0 (false) or 1 (true)**
- Legal in Java and in C:

```
i = 0;
if (i == 5)
   statement1;
else
   statement2;
```

Which statement is executed after the if statement test?

- Illegal in Java, but **legal** in C (often a typo!):

```
i = 0;
if (i = 5)
   statement1;
else
   statement2;
```

Assignment operators evaluate to the value that is assigned, so…. Which statement is executed after the if statement test?

x

Program Flow – Short Circuit or Minimal Evaluation

- In evaluation of conditional guard expressions, C uses what is called **short circuit** or **minimal** evaluation

```
if ((x == 5) || (y > 3))  // if x == 5 then y > 3 is not evaluated
```

- **Each** expression argument is evaluated **in sequence** from left to right including any side effects (modified using parenthesis), **before** (optionally) evaluating the next expression argument
- If after evaluating an argument, the value of the entire expression can be determined, then the remaining arguments are NOT evaluated *(for performance)*

x

Program Flow – Short Circuit or Minimal Evaluation

```
if ((a != 0) && func(b))      // if a is 0, func(b) is not called
    do_something();
```

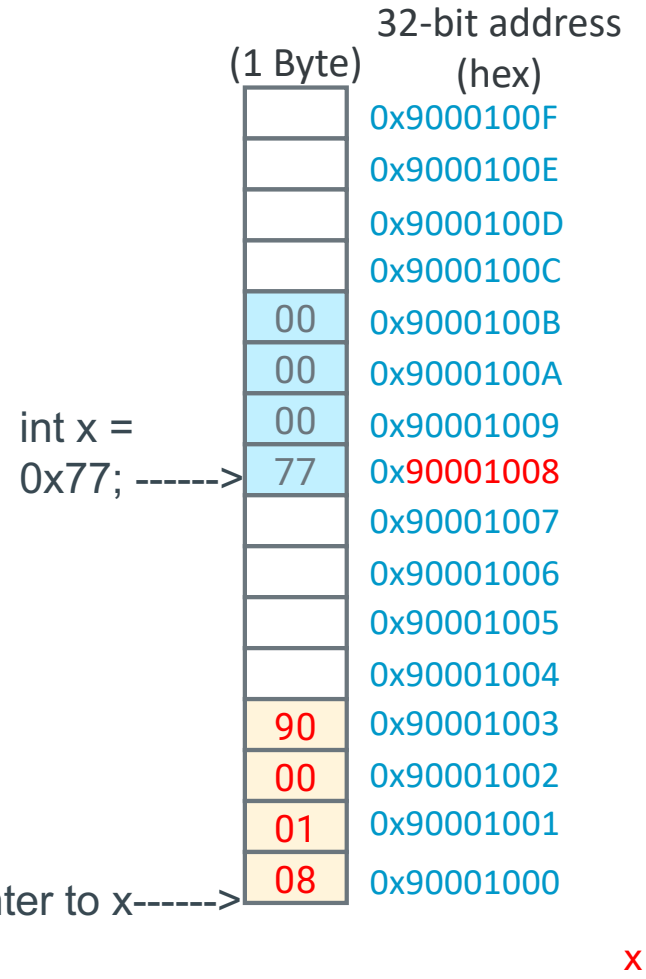
```
// if (((x > 0) && (c == 'Q')) evaluates to non zero (true)
// then (b == 3) is not tested

while (((x > 0) && (c == 'Q')) || (b == 3)) {  // c short circuit
    x = x / 2;
    if (x == 0) {
       return 0;
    }
}
```


x

Address and Pointers

- An address refers to a location in memory, the lowest or first byte in a contiguous sequence of bytes
- A pointer is a variable whose contents (or value) can be properly used as an address
  - The value in a pointer *should* be a valid address allocated to the process by the operating system
- The variable x is at memory address 0x90001008
- The variable pt is at memory location 0x90001000
- The contents of pt is the address of x 0x90001008

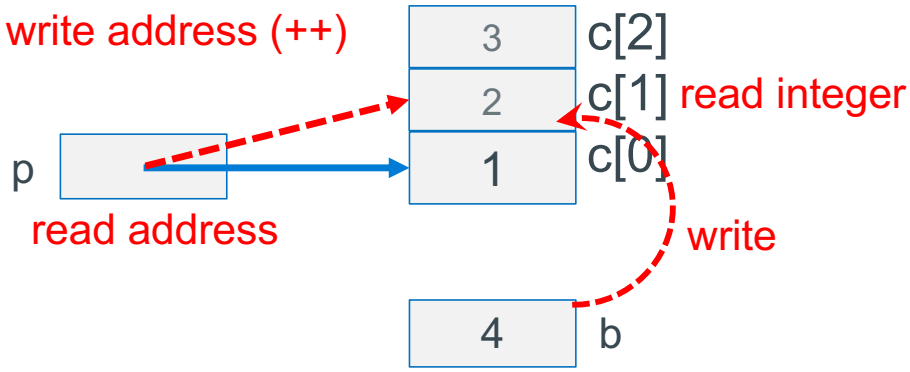


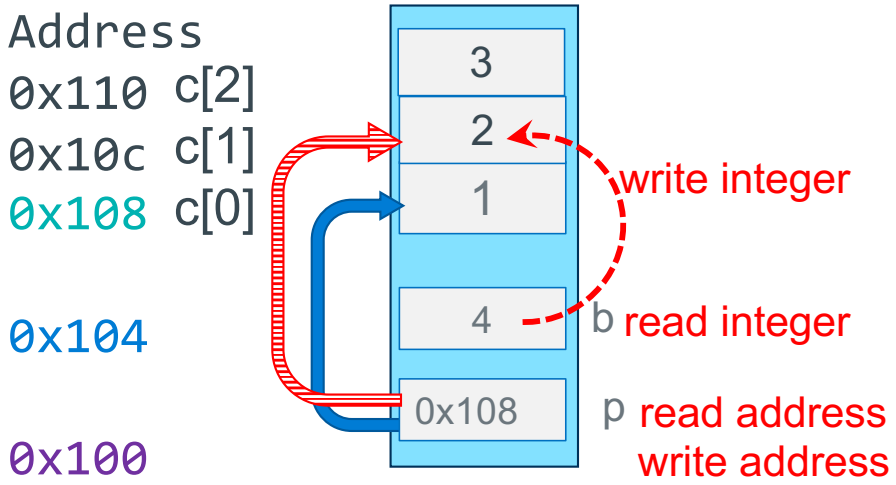
x

Each use of a * operator results in one additional read : both sides

```
int c[] = {1, 2, 3};
int b = 4;
int *p;

p = c;
*(++p) = b;
```





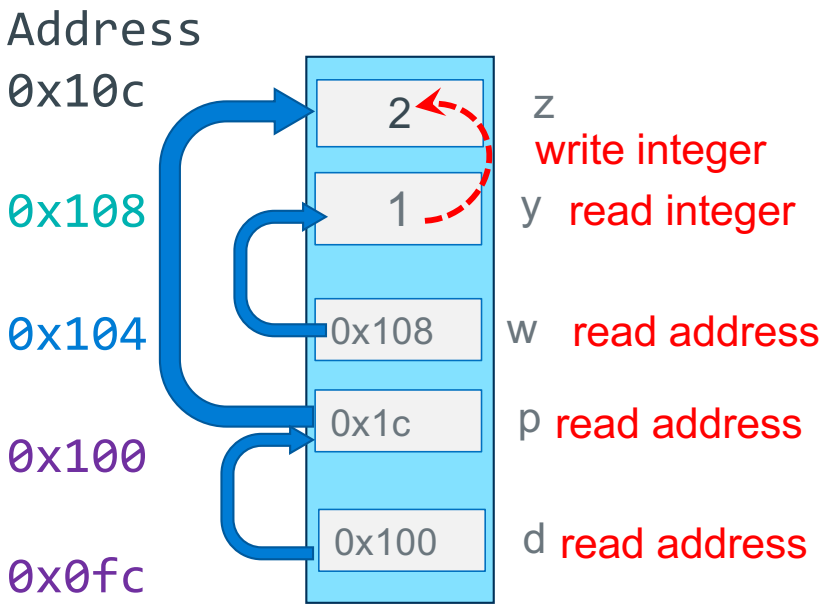
2 reads and 2 writes

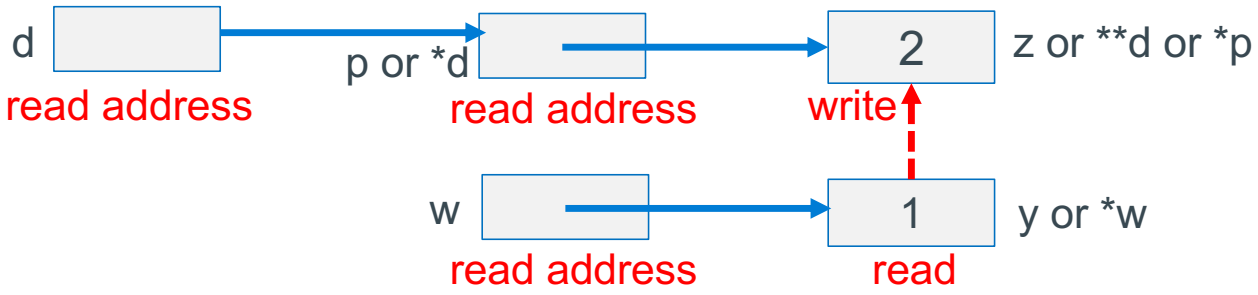
x

Double Indirection: Lside

```
int z = 2;
int y = 1;
int *w;
int *p;
int **d;

p = &z;
w = &y;
d = &p;
**d = *w;
```



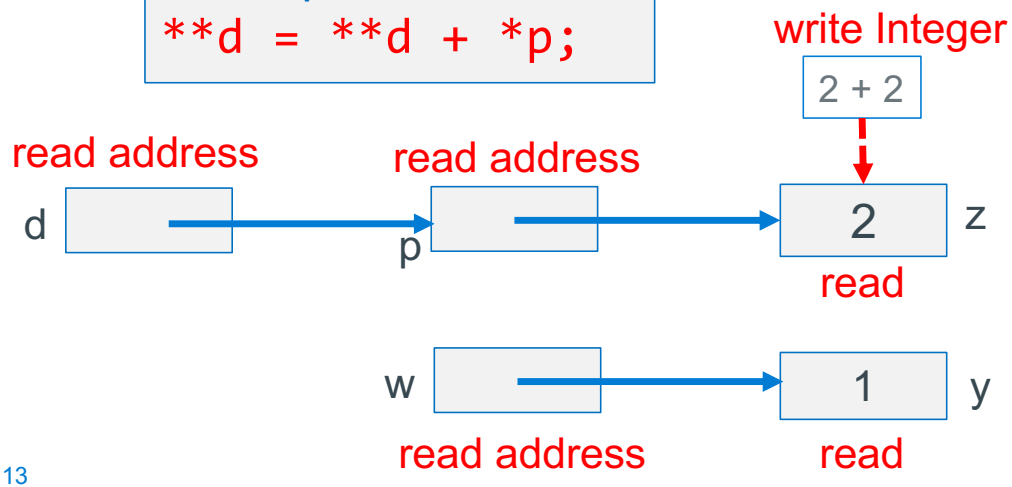


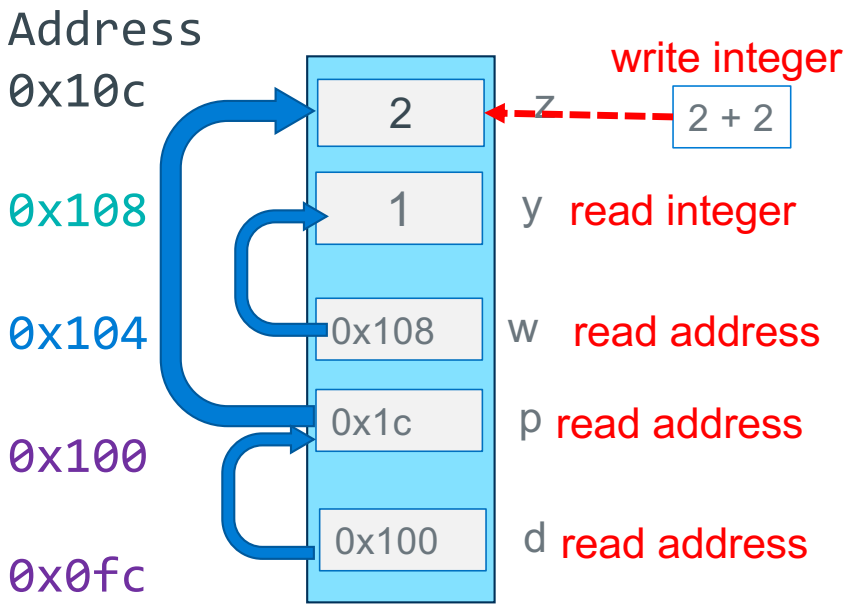
x

Double Indirection: Rside

```
int z = 2;
int y = 1;
int *w;
int *p;
int **d;

p = &z;
w = &y;
d = &p;
**d = **d + *p;
```





Important Observation

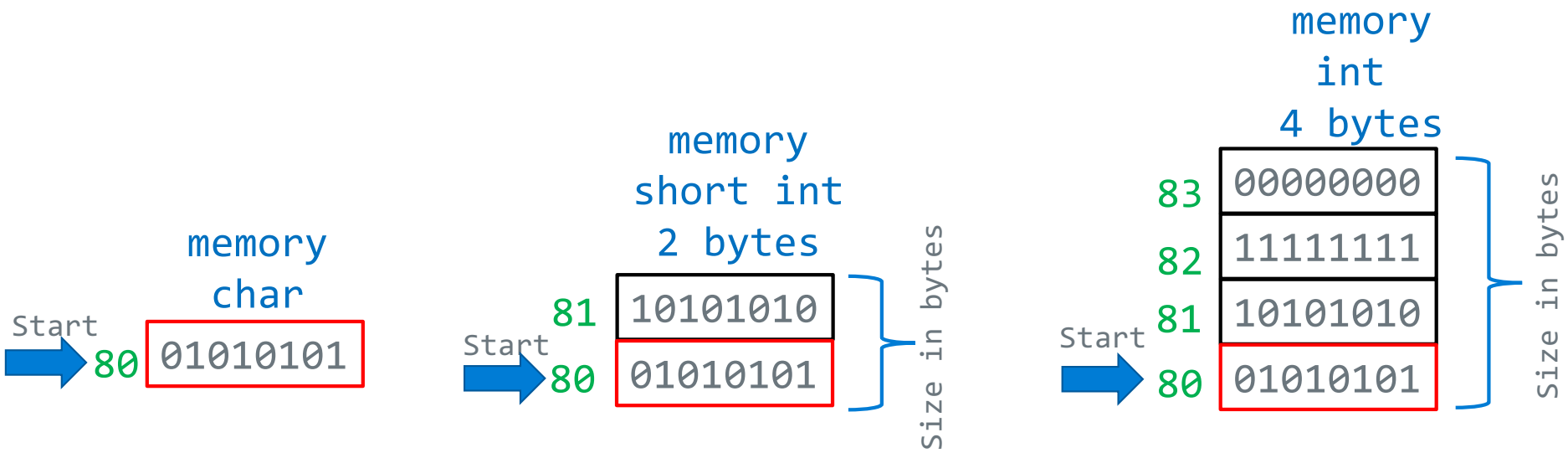
**d on Lside is two reads

**d on Rside is three reads

x

Variables in Memory: Size and Address

- The number of **contiguous bytes** a variable uses is based on the *type* of the variable
  - Different variable types require different numbers of contiguous bytes
- ***Variable names*** map to a *starting address in memory*
- Example Below: Variables all starting at address 0x80, each box is a byte



x

sizeof(): Variable Size (number of bytes) *Operator*

```
#include <stddef.h>
/* size_t type may vary by system but is always unsigned */
```

sizeof() operator returns a value of type size_t:

the number of bytes used to store a variable or variable type

```
size_t size = sizeof(variable_type);
```

or

```
size_t size = sizeof(variable_name); // preferred!
```

- The argument to `sizeof()` is often an expression:

```
size = sizeof(int * 10);
```

  - reads as:
    - number of bytes required to store **10 integers (an array of [10])**

x

Accessing Arrays Using Indexing

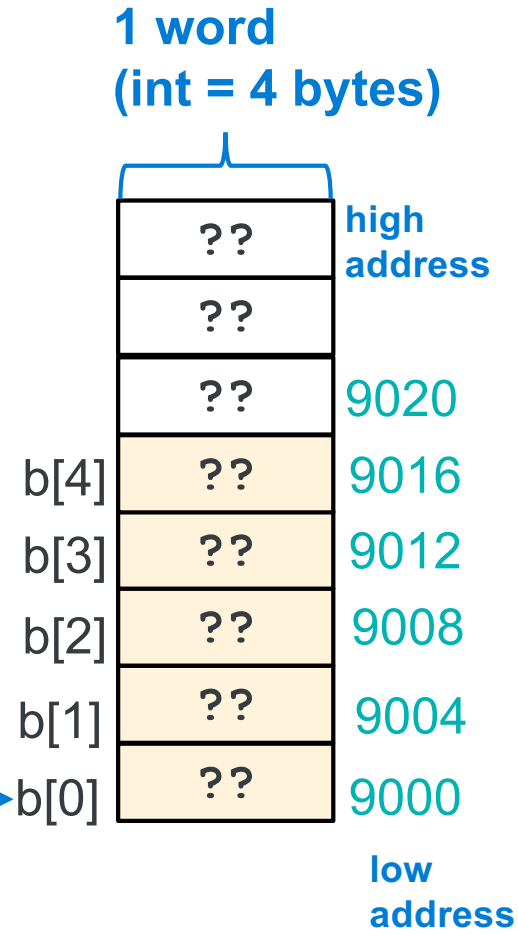
- **name**[**index**] selects the **index** element of the array
  - index **should be** unsigned
  - Elements range from: 0 to count – 1 (int x[count];)
- **name[index]** can be used as an assignment target or as a value in an expression

```
int a[2] = {1, 2};
a[0] = a[1];
```

- Array name (by itself with no [ ]) on the Rside evaluates to the address of the first element of the array

```
int b[5];
int *p = b;
```

p 9000



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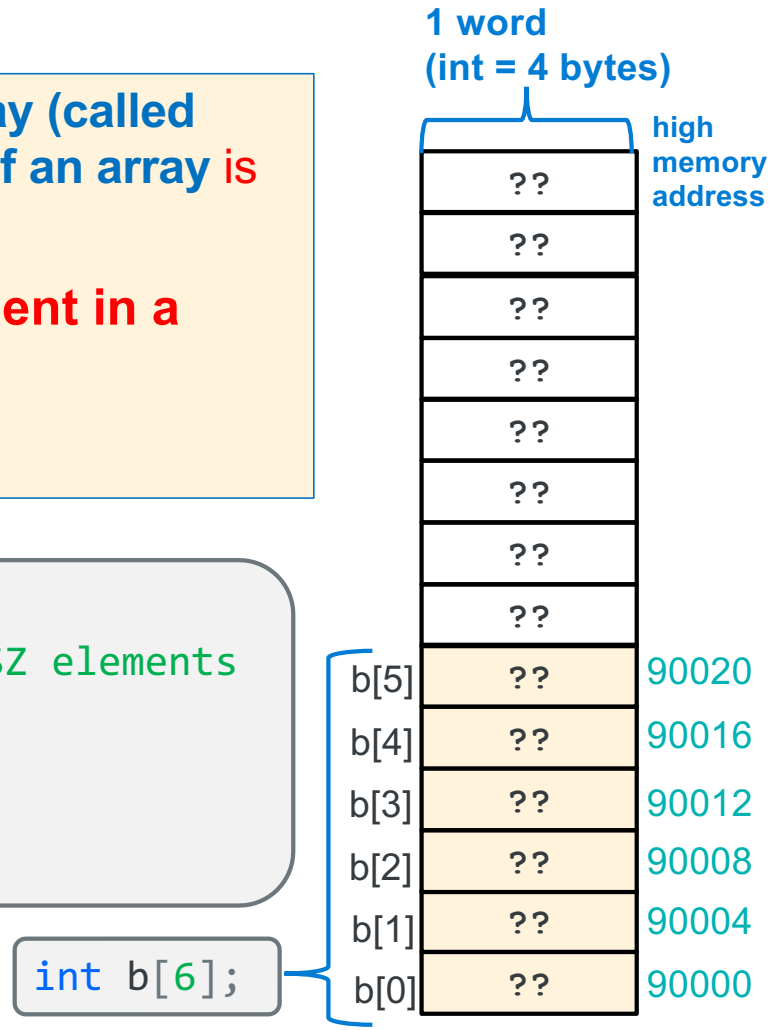
How many elements are in an array?

- **The number of elements of space allocated to an array (called element count) and indirectly the total size in bytes of an array** is not stored anywhere!!!!!!
- An **array name** is just the **address of the first element in a block of contiguous memory**
  - So, an array does not know its own size!

```
#define SZ 6
int block[SZ];       // you specify the array has SZ elements
int indx;            // use when SZ is defined

for (indx = 0; indx < SZ; indx++)
      block[indx] = 0;
```



x

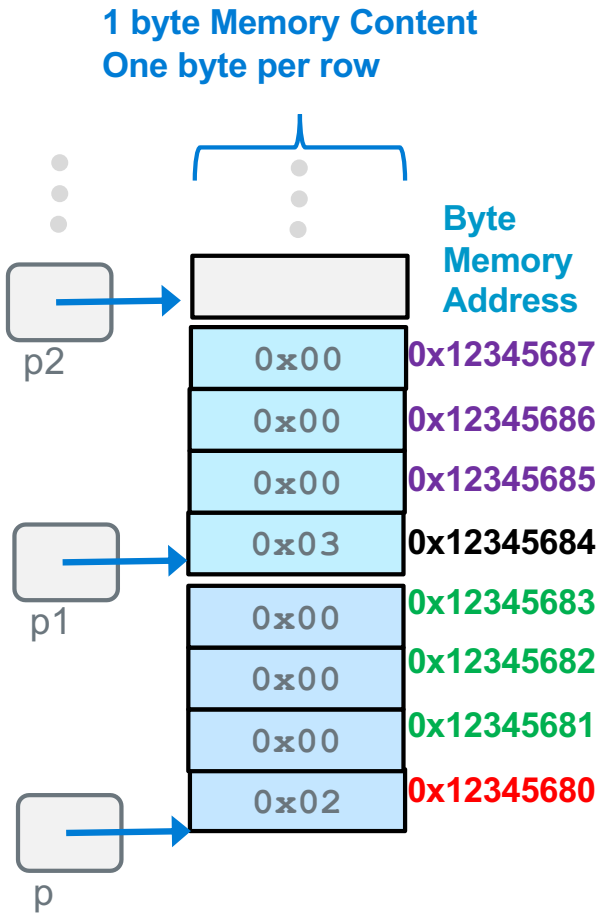
Pointers and Arrays - 1

- A few slides back we stated: Array name (by itself) on the Rside evaluates to the address of the first element of the array

```
int buf[] = {2, 3, 5, 6, 11};
```

- Array indexing syntax ([ ]) an operator that performs *pointer arithmetic*
- **buf and &buf[0] on the Rside are equivalent**, ***both evaluate*** to the address of the first array element

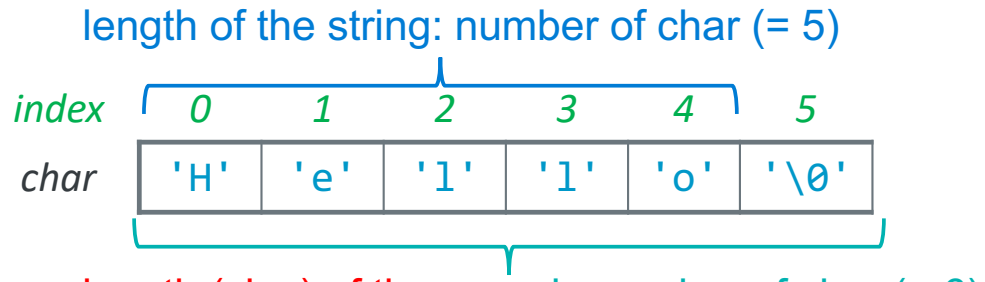
```
int *p = buf;          // or int *p = &buf[0];
int *p1 = &buf[1];
int *p2 = &buf[2];
int *p3 = &buf[3];
```



x

C Strings - 1

- **C does not** have a **dedicated type** for strings
- **Strings are** an **array of characters terminated by** a sentinel termination **character**
- `'\0'` is the **Null termination character;** has the **value of zero (do not confuse with '0')**
- An **array of chars** contains **a string only when** it is terminated by a '\0'
- **Length of a string** is the number of characters in it, not including the '\0'
- Strings in C are **not** objects
  - No embedded information about them, you just have a name and a memory location
  - You cannot use + or += to concatenate strings in C
  - For example, you must **calculate string length** using code at runtime looking for the sentinel



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Output Parameters (Mimics Call by Reference)

- Passing a pointer parameter with the **intent** that the called function will use the address it to store values for use by the calling function, then pointer parameter is called an **output parameter**
- To pass the address of a variable x use the **address operator** (&x) **or** the contents of a pointer variable that points at x, or the name of an array (the arrays address)
- To be receive an address in the called function, define the corresponding parameter type to be a pointer (add *)
  - It is common to describe this method as: "pass a pointer to x"
- C is still using "*pass by value*"
  - we pass the **value** of the address/pointer in a **parameter copy**
  - **The called routine** uses the address to change a variable in the caller's scope

```
void inc(int *p);
int
main(void)
{
    int x = 5;
    inc(&x);


}

void
inc(int *p)
{



}
```


x

Array Parameters: Call-By-Value or Call-By-Reference?

- `Type[]` array parameter is automatically "**promoted**" to a pointer of type `Type *`, and a **copy** of the ***pointer*** is ***passed by value***

```
void passa(int []);
int main(void)
{
  int numbers[] = {9, 8, 1, 9, 5};

  passa(numbers);
  printf("numbers size:%lu\n", sizeof(numbers)); // 20
  return EXIT_SUCCESS;
}
```

the name is the address, so this is passing a pointer to the start of the array

```
void passa(int a[])
{
    printf("a size:%lu\n", sizeof(a)); // 4
    return;
}
```

IMPORTANT:
See the size difference 20 in main() in passa() is 4 bytes (size of a pointer) on pi-cluster and 8 on ieng6

- Call-by-value pointer (callee can change the pointer parameter to point to something else!)
- Acts like call-by-reference (called function can change the contents caller's array)

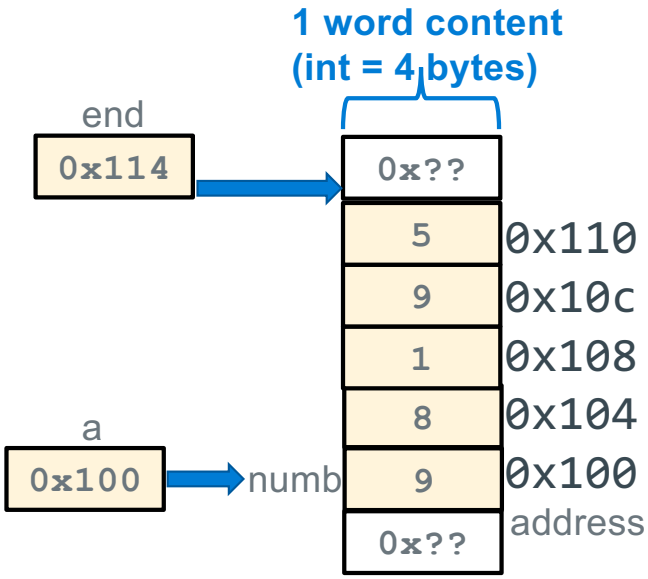
x

Arrays As Parameters, Approach 1: Pass the size

Two ways to pass array size

1. pass the count as an additional argument
2. add a sentinel element as the last element

remember you can only use sizeof() to calculate element count where the array is defined




```c
int sumAll(int *a, int size);
int main(void)
{
  int numb[] = {9, 8, 1, 9, 5};
  int cnt = (int)(sizeof(numb)/sizeof(numb[0]));

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

```c
int sumAll(int *a, int size)
{
  int sum = 0;
  int *end;
  end = a + size;

  while (a < end)
    sum += *a++;
  return sum;
}
```

same as:
sum = sum + *a;
a++;

x

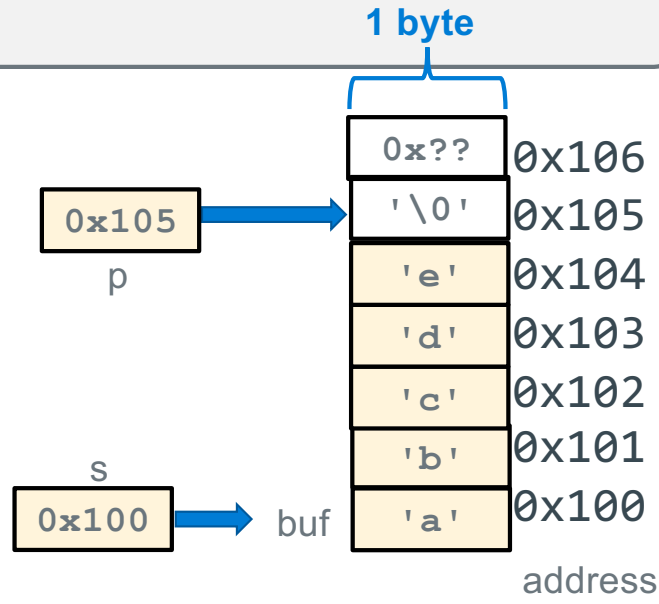
Arrays As Parameters, Approach 2: Use a sentinel element

- A sentinel is an element that contains a value that is not part of the normal data range
  - Forms of 0 are often used (like with strings). Examples: '\0', NULL

```c
int strlen(char *a);  // returns number of chars in string, not counting \0
int main(void)
{
  char buf[] = {'a', 'b', 'c', 'd', 'e', '\0'}; // or buf[] = "abcde";

  printf("Number of chars is: %d\n", strlen(buf));
  return EXIT_SUCCESS;
}
```

```c
/* Assumes parameter is a terminated string */
int strlen(char *s)
{
   char *p = s;
   if (p == NULL)
       return 0;
   while (*p != '\0')
       p++;
    return (p - s);
}
```



x

Returning a Pointer To a Local Variable (Dangling Pointer)

- There are many situations where a function will return a pointer, but a function must never return a pointer to a memory location that is no longer valid such as:

1. Address of a passed parameter copy as the caller may or will deallocate it after the call
2. Address of a local variable (automatic) that is invalid on function return

- These errors are called a dangling pointer

n is a parameter with the scope of bad_idea it is no longer valid after the function returns

```
int *bad_idea(int n)
{
    return &n; // NEVER do this
}
```

a is an automatic (local) with a scope and **lifetime** within bad_idea2 a is no longer a valid location after the function returns

```
int *bad_idea2(int n)
{
    int a = n * n;
    return &a; // NEVER do this
}
```

```
/*
 * this is ok to do
 * it is NOT a dangling
 * pointer
 */

int *ok(int n)
{
    static int a = n * n;
    return &a; // ok
}
```


x

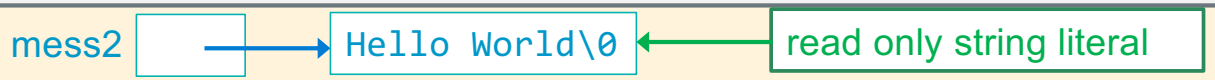
String Literals, Mutable and Immutable arrays - 1

- mess1 is a **mutable** array (type is char [ ]) with enough space to hold the string + '\0'

```
char mess1[] = "Hello World";
*(mess1 + 5) = '\0'; // shortens string to "Hello"
```

- mess2 is a **pointer** to an **immutable** array with space to hold the string + '\0'

```
char *mess2 = "Hello World";     // "Hello World" read only string literal
                                 // mess2 is a pointer NOT an array!
*(mess2 + 1)  = '\0';            // Not OK (bus error)
```



- mess3 is a pointer to a mutable array

```
char *mess3 = (char []) {"Hello World"};  // mutable string
*(mess3 + 1)  = '\0';                     // ok
```

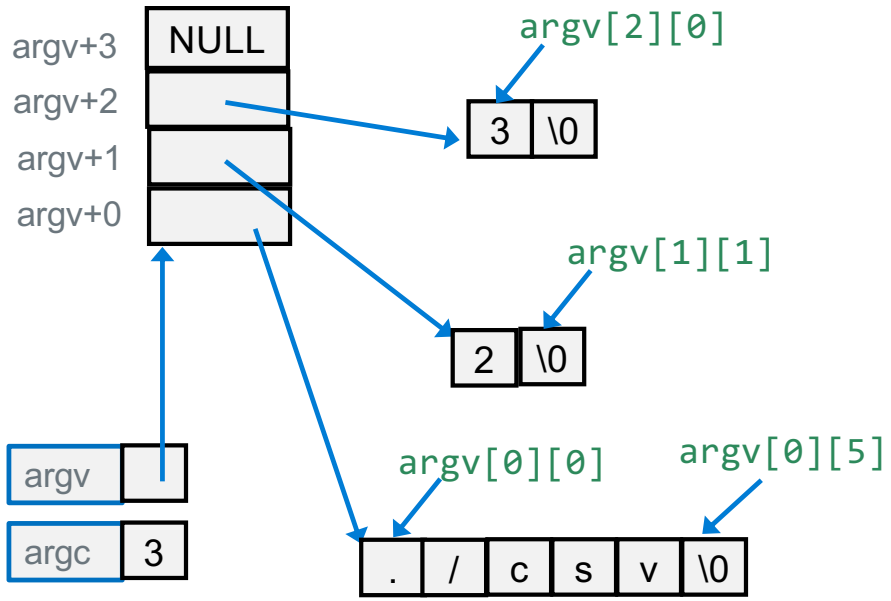
using the cast (char [ ]) makes it mutable

x

main() Command line arguments: argc, argv

- Arguments are passed to main() as a pointer to an array of pointers to char arrays (strings)`(**argv)`

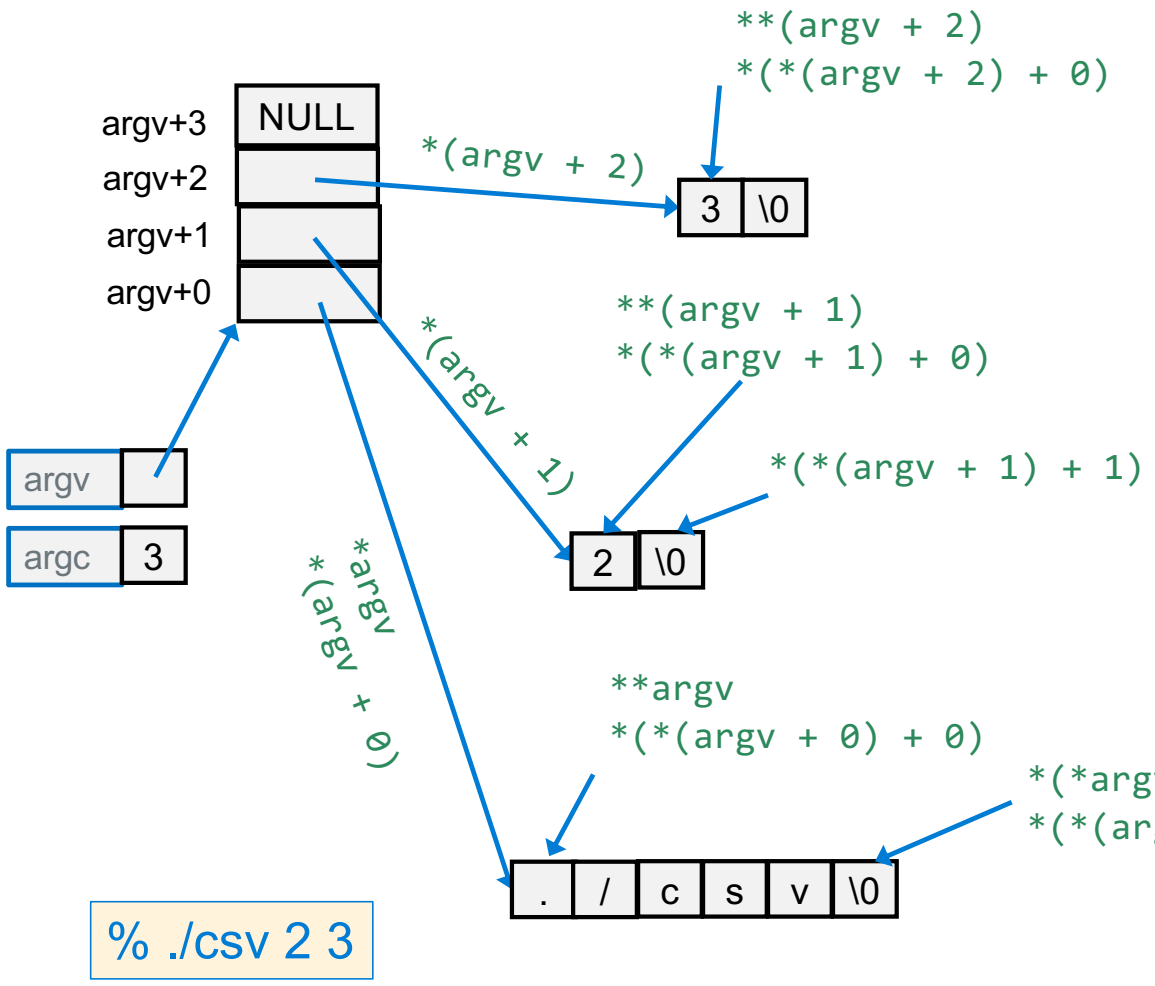
  `Conceptually: % *argv[0] *argv[1] *argv[2] ….`
- `argc` is the number of VALID elements (they point at something)
- `*argv (argv[0]) is` **usually** is the name of the executable file (% ./vim file.c)
- `argv[argc] or *(argv + argc)` always contains a NULL (0) sentinel
- `argv` elements point at **mutable** (fixed size) **strings**!



% ./csv 2 3

x

Accessing argv char at a time



% ./csv 2 3

- argv is a pointer variable, whose contents can be changed
- it is not an array name, which is just an address that cannot be changed

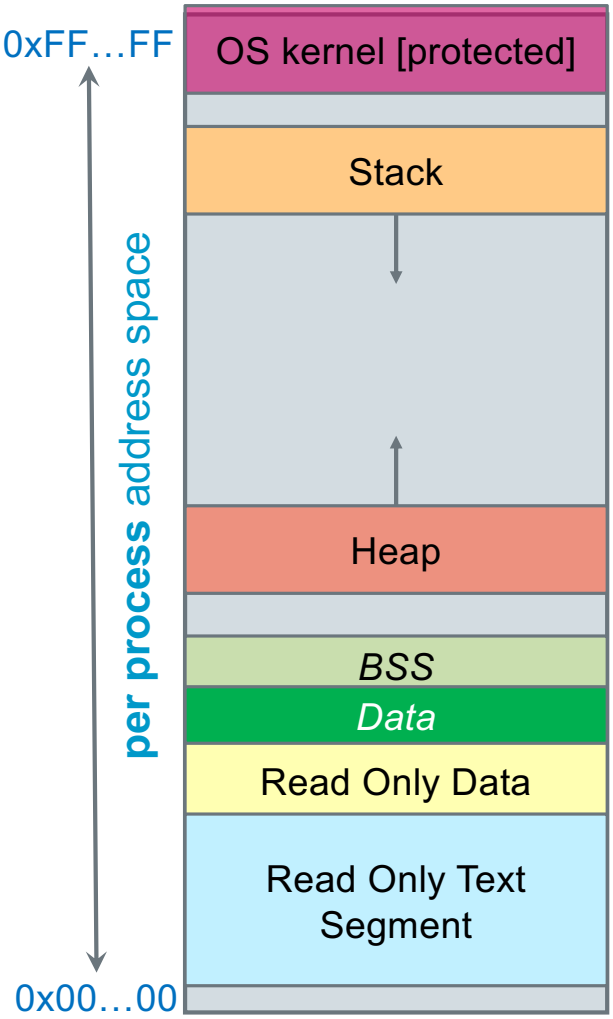
```
int main(int argc, char **argv)
{
    char *pt;
    (void)argc; // shut up the compiler

    while ((pt = *argv++) != NULL) {
       while (*pt != '\0')
           putchar(*pt++);
       putchar('\n');
    }
    return EXIT_SUCCESS;
}
```


x

Process Memory Under Linux

- When your program is running it has been loaded into memory and is called a process
- *Stack segment: Stores Local* variables
  - Allocated and freed at function call entry & exit
- *Data segment + BSS: Stores Global* and *static* variables
  - Allocated/freed when the process starts/exits
  - BSS - Static variables with an implicit initial value
  - Static Data - Initialized with an explicit initial value
- Heap segment: *Stores dynamically-allocated* variables
  - Allocated with a function call
  - Managed by the stdio library malloc() routines
- *Read Only Data: Stores immutable* Literals
- *Text*: Stores your code in machine language + libraries



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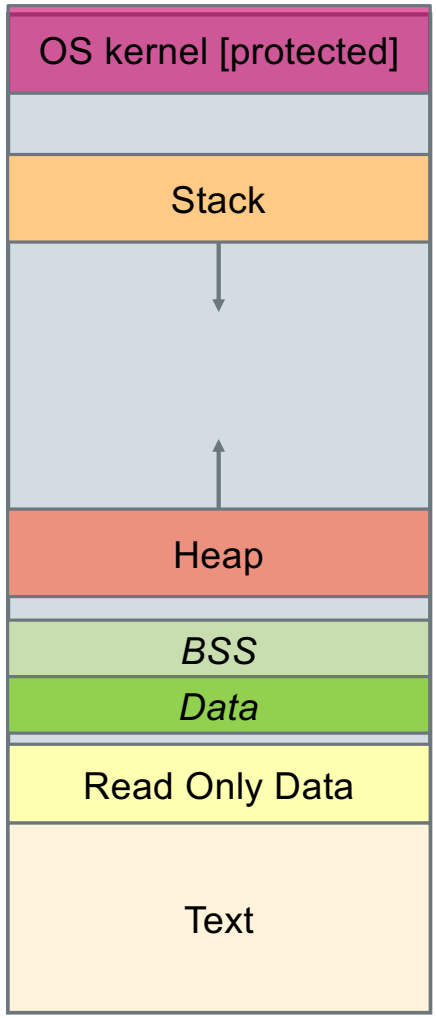
The Heap Memory Segment

- **Heap**: "pool" of memory that is available to a program
  - Managed by C runtime library and linked to your code; **not managed by the OS**
- Heap memory is **dynamically** *"borrowed"* *or* *"allocated"* by calling a library function
- When heap memory is no longer needed, it is *"returned"* *or* *deallocated* *for* **reuse**
- Heap memory has a lifetime from allocation until it is deallocated
  - Lifetime is independent of the scope it is allocated in (it is like a static variable)
- If too much memory has already been allocated, the library will attempt to borrow additional memory from the OS and will fail, returning a NULL



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Heap Dynamic Memory Allocation Library Functions

#include <stdlib.h>	args	Clears memory at runtime
void *malloc(…)	size_t size	no
void *calloc(…)	size_t nmemb, size_t memsize	yes
void free(...)	void *ptr	no

- **void *** means these library functions return a pointer to generic (untyped) memory
  - Be careful with void * pointers and **pointer math** as void * points **at untyped memory**
  - When assigned to a typed pointer, it *"converts"* it from a void * to the type of the pointer variable
- **size_t is** an unsigned integer data type, the result of a sizeof() operator

```
int *ptr = malloc(sizeof(*ptr) * 100); // allocate an array of 100 ints
```

- **please read: % man 3 malloc**

x

Use of Malloc

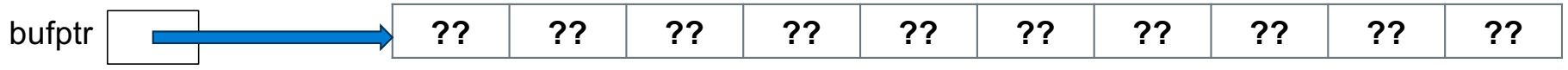
`void *malloc(size_t size)`

- Returns a pointer to a **contiguous** block of **`size`** bytes **of uninitialized memory** from the heap
  - The block is **aligned to an 8-byte (arm32) or 16-byte (64-bit arm/intel) boundary**
  - returns **`NULL`** if allocation failed (also sets **`errno`**) **always CHECK for NULL RETURN!**
- Blocks returned on **different calls to malloc()** are **not necessarily adjacent**
- **`void *`** is implicitly cast into **any pointer type on assignment to a pointer variable**

```
    char *bufptr;

    /* ALWAYS CHECK THE RETURN VALUE FROM MALLOC!!!! */

    if ((bufptr = malloc(cnt * sizeof(*bufptr))) == NULL) {
        fprintf(stderr, "Unable to malloc memory");
        return NULL;
    }
// allocates a character array with 10 elements
```



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Calloc()

```
void *calloc(size_t elementCnt, size_t elementSize)
```

- `calloc()` variant of **`malloc()`** but zeros out every byte of memory during program execution before returning a pointer to it (so this has a runtime cost!)
  - First parameter is the number of elements you would like to allocate space for
  - Second parameter is the size of each element

```
// allocate 10-element array of pointers to char, zero filled
char **arr;
arr = calloc(10, sizeof(*arr));
if (arr == NULL) // handle the error
```

- Originally designed to allocate arrays but works for any memory allocation
  - **`calloc()`** multiplies the two parameters together for the total size
- **`calloc()`** is more expensive at runtime (uses both cpu and memory bandwidth) than **`malloc()`** because it must zero out memory it allocates at runtime
- Use `calloc()` only when you need the buffer to be zero filled prior to FIRST use

x

Using and Freeing Heap Memory

- `void free(void *p)`
  - Deallocates the whole block pointed to by `p` to the pool of available memory
  - **Freed memory** is **used in future allocations** (expect the contents to change after freed)
  - Pointer `p` must be the same address as *originally returned* by one of the heap allocation routines **`malloc(), calloc(), realloc()`**
  - **Pointer argument to free() is not changed by the call to free()**
- Defensive programming: set the pointer to NULL after passing it to free()

```
char *bufptr;

  if ((bufptr = malloc(cnt * sizeof(*bufptr))) == NULL) {
      fprintf(stderr, "Unable to malloc memory");
      return NULL;
  }
  // other code
  free(bufptr);                 // returns memory to the heap
  bufptr = NULL;               // set bufptr to NULL
```


x

Mis-Use of Free() - 1

- Call **`free()`**
  - With the same address that you obtained with malloc() (or other allocators)
  - It is NOT an error to pass **`free()`** a pointer to NULL

```
char *bytes;
if ((bytes = malloc(1024 * sizeof(*bytes)) != NULL) {
    /* some code */
    free(bytes + 5); // Program aborts free(): invalid pointer
```

- **Freeing unallocated memory:** Only call free() to free memory address that you obtain from one of the allocators (malloc(), calloc(), etc.)

```
char *ptr = "cse30";
          …
   /* some code */
   free(ptr);              // Program aborts free(): invalid pointer
```


x

Mis-Use of Free() - 2

- Continuing to write to memory after you **`free() it`** is likely to corrupt the heap or return changed values
  - Later calls to heap routines (**`malloc(), calloc(), strdup()`** may fail or seg fault

```
char *bytes;
if ((bytes = malloc(1024 * sizeof(*bytes)) != NULL) {
    /* some code */
    free(bytes);
    strcpy(bytes, "cse30");   // INVALID! used after free
……
```

- **Double Free:** Freeing allocated memory more than once will cause your program to abort (terminate)

```
char *bytes;
if ((bytes = malloc(1024 * sizeof(*bytes)) != NULL) {
    /* some code */
    free(bytes);
    free(bytes); // Program abort double free detected….
……
```


x

More Dangling Pointers: Continuing to use "freed" memory

- Review: **Dangling pointer** points to a memory location that is no longer "valid"
- Really hard to debug as the use of the return pointers may not generate a seg fault

```
char *dangling_freed_heap(void)
{
    char *buff = malloc(BLKSZ * sizeof(*buff));
…
    free(buff);     // memory pointed at buf may be reused
    return buff;    // but it is returned to the caller anyway - bad
}
```

- `dangling_freed_heap()` **may cause** the allocators (**`malloc()`**and friends) to **seg fault when called later to allocate memory**
  - Why? Because it corrupts data structures the heap code uses to manage the memory pool (it often stores meta-data in the freed memory)

x

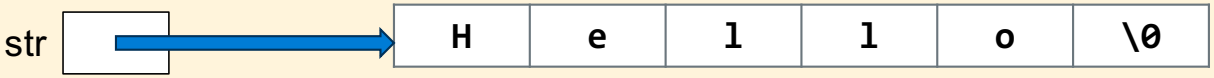
strdup(): Allocate Space and Copy a String

```
char *strdup(char *s);
```

- **`strdup`** is a function that has a **side effect** of returning a **null-terminated**, heap-allocated string copy of the provided text
- Alternative: **`malloc`** and copy the string with strncpy();
- The caller is responsible for freeing this memory when no longer needed

```
char *str = strdup("Hello");
*str = 'h';  // str points at a mutable string

free(str);  // caller correctly frees up space allocated by strdup()
str = NULL;
```



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Heap Memory "Leaks"

- A memory leak is when you **allocate memory** on the heap, **but never free it**

```
void
leaky_memory (void)
{
    char *buf = malloc(BLKSZ * sizeof(*bytes));
…
    /* code that never calls free() to deallocates the memory */
    return;  // you lose the address in buf when leaving scope
}
```

- Best practice: free up memory you allocated when you no longer need it
  - If you keep allocating memory, you may run out of memory in the heap!
- Memory leaks may cause long running programs to fault when they exhaust OS memory limits
- Valgrind is a tool for finding memory leaks (not pre-installed in all linux distributions though!)

x

Introduction to Structs – An Aggregate Data Type

- **Structs** are a **collection (or aggregation) of values** grouped under a **single name**
  - Each variable in a struct is called a **member** (sometimes **field** is used)
  - Each member is identified with a name
  - Each member can be (and quite often are) different types, include other structs
  - Like a Java class, but no associated methods or constructors with a struct
- Structure definition **does not** define a variable instance, nor does it allocate memory:
  - It creates a new variable type uniquely identified by its tagname:

  "struct tagname" includes the keyword struct and the tagname for this type

Easy to forget semicolon!

```
struct tagname {
  type1 member1;
  ...
  typeN memberN;
};
```

```
struct vehicle {
  char *state;
  char *plate;
  char *make;
  int year;
};
```


x

Creating a Node & Inserting it at the Front of the List

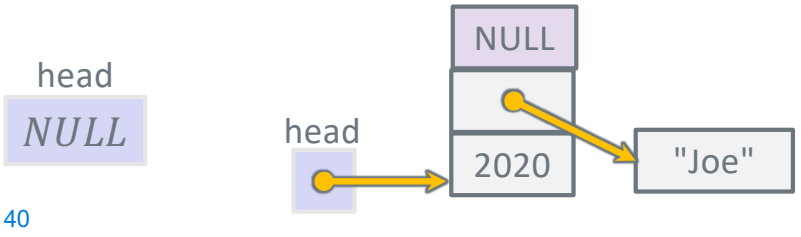
```c
// create node; insert at front when passed head
struct node *
creatNode(int year, char *name, struct node *link)
{
    struct node *ptr = malloc(sizeof(*ptr));
    if (ptr != NULL) {
        if ((ptr->name = strdup(name)) == NULL) {
            free(ptr);
            return NULL;
        }
        ptr->year = year;
        ptr->next = link;
    }
    return ptr;
}
```

```c
struct node {
  int year;
  char *name;
  struct node *next;
};
```

```c
// calling function body
struct node *head = NULL; // insert at front
struct node *ptr;

if ((ptr = creatNode(2020, "Joe", head)) != NULL) {
      head = ptr; // error handling not shown
}
if ((ptr = creatNode(1955, "Sam", head)) != NULL) {
      head = ptr; // error handling not shown
}
```

Never use head here!
you can lose your linked list
if creatNode() fails!



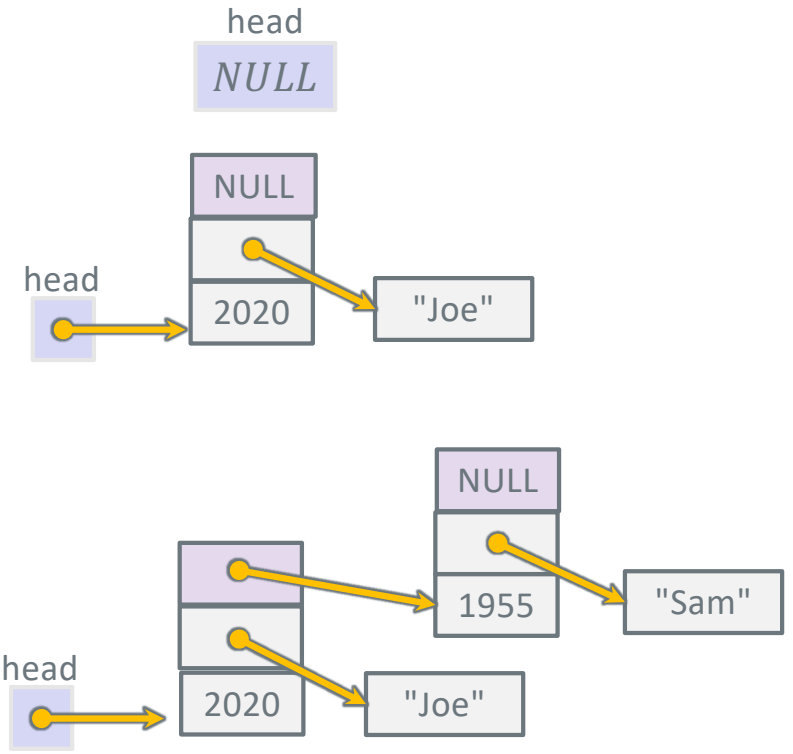
x

Creating a Node & Inserting it at the End of the List

```
// create a node and insert at the end of the list
struct node *
insertEnd(int year, char *name, struct node *head)
{
    struct node *ptr = head;
    struct node *prev = NULL;  // base case
    struct node *new;

    if ((new = creatNode(year, name, NULL)) == NULL)
        return NULL;

    while (ptr != NULL) {
        prev = ptr;
        ptr = ptr->next;
    }
    if (prev == NULL)
        return new;
    prev->next = new;
    return head;
}
```



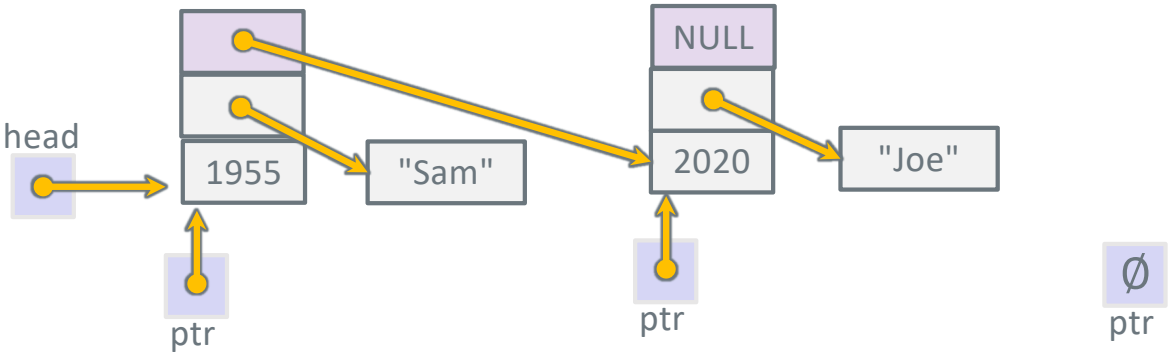

```
struct node *head = NULL;  // insert at end
struct node *ptr;
if ((ptr = insertEnd(2020, "Joe", head)) != NULL)
    head = ptr;
if ((ptr = insertEnd(1955, "Sam", head)) != NULL)
    head = ptr;
```


x

"Dumping" the Linked List

"walk the list from head to tail"

```
struct node {
  int year;
  char *name;
  struct node *next;
};
```




```
struct node *head;
struct node *ptr;
…
printf("\nDumping All Data\n");
ptr = head;
while (ptr != NULL) {
    printf("year: %d name: %s\n", ptr->year, ptr->name);
    ptr = ptr->next;
}
```

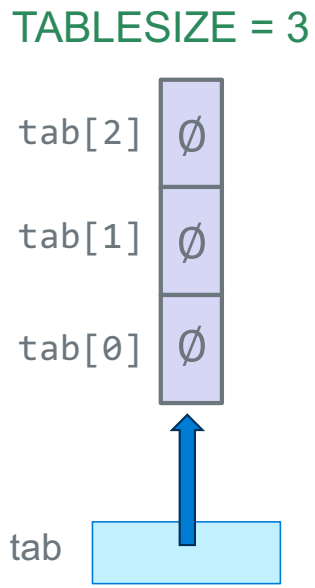
```
Dumping All Data
year: 1955 name: Sam
year: 2020 name: Joe
```


x

Allocating an empty Hash Table
Good use for calloc() to initialize all entries with NULL

```
#define TBSZ 3
int main(void)
{
    struct node *ptr;
    struct node **tab; // pointer to hashtable
    uint32_t index;

    if ((tab = calloc(TBSZ, sizeof(*tab))) == NULL) {
        fprintf(stderr,"Cannot allocate hash table\n");
        return EXIT_FAILURE;
    }
// continued on next slide
```



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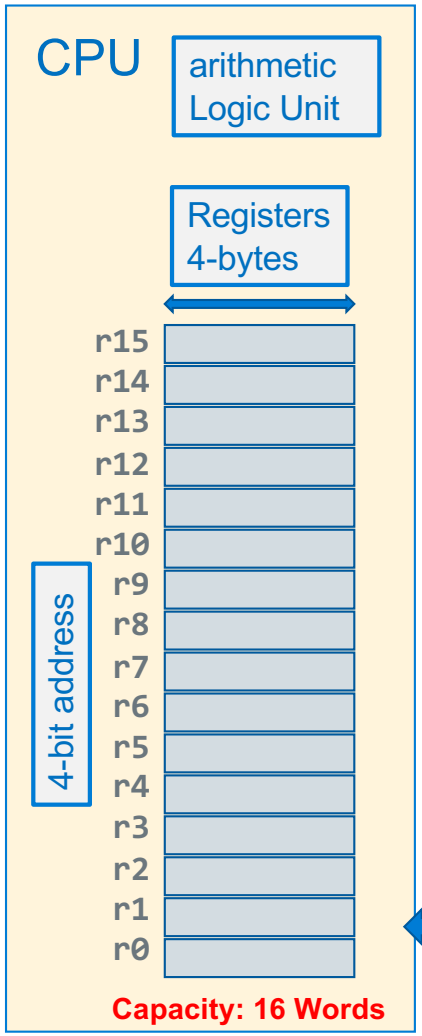
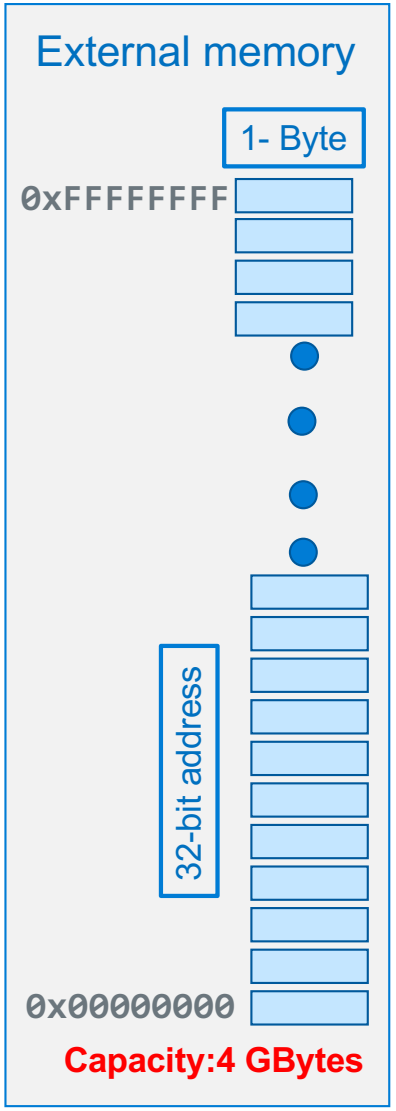
32-Bit Arm - Registers



- Registers are ***memory*** located within the **CPU**
- **Registers are the fastest** read and write storage
- Register is **word size in length** stores 32-bit values
  - Memory is accessed using pointers in registers
- In assembly language, register "addresses" are specified using predefined names starting with an r to differentiate them from main memory addresses which are labels (address)
- 16 registers: from r0 to r15 (encoded: 0x0 – 0xf)

CPU Memory Bus consists of two parts:

Address bus + Data bus



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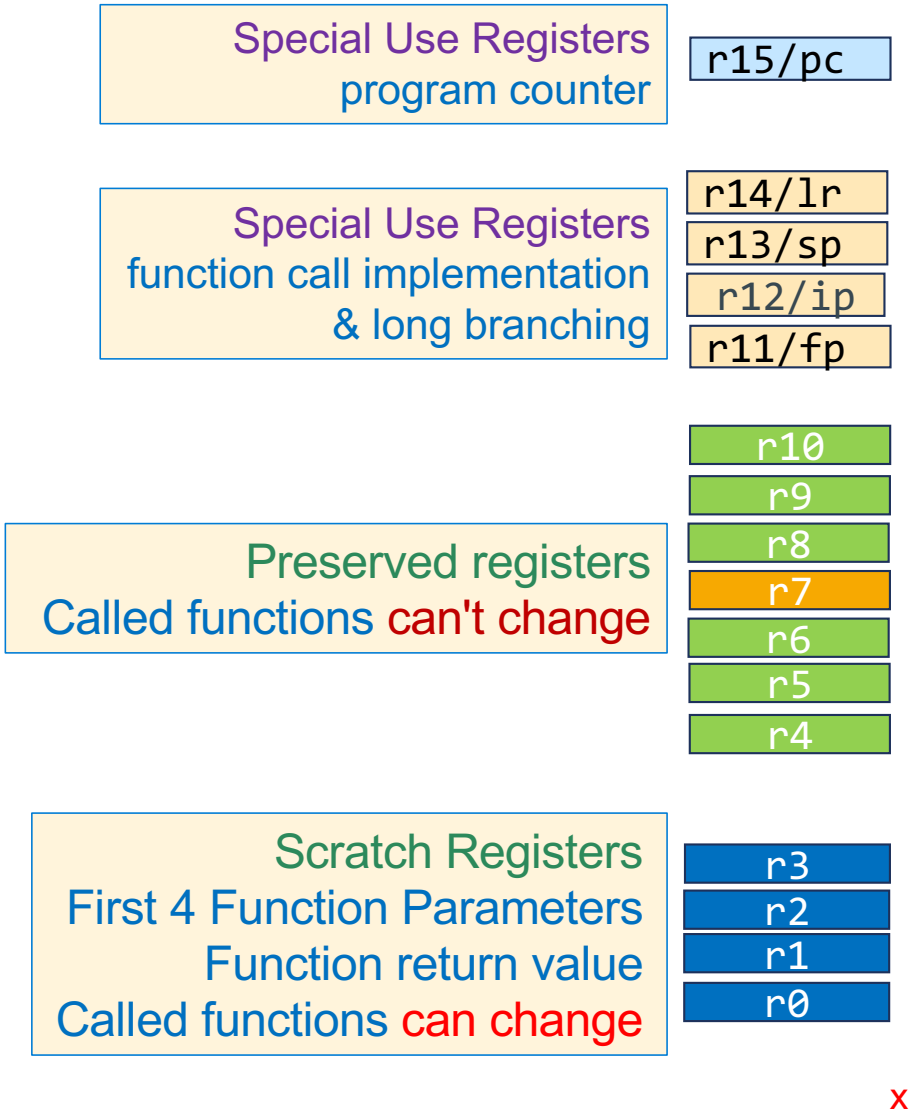
Using Arm-32 Registers

- There are two basic groups of registers, general purpose and special use
- General purpose registers can be used to contain up to 32-bits of data, but you must follow the **rules** for their use
  - Rules specify how registers are to be used so software can communicate and share the use of registers (later slides)
- Special purpose registers: have a dedicated hardware use (r15 the pc) or special use when used with certain instructions (r13 & r14)
- r15/pc is the program counter that contains the address of an instruction being executed (not exactly … later)



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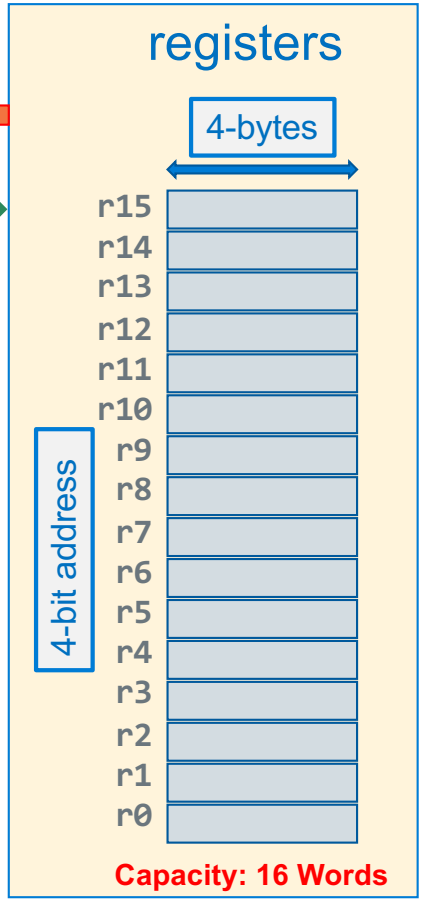
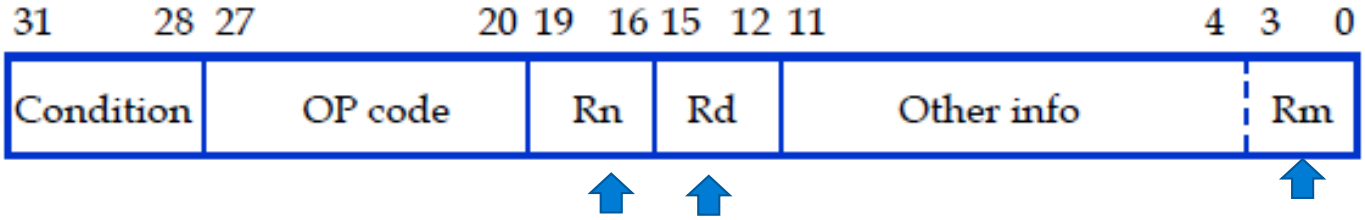
32-Bit Arm - Registers

All computations (add, subtract, etc.) are performed in the ALU

Arithmetic & Logic Unit (ALU)



- Almost all arithmetic, logic operations and data movement operations involve at least one register
- As a result, Register addresses are **directly** encoded into 4-bit fields in machine instructions (see below)



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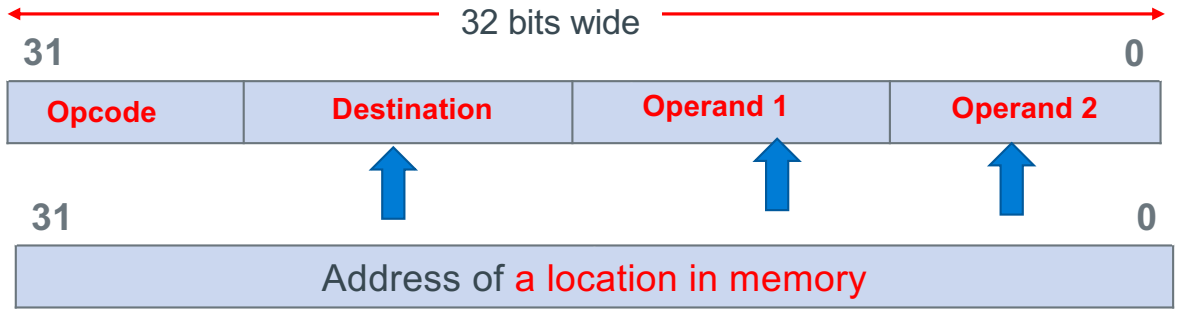
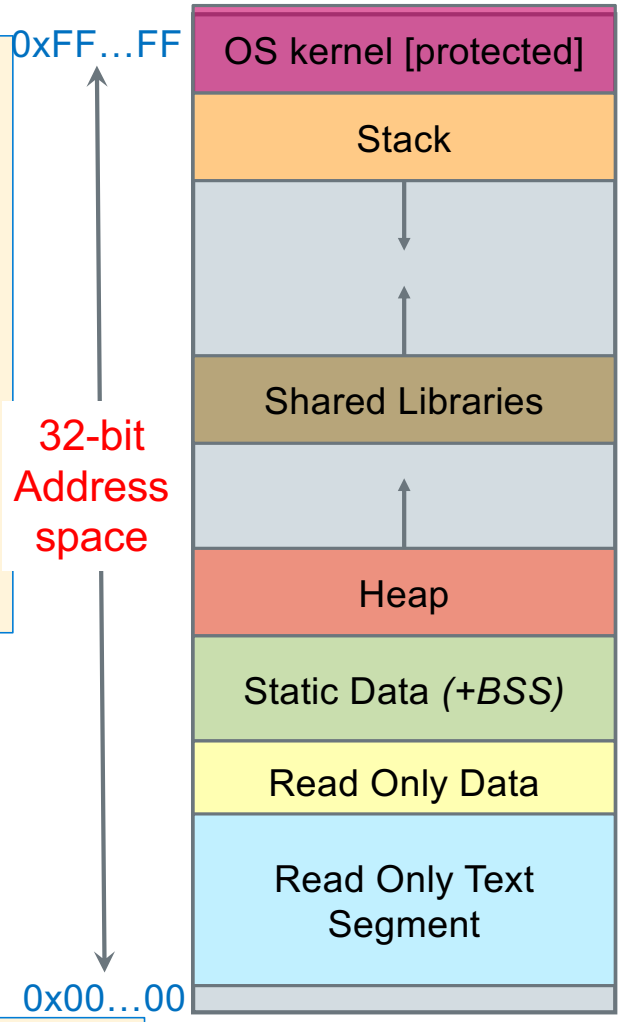
How to Access Memory?

- Consider a = b + c are operands are in memory
  - Operation code: add Destination: a
  - Operand 1: b Operand 2: c
- Aarch32 Instructions are always word size: 32 bits wide
  - Some bits must be used to specify the operation code
  - Some bits must be used to specify the destination
  - Some bits must be used to specify the operands
- Address space is 32 bits wide so put a POINTER in a register





NOT ENOUGH BITS for FULL Addresses to be stored in the instruction

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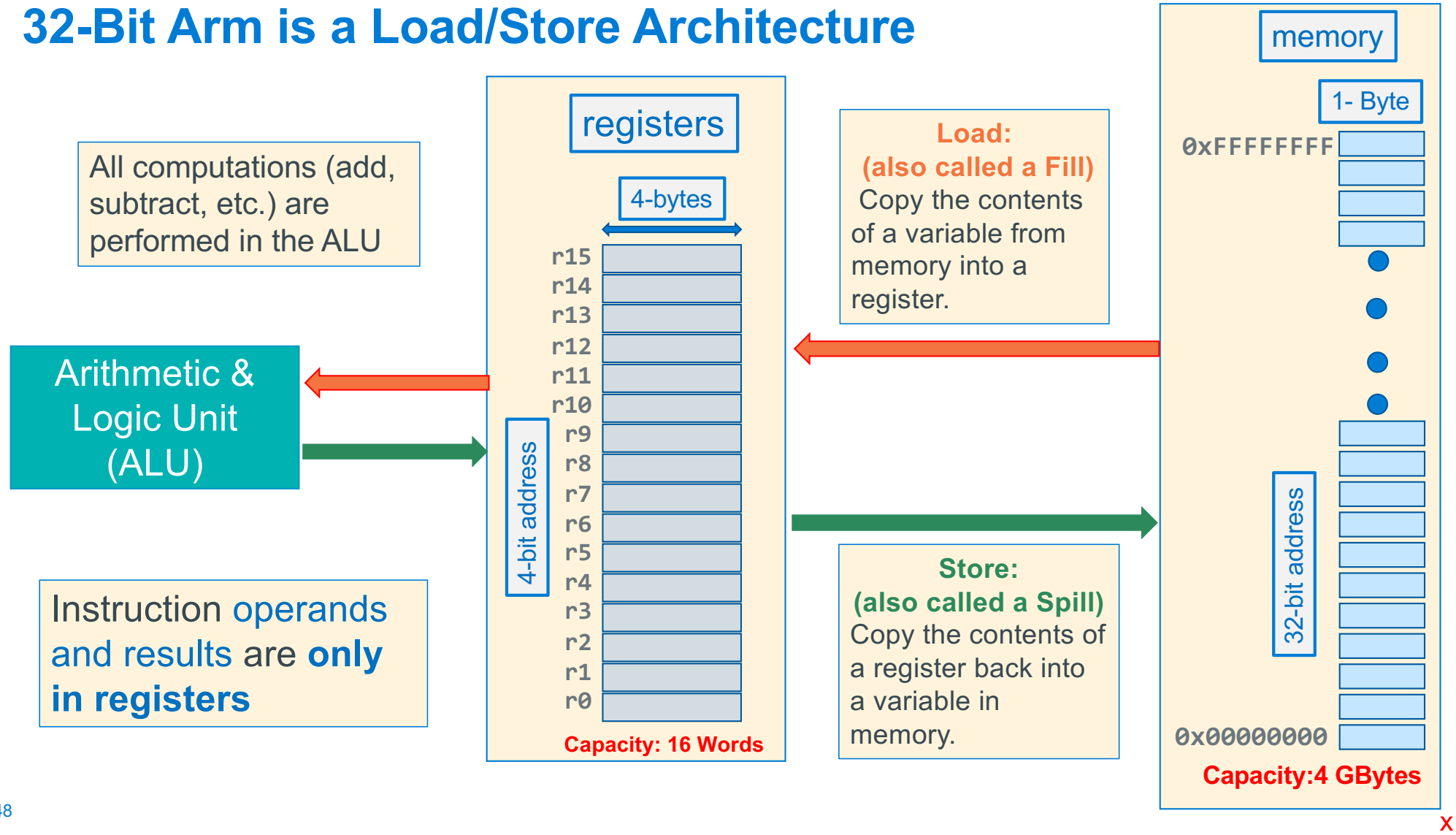
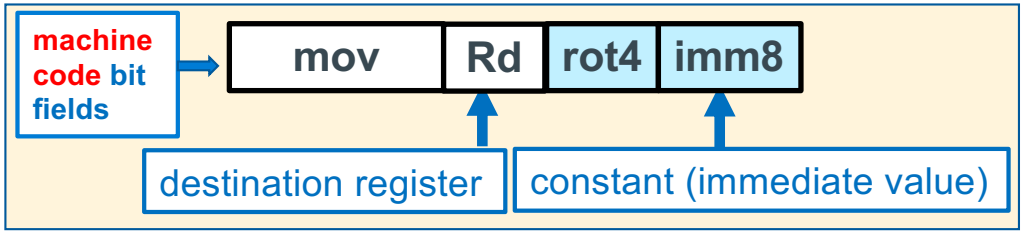
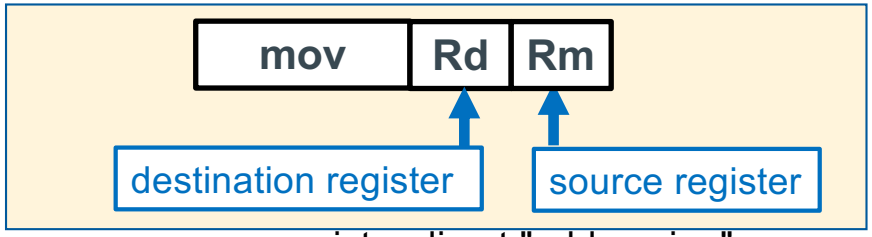
32-Bit Arm is a Load/Store Architecture



mov – Copies Register Content between registers



Immediate "addressing"



register direct "addressing"

	4	3	4	1	4	4	8	4
R type:	1110	000	Opcode	S	0000	Rd	00000000	Rm
I type:	1110	001	Opcode	S	0000	Rd	Rotate	Imm8

1101 - MOV
1111 - MVN

imm8 is 8 bits in size!

IMPACT: limited range of values

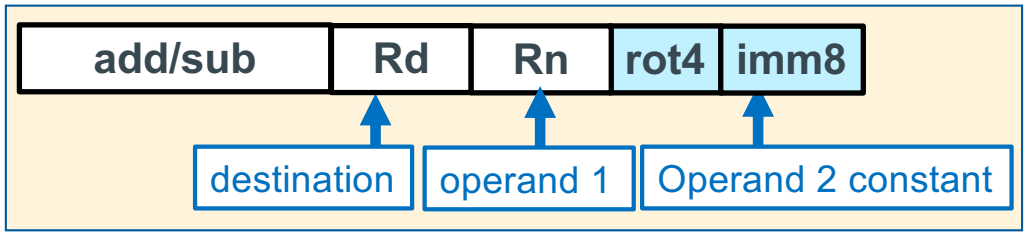
```
mov  Rd, constant   // Rd = constant
mov  Rd,  Rm        // Rd = Rm
```

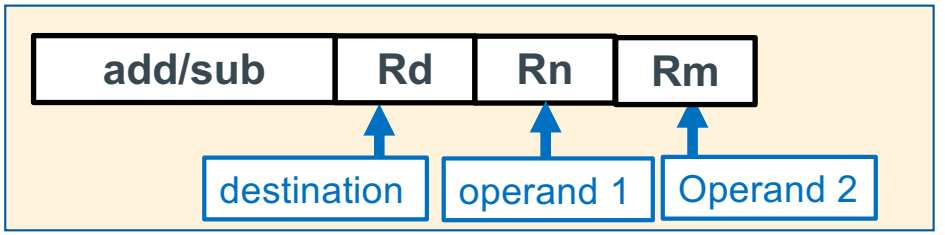
(**-256**) <= imm8 <= 255 + values from "rotating" bits - later

```
mov  r1, r5          // r1 = r5
mov  r1, 1           // r1 = 1
mov  r1, -4          // r1 = -4
```


x

add/sub – Add or Subtract two integers



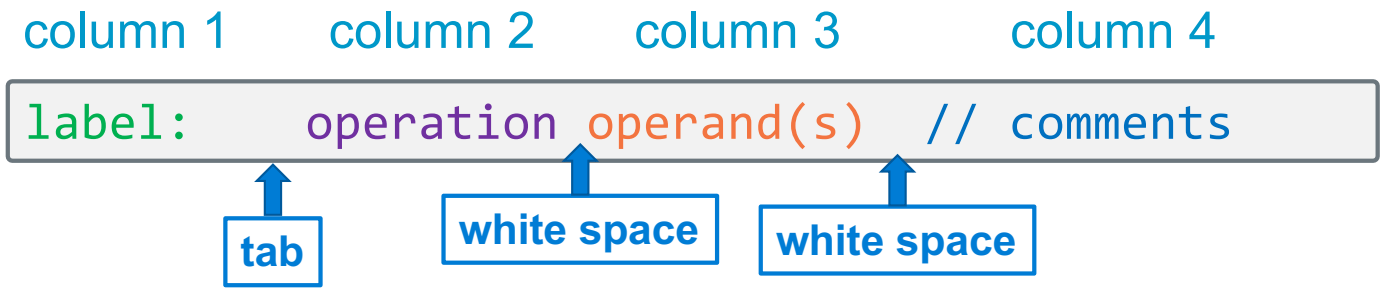



```
add   Rd, Rn, constant     // Rd = Rn + constant
sub   Rd, Rn, constant     // Rd = Rn - constant
add   Rd,  Rn,  Rm         // Rd = Rn + Rm
sub   Rd,  Rn,  Rm         // Rd = Rn - Rm
```

```
add    r1, r2, r3    // r1 = r2 + r3
sub    r1, r1, 1     // r1 = r1 – 1; or r1--
add    r1, r2, 234   // r1 = r2 + 234
```


x

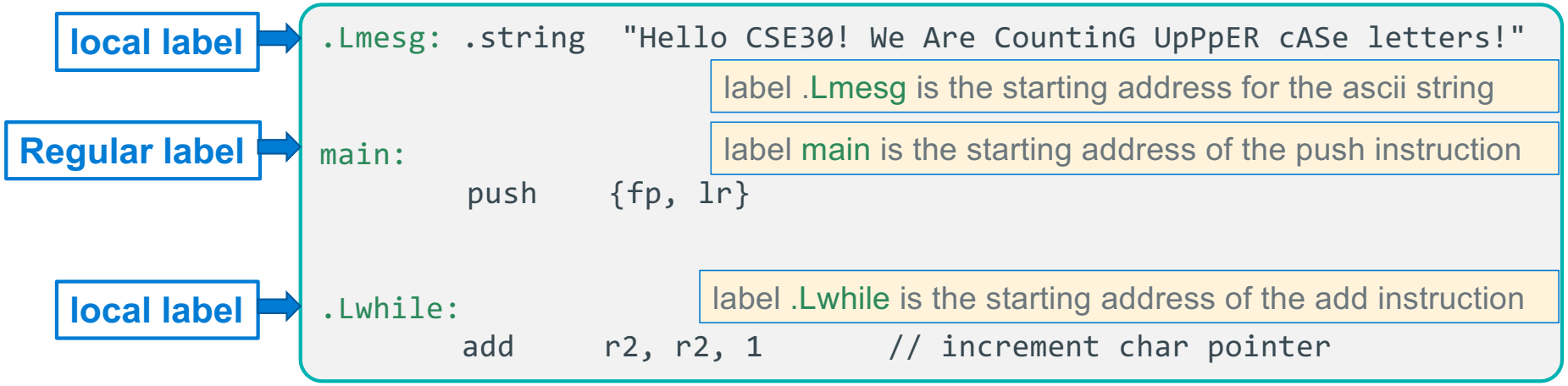
Line Layout in an Arm Assembly Source



- Assembly language source text files are **line oriented** (each ending in a '\n')
- **Each line represents** a **starting address in memory** and does **one** of:
  1. Specifies the contents of memory for a variable (segments containing data)
  2. Specifies the contents of memory for an instruction (text segment)
  3. **Assembler directives** tell the assembler to do something (for example, change label scope, define a macro, etc.) that does not allocate memory
- **Each line** is **organized into up to four columns**
  - Not every column is used on each line
  - Not every line will result in memory being allocated

x

Labels in Arm Assembly - 2



- Remember, a Label associates a name with memory location
- **Regular Label:**
  - Used with a Function name (label) or all static variables in any of the data segments
- **Local Label:** Name starts with `.L` (local label prefix) only usable in the same file
  1. Targets for
     a) branches: if switch, goto, break, continue,
     b) loops: for, while, do-while
  2. Anonymous variables (the address of literal not the address of foo in the following)

```
char *foo = "literal";
```


x

Unconditional Branching – Forces Execution to Continue at a Specified Label (goto)

b	imm24

imm24 is Relative direction
from the branch instruction (in +/- instructions)

Unconditional Branch instruction *(branch to only local labels in CSE30)*

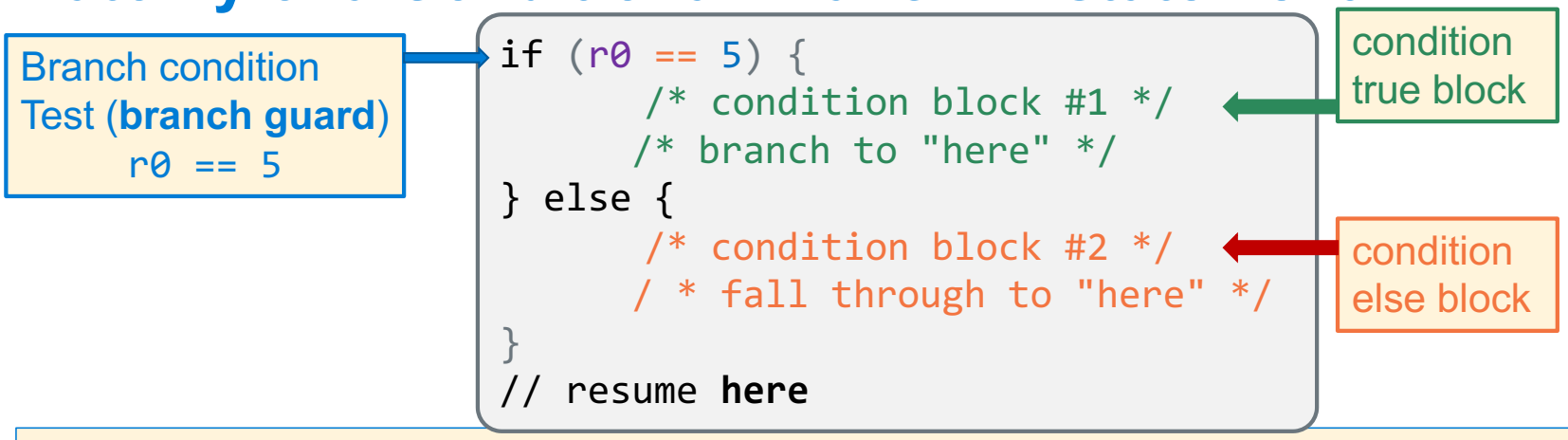
```
b .Llabel
```

- Causes an unconditional branch (aka goto) to the instruction with the address .Llabel
- .Llabel is called a **branch target label** (the *"target"* of a branch instruction)
- **Be careful! do not to branch to a function label!**
- .Llabel: translates into an number offset being imm24 shifted left two bits (+/- 32 MB)

```
        b     .Ldone                        // goto .Ldone
                :
.Ldone:
       add    r0, EXIT_SUCCESS        // set return value
```

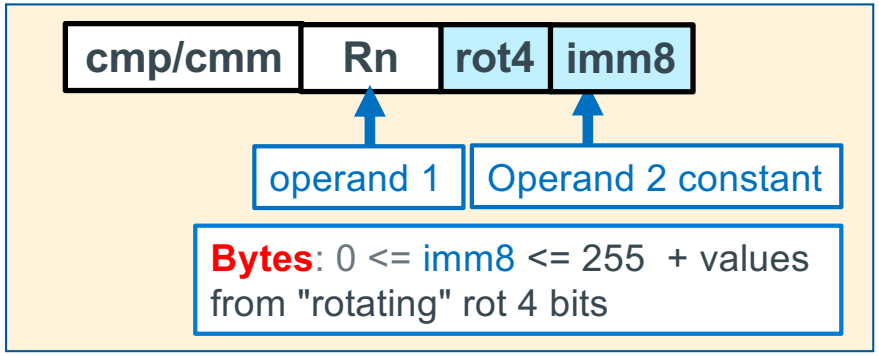

x

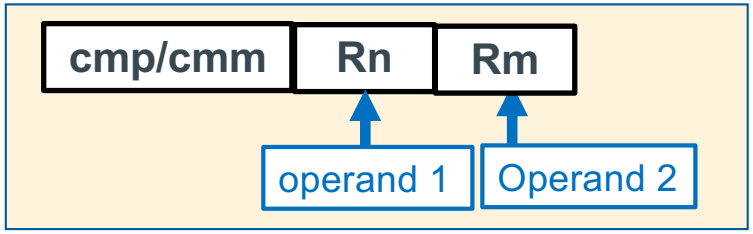
Anatomy of a Conditional Branch: If statement



- **Branch guard**: determines when to execute the "condition true block" or the "condition false block"
- **In C**, when the branch guard (condition test) evaluates **non-zero** you ***fall through*** to the ***condition true*** block, otherwise you branch to the ***condition false (else)*** block
- Step 1: evaluate the branch guard(s) (involves one or more compares/tests)
- Step 2: If branch guard evaluates to be **false**
  - **branch around** the **true block** and execute the **else block**
  - otherwise **"fall through"** and execute the true block
- **Block order** in C is where the True Block appears above the False block

cmp/cmm – Making Conditional Tests






```
cmp   Rn, constant      // Rn – constant; then sets condition flags
cmm   Rn, constant      // Rn + constant; then sets condition flags
cmp   Rn,  Rm           // Rn – Rm; then sets condition flags
cmm   Rn,  Rm           // Rn + Rm; then sets condition flags
```

The values stored in the registers Rn and Rm are not changed
The assembler will automatically substitute **cmn** for negative immediate values

```
cmp    r1, 0        // r1 – 0 and sets flags on the result
cmp    r1, r2       // r1 – r2 and sets flags on the result
```


x

Conditional Tests: Implementing ARM Branch guards

imm24 is Relative direction from the branch instruction (in +/- instructions)

Branch instruction

```
bsuffix .Llabel
```

Use a local label with branch instructions

Condition	*Meaning*	*Flag Checked*
BEQ	Equal	Z = 1
BNE	Not equal	Z = 0
BGE	Signed ≥ ("Greater than or Equal")	N = V
BLT	Signed < ("Less Than")	N ≠ V
BGT	Signed > ("Greater Than")	Z = 0 && N = V
BLE	Signed ≤ ("Less than or Equal")	Z = 1 || N ≠ V
BMI	Minus/negative	N = 1
BPL	Plus - positive or zero (non-negative)	N = 0
B	Branch Always (unconditional)	

- Bits in the condition field specify the **conditions** when the branch happens
- If the condition evaluates to be true, next instruction executed is at `.Llabel:`
- If the condition evaluates to be false, next instruction executed is immediately after the branch
- Unconditional branch is when the condition is *"always"*

x

Program Flow: Simple If statement, No Else

C source Code	*Incorrect Assembly*	*Correct Assembly*

`int r0;`
`if (r0 > 10) {`
`  // True Block`
`}`
	`  cmp r0, 10`
	`  bgt .Lendif`
	`  // True Block`
	`.Lendif:`
		`  cmp r0, 10`
		`  ble .Lendif`
		`  // True Block`
		`.Lendif:`

- **Realize that in ARM assembly you can only either "fall through" to the next instruction or branch to a specific instruction**
- **Approach: adjust** the conditional test then **branch around** the **true block**
- Use a **conditional test** that **specifies the inverse of the condition used in C**
  - **This preserves C block order**

x

Branch Guard "*Adjustment*" Table Preserving C Block Order In Assembly

Compare in C	*"Inverse"* Compare in C	*Assembly using Inverse Compare*
==	!=	bne
!=	==	beq
>	<=	ble
>=	<	blt
<	>=	bge
<=	>	bgt

```
if (r0 compare 5)
    /* condition true block */
    /* then fall through */
}
```

```
    cmp r0, 5
    inverse compare .Lelse
    // condition true block
    // then fall through
.Lendif:
```


x

Arm Conditional Branching *Simple IF no else*

C If statement

```
int r0;
if (r0 == 5) {
    /* condition true block */
    /* then fall through */
}
/* branch around to this code */
```

If r0 == 5 true
then ***fall through*** to
the true block

ARM If statement

```
    cmp r0, 5
    bne .Lendif
    /* condition true block */
    /* then fall through */
.Lendif:
/* branch around to this code */
```

If r0 == 5 false
then branch ***around***
the true block

- If statements in ARM
- **Step 1:** make a conditional test using a **cmp** instruction
- **Step 2:** if test evaluates to FALSE, **branch around** the **condition true** block with a one of the conditional branch instruction

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Program Flow: If with an Else

Approach:

1. **adjust** the conditional test to branch to the **False Block**
2. **Fall through** to the **True Block**
3. Bottom of the **True Block** **unconditionally branches** around the **False block**

C source Code	*Assembly*

`int r0;`
`if (r0 > 10) {`
 	
`  // true block`
`  // branch always around the false block`
`} else {`
 	
`  // false block`
 	
`}`
	`  cmp r0, 10`
	`  ble .Lelse`
	`  /fall through`
	`  // true block`
	`  b .Lendif`
	`.Lelse:`
	
	`  // false block`
	`  // fall through`
	`.Lendif:`

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Review – Short Circuit or Minimal Evaluation

- In evaluation of conditional guard expressions, C uses what is called **short circuit** or **minimal** evaluation

```
if ((x == 5) || (y > 3))  // if x == 5 then y > 3 is not evaluated
```

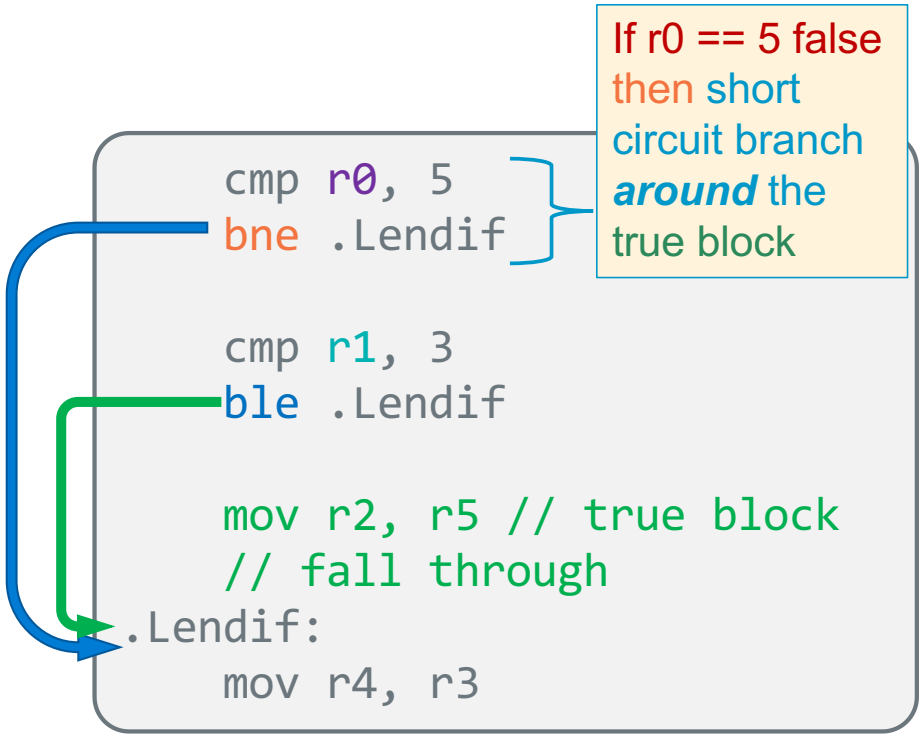
- **Each** expression argument is evaluated **in sequence** from left to right including any side effects (modified using parenthesis), **before** (optionally) evaluating the next expression argument
- If after evaluating an argument, the value of the entire expression can be determined, then the remaining arguments are NOT evaluated *(for performance)*

```
if ((a != 0) && func(b))      // if a is 0, func(b) is not called
    // do something
```


x

Program Flow – If statements && compound tests - 1

```
if ((r0 == 5) && (r1 > 3)) {
    r2 = r5;  // true block
    /* fall through */
}
r4 = r3;
```



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Program Flow – If statements && compound tests - 2

test1 test2

```
if ((r0 == 5) && (r1 > 3))
{
    r2 = r5; // true block
    // branch around else
} else {
    r5 = r2; False block */
    /* fall through */
}
r4 = r3;
```

```
    cmp r0, 5  // test 1
    bne .Lelse

    cmp r1, 3  // test 2
    ble .Lelse

    mov r2, r5 // true block
    // branch around else
    b .Lendif
.Lelse:
    mov r5, r2 // false block
    // fall through

.Lendif:
   mov r4, r3
```

if r0 == 5 false then short circuit branch ***to*** the false block

if r1 > 3 false then branch ***to*** the false block

x

Program Flow – If statements && compound tests - 3

```
if (test1 && test2 & … & testn) {
    // true block
    // branch around else
} else {
    // False block
    /* fall through */
}
```

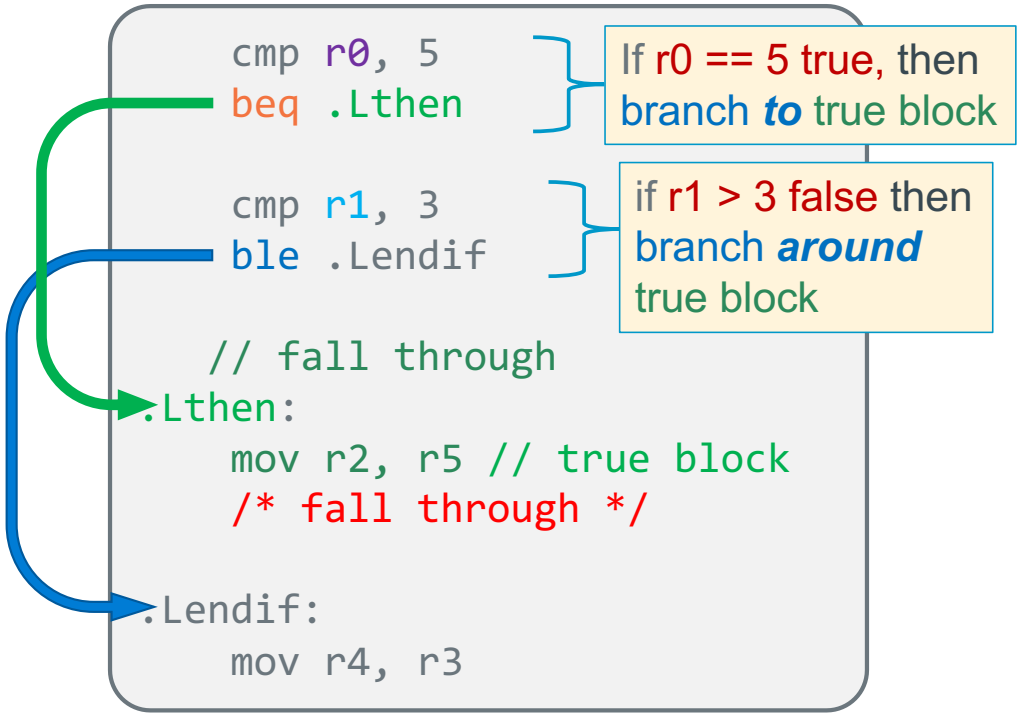
All compound && tests use an inverse test and if they evaluate to **true** branch ***to*** the false block

```
    cmp  xx,xx  // test 1
    inverse test branch .Lelse

    cmp xx, xx  // test 2
    inverse test branch .Lelse

       // more tests

    cmp xx, xx  // test n
    inverse test branch .Lelse

    mov r2, r5 // true block
    // branch around else
    b .Lendif
.Lelse:
    mov r5, r2 // false block
    // fall through

.Lendif:
   mov r4, r3
```


x

Program Flow – If statements || compound tests - 1

```
if ((r0 == 5) || (r1 > 3)) {
    r2 = r5; // true block
    /* fall through */
}
r4 = r3;
```



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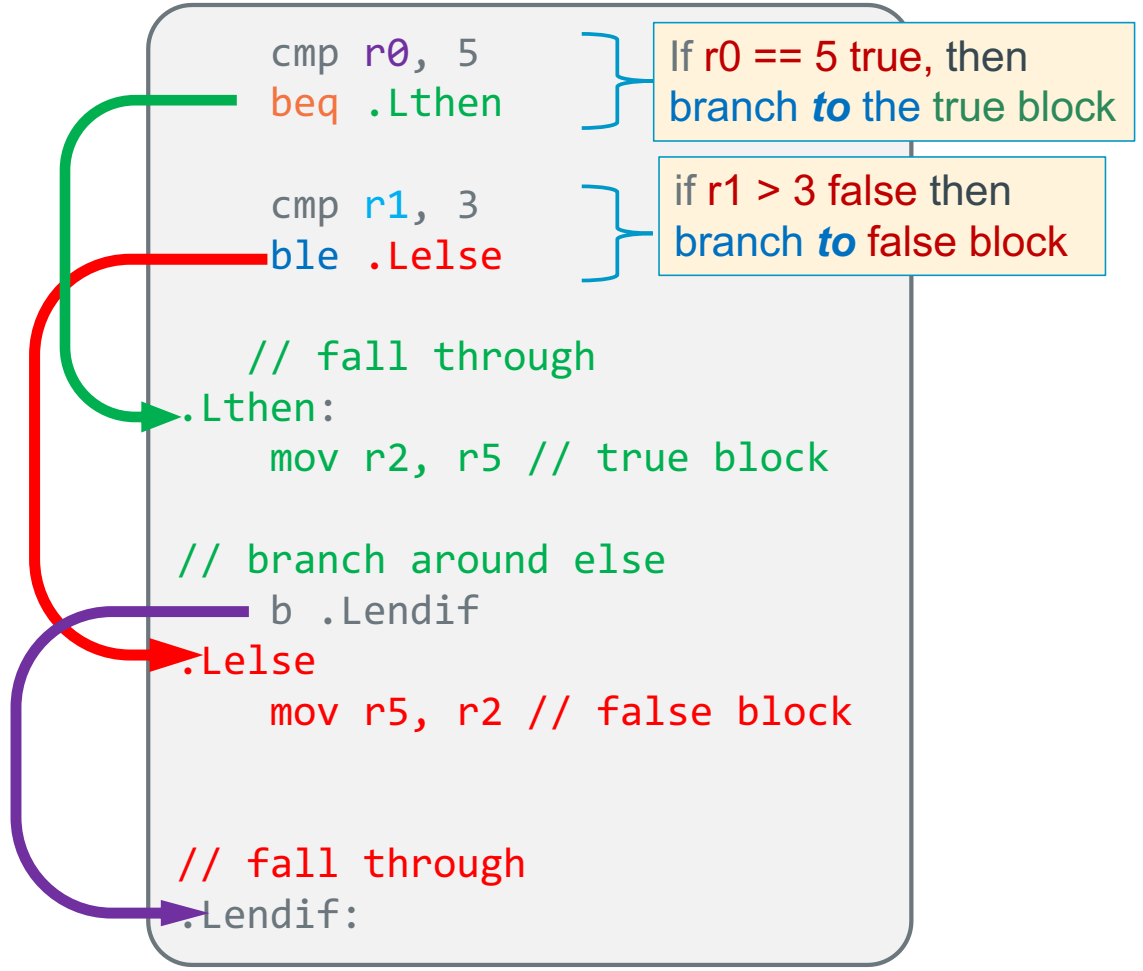
Program Flow – If statements || compound tests - 2

```
if ((r0 == 5) || (r1 > 3)) {
    r2 = r5; // true block
    /* branch around else */
} else {
    r5 = r2; // false block
    /* fall through */
}
```



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Program Flow – If statements || compound tests - 3

```
if (test1 || test2 || .. || testn) {
    // true block
    /* branch around else */
} else {
    // false block
    /* fall through */
}
```

All compound || tests (except the last one) use the same test as C and if they evaluate to true branches ***to*** the true block

The last (leftmost) compound || test uses an inverse test and if it evaluates to true branches ***to*** false block

```
    cmp XX, XX      // test 1
    same test branch .Lthen

    cmp XX, XX      // test 2
    same test branch .Lthen

    // other tests

    cmp XX, XX      // test n
    inverse test branch .Lelse

   // fall through
.Lthen:
   // true block
   // branch around else
   b .Lendif
.Lelse
   // false block
    // fall through
.Lendif:
```


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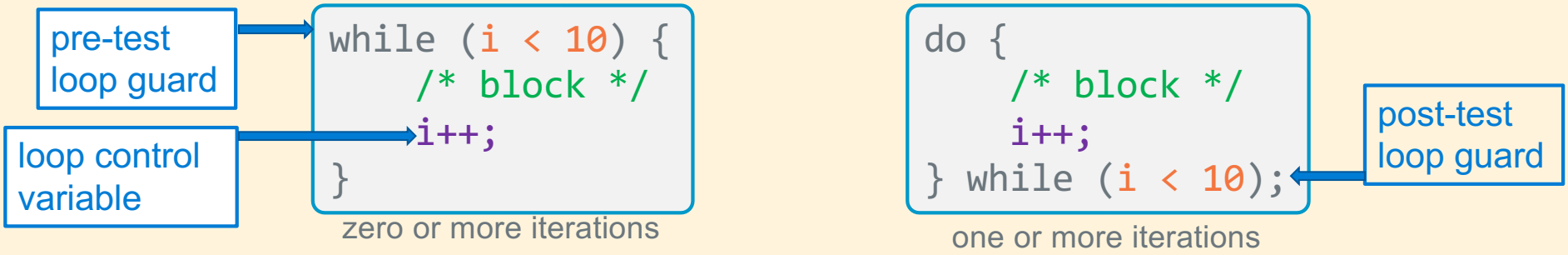
Program Flow – Pre-test and Post-test Loop Guards

- loop guard: code that must evaluate to true before the next iteration of the loop
- If the loop guard test(s) evaluate to true, the *body of the loop* is executed again
- pre-test loop guard is at the top of the loop
  - If the test evaluates to true, execution falls through to the loop body
  - if the test evaluates to false, execution **branches** around the loop body



- post-test loop guard is at the bottom of the loop
  - If the test evaluates to true, execution **branches** to the top of the loop
  - If the test evaluates to false, execution falls through the instruction following the loop

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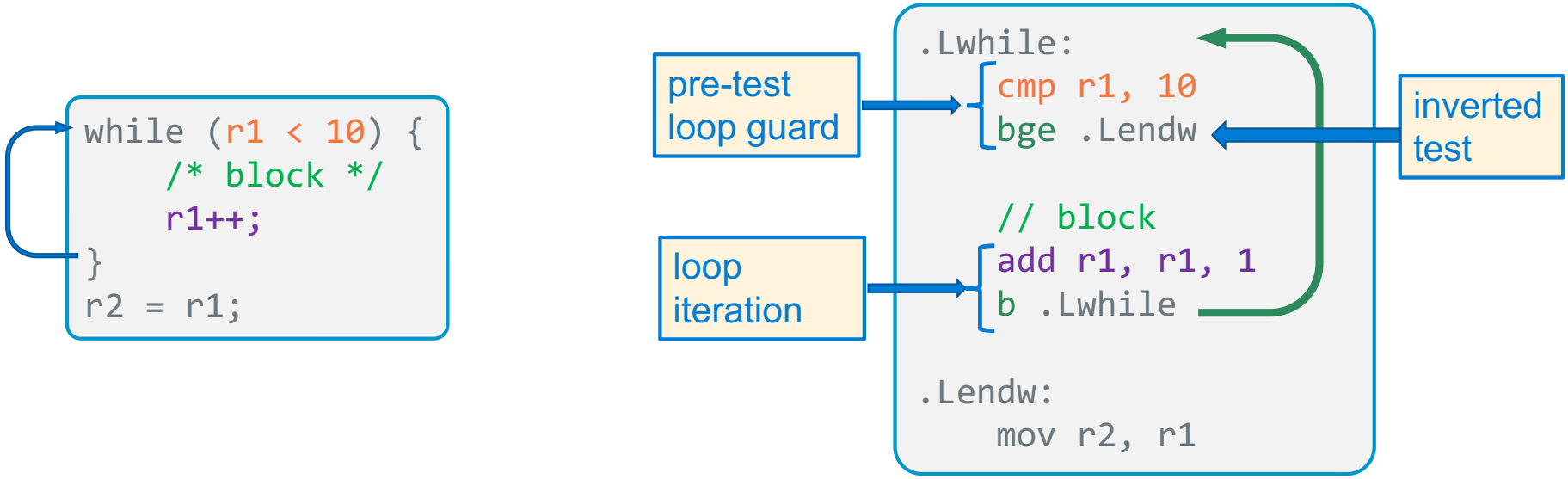
Pre-Test Guards - While Loop



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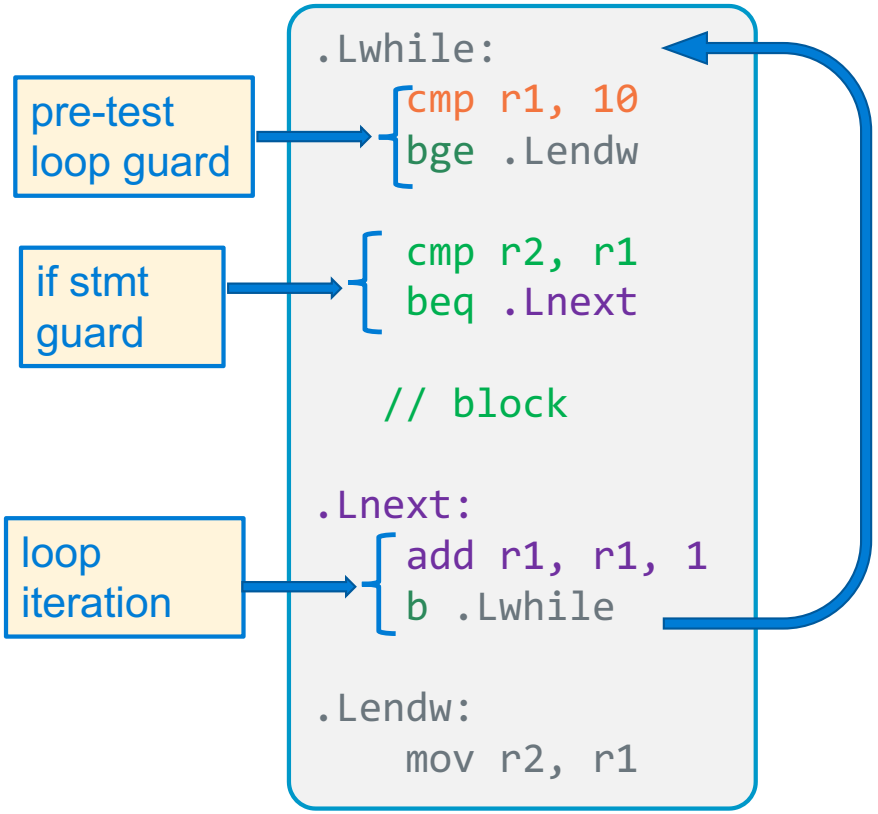
Pre-Test Guards - While Loop

```
while (r1 < 10) {
    if (r2 != r1) {
        /* block */
    }
    r1++;
}
r2 = r1;
```



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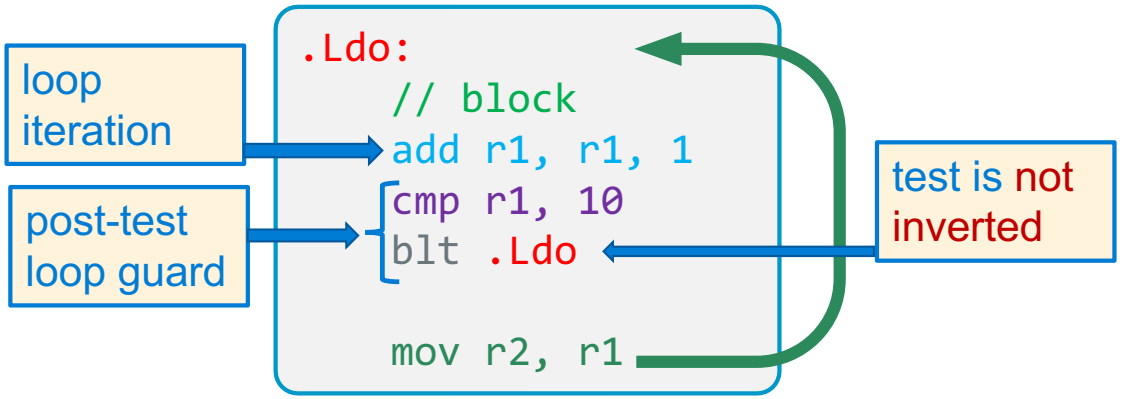
Post-Test Guards – Do While Loop

```
do {
    /* block */
    r1++;
} while (r1 < 10);

r2 = r1;
```



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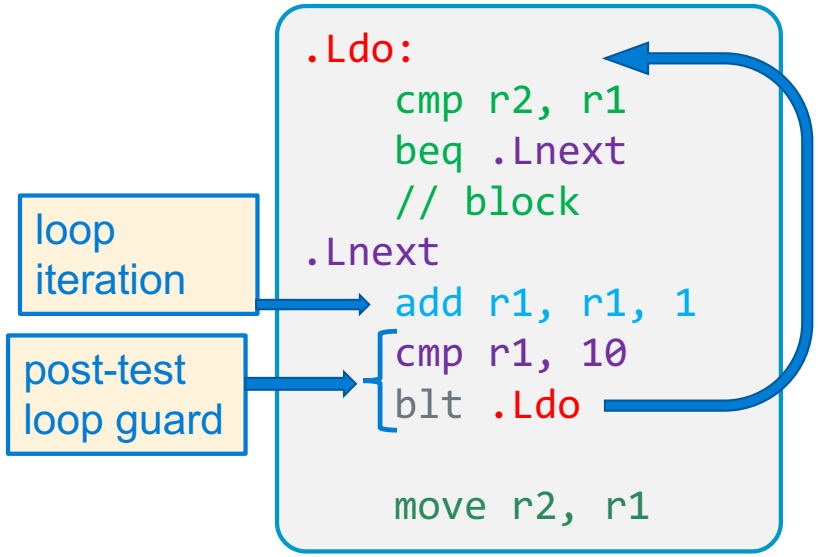
Post-Test Guards – Do While Loop

```
do {
    if (r2 != r1) {
        /* block */
    }
    r1++;
} while (r1 < 10);

r2 = r1;
```



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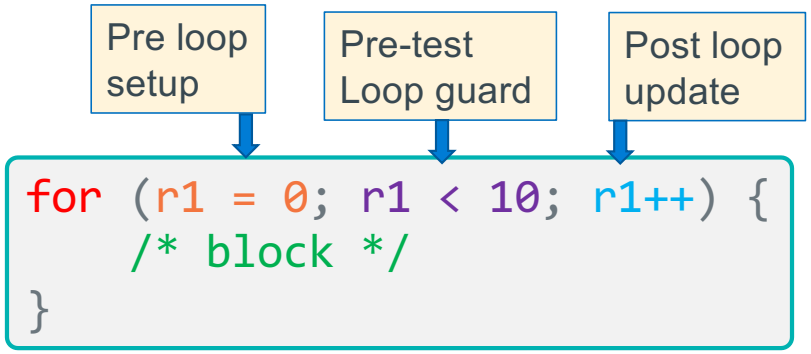
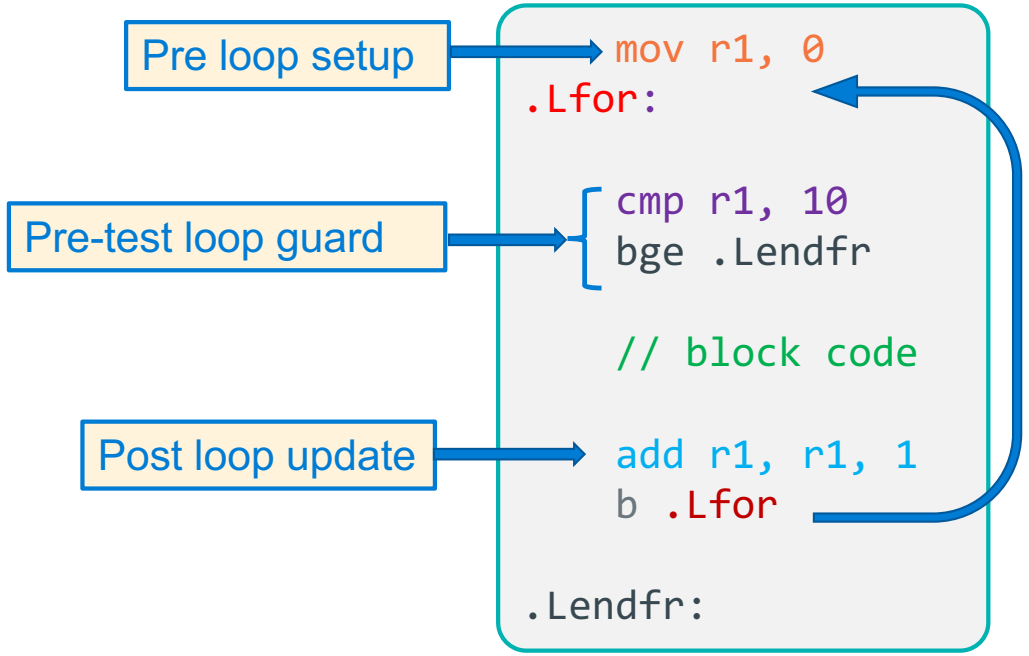
Program Flow – Counting (For) Loop Version 1



A **counting loop** has three parts:

1. Pre-loop setup
2. Pre-test loop guard conditions
3. Post-loop update



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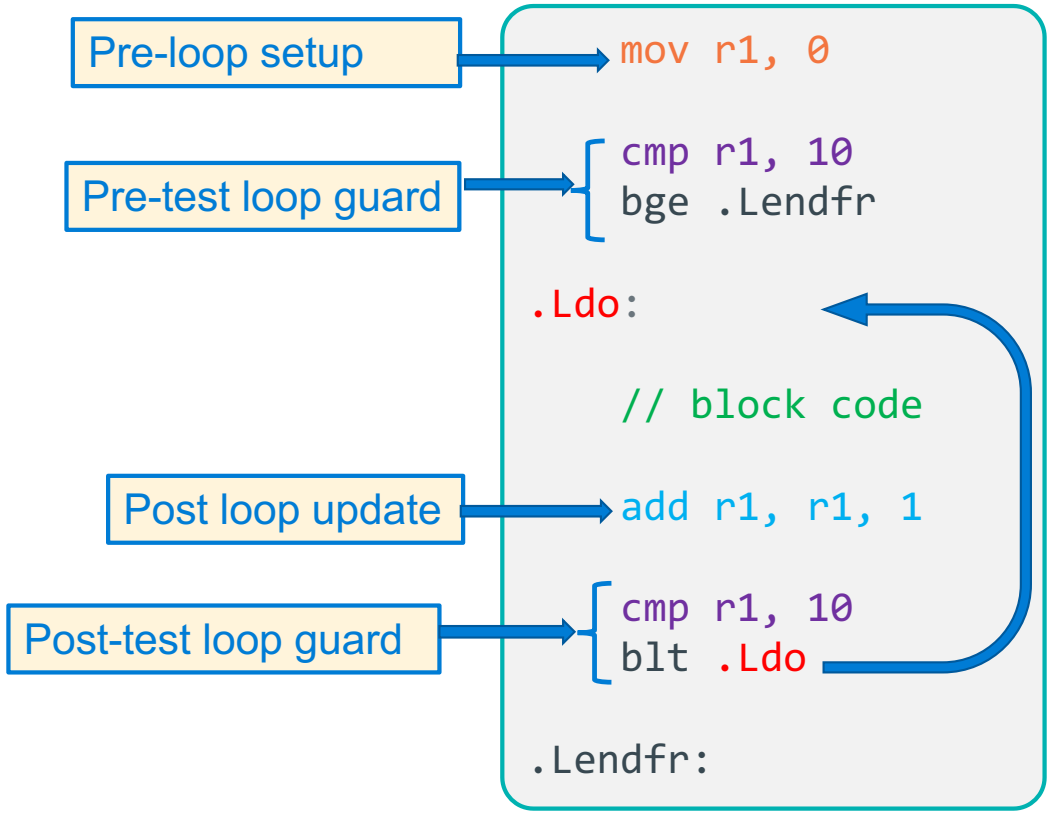
Program Flow – Counting (For) Loop – Version 2

Pre loop setup

Pre-test Loop guard

Post loop update

```
for (r1 = 0; r1 < 10; r1++) {
    /* block */
}
```



- Alternative:
- move Pre-test loop guard before the loop
- Add post-test loop guard
  - *converts* to *do while*
  - **removes** an **unconditional branch**

x

Nested loops

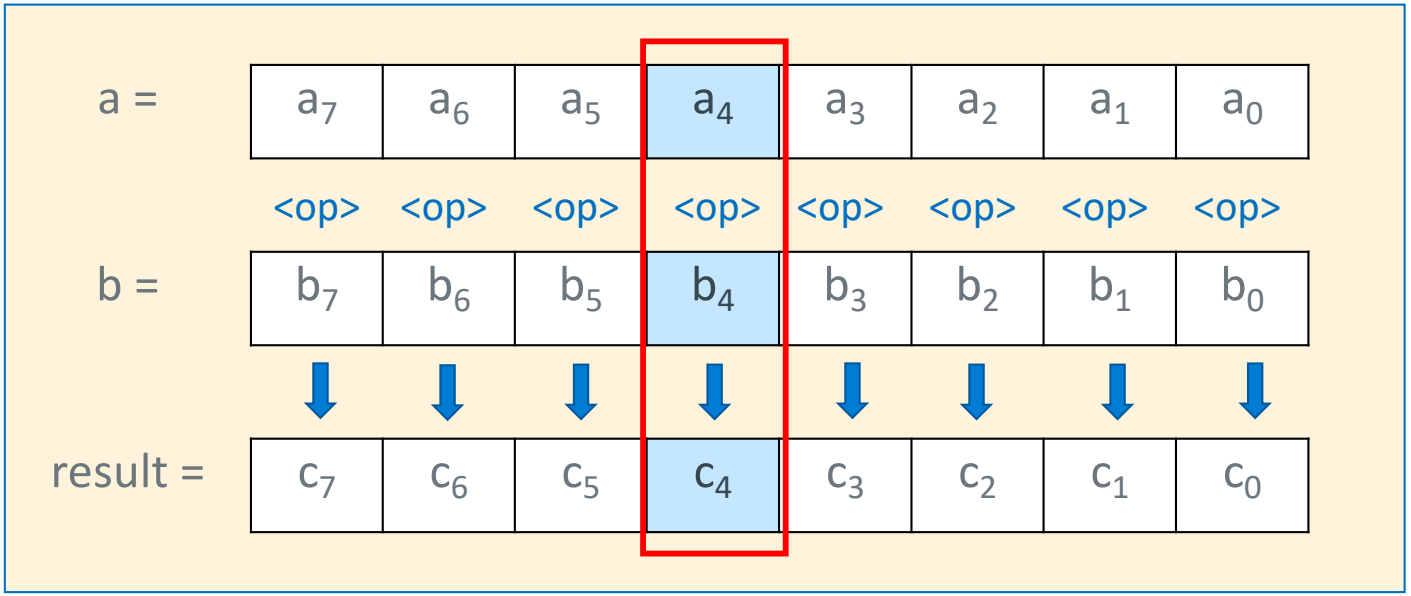
```
for (r3 = 0; r3 < 10; r3++) {
    r0 = 0;

    do {
        r0 = r0 + r1++;
    } while (r1 < 10);

    // fall through
    r2 = r2 + r1;
}
r5 = r0;
```

```
    mov r3, 0
.Lfor:
    cmp r3, 10      // loop guard
    bge .Lendfor

    mov r0, 0

.Ldo:
    add r0, r0, r1
    add r1, r1, 1

    cmp r1, 10   // loop guard
    blt .Ldo

    // fall through
    add r2, r2, r1

    add r3, r3, 1 // loop iteration
    b .Lfor
.Lendfor:
    mov r5, r0
```

- Nest loop blocks as you would in C or Java

x

What is a Bitwise Operation?



- Bitwise operators are applied independently to each of the corresponding bit positions in each variable
- Each bit position of the result depends only on bits in the same bit position within the operands

x

Bitwise (Bit to Bit) Operators in C

`output = ~a;`

a	~a
0	1
1	0

`output = a & b;`

a	b	a & b
0	0	0
0	1	0
1	0	0
1	1	1

& with 1 to let a **bit through**
& with 0 to **set a bit to 0**

`output = a | b;`

a	b	a | b
0	0	0
0	1	1
1	0	1
1	1	1

| with 1 to **set a bit to 1**
| with 0 to let a **bit through**

`output = a ^ b; //EOR`

a	b	a ^ b
0	0	0
0	1	1
1	0	1
1	1	0

^ with 1 **will flip the bit**
^ with 0 to let a **bit through**

Bitwise NOT

```
~ 1100
  ----
  0011
```

Bitwise AND

```
  0110
& 1100
  ----
  0100
```

Bitwise OR

```
  0110
| 1100
  ----
  1110
```

Bitwise EOR

```
  0110
^ 1100
  ----
  1010
```


x

Bitwise Not (vs Boolean Not)

```
in C
int output = ~a;
```

a	~a
0	1
1	0

Bitwise NOT

```
~ 1100
  ----
  0011
```

	Bitwise Not
number	0101 1010 0101 1010 1111 0000 1001 0110
~number	1010 0101 1010 0101 0000 1111 0110 1001

Meaning	*Operator*	*Operator*	*Meaning*
Boolean NOT	!b	~b	Bitwise NOT

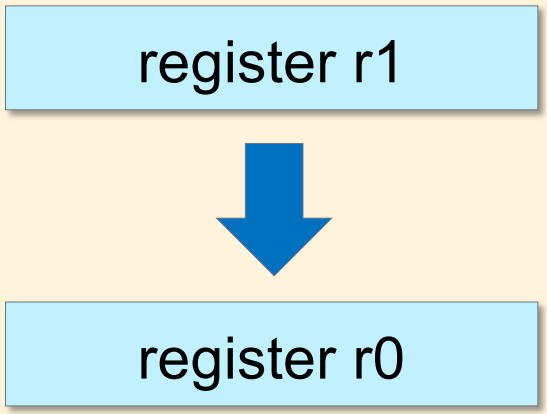
Boolean operators act on the entire value not the individual bits

Type	*Operation*	result
bitwise	~0x01	1111 1111 1111 1111 1111 1111 1111 1110
Boolean	!0x01	0000 0000 0000 0000 0000 0000 0000 0000

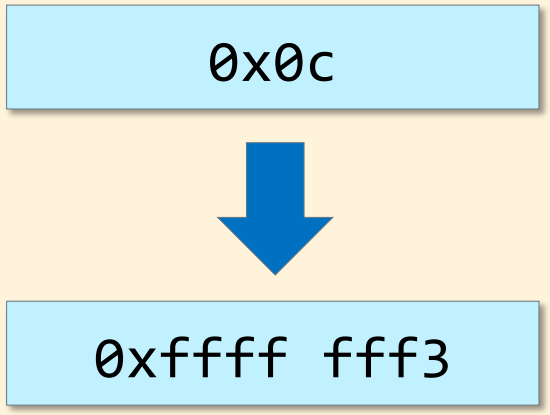
x

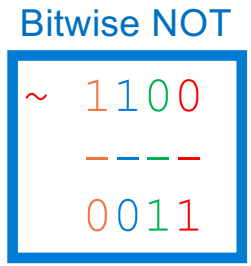
MVN (not)

```
mvn   r0, r1

// Copies all 32 bits
// of the value held
// in register r1 into
// the register r0
// then does a bitwise NOT
```

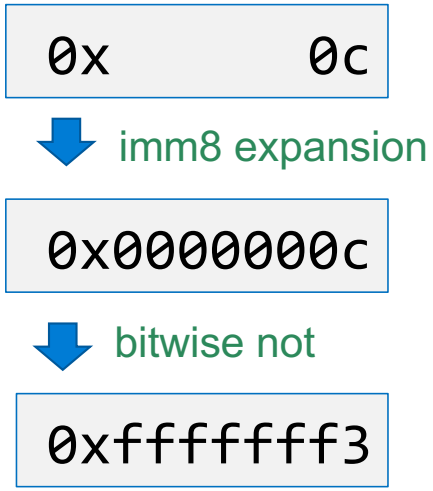



```
mvn   r0, 12

// Expands an imm8 value 0x0c
// stored in the instruction
// into a register then does
// a bitwise NOT
```



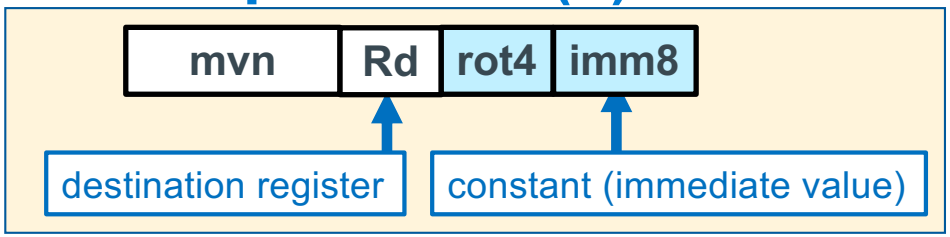


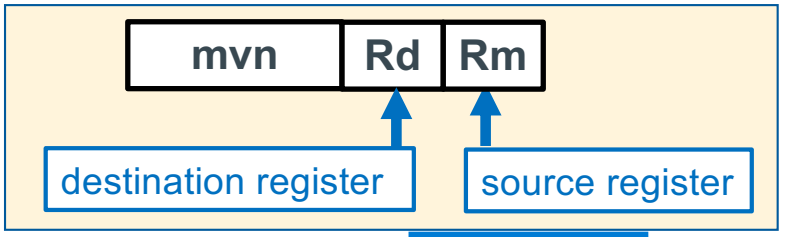
- A **bitwise NOT** operation



x

mvn – Copies NOT (~)






```
mvn   Rd, constant    // Rd = constant
mvn   Rd,  Rm         // Rd = Rm
```

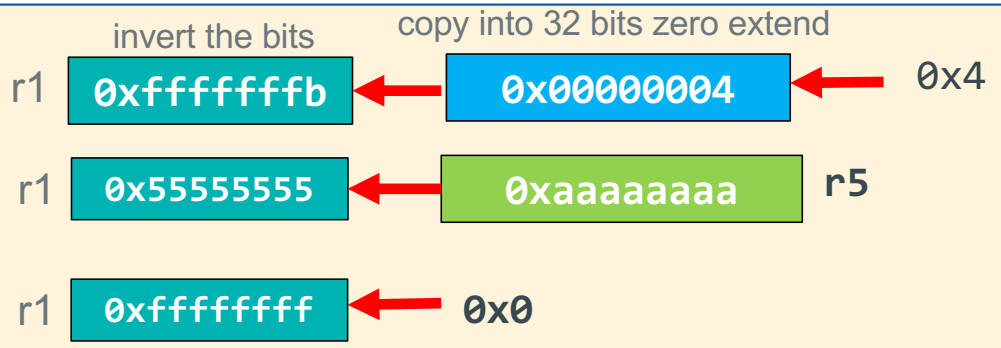
```
~ 1100
  ----
  0011
```

Bitwise NOT

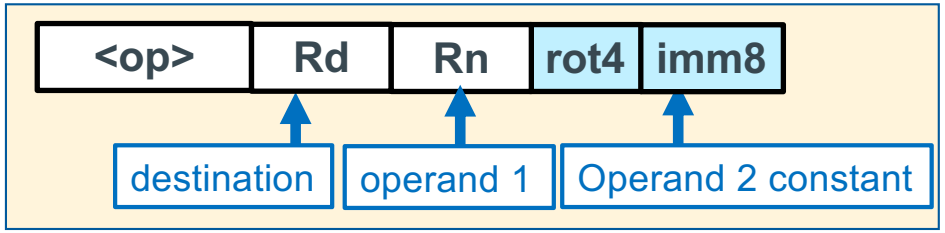
bitwise NOT operation. Immediate (constant) version copies to 32-bit register, then does a bitwise NOT

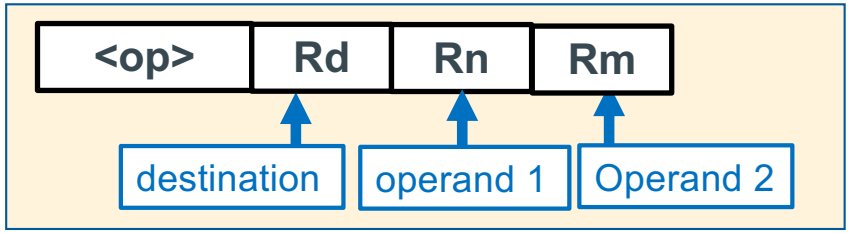
imm8	extended imm8	inverted imm8	signed base 10
0x00	0x00 00 00 00	0xff ff ff ff	-1
0xff	0x00 00 00 ff	0xff ff ff 00	-256

```
mvn    r1, 4          // x = ~4
mvn    r1, r5         // x = ~y in C
mvn    r1, 0          // x = -1
```



Bitwise Instructions






```
<op>   Rd,   Rn, constant    // Rd = Rn <op> constant
<op>   Rd,   Rn,  Rm         // Rd = Rn <op> Rm
```

Bytes: 0 <= imm8 <= 255 + values from "rotating" rot 4 bits

Bitwise <op> description	C Syntax	*Arm <op> Syntax Op2: either register or constant value*	*Operation*
Bitwise **AND**	`a & b`	`and` R_d, R_n, Op2	$R_d = R_n$ & Op2
Bitwise **OR**	`a | b`	`orr` R_d, R_n, Op2	$R_d = R_n$ | Op2
Exclusive **OR**	`a ^ b`	`eor` R_d, R_n, Op2	$R_d = R_n$ ^ Op2
Bitwise **NOT**	`a = ~b`	`mvn` R_d, R_n	$R_d = \sim R_n$

x

Bitwise versus C Boolean Operators

Boolean Operators			Bitwise Operators	
Meaning	*Operator*		*Operator*	*Meaning*
Boolean AND	a && b		a & b	Bitwise AND
Boolean OR	a || b		a | b	Bitwise OR
Boolean NOT	!b		~b	Bitwise NOT

Boolean operators **act on the entire value not the individual bits**

bitwise & versus Boolean &&

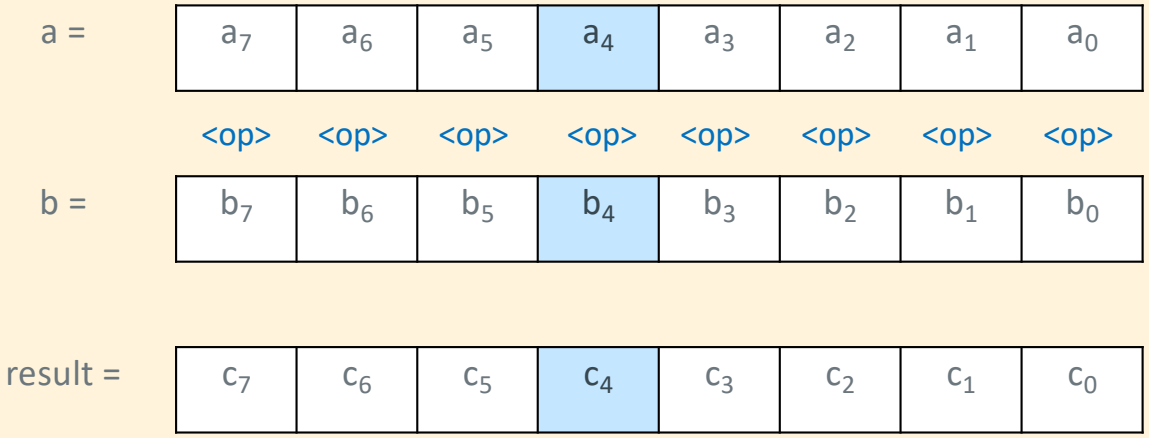
```
0x10 &  0x01 = 0x00 (bitwise)
0x10 && 0x01 = 0x01 (Boolean)
```

bitwise ~ versus Boolean !

```
~0x01 = 0xfffffffe (bitwise)
!0x01 = 0x0 (Boolean)
!0xff = 0x0 (Boolean)
```


x

The act (operation) of *Masking*



- Bit masks access/modify specific bits in memory
- Masking act of applying a mask to a value with a specific op:
- `orr:` 0 passes bit unchanged, 1 sets bit to 1 `(a = b | c; // in C)`
- `eor:` 0 passes bit unchanged, 1 inverts the bit `(a = b ^ c; // in C)`
- `and:` 0 clears the bit, 1 passes bit unchanged `(a = b & c; // in C)`

x

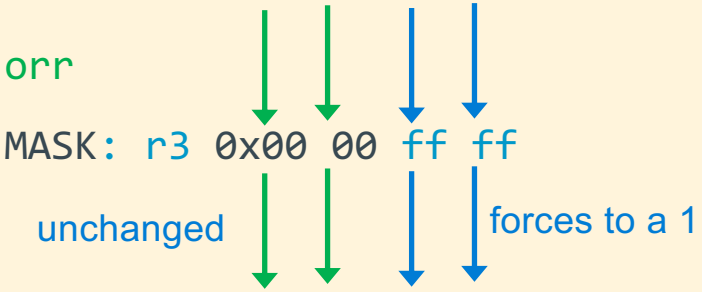
Mask on

force bits to 1 "**mask on**" operation

- 1 to **set a bit to 1**
- 0 to let a **bit through unchanged**

```
orr  r1, r2, r3
r1 = r2 | r3; // in C
```

Example: force lower 16 bits to 1



Example: force lower 8 bits to 1

```
DATA: r2 0xab ab ab 77
orr   r1   r2, 0xff
r1 = r2 | 0xff; // in C
RSLT: r1 0xab ab ab ff
```


x

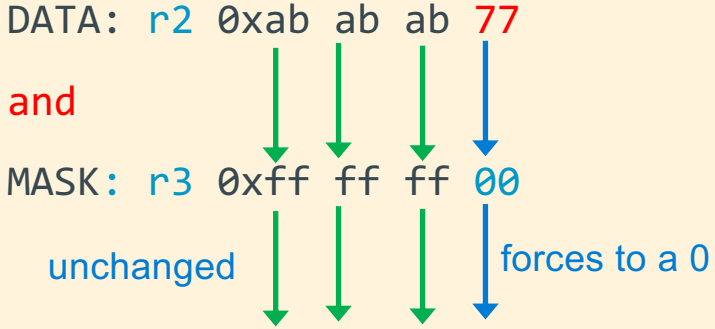
Mask off

force bits to 0 "**mask off**" operation

- 0 to **set a bit to 0** ("clears the bit")
- 1 to let a **bit through unchanged**

```
and  r1, r2, r3

r1 = r2 & r3; // in C
```

Example: force lower 8 bits to 0



Example: force lower 8 bits to 0

```
DATA: r2 0xab ab ab 77

and r1  r2, 0xffffff00

r1 = r2 & 0xffffff00; // in C

RSLT: r1 0xab ab ab 00
```

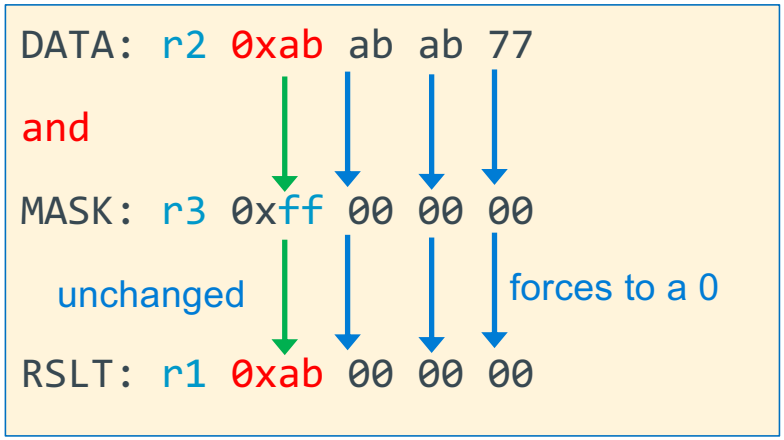

x

Extracting (Isolate) a Field of Bits with a mask

extract top 8 bits of r2 into r1

- 0 to **set a bit to 0** ("clears the bit")
- 1 to let a **bit through unchanged**

```
and  r1, r2, r3
```



extract top 8 bits of r2 into r1

```
DATA: r2 0xab ab ab 77
and  r1, r2, 0xff000000
RSLT: r1 0xab 00 00 00
r1 = r2 & 0xff000000;  // in C
```


x

Finding if a bit is set

query the status of a bit "**bit status**" operation

- 0 to **set a bit to 0** ("clears the bit")
- 1 to let a **bit through unchanged**

```
    and  r1, r2, 0x02
    cmp r1, 0
    beq .Lendif
    // code for is set
.Lendif:
```

```
Example is bit 1 set

DATA: r2 0xab ab ab 77
and
MASK:    0x00 00 00 02   is bit 1 set?
forces to a 0    unchanged
RSLT: r1 0x00 00 00 02   != 0 if set
```

```
unsigned int r1, r2;
// code
r1 = r2 & 0x02
if  (r1 != 0) {
    // code for is set
}
```

```
unsigned int r2;
// code
if ((r2 & 0x02) != 0) {
    // code for is set
}
```

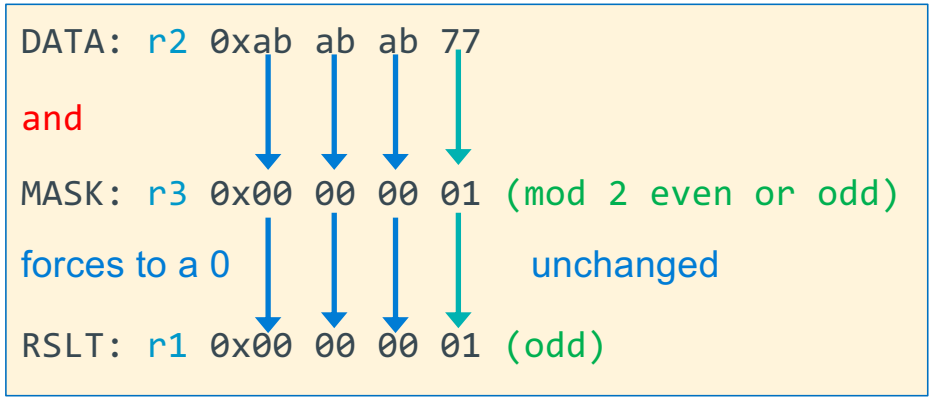

x

Even/Odd

Even or odd, check LSB (same as mod %2)

```
check LSB (bit 0) if set then odd, else even
       and  r1, r2, 0x01
       cmp  r1, 0x01
       bne .Lendif
       // code for handling odd numbers
.Lendif:
```

```
unsigned int r2;
// code
if ((r2 & 0x01) != 0) {
    // code for handling odd numbers
}
```



x

MOD %<power of 2>

remainder (mod): num % d where num ≥ 0 and d = 2^k

```
mask = 2^k -1 so for mod 16, mask = 16 -1 = 15
and  r1, r2, r3
```

```
Example: %2
DATA: r2 0xab ab ab 77
and
MASK: r3 0x00 00 00 01 (mod 2 even or odd)
 forces to a 0          unchanged
RSLT: r1 0x00 00 00 01 (odd)
```

```
Example: Mod 16
DATA: r2 0xab ab ab 77
and
MASK: r3 0x00 00 00 0f (mod 16)
 forces to a 0          unchanged
RSLT: r1 0x00 00 00 07
```


x

Flipping bits: bit toggle
Used in PA7/PA8

invert (*flip*) bits "**bit toggle**" operation

- 1 **will flip the bit**
- 0 to let a **bit through**

```
eor  r1, r2, r3
```

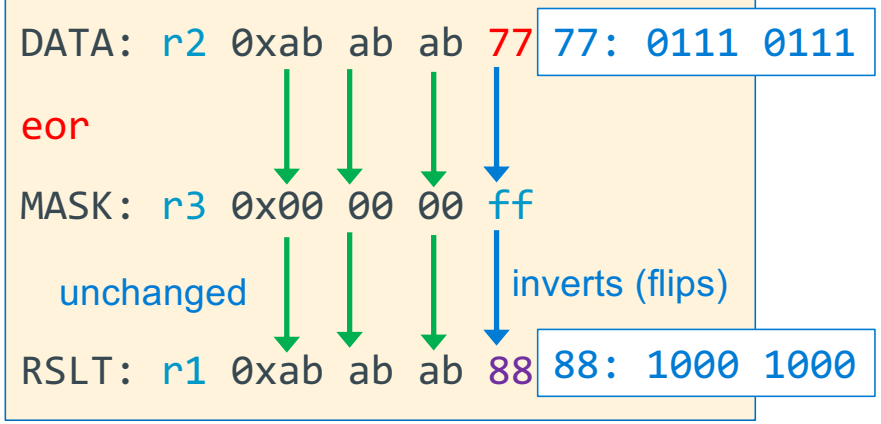
- Observation: When applied twice, it returns the original value (symmetric encoding)
- With a mask of all 1's is a 1's compliment

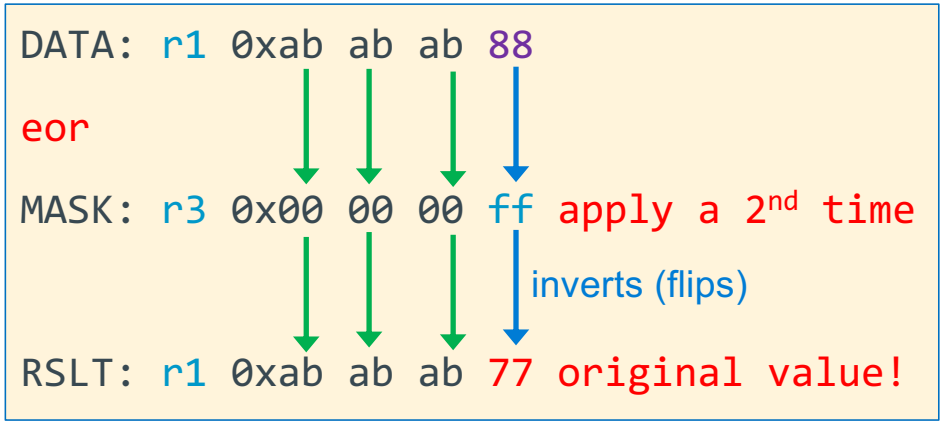
Example: *flip* the lower 8-bits

```
eor  r1, r2, 0xff
```

```
unsigned int r1, r2;
r1 = r2 ^ 0xff;
```

Example: invert (*flip*) the lower 8-bits





x

Unsigned Integers (positive numbers) with Fixed # of Bits

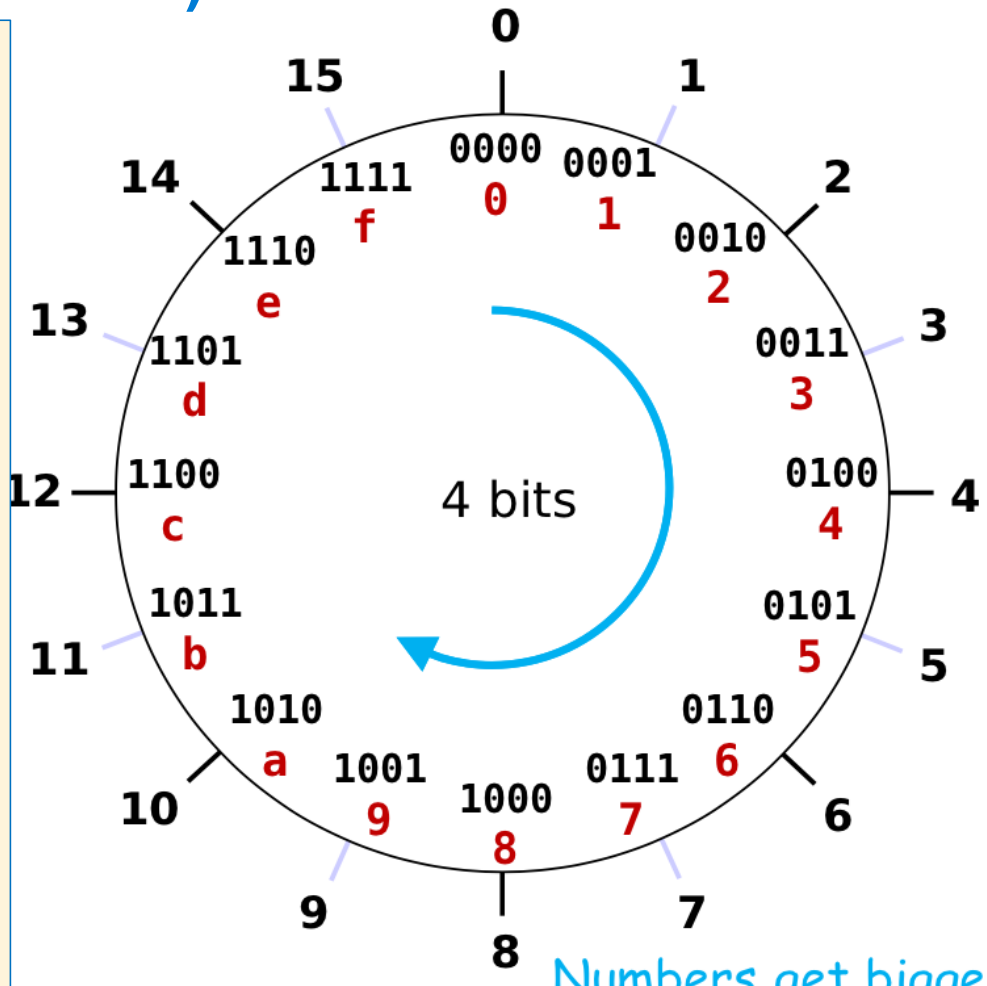
- 4 bits is 2^4 = ONLY 16 distinct values
- **Mod**ular (C operator: %) or clock math
  - Numbers start at 0 and "wrap around" after 15 and go back to 0
- Keep adding 1

  wraps (clockwise)

  0000 -> 0001 … -> 1111 -> 0000
- Keep subtracting 1

  wraps (counter-clockwise)

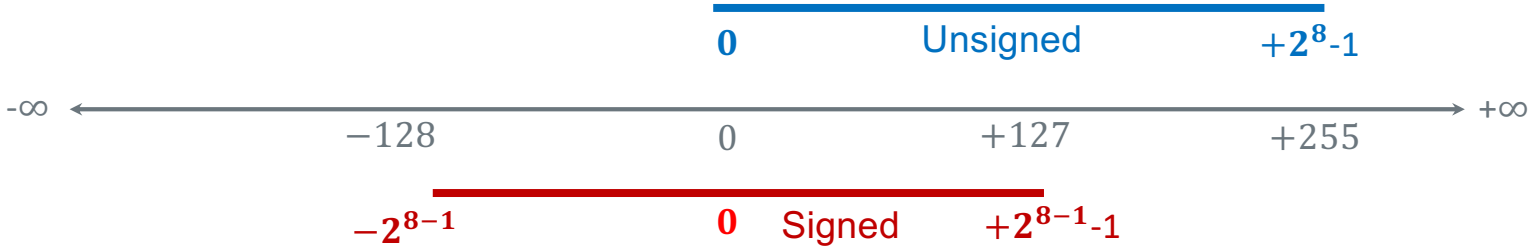
  1111 -> 1110 … -> 0000 -> 1111
- Addition and subtraction use normal "carry" and "borrow" rules, just operate in binary



x

Problem: How to Encode Both Positive and Negative Integers

- How do we represent the negative numbers within a fixed number of bits?
  - Allocate some bit patterns to negative and others to positive numbers (and zero)
- 2^n distinct bit patterns to encode positive and negative values
- **Unsigned values:** 0 ... 2^n–1 ← -1 comes from counting 0 as a "positive" number
- **Signed values:** -2^{n-1} … 2^{n-1}–1 (dividing the range in ~ half including 0)
- **On a number line (below):** 8-bit integers – signed and unsigned (*e.g.*, **`char in C`**)



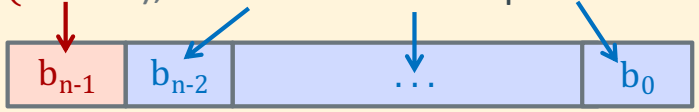
Same “width” (same number of encodings), just shifted in value

x

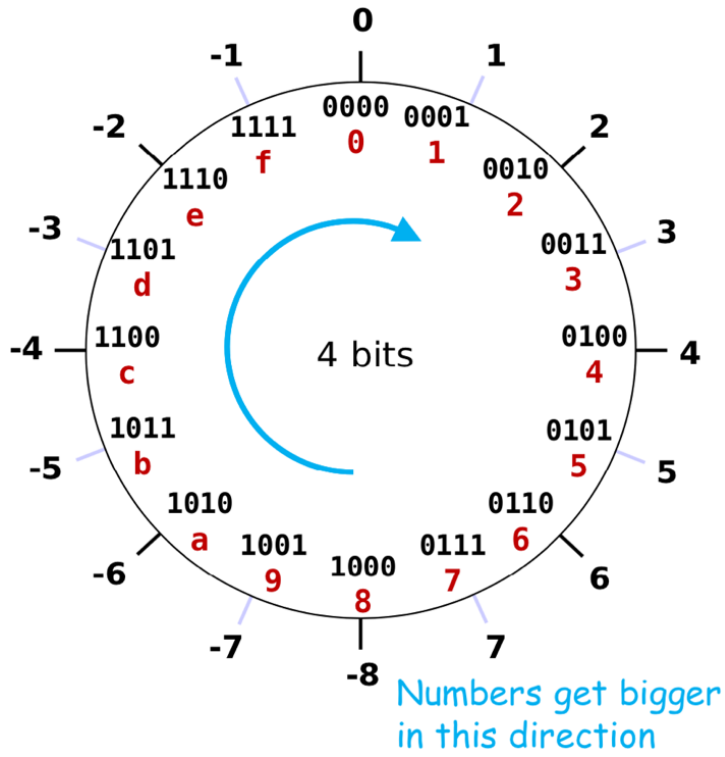
Two's Complement: The MSB Has a *Negative Weight*

$$2's\ Comp = -b_{n-1}2^{n-1} + b_{n-2}2^{n-2} + \ldots + b_1 2^1 + b_0 2^0$$

b_{n-1} weight is (-2^{n-1}), all other bits: have positive weights $(+2^i)$



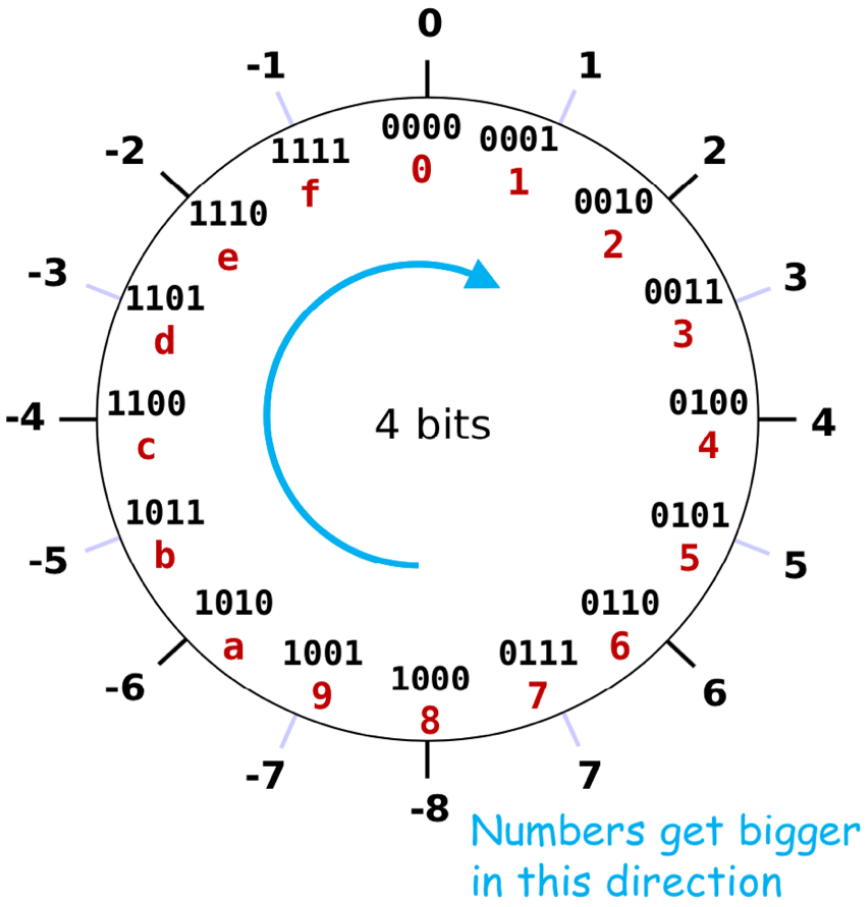
- 4-bit (w = 4) weight = -2^{4-1} = -2^3 = -8
  - 1010_2 **unsigned**:
    $1x2^3 + 0x2^2 + 1x2^1 + 0x2^0$ = **10**
  - 1010_2 **two's complement**:
    $-1x2^3 + 0x2^2 + 1x2^1 + 0x2^0$ = -8 + 2 = **–6**
  - -8 in **two's complement:**
    1000_2 = $-2^3 + 0$ = -8
  - -1 in **two's complement:**
    1111_2 = $-2^3 + (2^3 - 1)$ = -8 + 7 = **-1**



x

2's Complement Signed Integer Method

- Positive numbers encoded same as unsigned numbers
- All negative values have a one in the leftmost bit
- All positive values have a zero in the leftmost bit
  - This implies that 0 is a positive value
- Only one zero
- **For n bits, Number range is $-(2^{n-1})$ to $+(2^{n-1} - 1)$**
  - Negative values "go 1 further" than the positive values
- Example: the range for 8 bits:
  -128, -127, .. 0, .. 126, **+127**
- Example the range for 32 bits:
  -2147483648 .. 0, .. **+2147483647**
- *Arithmetic is the same as with unsigned binary!*



x

Sign Extension (how type promotion works)

- Sometimes you need to work with integers encoded with different number of bits

  8 bits (char) -> (16 bits) **`short`** -> (32 bits) **`int`**

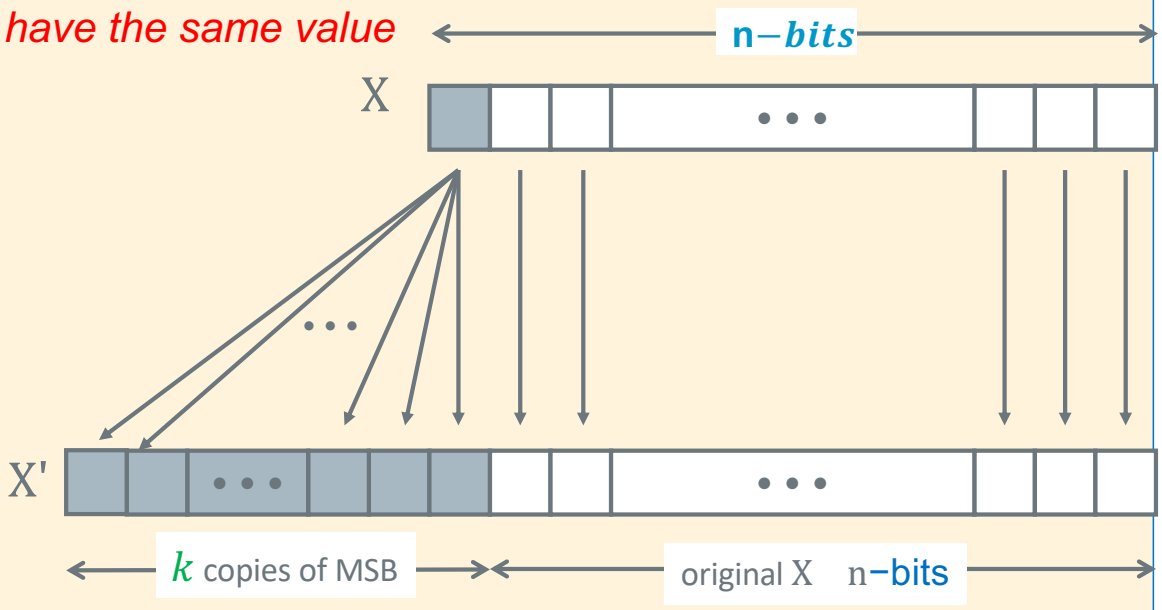
- **Sign extension increases the number of bits: n-bit** wide signed integer X, ***EXPANDS*** to a ***wider*** n−bit + k-bit signed integer X′ where *both have the same value*

Unsigned

- Just add leading zeroes to the left side

Two's Complement Signed:

- If positive, add leading zeroes on the left
  - Observe: Positive stay positive
- If negative, add leading ones on the left
  - Observe: Negative stays negative



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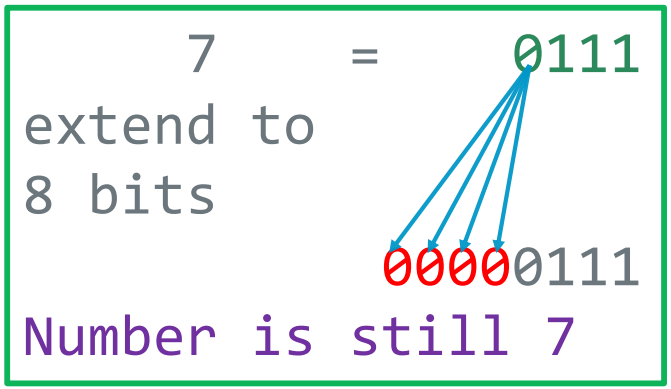
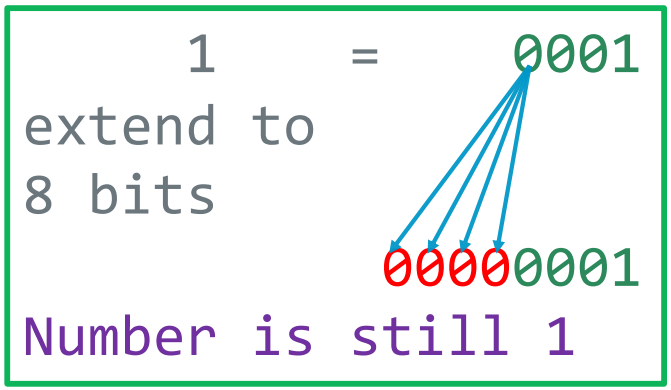
Example: Two's Complement Sign or bit Extension - 1

- Adding 0's in front of a positive numbers does not change its value





x

Example: Two's Complement Sign or bit Extension -2

- Adding 1's if front of a negative number does not change its value

```
      7 = 0111
          ||||
invert = 1000
add 1  +    1
     -7   1001
```

```
    -7    =    1001
extend to
8 bits
                11111001
```

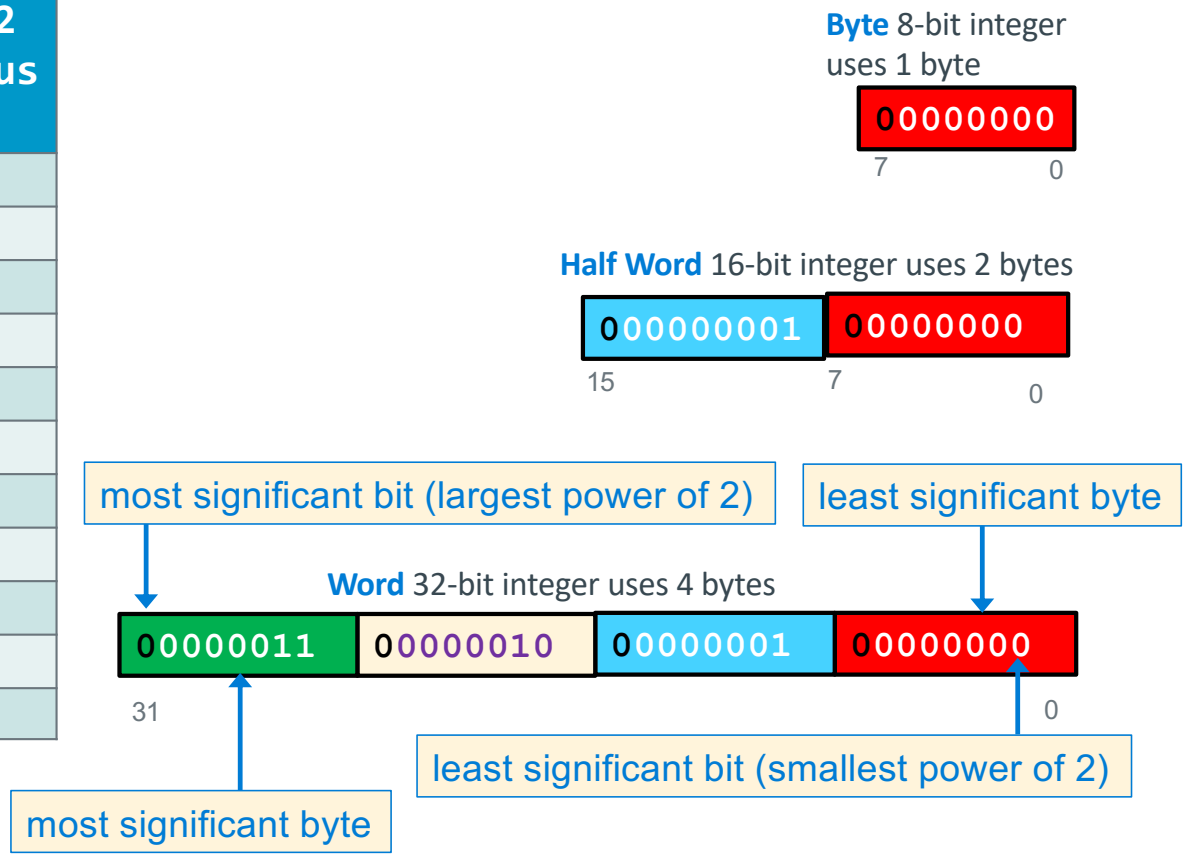
```
1001 = -8 + 1 = -7
11111001 =
(-128 + 64 + 32 + 16 + 8) + 1
= -8 + 1 = -7
```

```
      7 = 00000111
          ||||||||
invert = 11111000
add 1  +        1
     -7   11111001
```


x

Different Type of Numbers each have a Fixed # of Bits
Spanning one or more contiguous bytes of memory

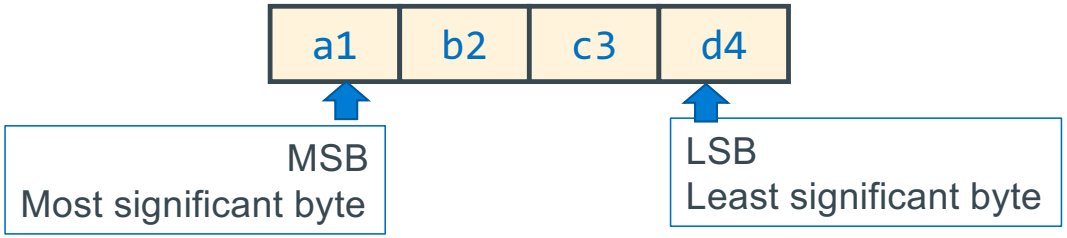
C Data Type	AArch-32 contiguous Bytes
char (arm unsigned)	1
short int	2
unsigned short int	2
int	4
unsigned int	4
long int	4
long long int	8
float	4
double	8
long double	8
pointer *	4

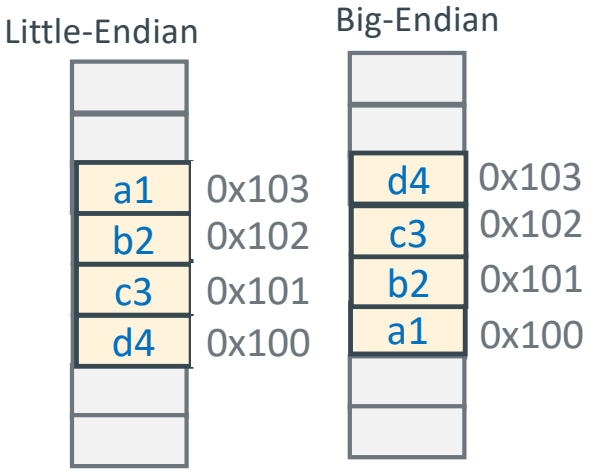


x

Byte Ordering of Numbers In Memory: Endianness

- Two different ways to place multi-byte integers in a byte addressable memory
- Big-endian: Most Significant Byte ("big end") starts at the *lowest (starting)* address
- Little-endian: Least Significant Byte ("little end") starts at the *lowest (starting)* address
- Example: 32-bit integer with 4-byte data



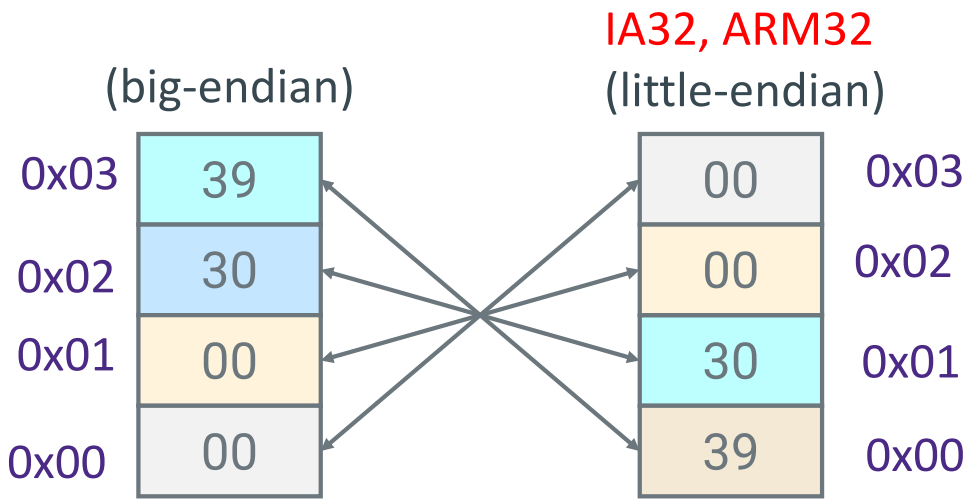


x

Byte Ordering Example

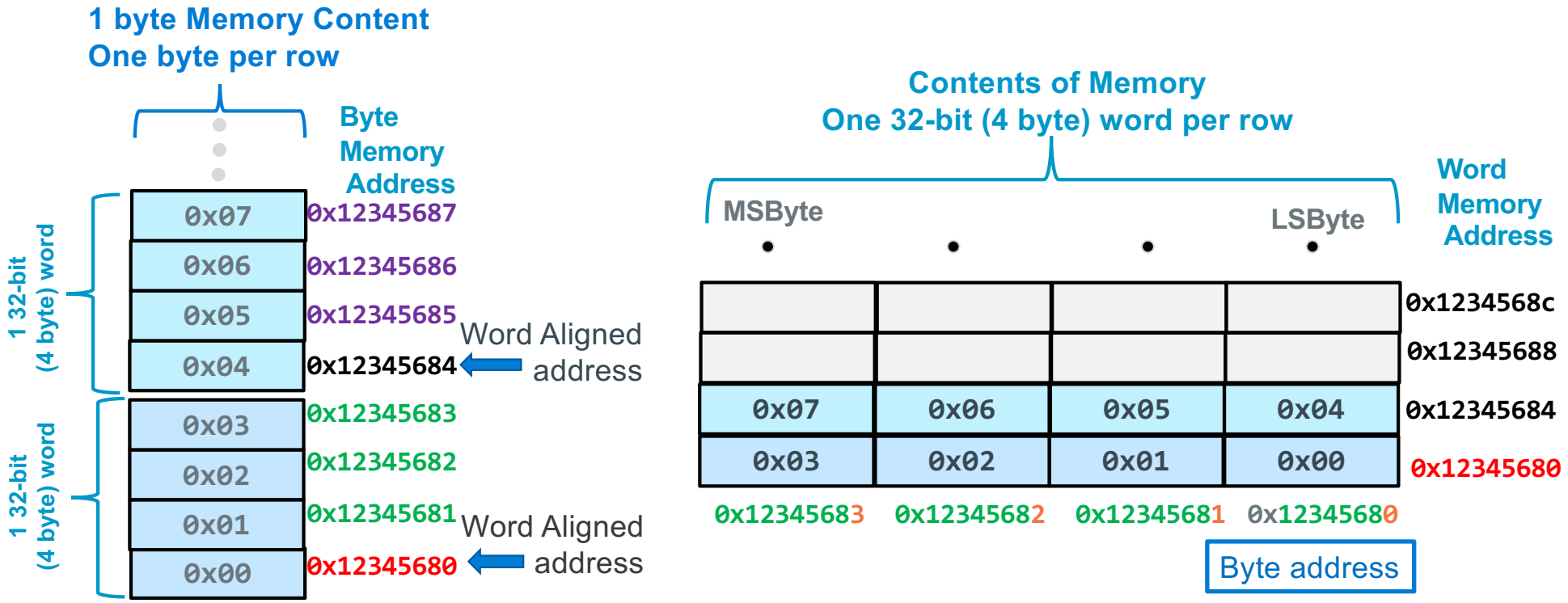
```
Decimal:   12345
Binary:     0011  0000  0011  1001
Hex:          3     0     3     9
```

```
int x = 12345;
// or x = 0x00003039;  // show all 32 bits
```



x

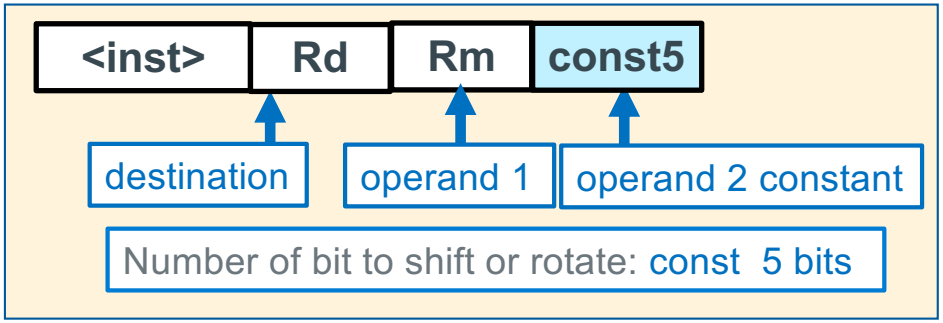
Byte Addressable Memory Shown as 32-bit words

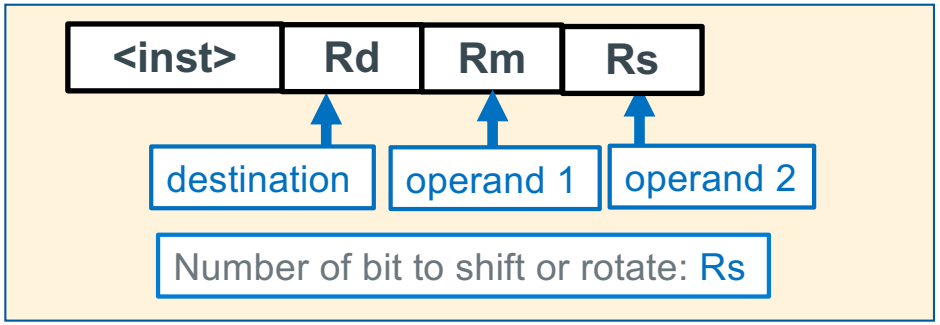


Observation
32-bit aligned addresses
rightmost 2 bits of the address are always 0

x

Bit Shifting ARM and C Equivalents



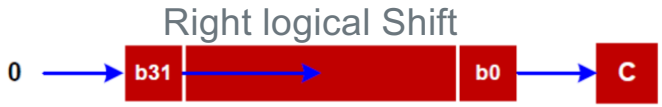


Instruction	*ARM*	*C*	*Diagram*
Logical Shift Left 0 fills on right 0 <= n <= 32 bits	lsl R_d, R_m, *n* lsl R_d, R_m, R_s	int x; or unsigned int x x << n;	
Logical Shift Right 0 fills on left 0 <= n <= 32 bits	lsr R_d, R_m, *n* lsr R_d, R_m, R_s	unsigned int x; x >> n;	
Arithmetic Shift Right Sign extends on left 0 <= n <= 32 bits	asr R_d, R_m, *n* asr R_d, R_m, R_s	int x; x >> n;	
Rotate Right 0 <= n <= 32 bits	ror R_d, R_m, *n* ror R_d, R_m, R_s	ror n in a 32-bit registers unsigned int x; x = (x >> n) | (x << (32 - n));	

x

Shift Operations in C

- n is number of bits to shift a variable x of width w bits
- Shifts by `n < 0` or `n ≥ w` are *undefined*
- Left shift (`x << N`) – **Multiplies by 2^N**
  - Shift N bits left, Fill with 0s on right
- **In C:** behavior of >> is determined by compiler
  - gcc: it depends on data type of `x` (signed/unsigned)
- Right shift (`x >> N`) - **Divides by 2^N**
  - Logical shift (for unsigned variables)
    - Shift N bits right, Fill with 0s on left
  - Arithmetic shift (for signed variables) – Sign Extension
    - Shift N bits right while **Replicating** the most significant bit on left
    - Maintains sign of `x`
- **In Java:** logical shift is **>>>** and arithmetic shift is >>

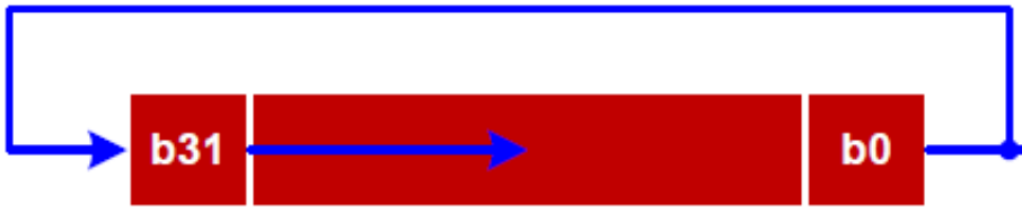


x

Logical Shift & Rotate Operations


```
lsr r2, r0, 8

r0 0xab ab ab 77
r2 0x00 ab ab ab
```


```
lsl r2, r0, 8

r0 0xab ab ab 77
r2 0xab ab 77 00
```



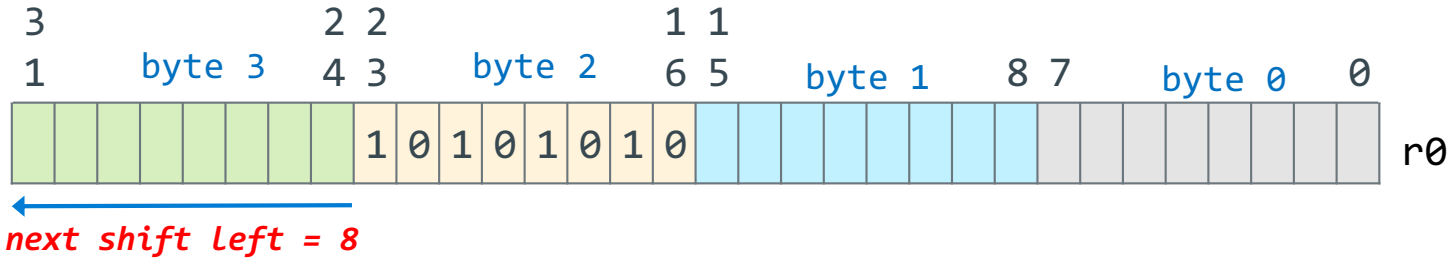

```
ror r2, r0, 8

r0 0xab ab ab 77
r2 0x77 ab ab ab
```

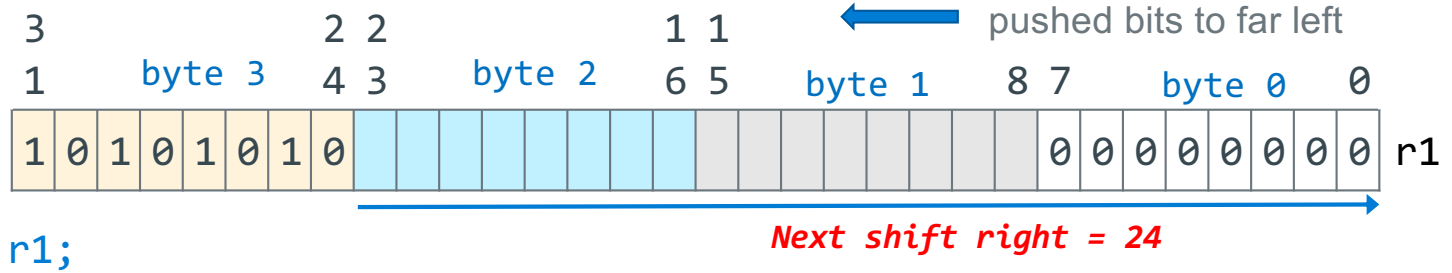

x

Extracting/Isolating Unsigned Bitfields

Hint: Useful for PA7

- Move byte 2 in r0 to byte 0 in r1





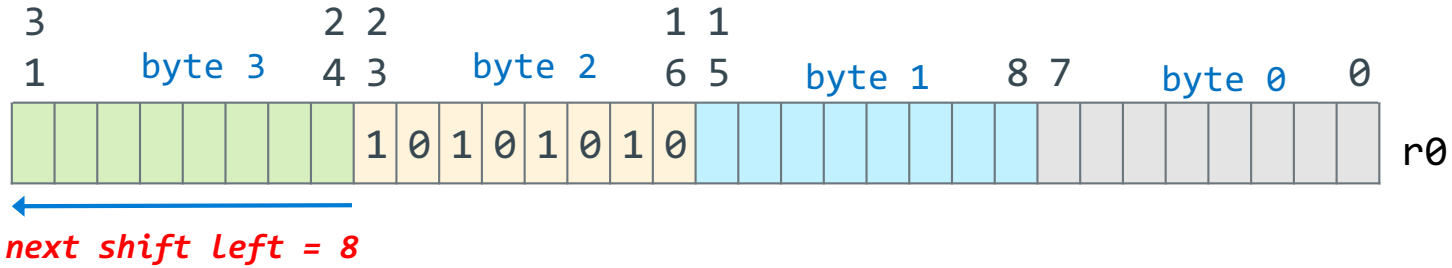

```
lsl  r1, r0, 8

unsigned int r0,r1;
r1 = r0 << 8;
```


```
lsr  r1, r1, 24
r1 = r1 >> 24;
```

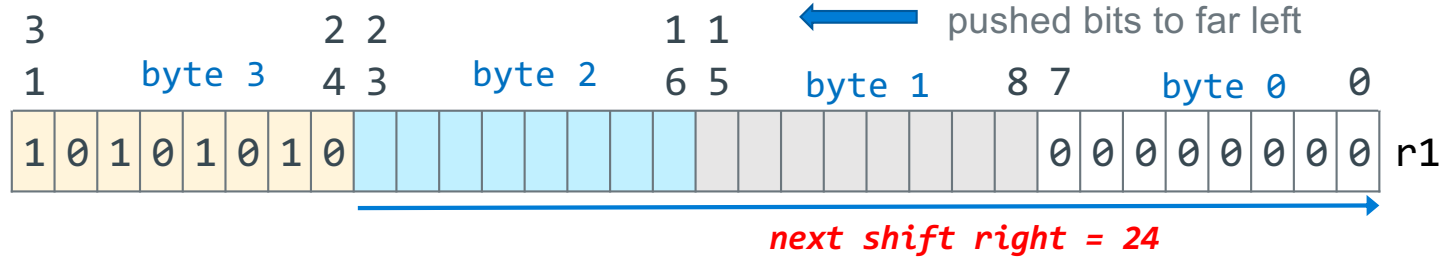

x

Extracting Signed Bitfields

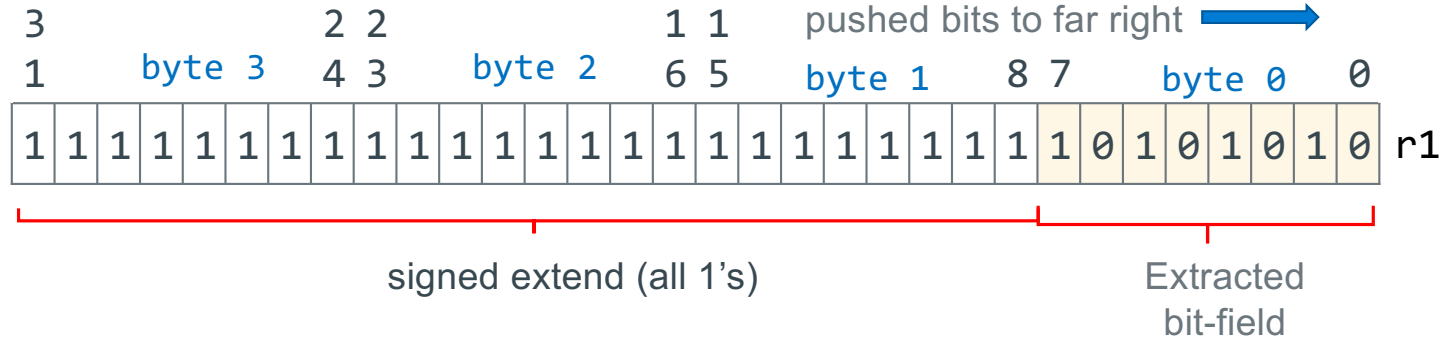
- Move byte 2 in r0 to byte 0 in r1




```
lsl  r1, r0, 8
int r0,r1;
r1 = r0 << 8;
```




```
asr  r1, r1, 24
r1 = r1 >> 24;
```



x

Inserting Bitfields – Inserting Source Field into Destination Field

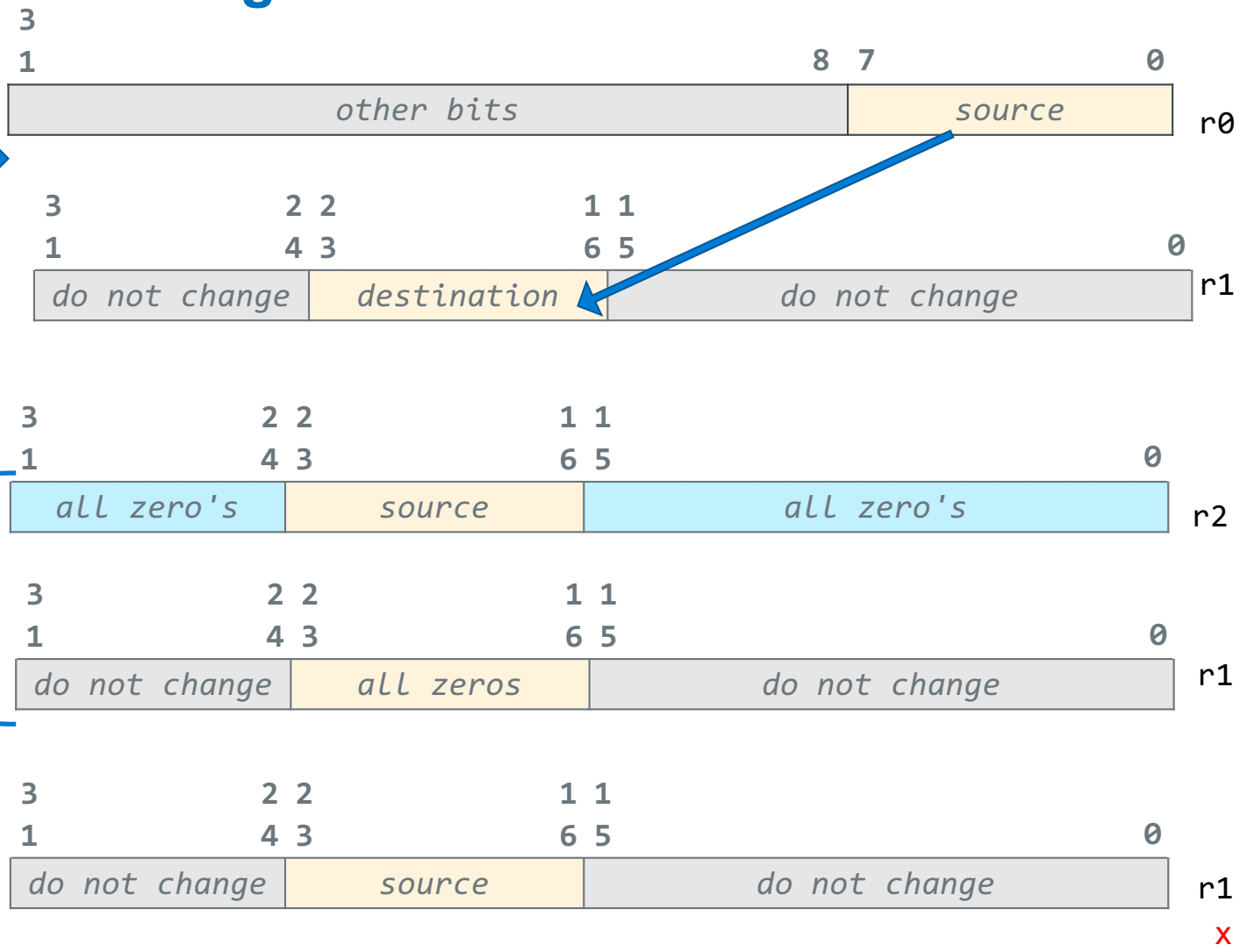
Task: Insert source into destination

a	b	a | b
0	0	0
0	1	1
1	0	1
1	1	1

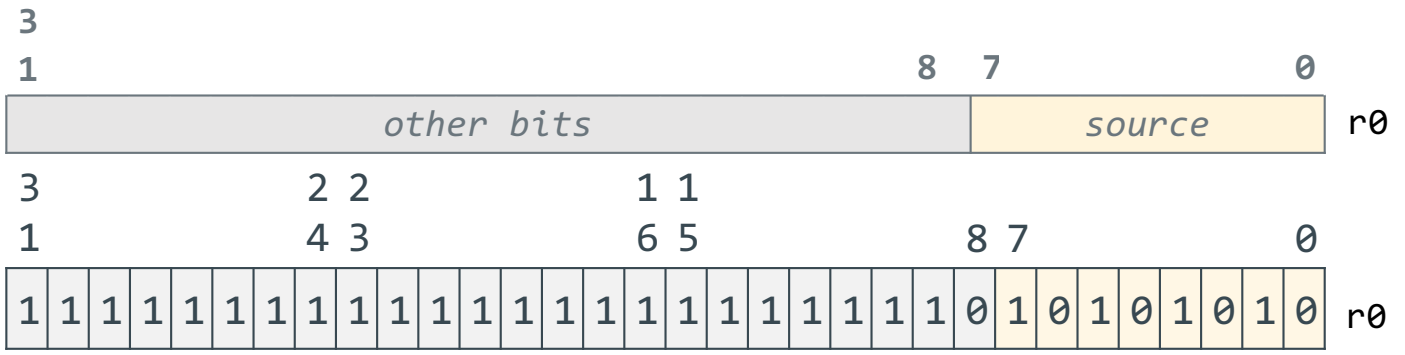
Approach
(1) isolate source field
(2) clear destination field
(3) Bitwise or together

```
orr    r1, r1, r2
r1 =   r1 | r2;
```

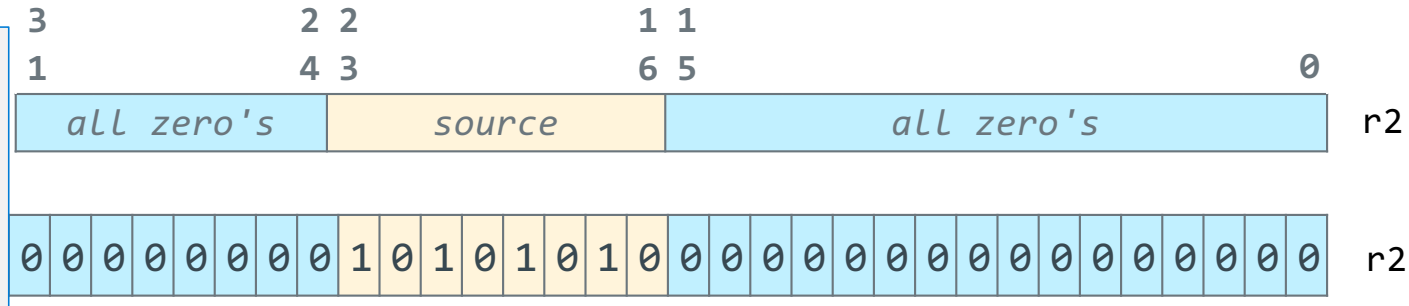
results in



Inserting Bitfields – Isolating the Source Field

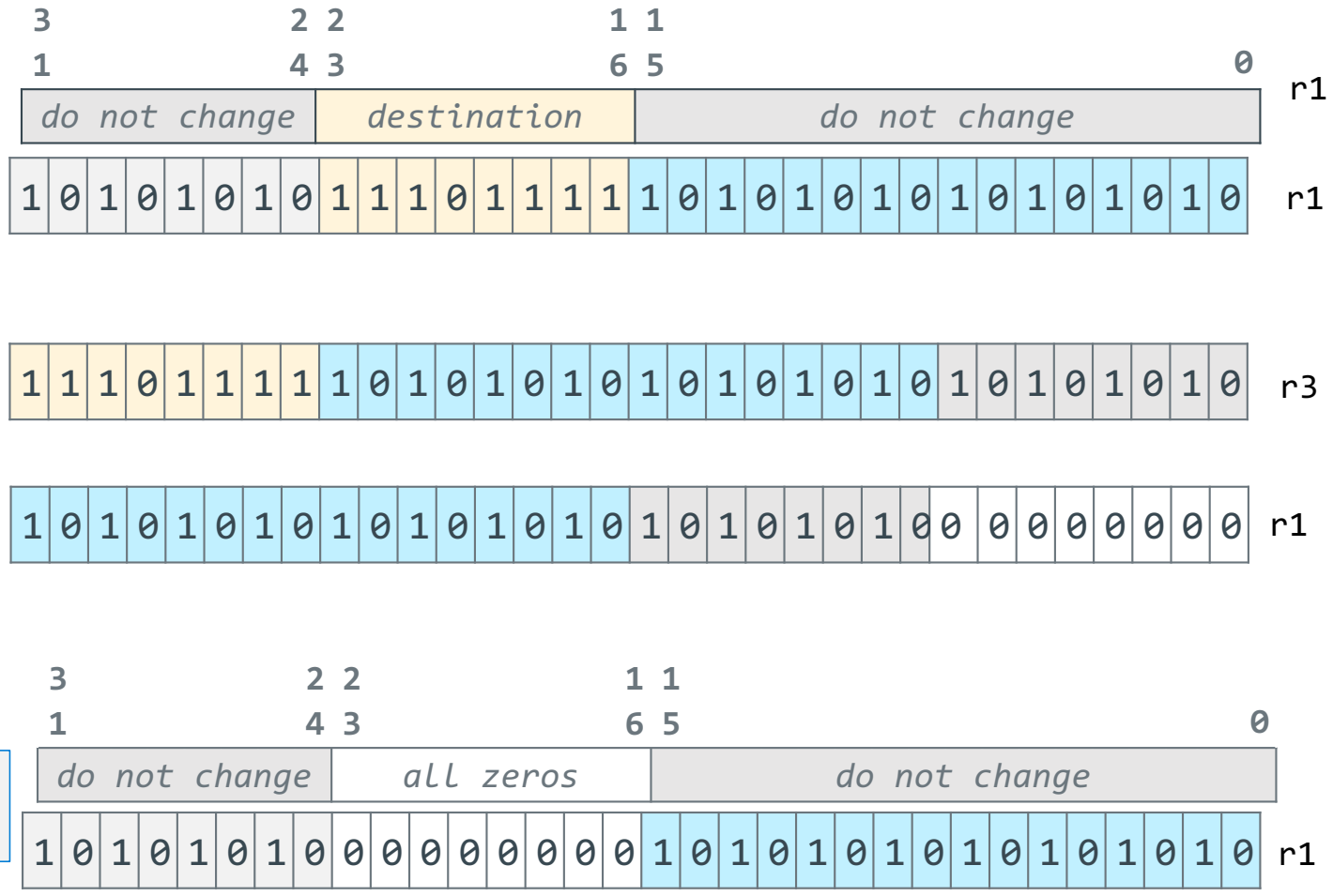



```
isolate source field

lsl    r2, r0, 24
lsr    r2, r2, 8

r2 = r0 << 24;
r2 = r2 >> 8;
```



x

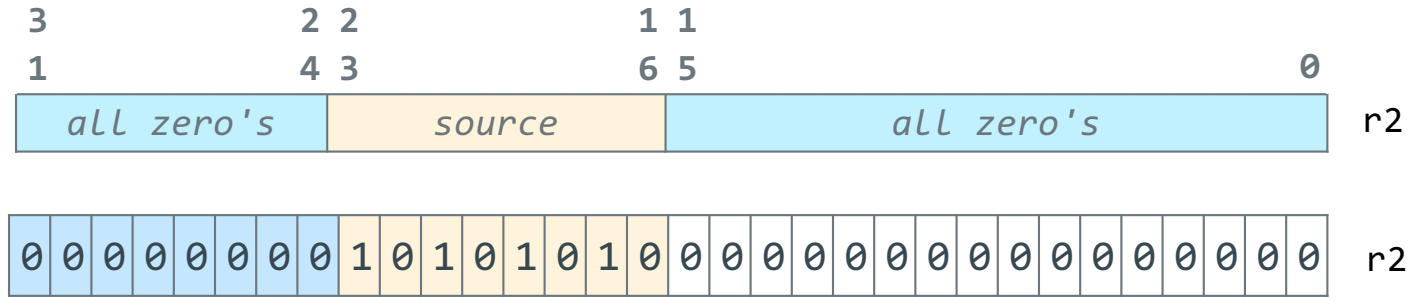
Inserting Bitfields – Clearing the Destination Field



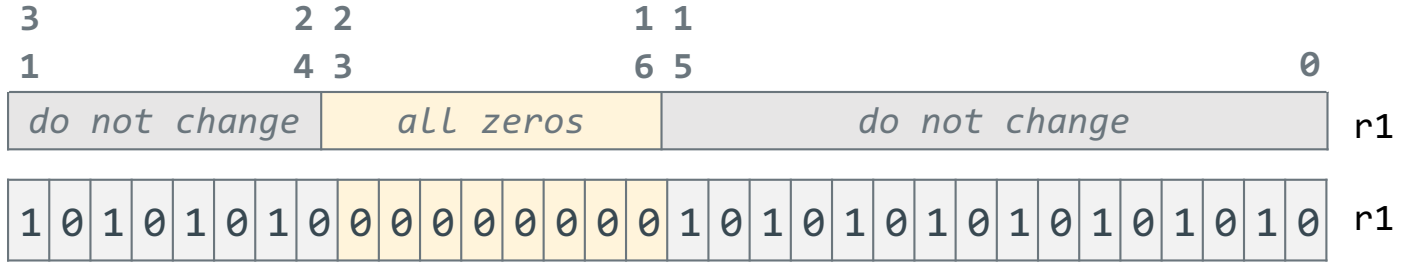
x

Inserting Bitfields – Combining Isolated Source and Cleared Destination

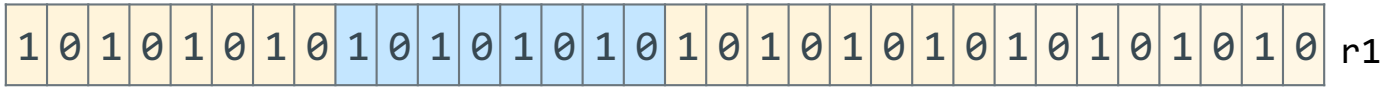
```
isolated source
```




```
field cleared in
destination
```

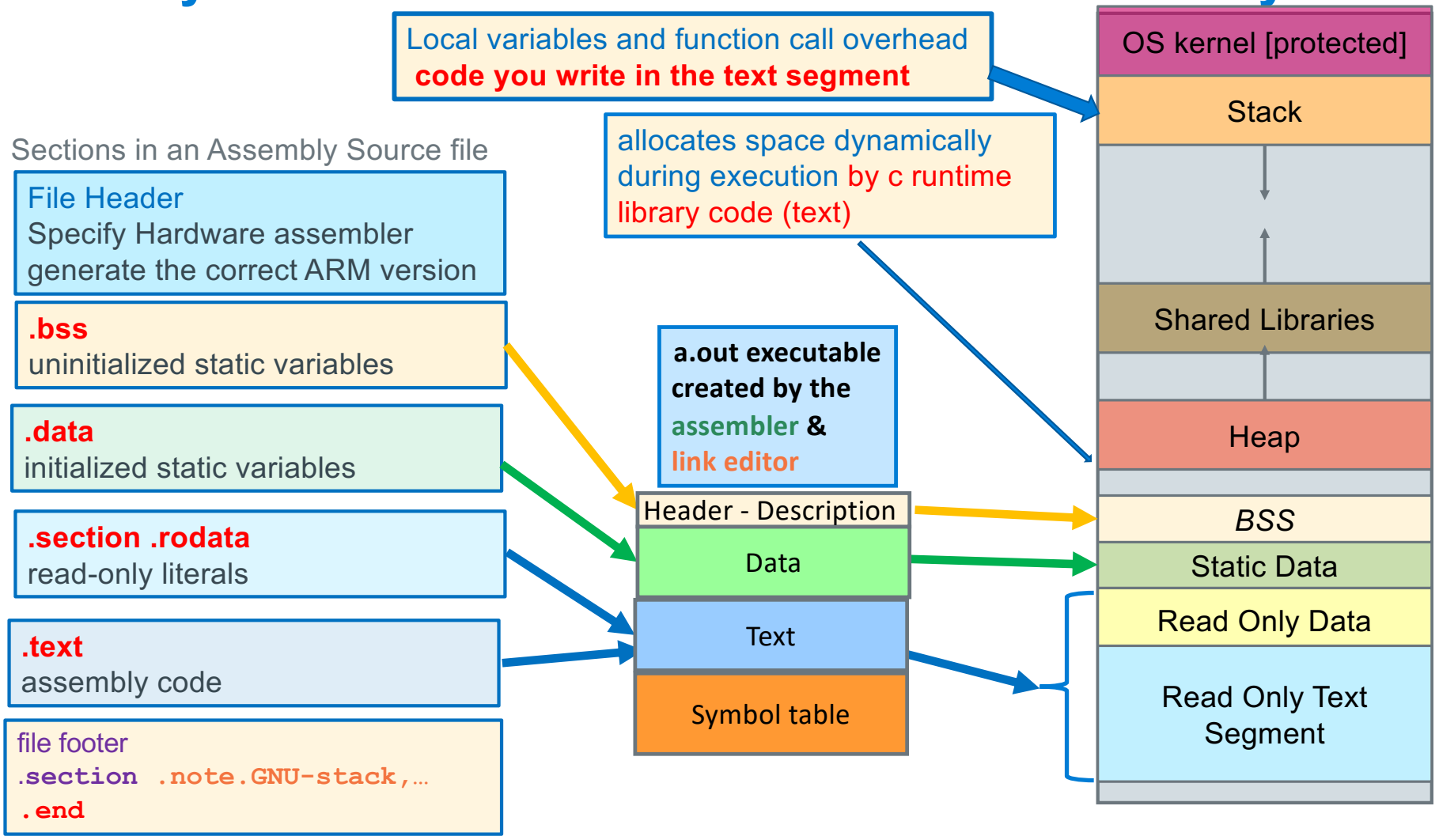



```
inserted field
orr    r1, r1, r0
r1 = r1 | r0;
```



x

Assembly Source File to Executable to Linux Memory



x

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`

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

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
```

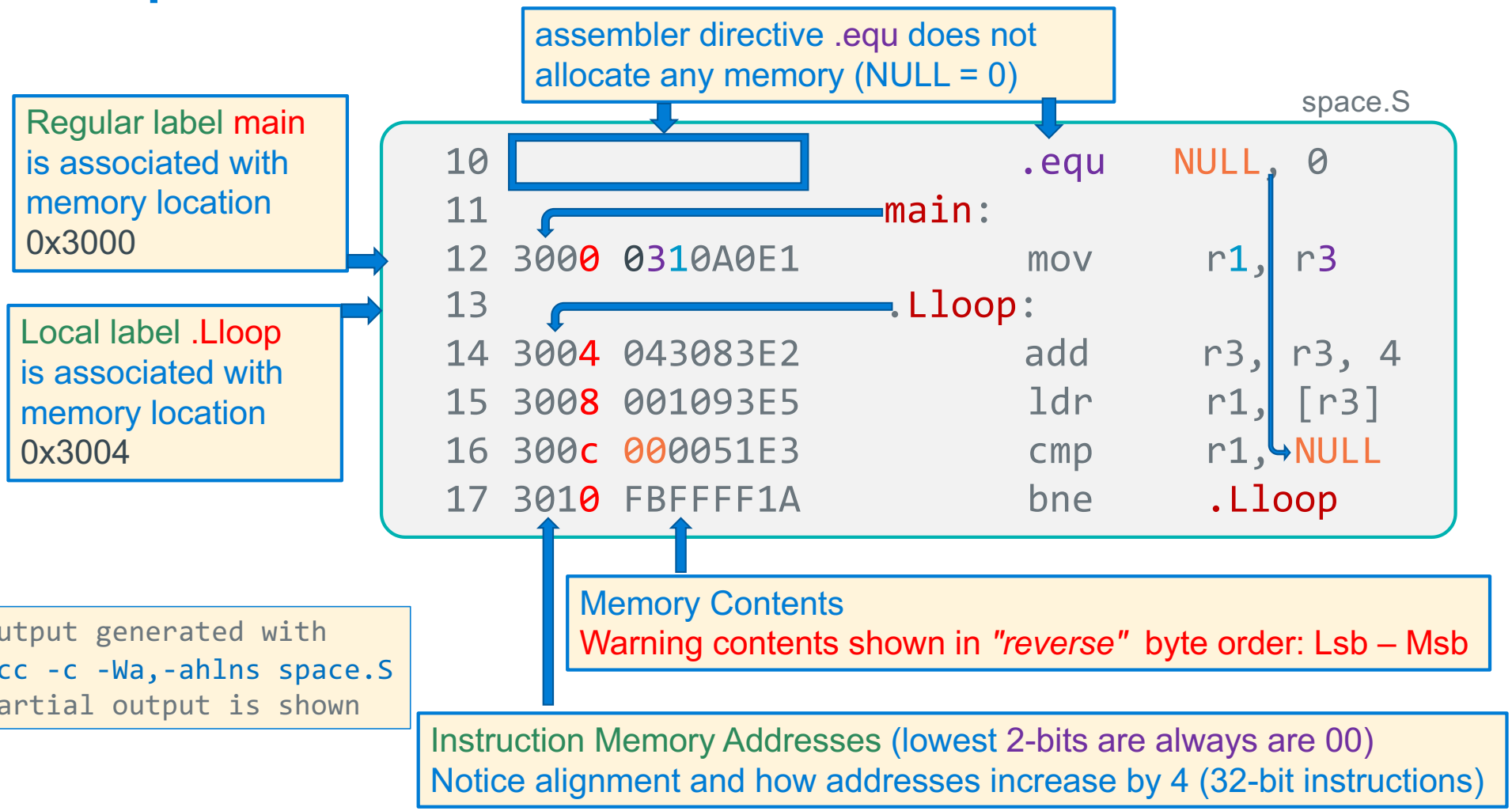
`.equ <symbol>, <expression>`

- 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



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

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

```
        .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)
```


x

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

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
```

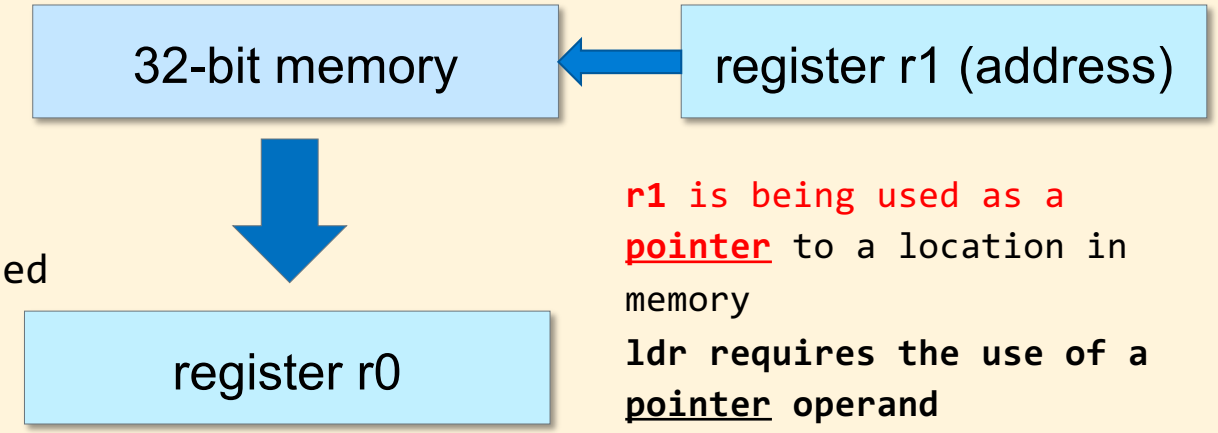
We will cover this when we do stack frames

We will cover this when we do stack frames

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

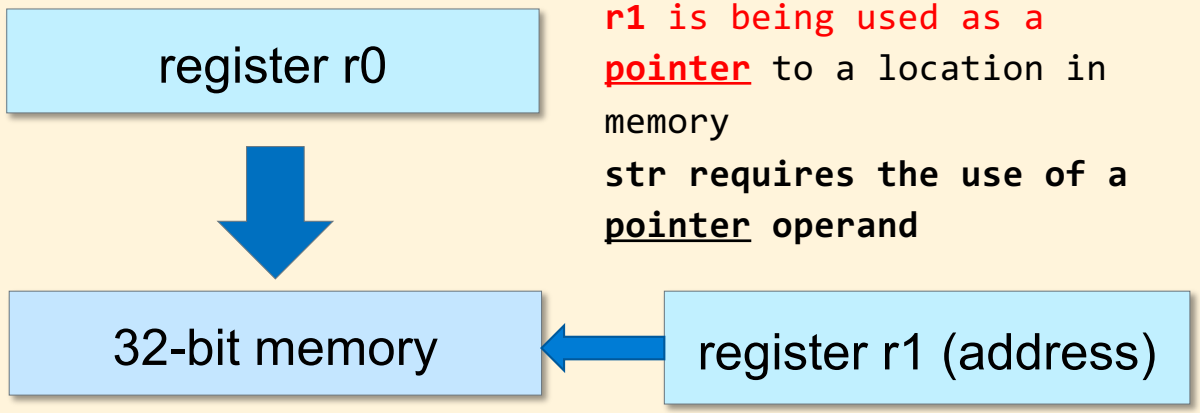


r1 is being used as a **pointer** to a location in memory

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)

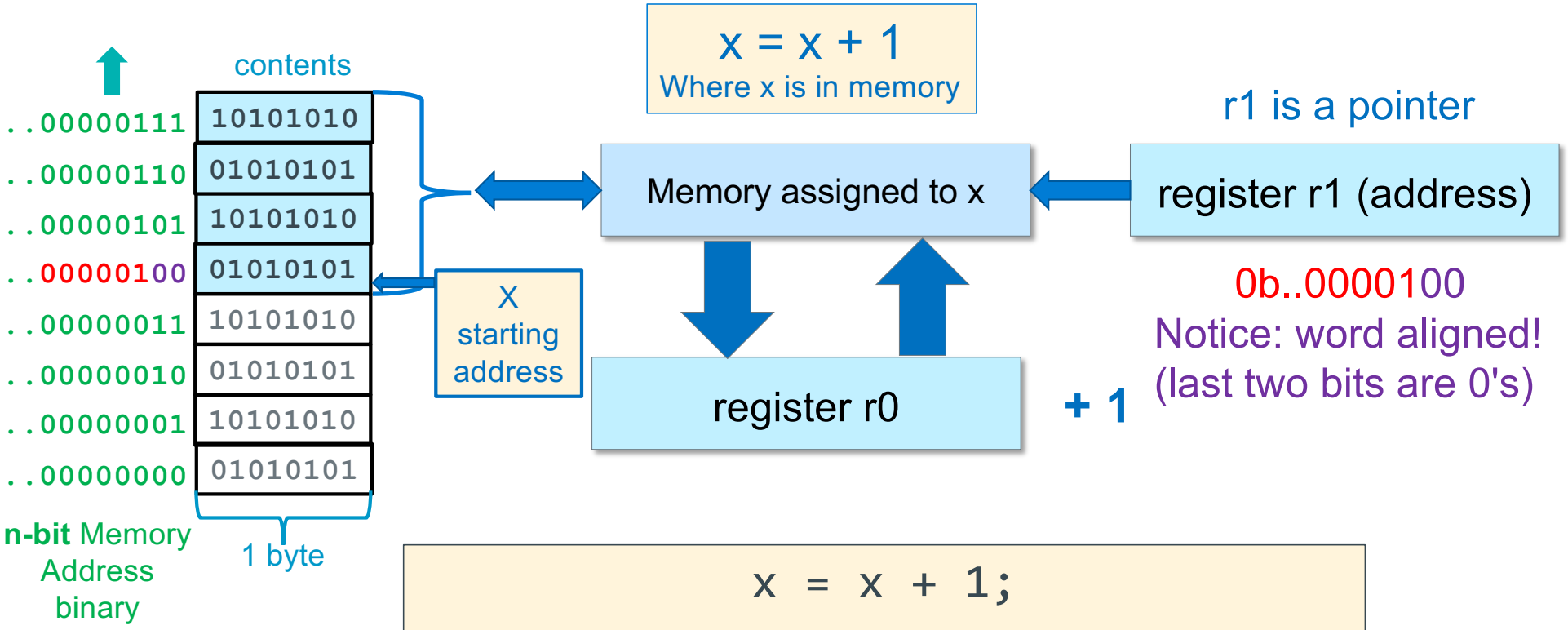


r1 is being used as a **pointer** to a location in memory

str requires the use of a pointer operand

x

Example Base Register Addressing Load – Modify – Store



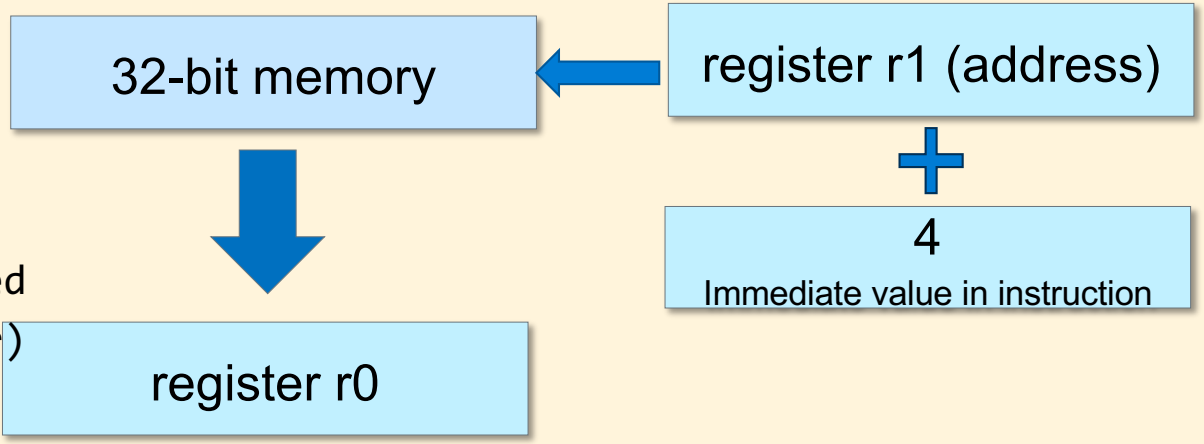

```
                x = x + 1;
ldr r0, [r1]          // r0 = *r1 (read x)
add r0, r0, 1         // r0 = r0 + 1 (x++)
str r0, [r1]          // *r1 = r0 write x
```


x

Load/Store: Register Base Addressing + Immediate

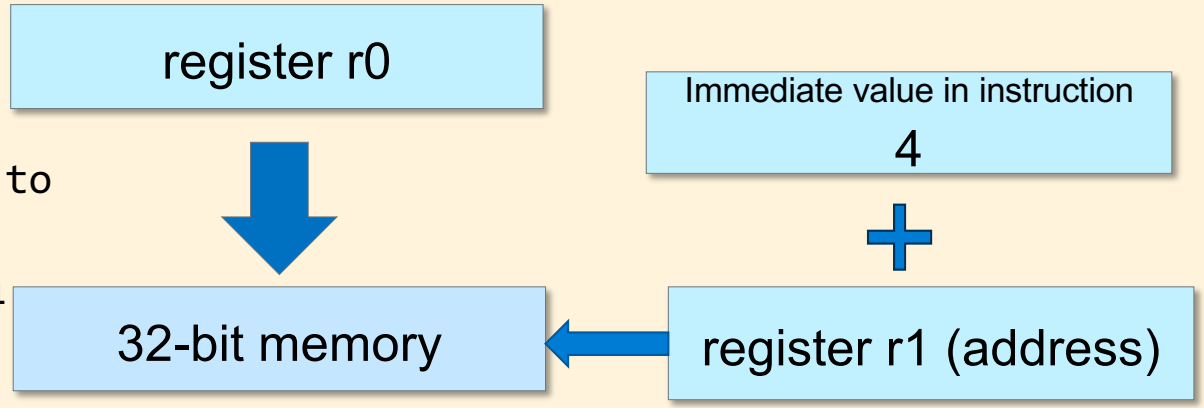
```
ldr r0, [r1, 4]
```

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



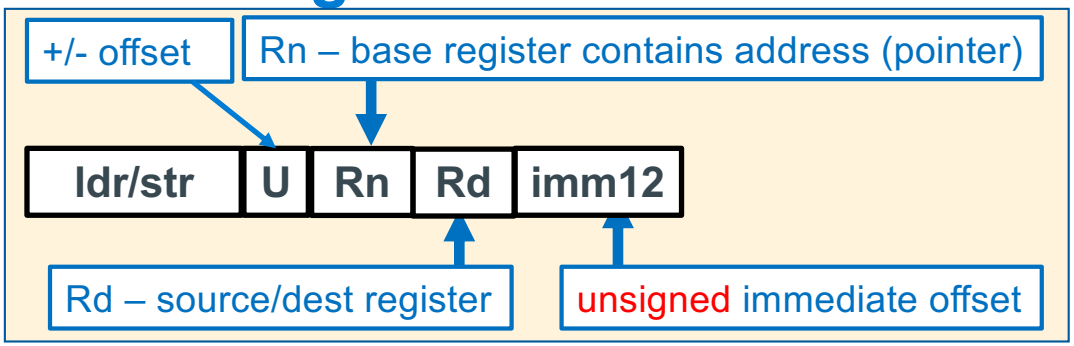

```
str   r0, [r1, 4]
```

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



x

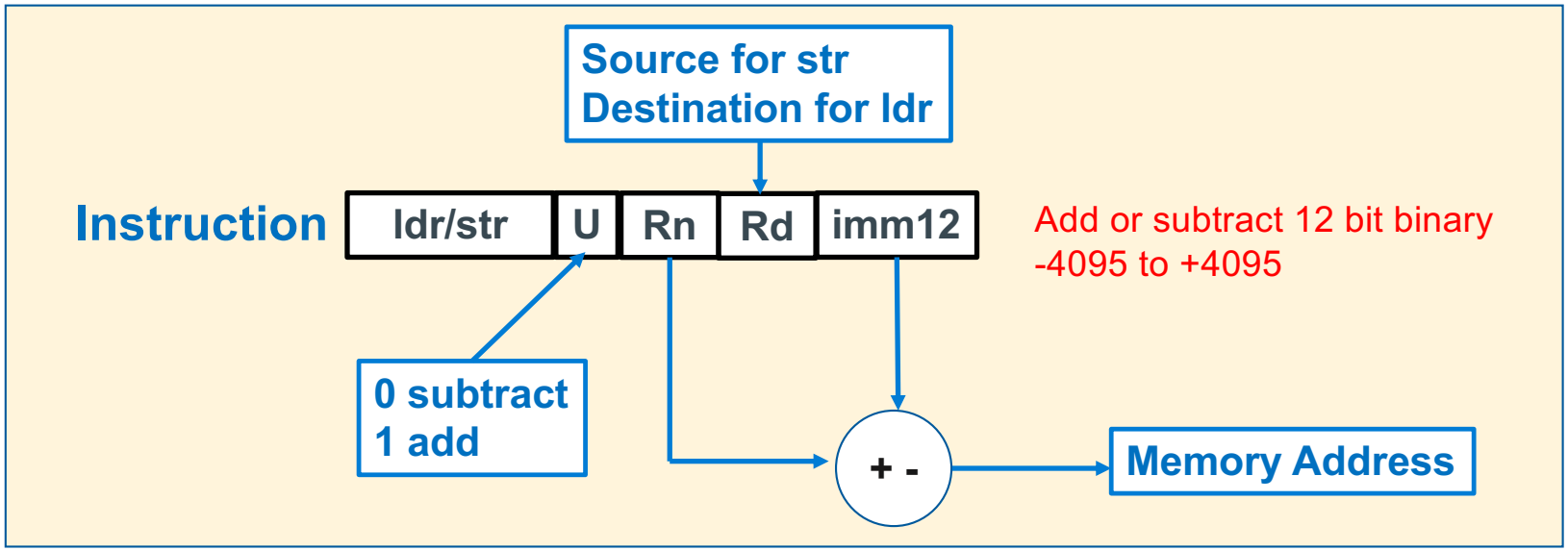
LDR/STR – Base Register + Immediate Offset Addressing



- **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
  - 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

x

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

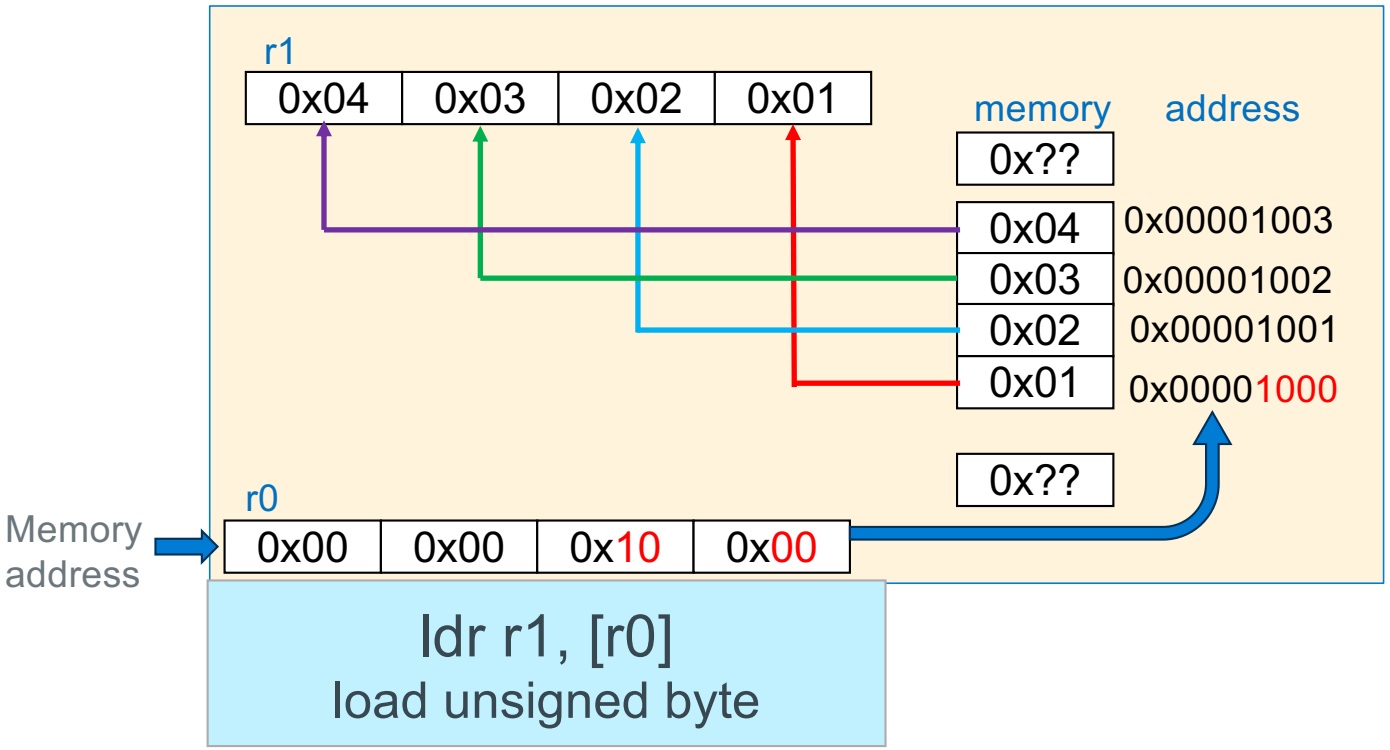
Loading and Storing: Variations List

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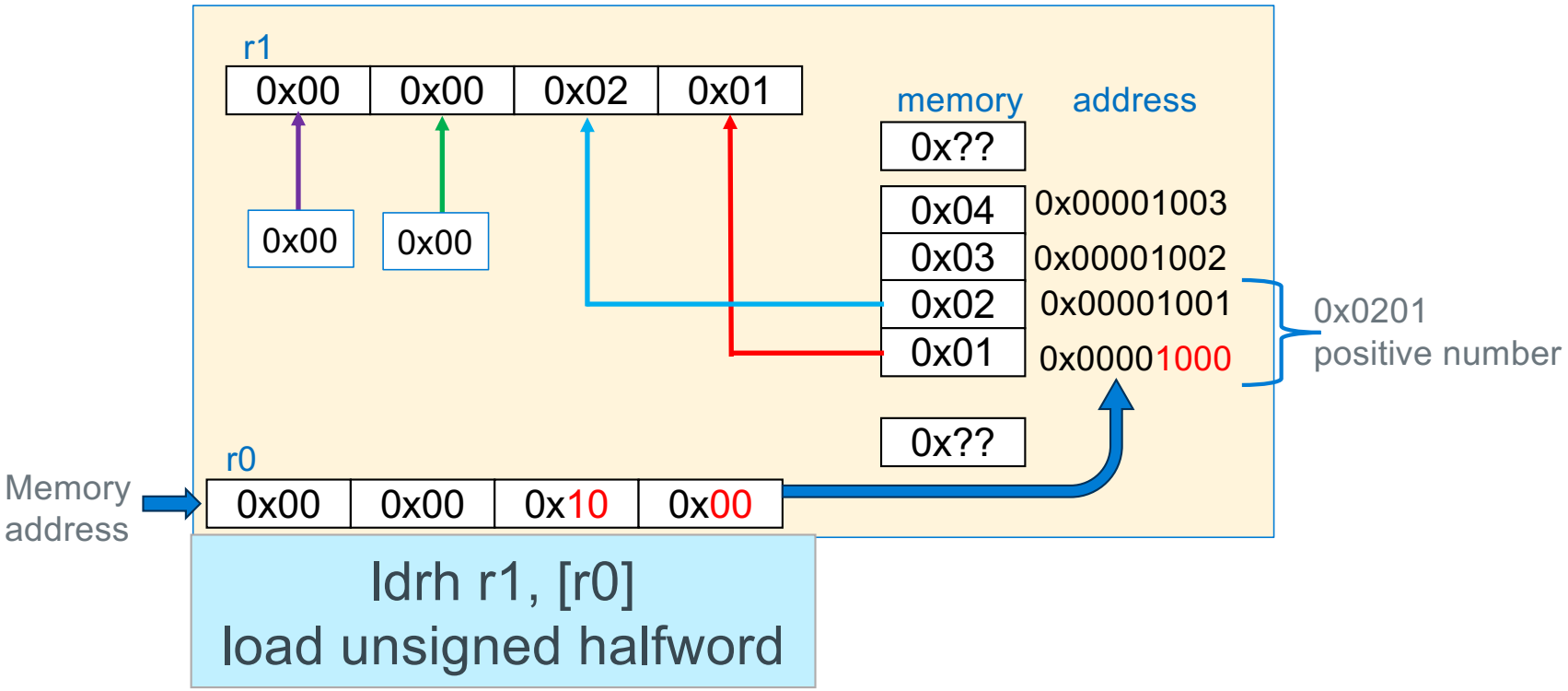
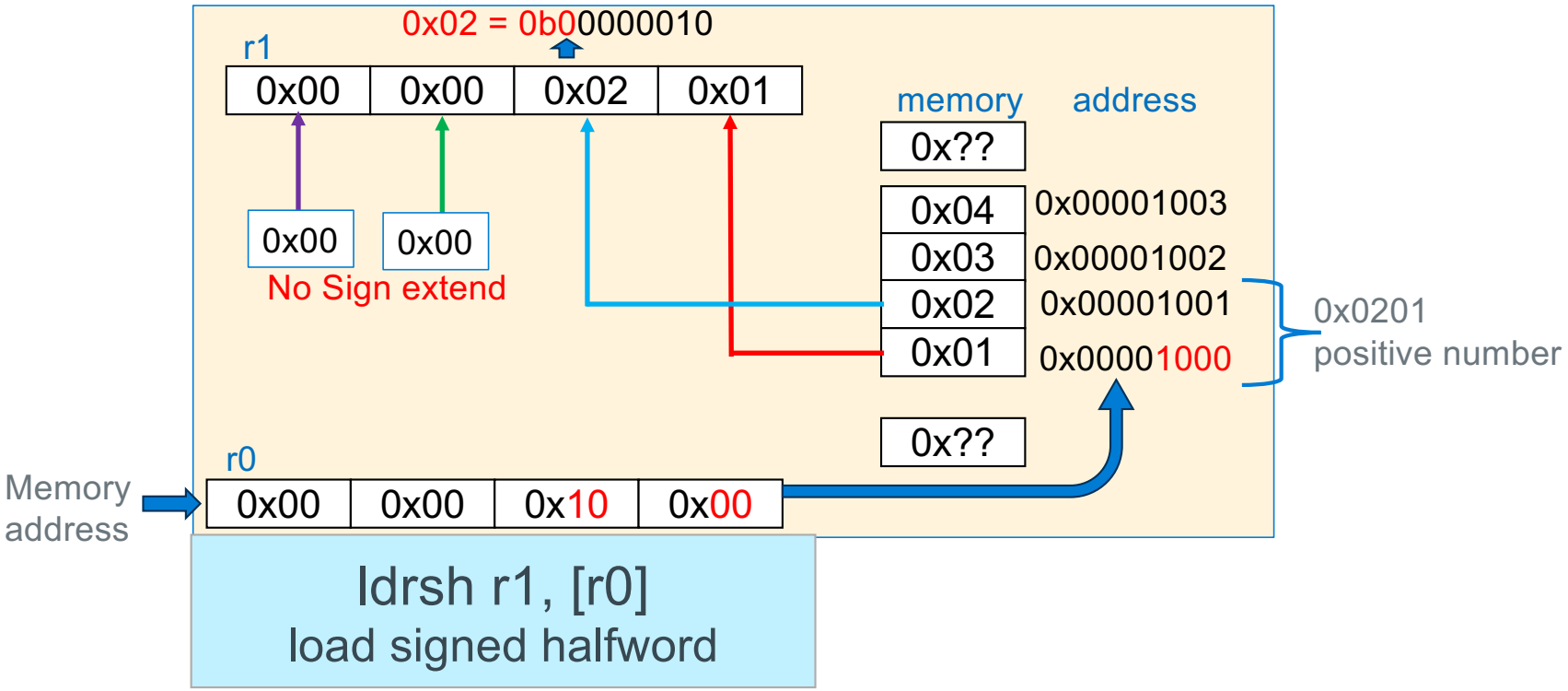
Loading 32-bit Registers From Memory, 16-bit



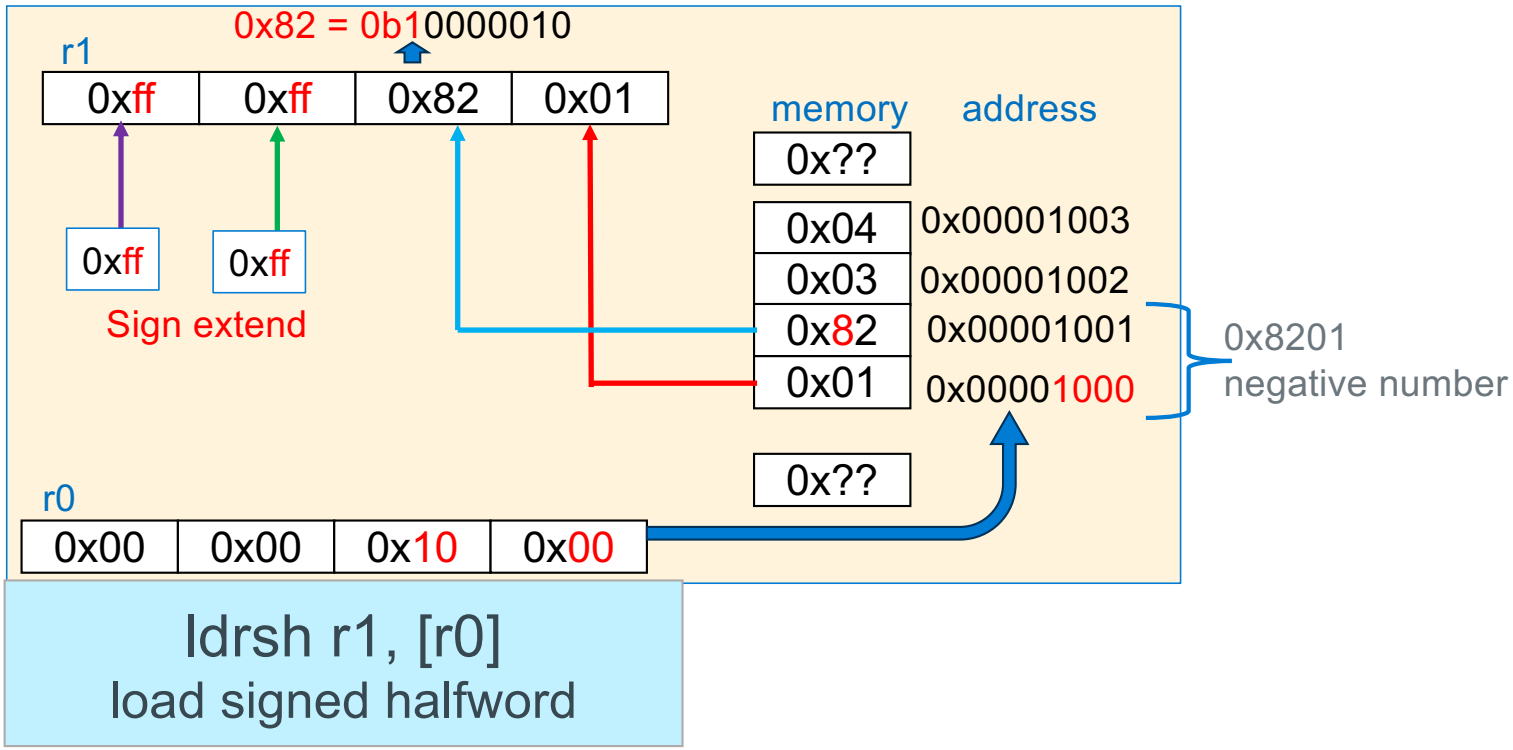
x

Loading 32-bit Registers From Memory, 16-bit



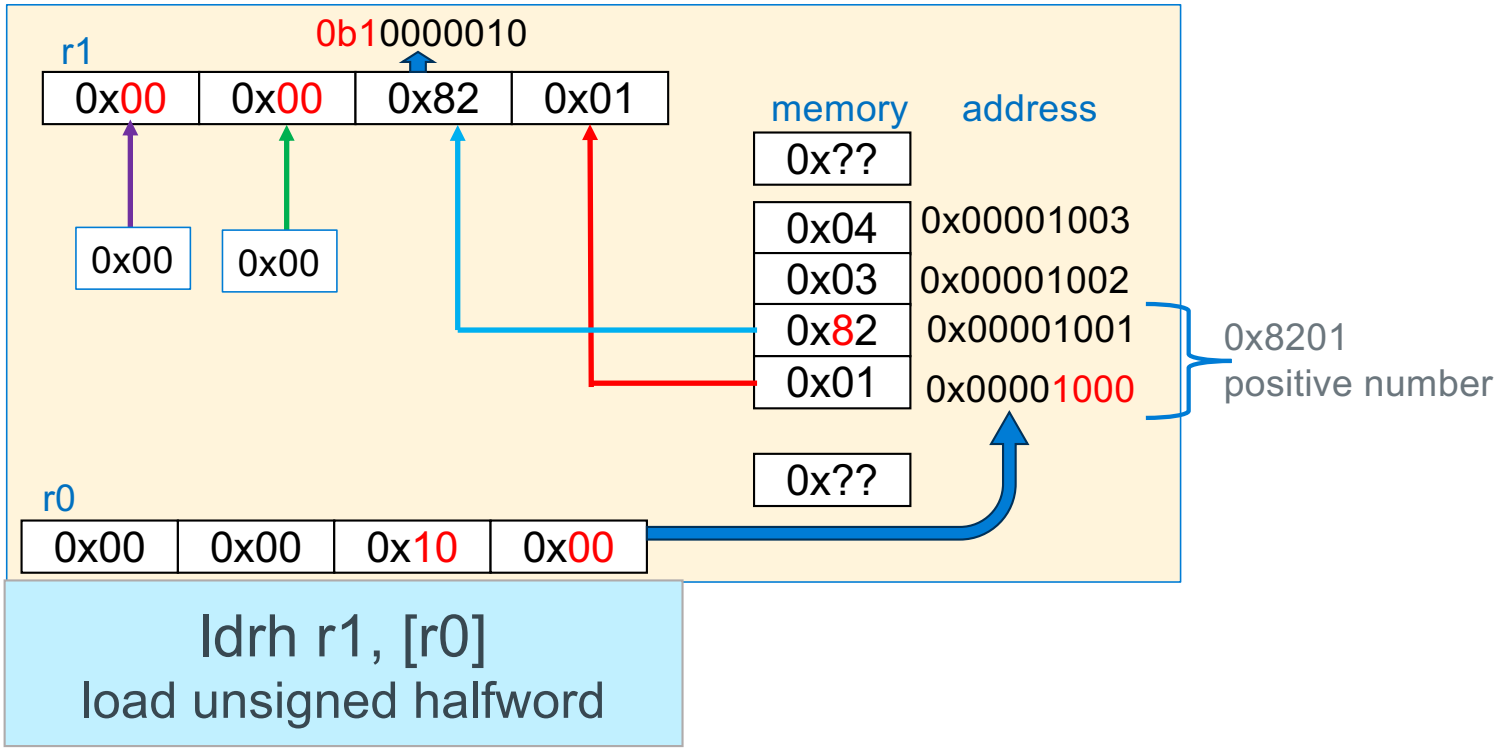
x

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



x

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



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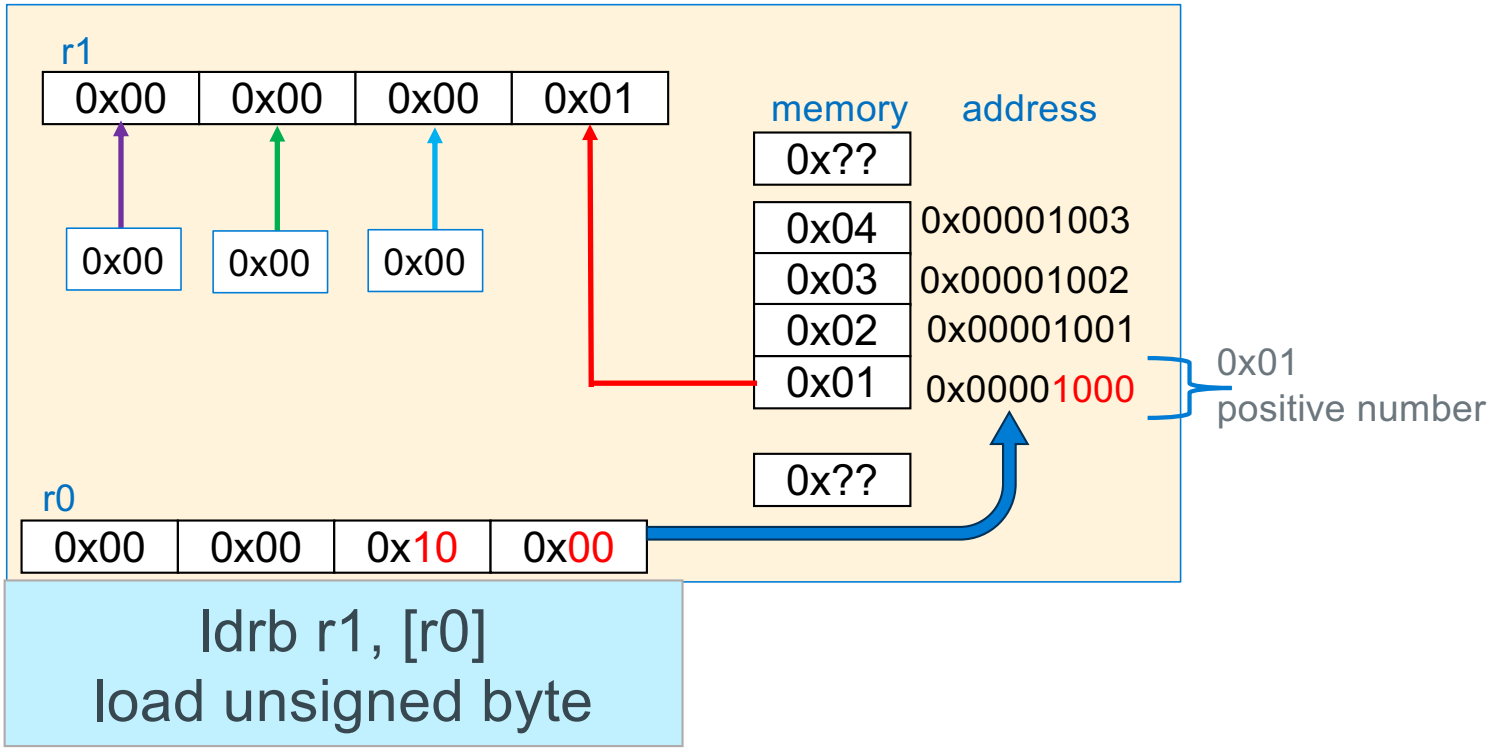
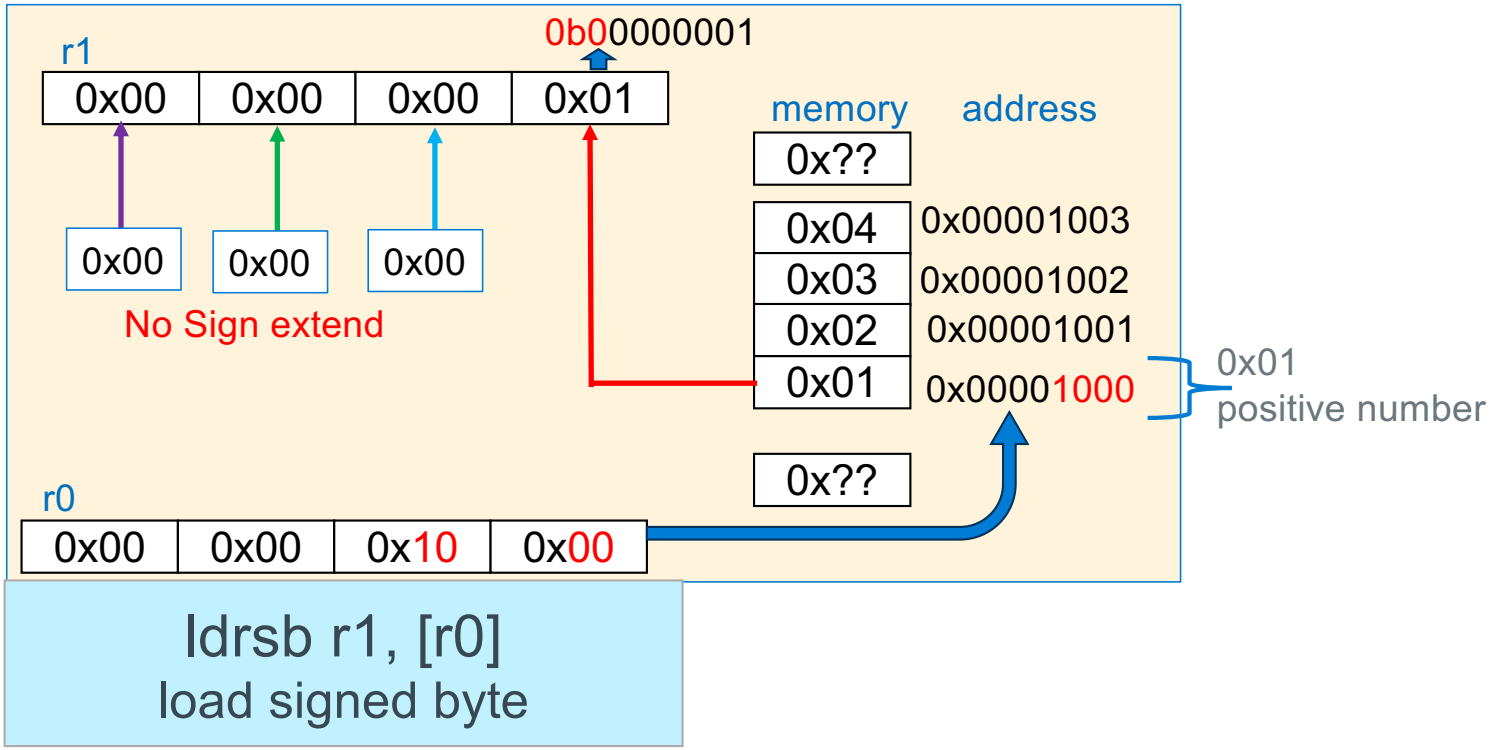
Loading 32-bit Registers From Memory, 8-bit



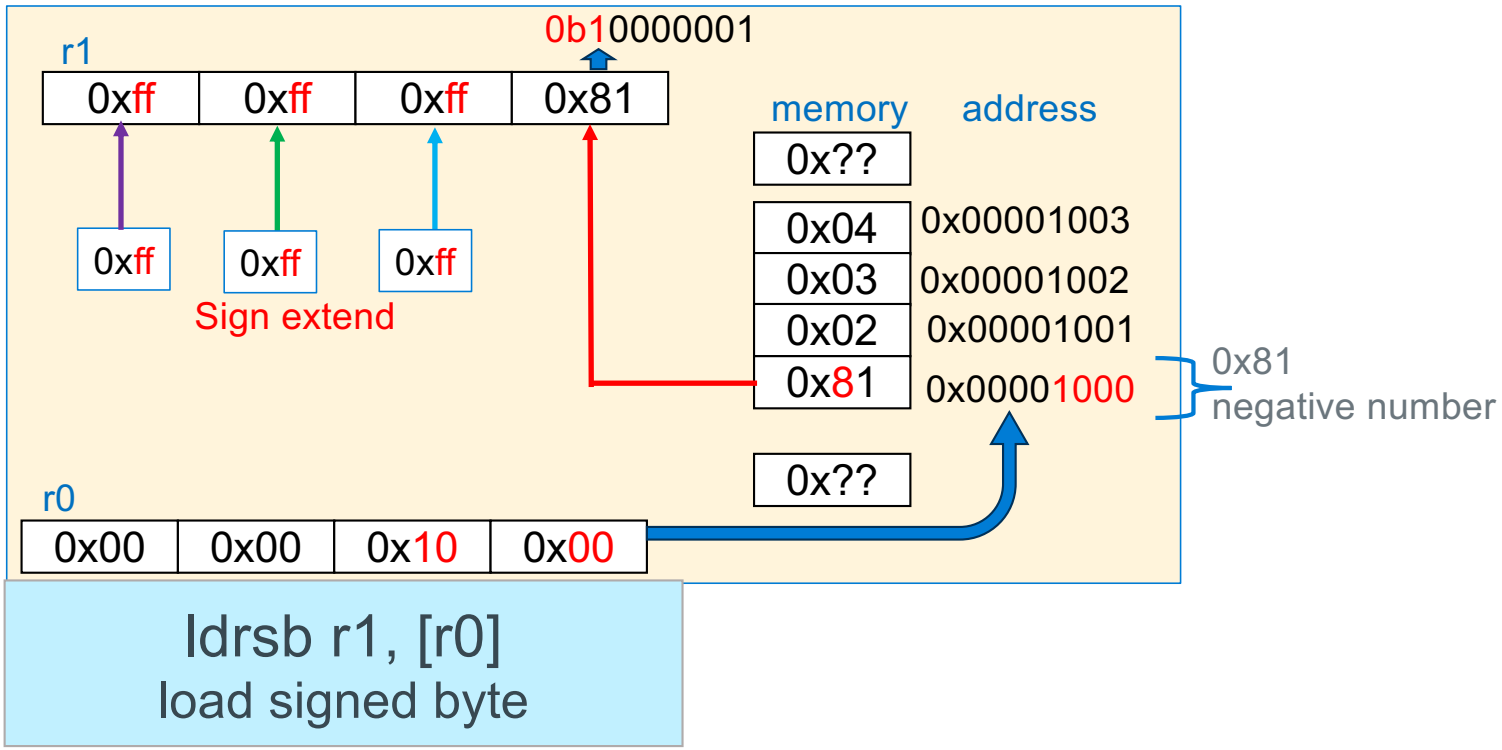
x

Loading 32-bit Registers From Memory, 8-bit



x

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



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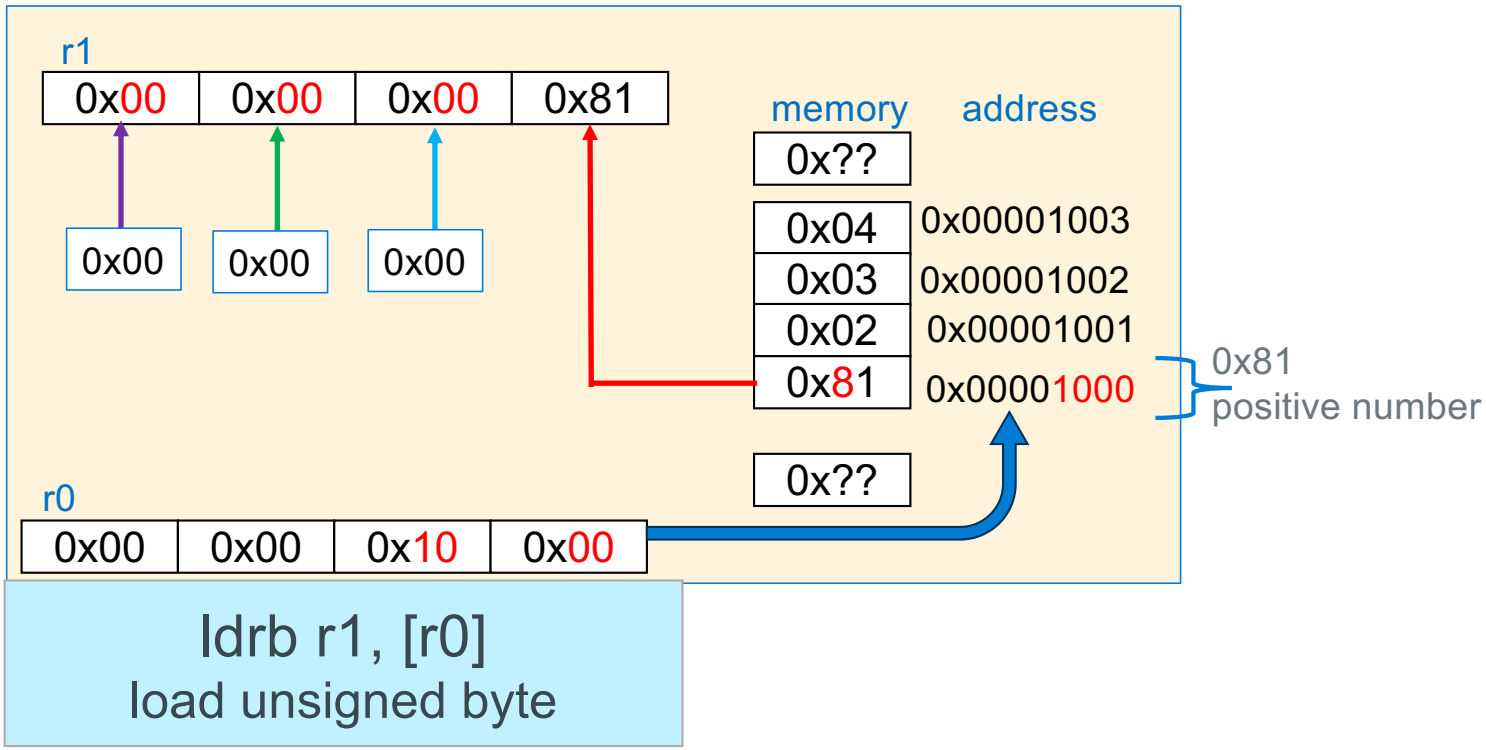
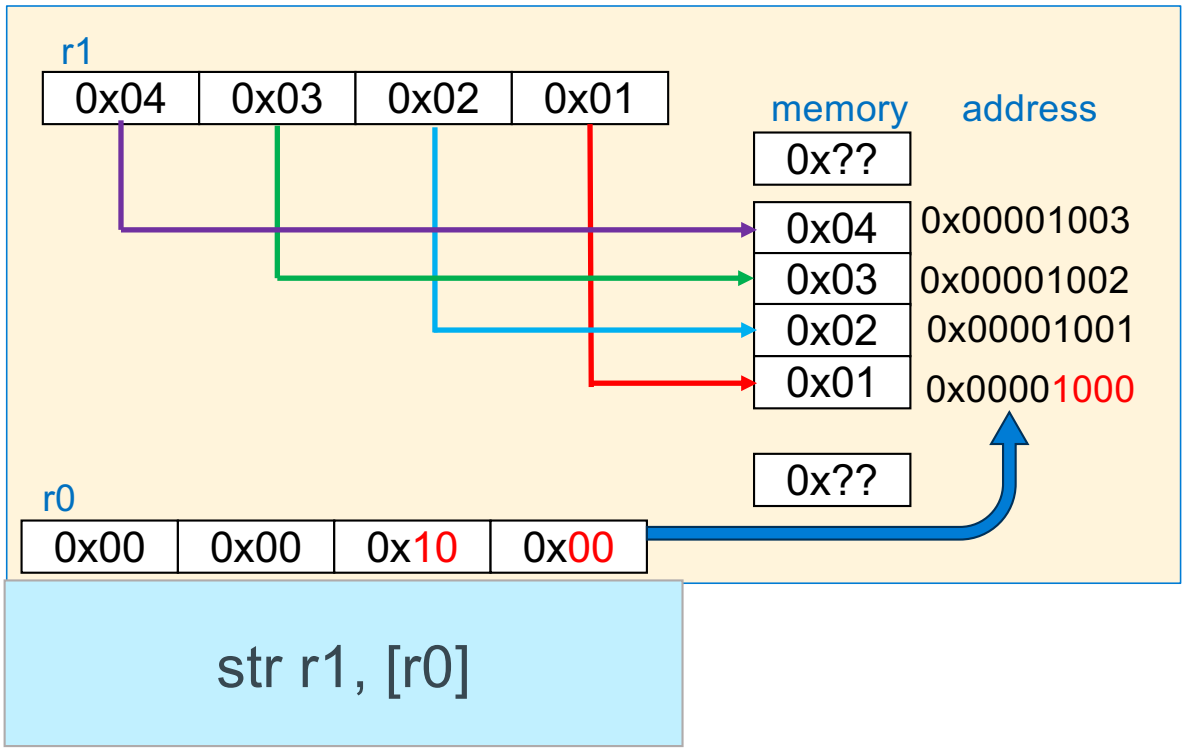
Loading 32-bit Registers From Memory, 8-bit Signed



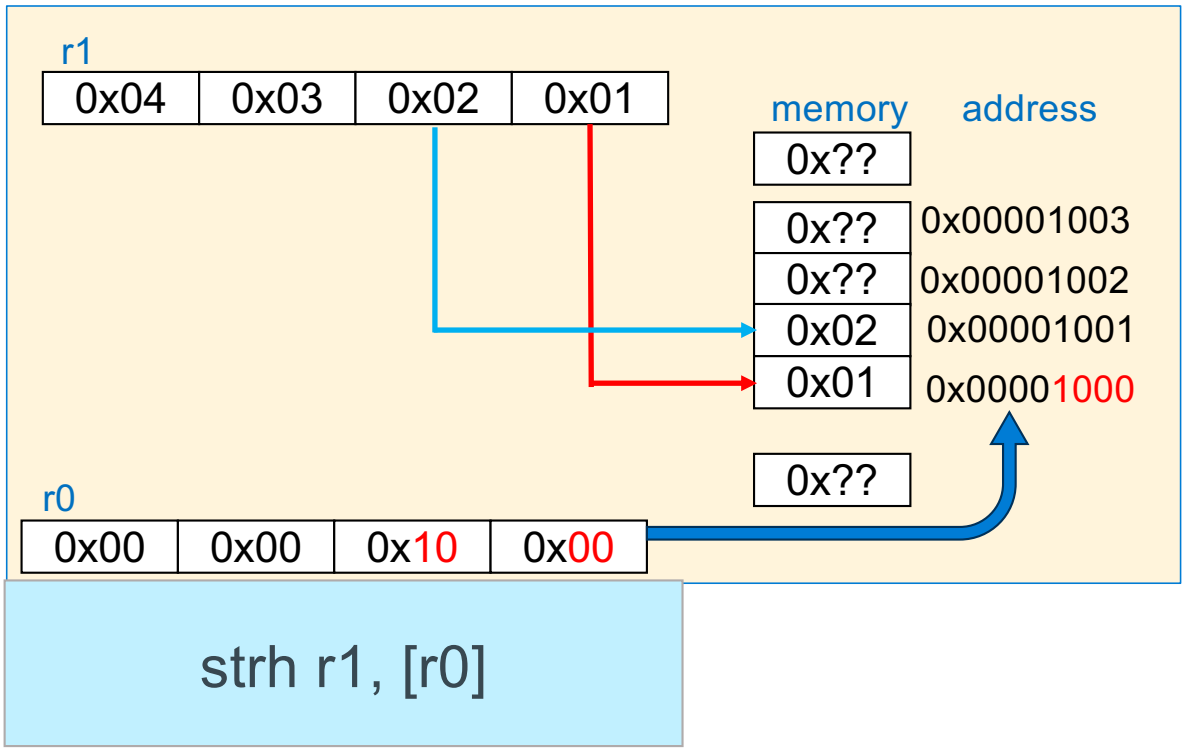
x

Storing 32-bit Registers To Memory, 32-bit



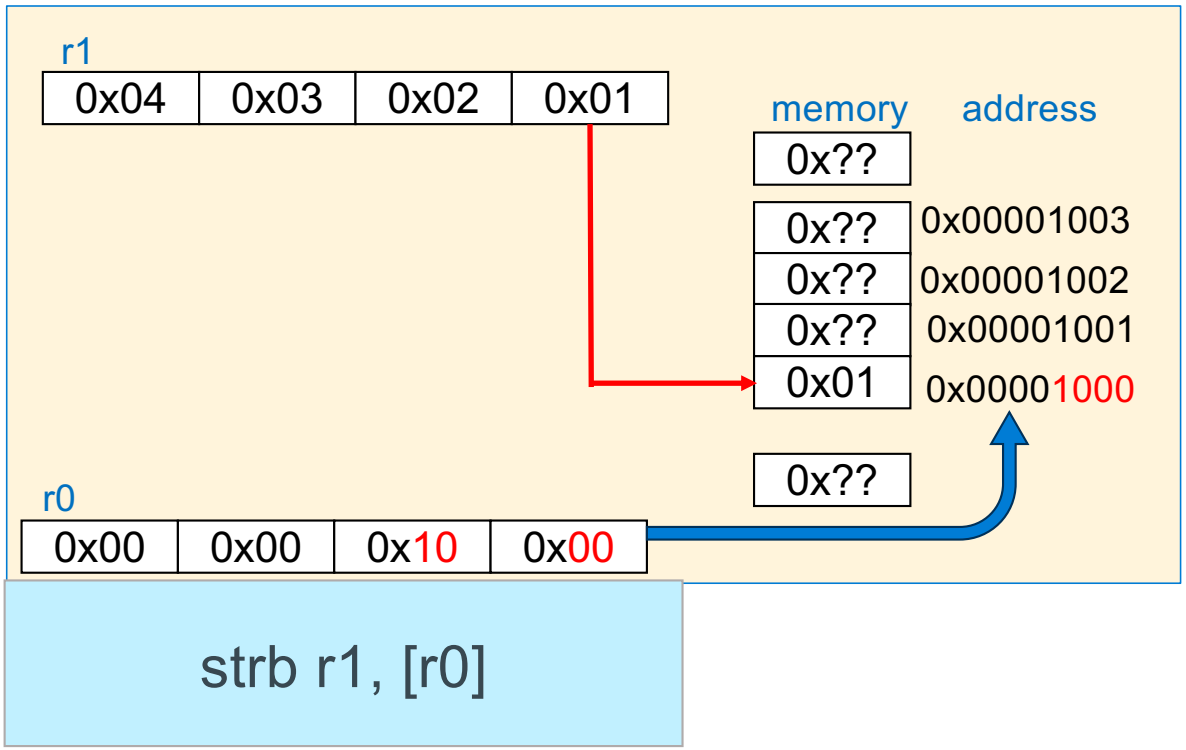
x

Storing 32-bit Registers To Memory, 16-bit



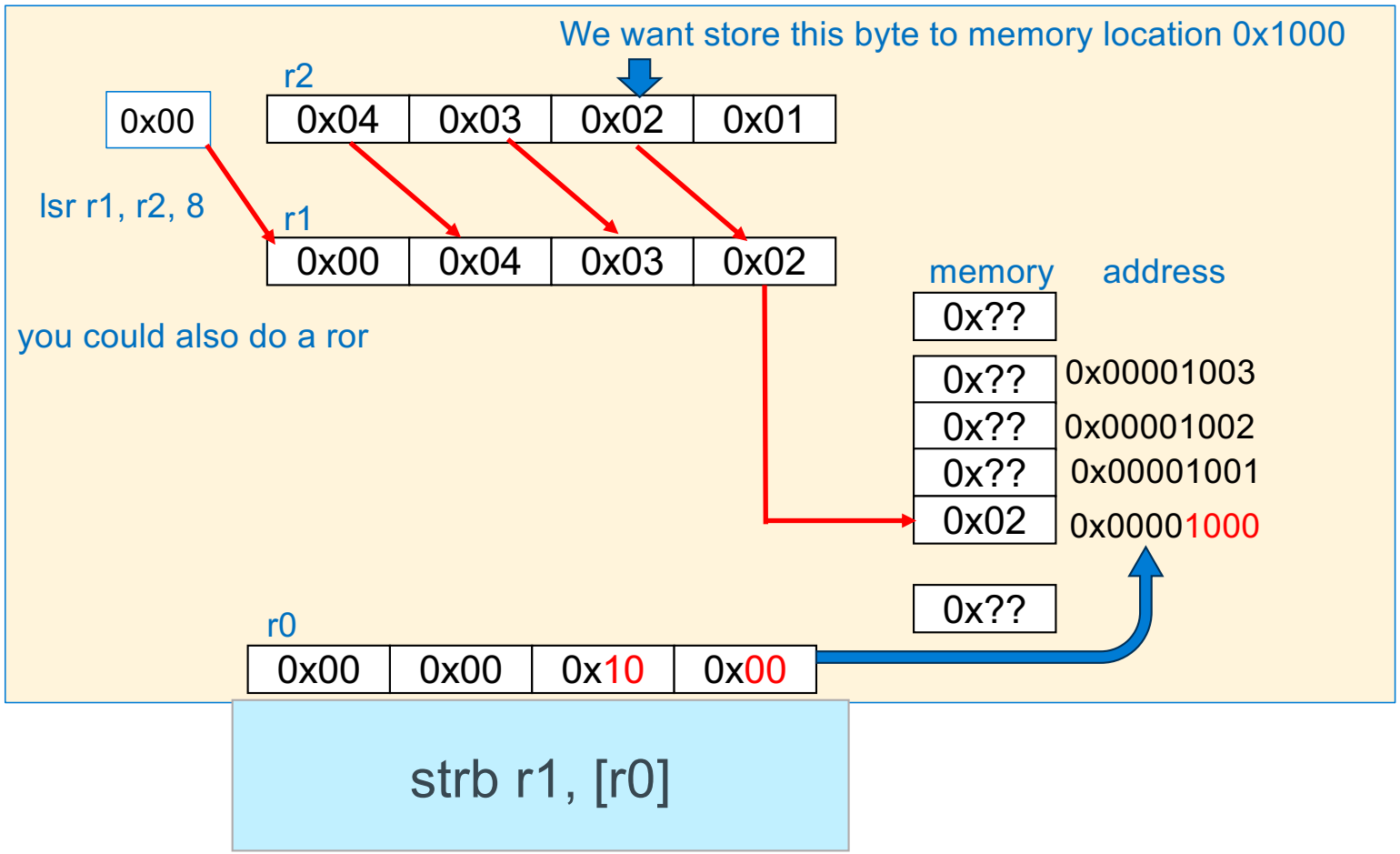
x

Storing 32-bit Registers To Memory, 8-bit



x

Storing 32-bit Registers To Memory, 8-bit – Storing different byte



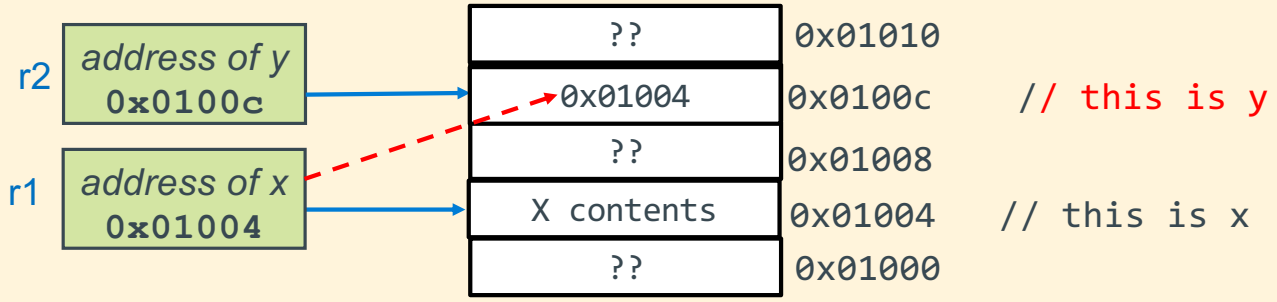
x

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
```

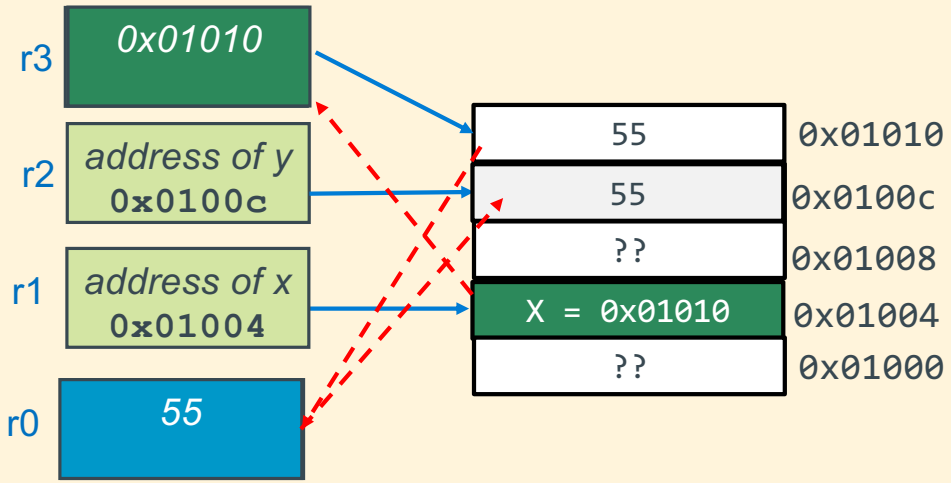

x

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 + cnt;

    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

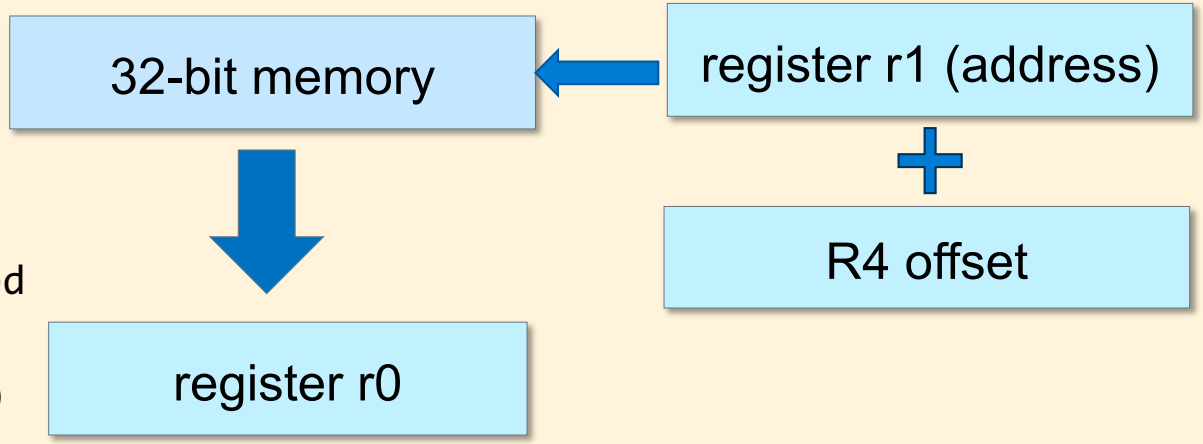
loop guard

x

Load/Store: Register Base Addressing + Register Offset

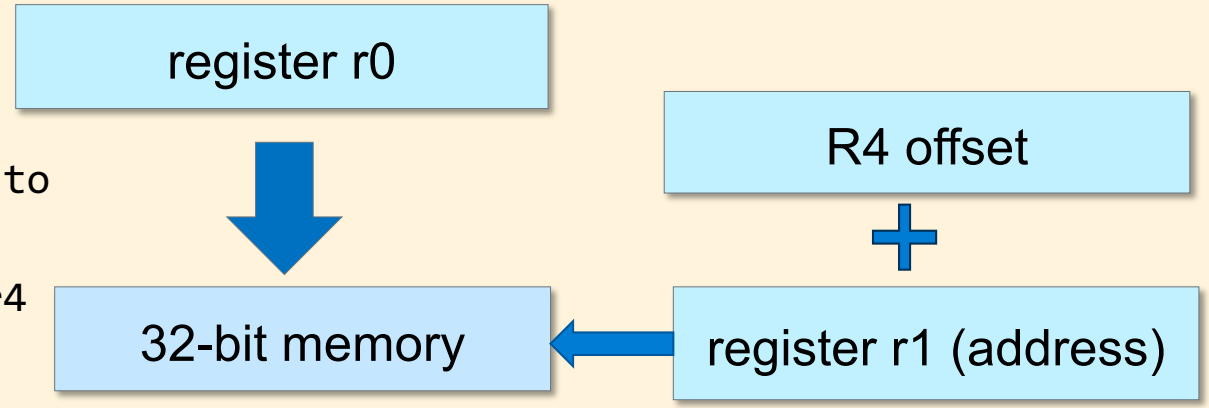
```
ldr r0, [r1, r4]
```

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



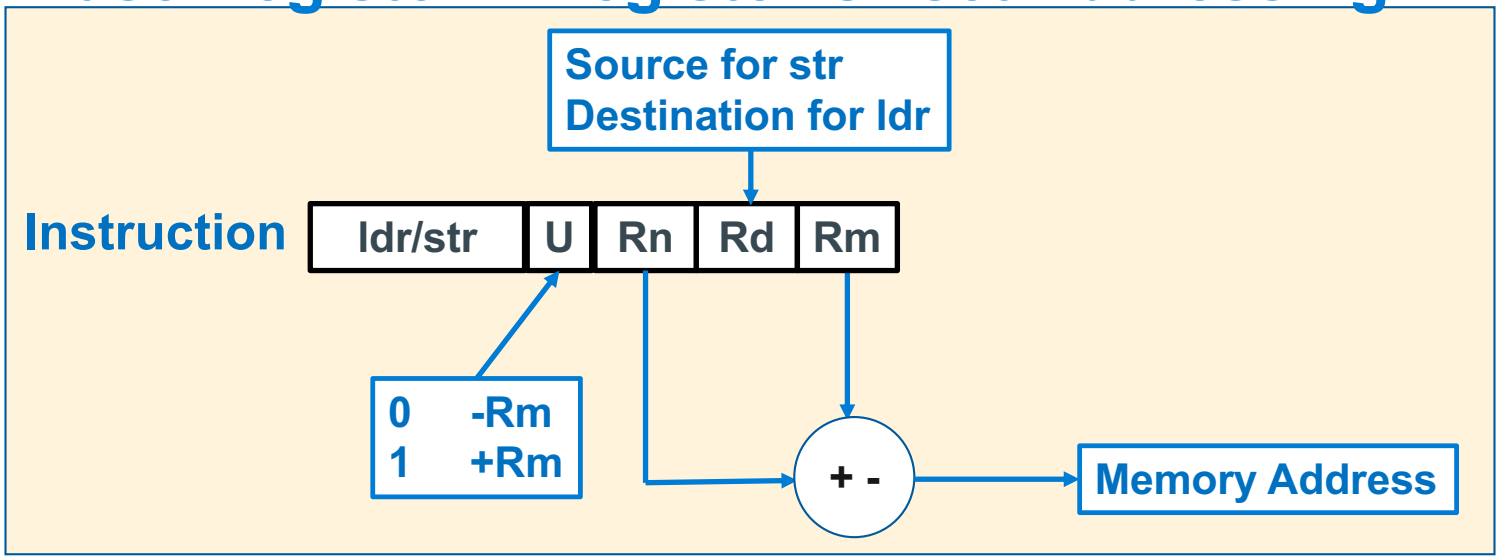

```
str   r0, [r1, r4]
```

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



x

ldr/str Base Register + Register Offset Addressing



Pointer Address = Base Register + Register Offset

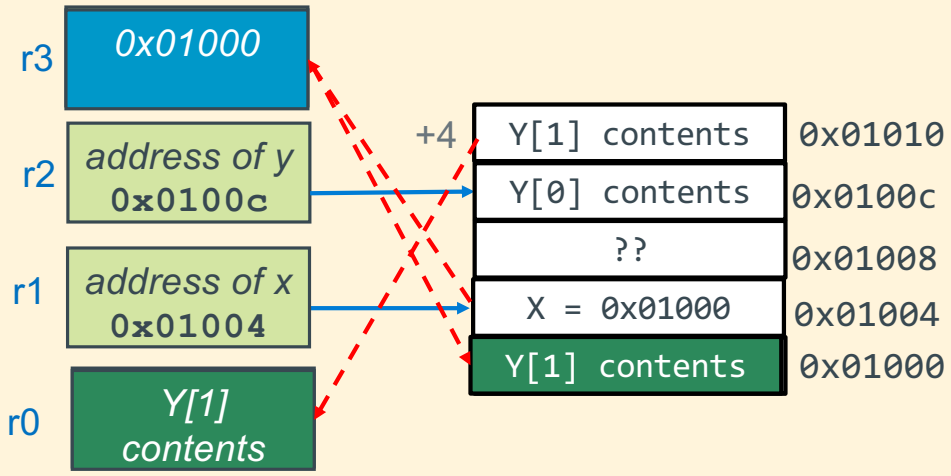
- **Unsigned** offset integer **in a register (bytes)** is either added/subtracted from the **pointer address** in the **base register**

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];
```

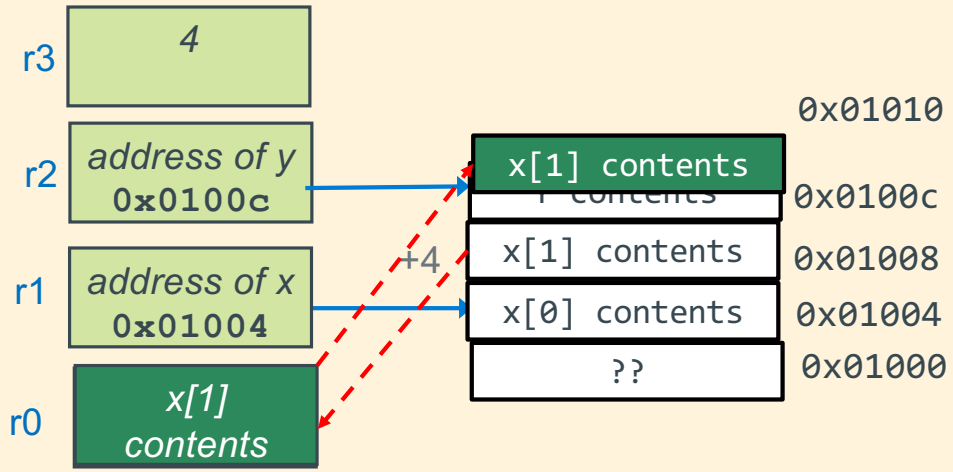



```
ldr    r0, [r2, 4]        // r0 ← y[1]

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,…

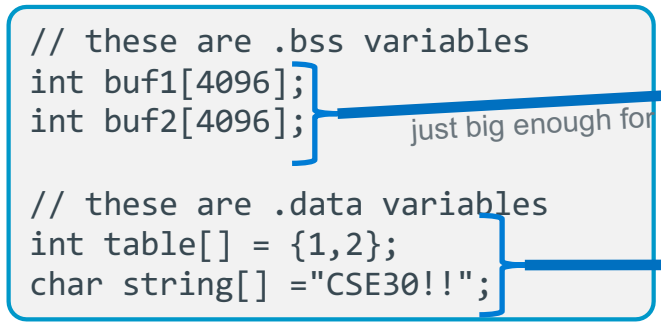
```
count:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF

    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
```

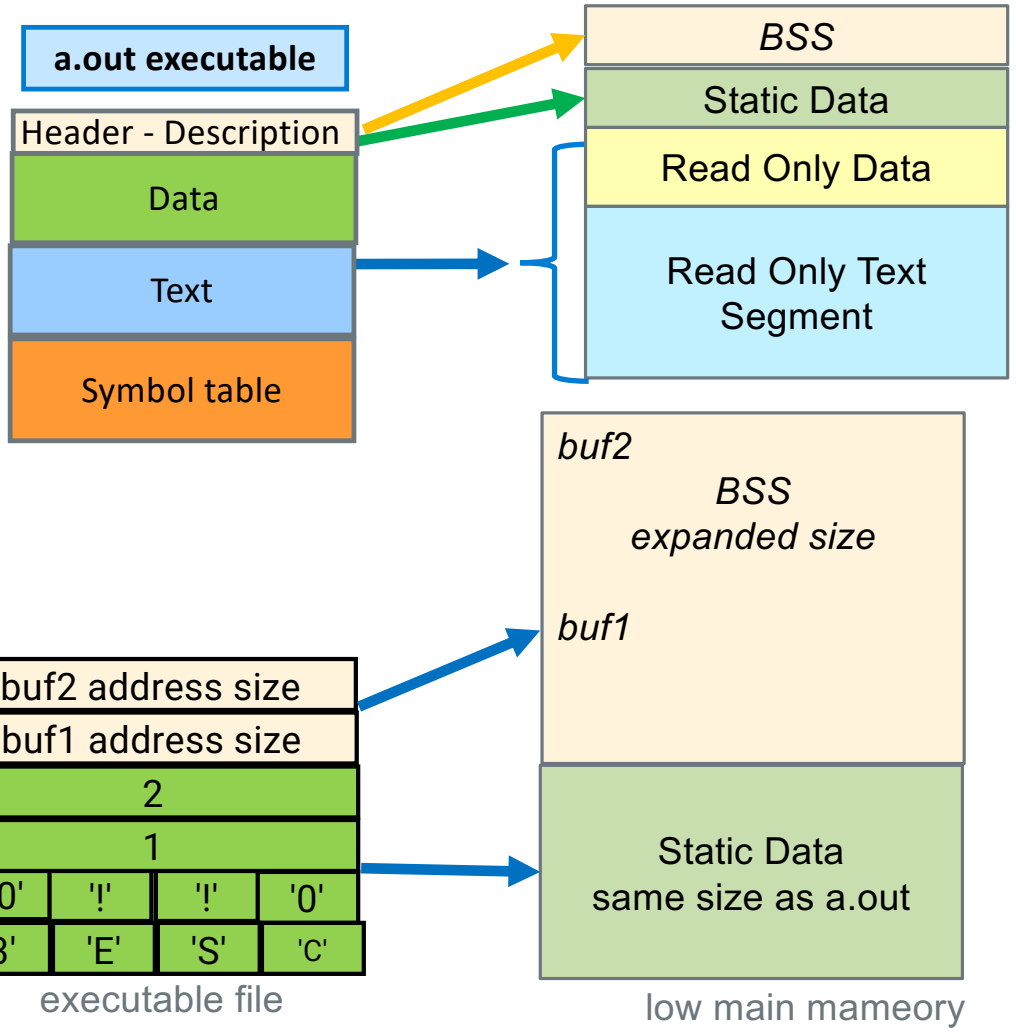
loop guard

x

What is the conceptual difference between .bss and .data?

- All static variables that do not specify an initial value default to an initial value of 0 and are placed in .bss segment
- To save file system space in the executable file (the a.out file) the assembler collapses these .bss variables to a location and size "table"
- .data segment variables use the same space in the executable file as they have in memory
- .section .rodata is handled the same as .data





Variable Alignment In .data, .bss and .section .rodata

Use .align directive to force the assembler to align the address of the next variable defined after the .align

char 1 any address

short 2 bytes addresses that end in 0b0

integer 4 bytes addresses that end in 0b00

SIZE Alignment Requirements	Starting Address must end in	Align Directive
8-bit char -1 byte	0b..0 or 0b..1	
16-bit int -2 bytes	0b..0	.align 1
32-bit int -4 bytes pointers, all arrays	0b..00	.align 2

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 = 0xaa55;
			int array[] = {12,~0x1,0xCD,-1};
				dist: .word 5
				distptr: .word dist
				mask: .word 0xaa55
				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

Rule: use .align 2 before every array regardless of type

Rule: place variables with explicit initialized values in a .data segment

Rule: place variables with no explicit initiali value (default to 0) in .bss segment

Rule: place string literals in .section .rodata and use a local label (.Llabel:)
```


x

Loading Static variables into a register

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

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

- Tell the assembler load the contents into a register
- `ldr  R0, [Rd] // Rd = address`
- *Example to the right: y = x;*

load a static **memory** variable

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

store to a static **memory** variable

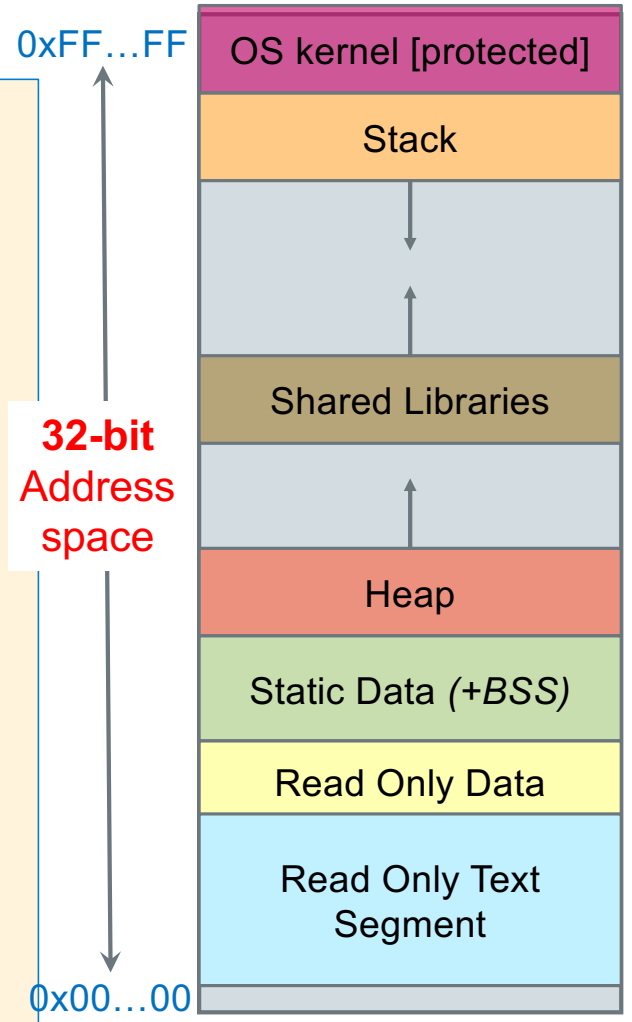
1. load the pointer to the memory
2. write (store) to *pointer

```
        .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

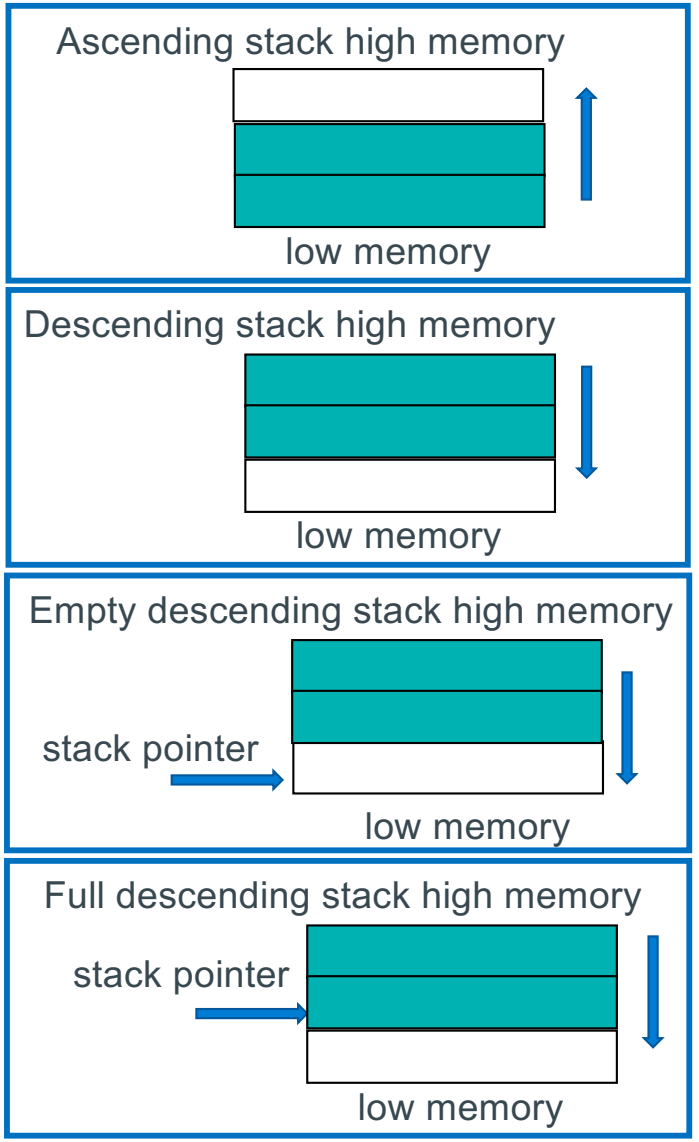
Stack Segment: Support of Functions

- 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)



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**



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;
}
```

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

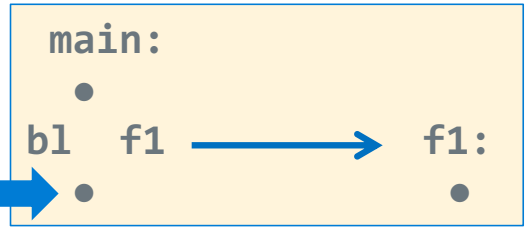
Branch with Link Indirect (function call) instruction

```
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

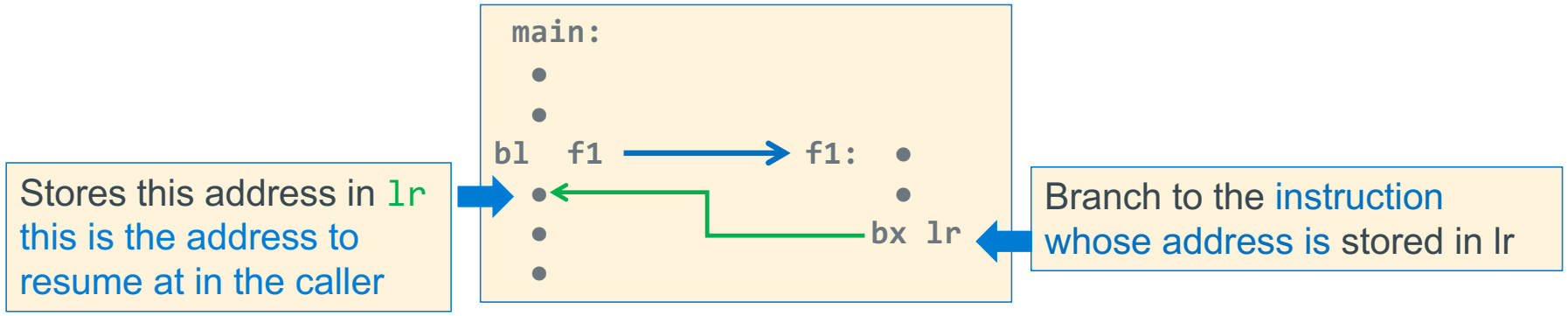
Branch & exchange (function return) instruction

`bx lr`

bx	Rn

`// we will always use lr`

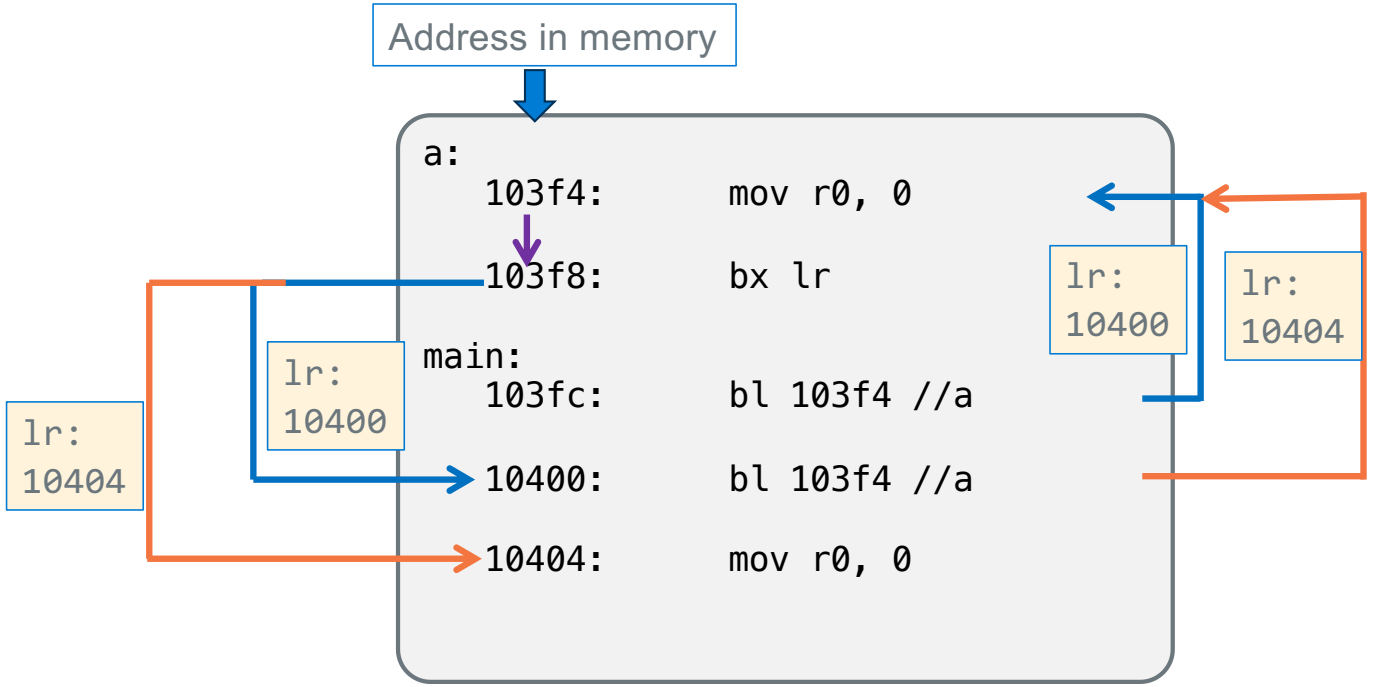
- Causes a branch to the instruction **whose address is stored** in register <`lr`>
  - It copies `lr` to the PC
- This is often used to implement a return from a function call (exactly like a C return) when the function is called using either `bl label, or blx Rm`



x

Understanding bl and bx - 1

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



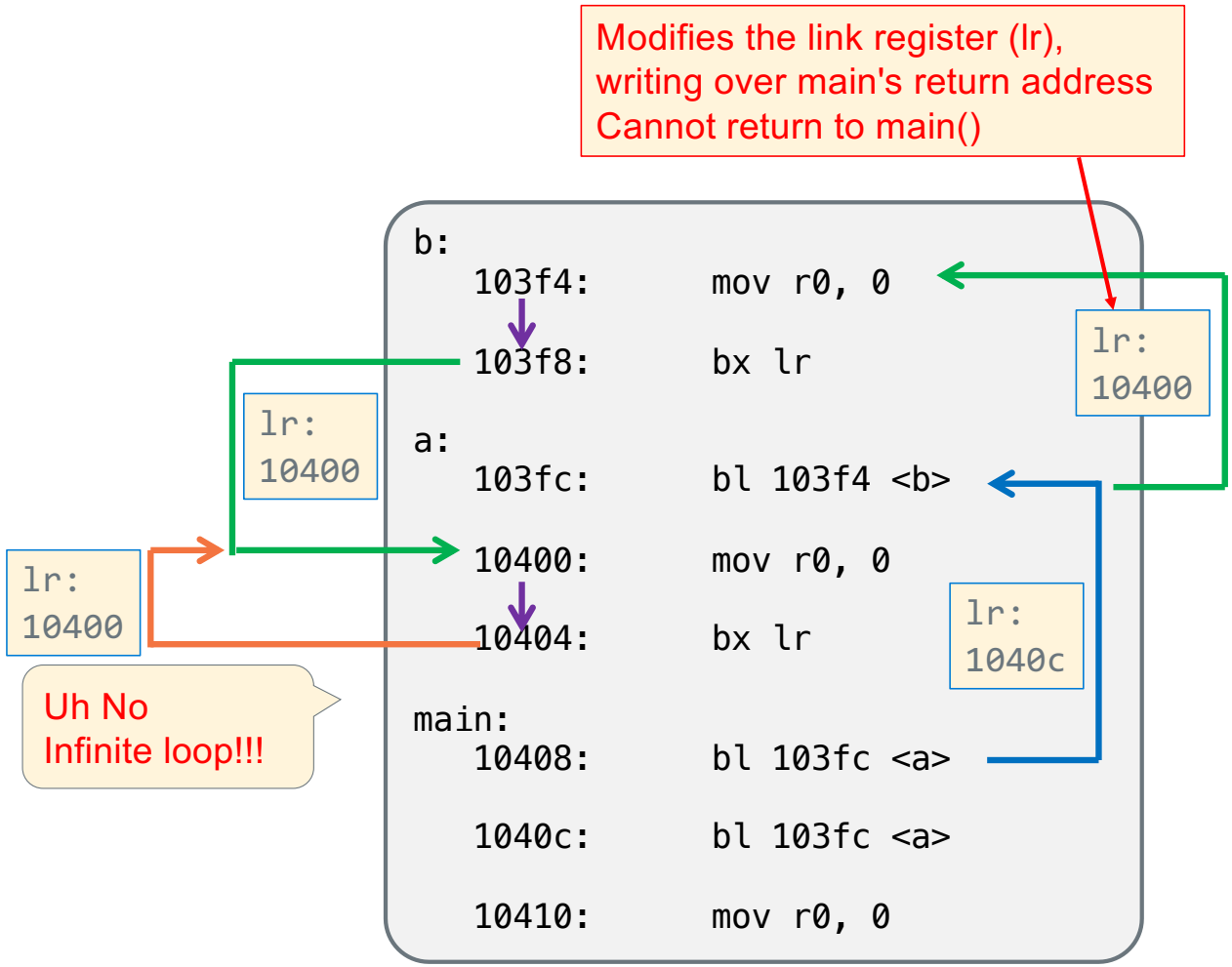
But there is a problem we must address here – next slide

x

Understanding bl and bx - 2

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

We need to preserve the lr!



x

Understanding bl and blx - 3

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

int (*func)() = a;

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

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

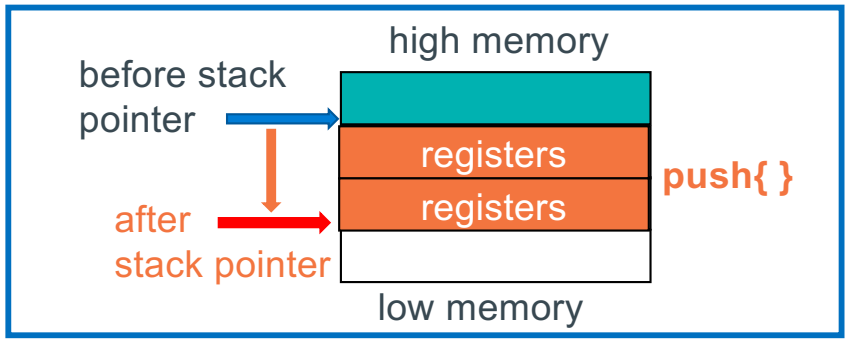
```
     .data
func:.word a // func initialized with address of a()

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

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


x

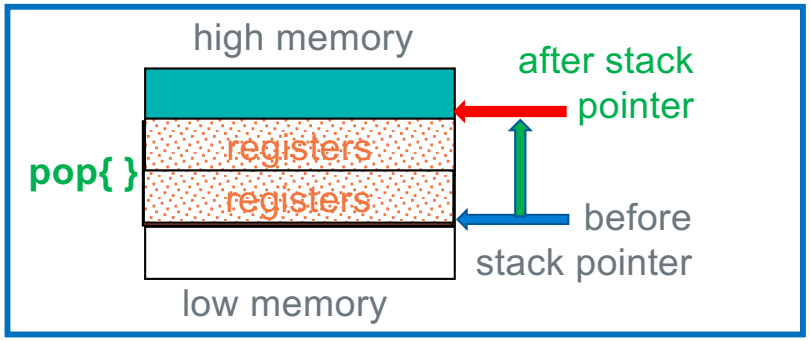
Preserving and Restoring Registers on the stack - 1

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

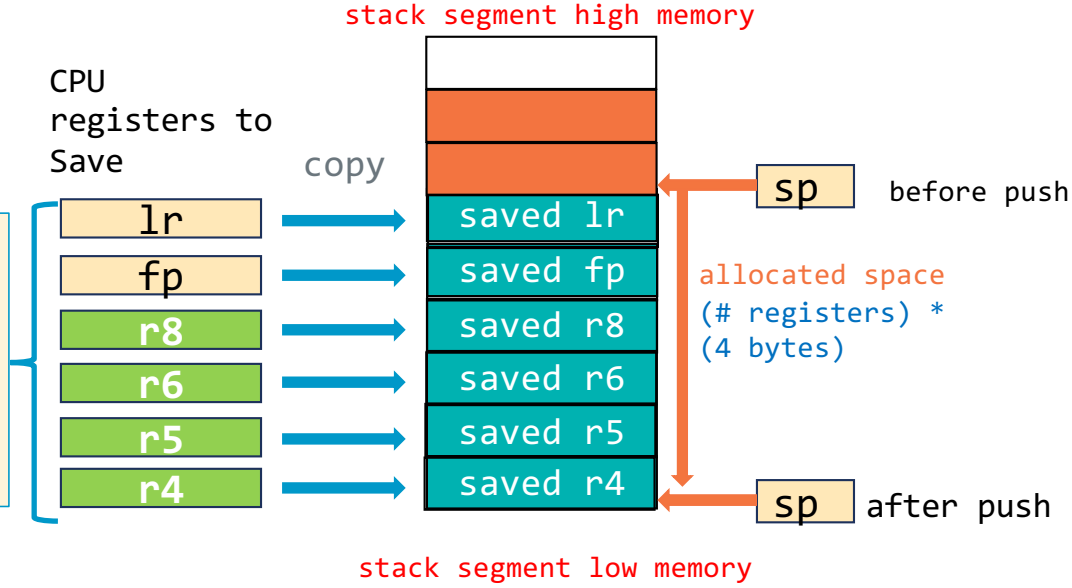
x

push: Multiple Register Save to the stack

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

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

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



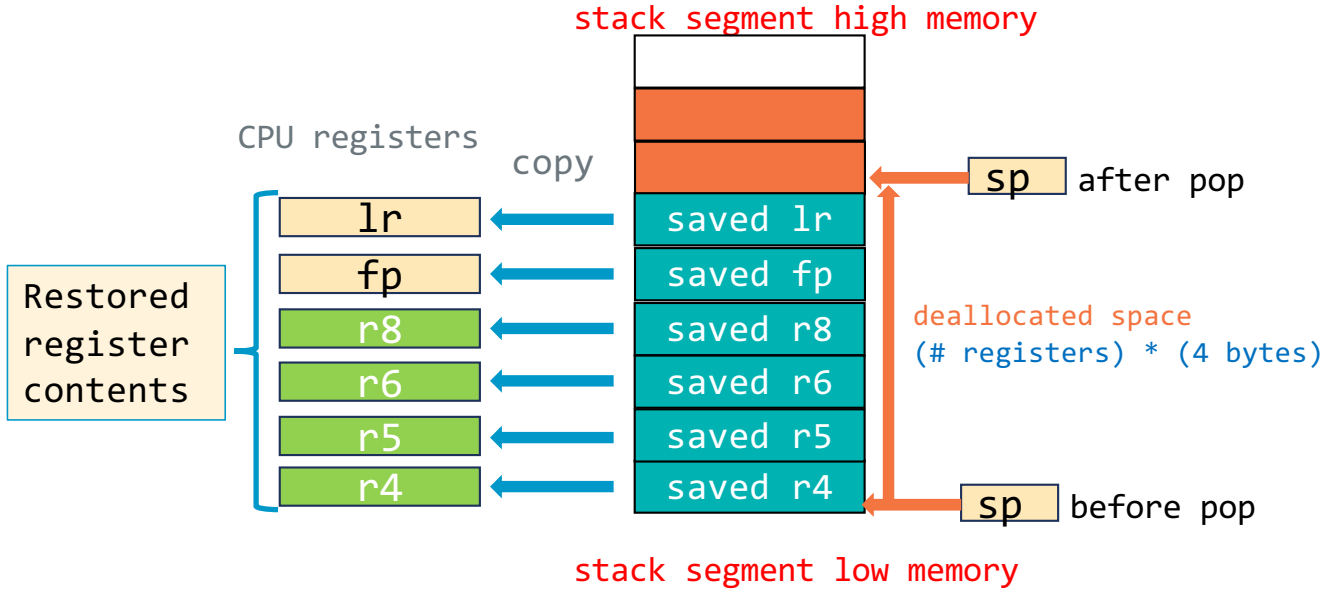
- `push` copies the contents of the `{reg list}` to stack segment memory
- `push` subtracts (# of registers saved) * (4 bytes) from the `sp` to ***allocate*** space on the stack
  - sp = sp – (# registers_saved * 4)
- **this must always be true: sp % 8 == 0**

x

pop: Multiple Register Restore from the stack

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

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



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

x

Registers: Rules For Use

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

x

Return Value and Passing Parameters to Functions

(Four parameters or less)

Register	*Function Call Use*	*Function Body Use*	*Save before use* *Restore before return*
r0	arg1 and return value	scratch registers	No
r1-r3	arg2 to arg4	scratch registers	No

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

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

- Each **parameter and return value is limited to data that can fit in 4 bytes or less**
- **Calling function:**
  - copy up to the first four parameters into these four registers before calling a function
  - **MUST 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**
- **Called function:**
  - you receive the first four parameters in these four registers (r0 – r3)

x

Return Value and Passing Parameters to Functions

(Four parameters or less)

Register	*Function Call Use*	*Function Body Use*	*Save before use* *Restore before return*
r0	arg1 and return value	scratch registers	No
r1-r3	arg2 to arg4	scratch registers	No

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

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

- For parameters, whose size is larger than 4 bytes, pass a pointer to the parameter (we will cover this later)
- **One arg value per register!** – NO arrays across multiple registers
  - chars, shorts and ints are directly stored
  - Structs (not always), and arrays (always) are passed via a pointer
  - **Pointers** passed as output parameters contain an address ***that points at*** the stack, BSS, data, or heap

x

What it means to be a Temporary/argument register

```
int a(void)
{
     // not shown
}
int main(void)
{
    int r0 = 0;
    int r1 = 1;
    int r2 = 2;
    int r3 = 3;
    r0 = a();
    // in C r1 and r3 would have the same values
    // after the call
```

```
// main()
// code not shown
mov r0, 0
mov r1, 1
mov r2, 2
mov r3, 3
bl a
// r0 = return value
// r1-r3 values are unknown as a() has right to change them as it wants
```

Preserved Registers

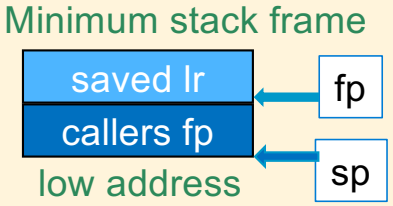
Register	*Function Call Use*	*Function Body Use*	*Save before use Restore before return*
r4-r10	preserved registers	contents preserved across function calls	Yes
r11/fp	stack frame pointer	Use to locate variables on the stack	Yes
r13/sp	stack pointer	stack space allocation	Yes
r14/lr	link register	contains return address for function calls	Yes

- **Any value** you have in a preserved register before a function call **will still be there after the function returns** (Contents are "preserved" across function calls)
- If the function **wants to use a preserved register** it must:
  1. *Save* the value contained in the register at function entry
  2. Use the register in the body of the function
  3. *Restore* the original saved value to the register at function exit (before returning to the caller)
- You use a preserved register when a function makes calls another function and you have:
  1. Local variables allocated to be in registers
  2. Parameters passed to you (in `r0-r3`) that you need to continue to use after calling another function

x

Minimum Stack Frame (Arm Arch32 Procedure Call Standards)

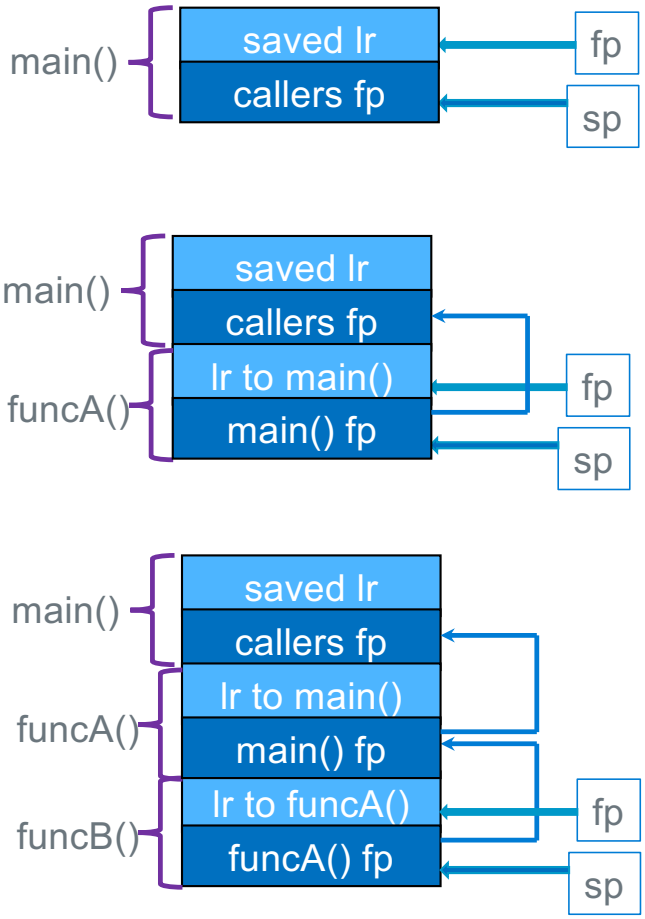
- **Minimal frame: allocating at function entry:** `push {fp, lr}`



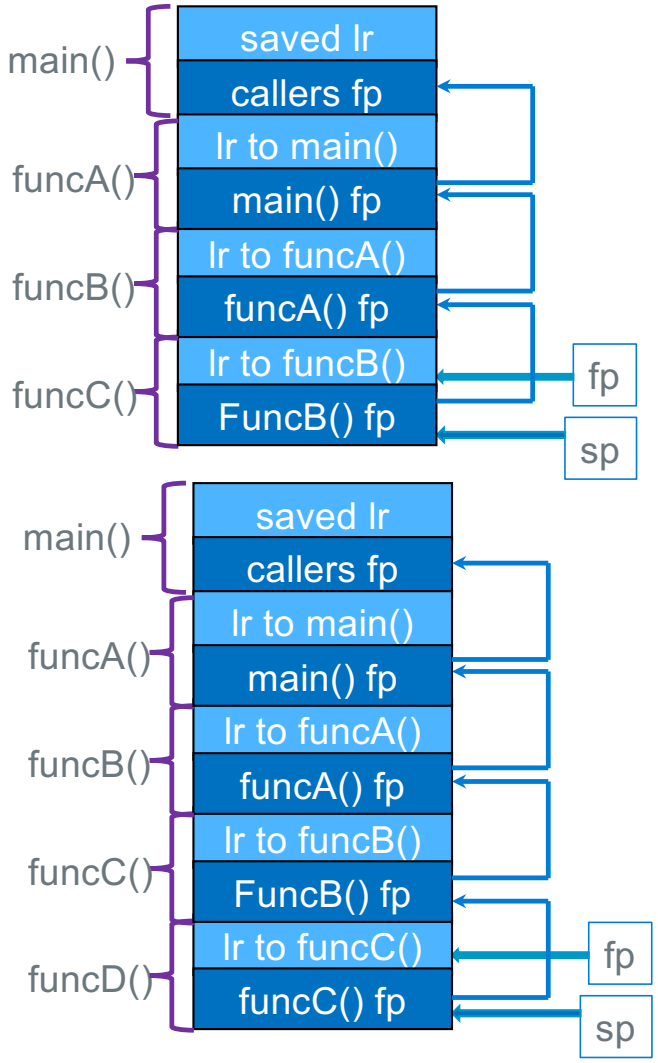
- `sp` always points at top element in the stack (lowest byte address)
- `fp` always points at the bottom element in the stack
  - Bottom element is always the saved `lr` (contains the return address of caller)
  - A saved copy of callers fp is always the next element below the lr
  - fp will be used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

x

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



How gdb finds stack frames

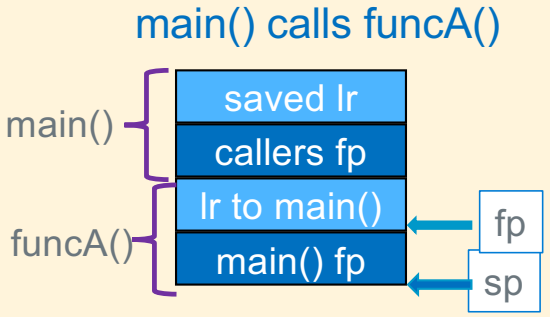


x

Minimum Stack Frame (Arm Arch32 Procedure Call Standards)

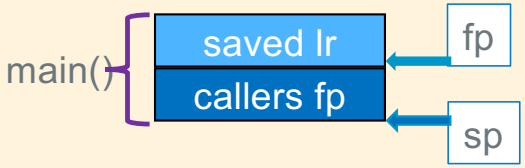
- Function entry (Function **Prologue**):
  1. save lr and fp registers (push)
  2. set fp to top entry in stack
  3. allocate space for local vars – later slides

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



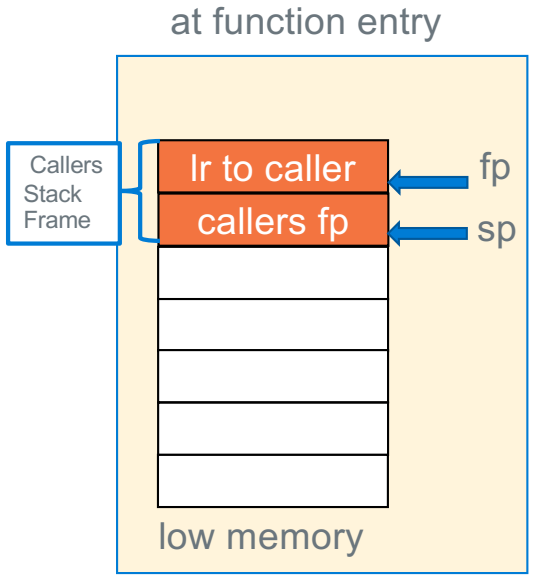
- Function return (Function **Epilogue**):
  1. deallocate space for locals -later
  2. restores lr and fp registers (pop)
  3. Return To Caller

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

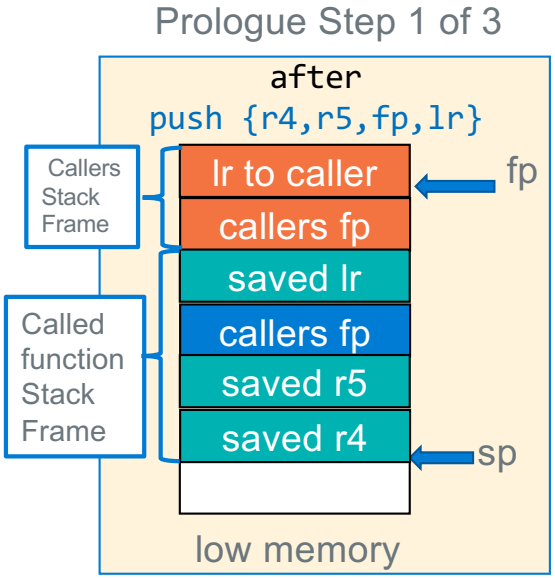


x

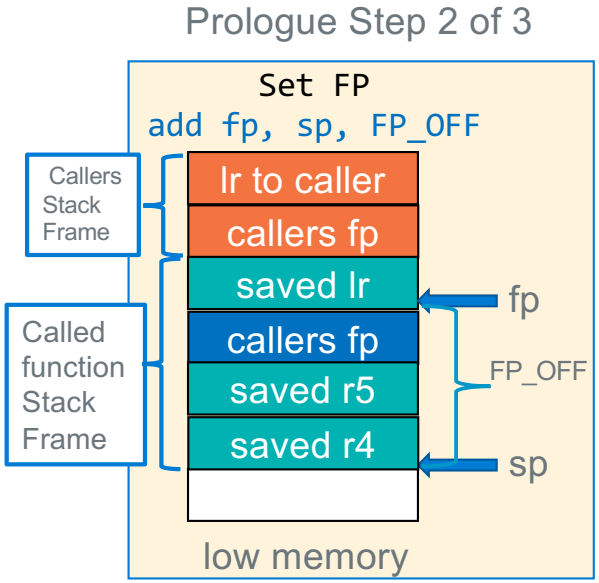
Function Prologue: Allocating the Stack Frame -1



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



using a push, save lr, fp and those preserved registers it wants to use on the stack



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

Function Prologue

```
myfunc:
    push    {fp, lr}            // push (save) fp and lr on stack
    add     fp, sp, FP_OFF      // set fp for this function
    add     sp, sp, -FRMADD     // allocate FRMADD bytes for local vars
                                // by moving sp
```


x

Function Prologue: Allocating the Stack Frame - 2

Prologue Step 3 of 3

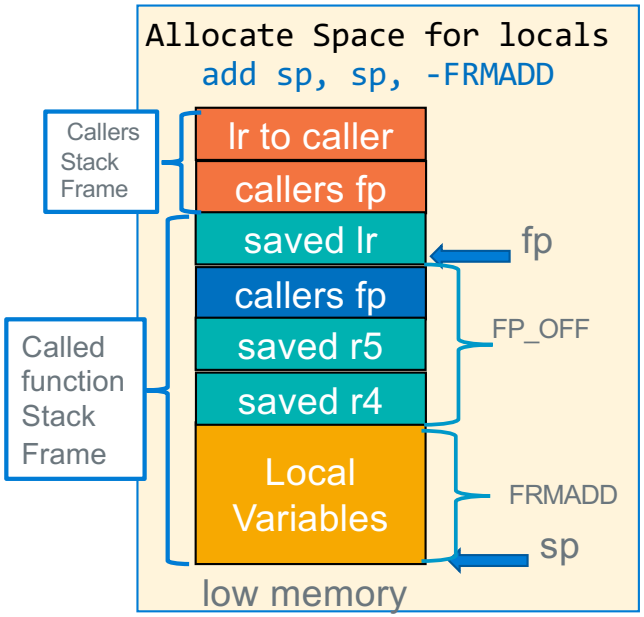
- Space for local variables is allocated on the stack right below the lowest pushed register
- **Add memory to the stack frame for local variables** by **moving** the sp towards low memory
- The amount moved is the total size of all local variables in bytes **plus** memory alignment **padding**

FRMADD = total local var space (bytes) + padding

- Allocate the space after the register push by

```
add   sp, sp, -FRMADD
```

- fp (frame pointer) is used as a **pointer (base register)** to access all stack variables – later slides



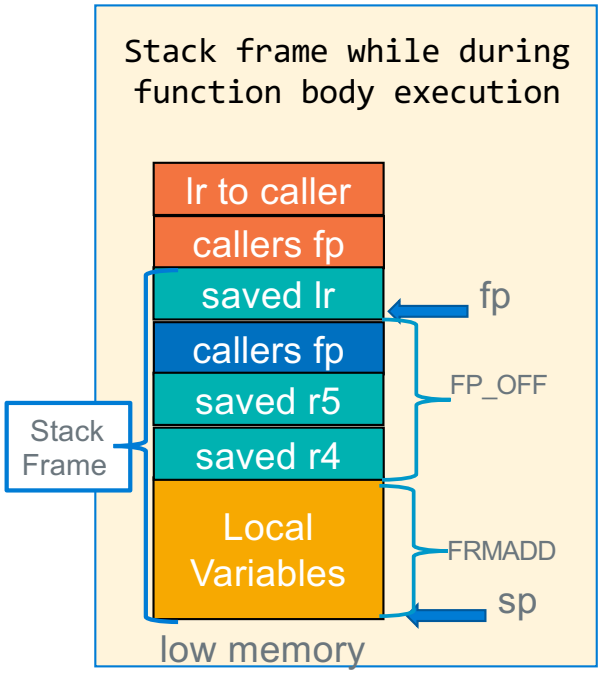
Allocate Space for Local Variables

Function Prologue

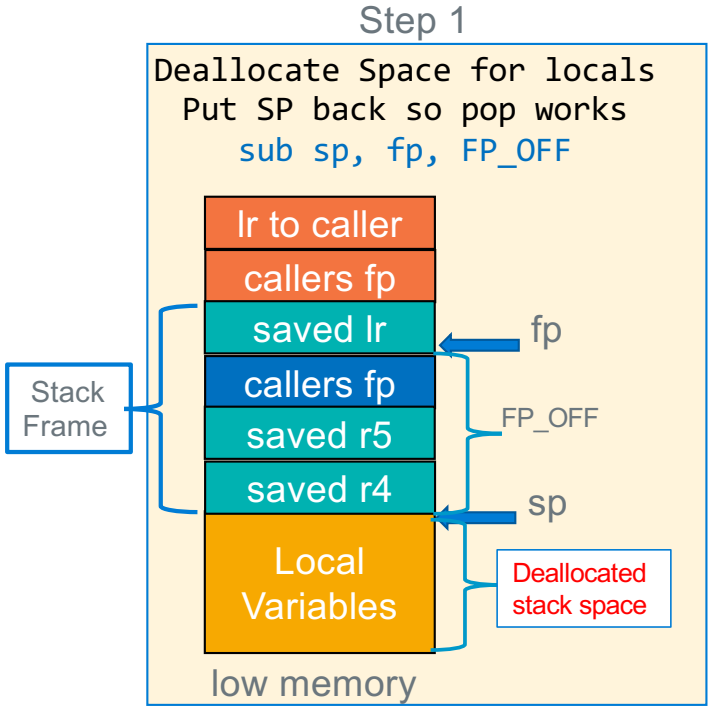
```
myfunc:
    push    {fp, lr}              // push (save) fp and lr on stack
    add     fp, sp, FP_OFF        // set fp for this function
    add     sp, sp, -FRMADD       // allocate FRMADD bytes for local vars
                                  // by moving sp
```


x

Function Epilogue: Deallocating the Stack Frame - 1



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



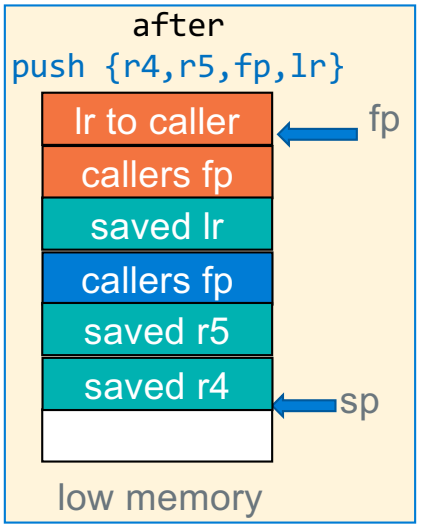
Move SP back to where it was after the push in the prologue.
So, pop works properly (this also deallocates the local variables)

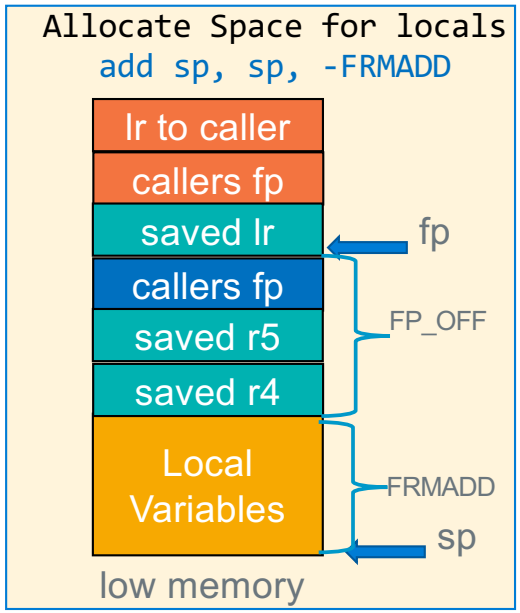
function Epilogue

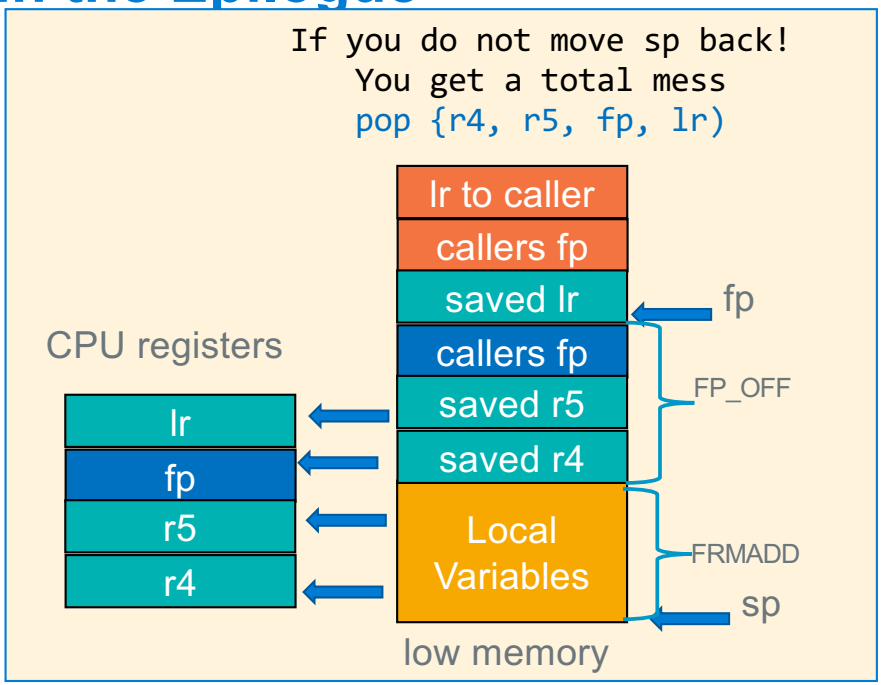
```
sub     sp, fp, FP_OFF          // deallocate local variables by moving sp
pop     {fp, lr}                // pop (restore) fp and lr from stack
bx      lr                      // return to caller
```


x

Why You must move SP before POP in the Epilogue





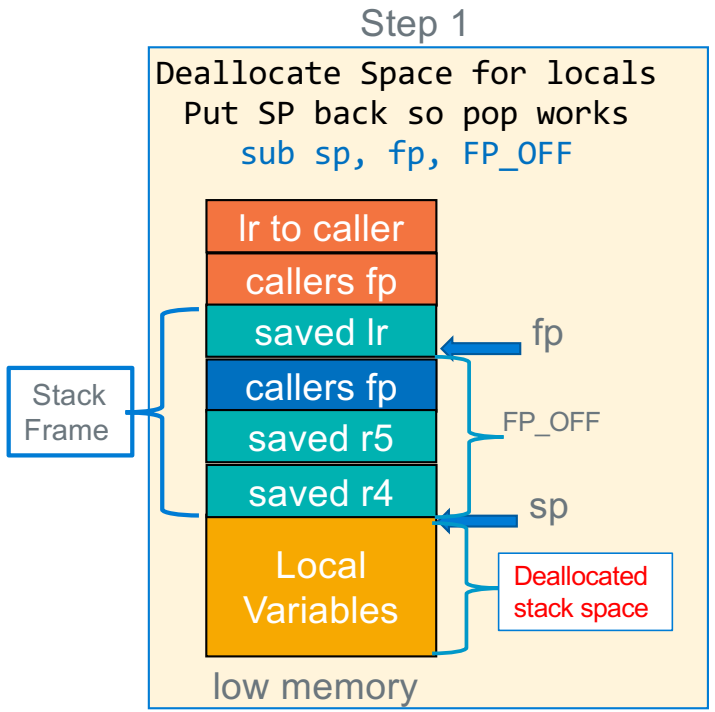


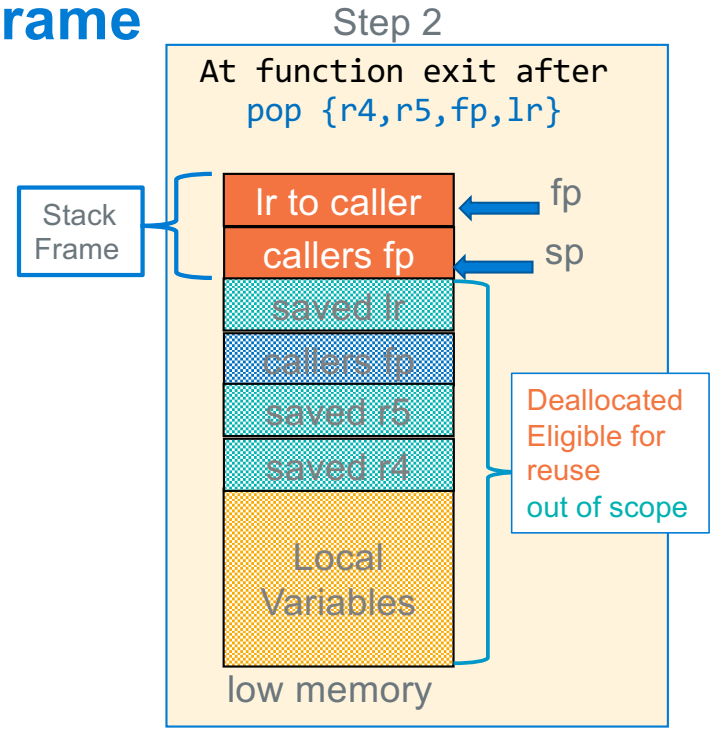
function Epilogue

```
sub     sp, fp, FP_OFF          // deallocate local variables by moving sp
pop     {fp, lr}                // pop (restore) fp and lr from stack
bx      lr                      // return to caller
```


x

Function Epilogue: Deallocating the Stack Frame





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

Use pop to restore the registers to the values they had at function entry

function Epilogue

```
sub     sp, fp, FP_OFF          // deallocate local variables by moving sp
pop     {fp, lr}                // pop (restore) fp and lr from stack
bx      lr                      // return to caller
```

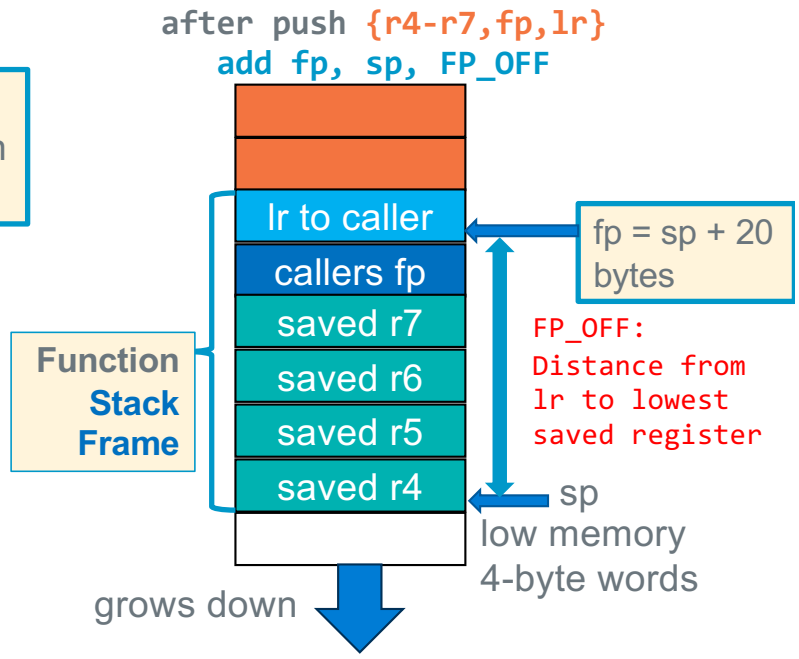

x

How to Set FP

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

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

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



# regs saved	FP_OFF in Bytes Distance from lr to lowest saved register
2	4
3	8
4	12
5	16
6	20
7	24
8	28
9	32

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

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

x

Reference Table: Global Variable access

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

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

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

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

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

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

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

stdin, stdout and stderr are global variables

x

Passing global variables as a parameter: fprintf()

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

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

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

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

    return EXIT_SUCCESS;
}
```

We are going to put these variables in temporary registers

r0, r1, r2

three passed args in this use of fprintf

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

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

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

x

Putchar/getchar: The while loop

initialize count

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

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

did getchar() return EOF if not loop

saw EOF, print count

```
mov     r4, 0  //count
bl      getchar
cmp     r0, EOF
beq     .Ldone
.Lloop:
bl      putchar
bl      getchar
add     r4, r4, 1
cmp     r0, EOF
bne     .Lloop
.Ldone:
mov     r1, r4      //arg2
ldr     r0, =.Lst   //arg1
bl      printf
```

address of string literal variable

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

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

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

File header and footers are not shown

x

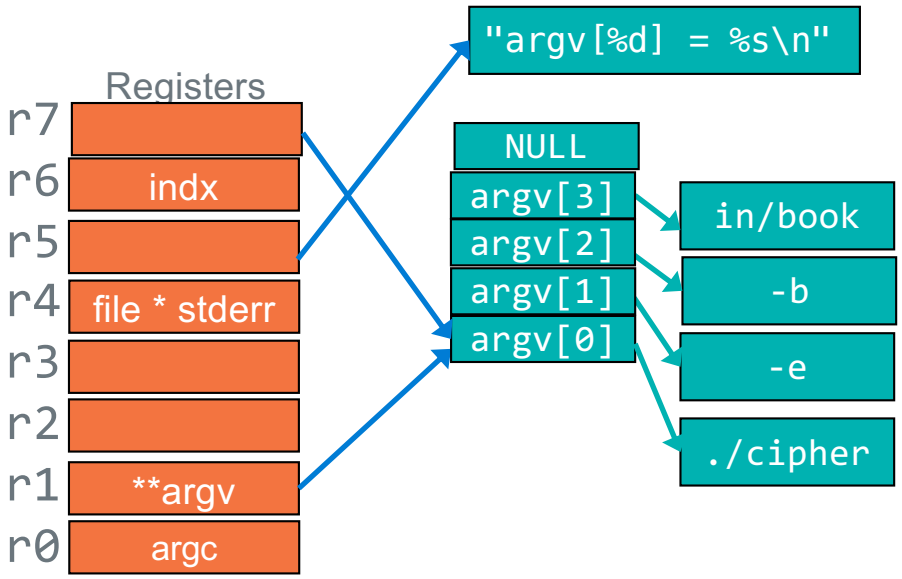
Accessing Pointers (argv) in ARM assembly

```
    .extern printf
    .extern stderr
    .section .rodata
.Lstr:  .string "argv[%d] = %s\n"
    .text
    .global main    // main(r0=argc, r1=argv)
    .type   main, %function
    .equ    FP_OFF,     20
main:
    push    {r4-r7, fp, lr}
    add     fp, sp, FP_OFF
    mov     r7, r1              // save argv!
    ldr     r4, =stderr         // get the address of stderr
    ldr     r4, [r4]            // get the contents of stderr
    ldr     r5, =.Lstr          // get the address of .Lstr
    mov     r6, 0               // set indx = 0;

// see next slide

.Ldone:
    mov     r0, 0
    sub     sp, fp, FP_OFF
    pop     {r4-r7, fp, lr}
    bx      lr
```

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

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

r0-r3 lost due to fprintf call




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


x

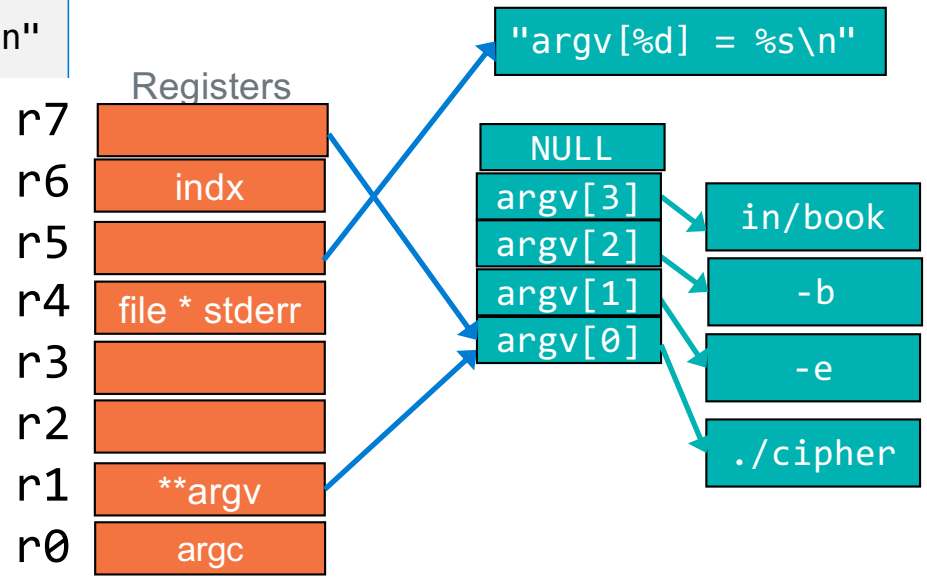
Accessing Pointers (argv) in ARM assembly

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

observe the different increment sizes

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

r0-r3 lost due to fprintf call



x

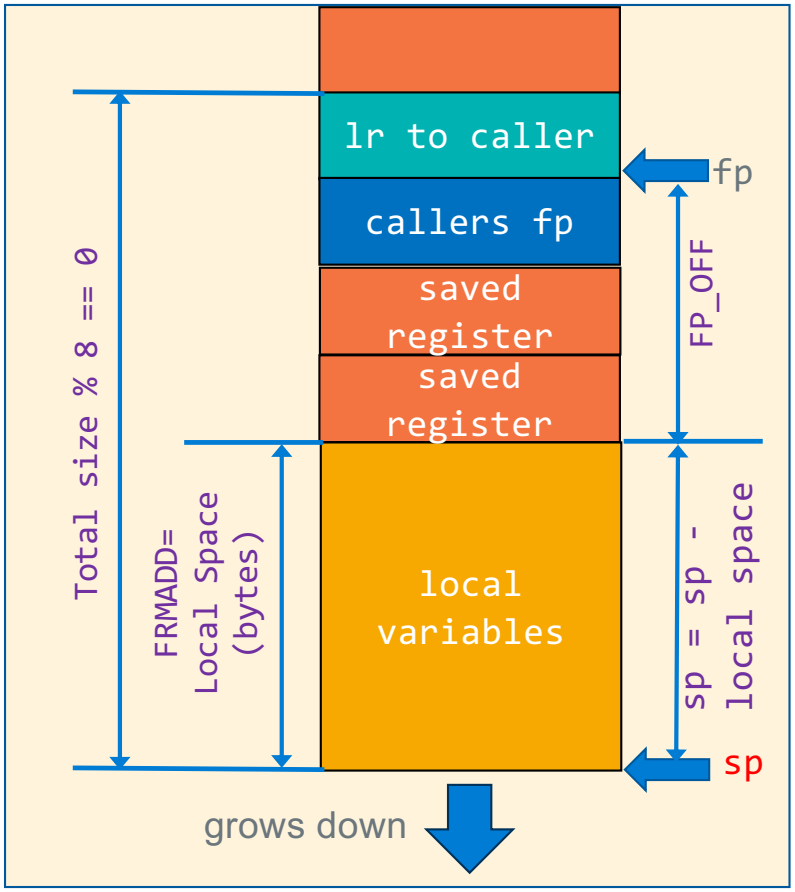
Allocating Space For Locals on the Stack

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

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

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

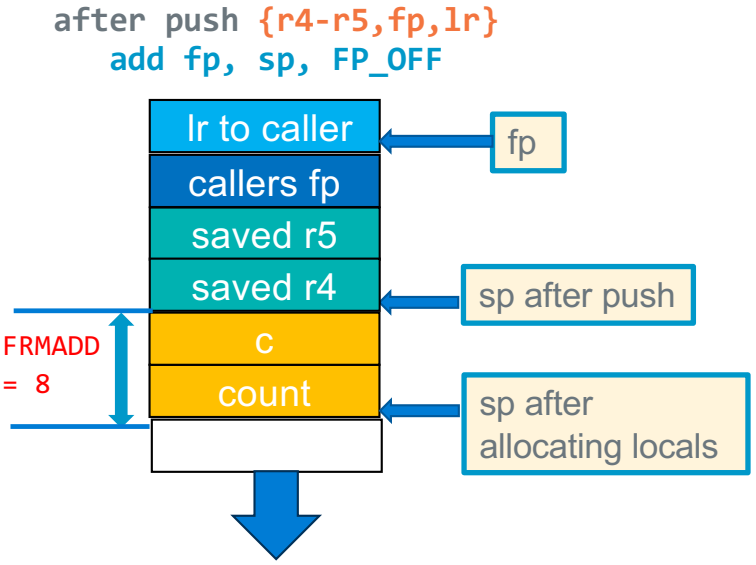
  sp % 8 == 0
- **Padding (as required):**
  1. Additional space between variables on the stack to meet memory alignment requirements
  2. Additional space so the frame size is evenly divisible by 8
- fp (frame pointer) is used as a **pointer (base register)** to access all stack variables – later slides



x

Local Variables on the stack

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




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

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

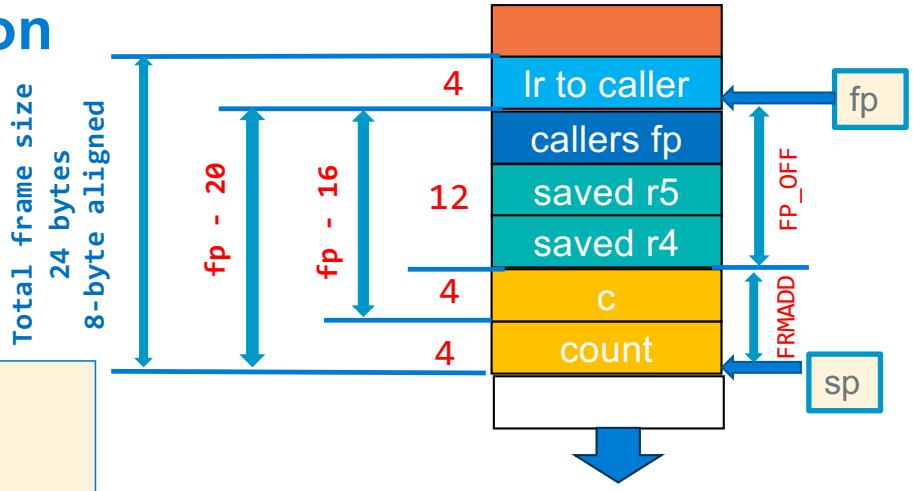
- In this example we are allocating two variables on the stack
- When writing assembly functions, in many situations you may choose allocate these to registers instead

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

x

Accessing Stack Variables: Introduction

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



low memory 4-byte words

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

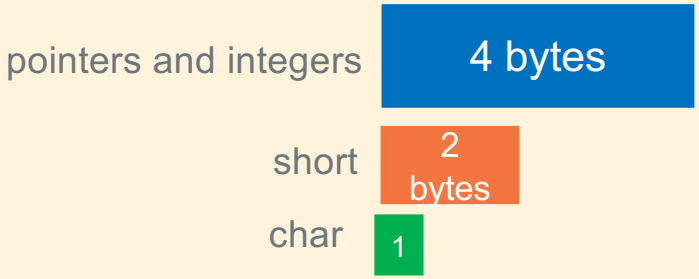
Variable	distance from fp	Read variable	Write Variable
`int c`	-16	`ldr r0, [fp, -16]`	`str r0, [fp, -16]`
`int count`	-20	`ldr r0, [fp, -20]`	`str r0, [fp, -20]`

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

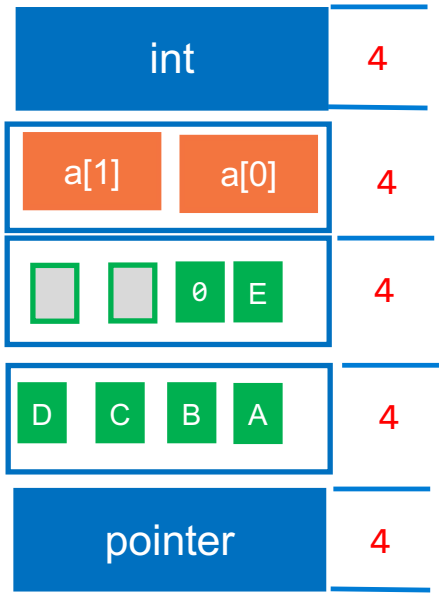

x

Stack Frame Design – Local Variables

- When writing an ARM equivalent for a C program, for CSE30 we will not re-arrange the order of the variables to optimize space (covered in the compiler course)
- Arrays start at a 4-byte boundary (even arrays with only 1 element)
  - Exception: double arrays [ ] start at an 8-byte boundary
  - struct arrays are aligned to the requirements of largest member
- Single chars (and shorts) can be grouped together in same 4-byte word (following the alignment for the short)
- Padding may be required (see next slide)



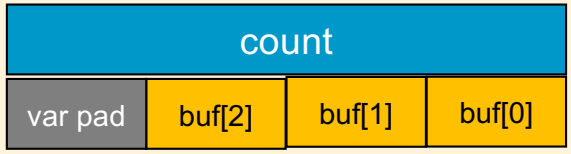
Rule: When the function is entered the stack is already 8-byte aligned



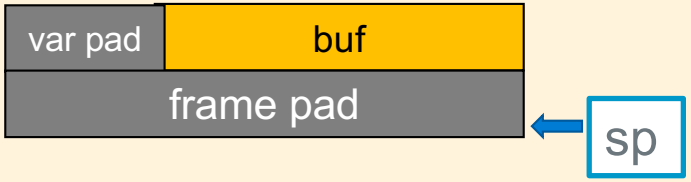
x

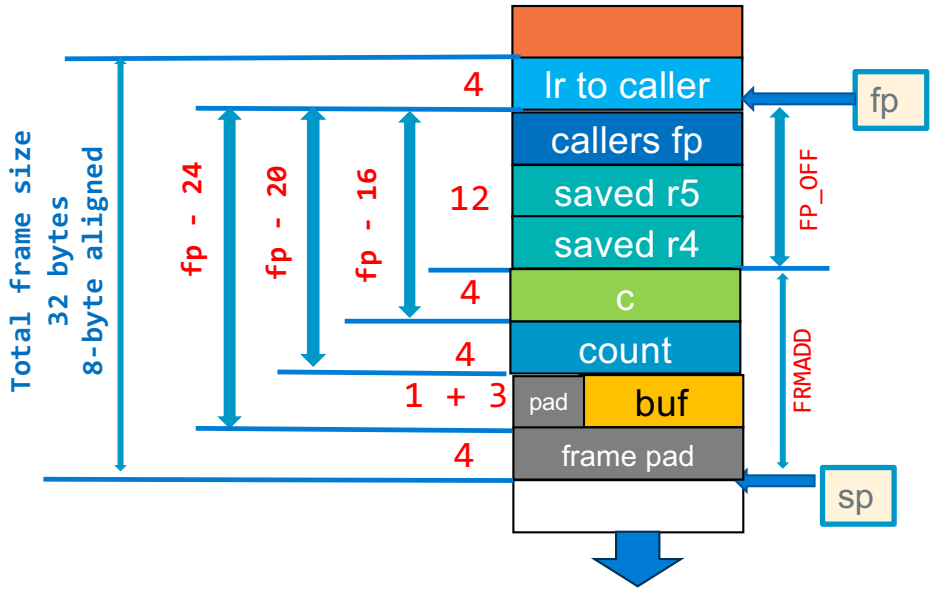
Stack Variables: Padding

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



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






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

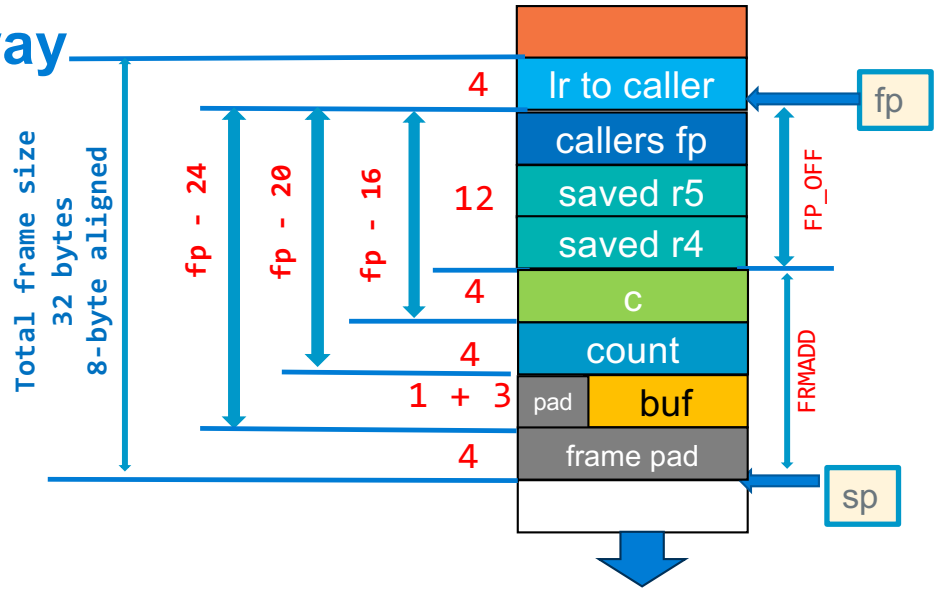
```
 .text
    .type   main, %function
    .global main
   .equ    FP_OFF,     12
   .equ    FRMADD,     16
main:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
    add     sp, sp, -FRMADD
// but we are not done yet!
```


x

Accessing Stack Variables, the hard way

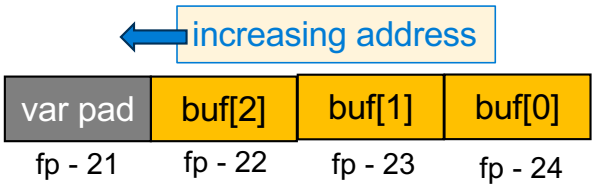
```
int main(void)
{
    int c;
    int count = 0;
    char buf[] = "hi";
    // rest of code
}
```

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



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

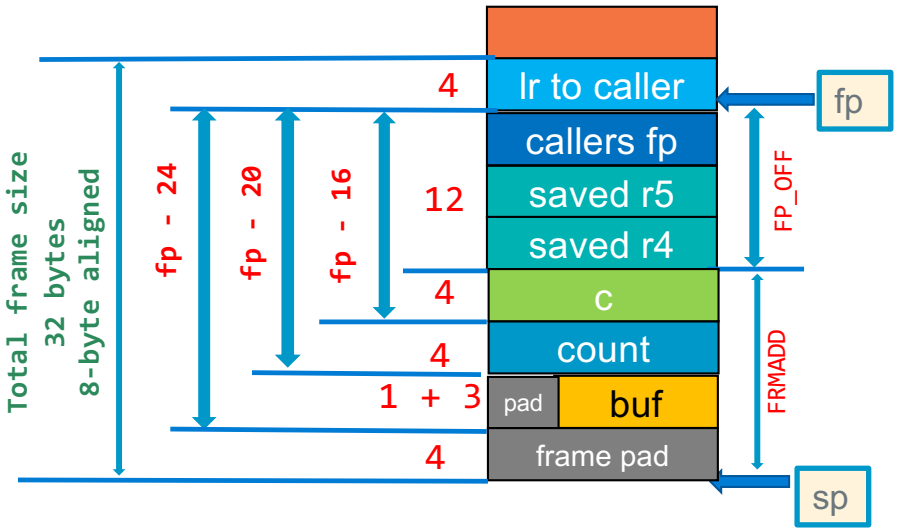
Variable	distance from fp	Read variable	Write Variable
int c	16	ldr r0, [fp, -16]	str r0, [fp, -16]
int count	20	ldr r0, [fp, -20]	str r0, [fp, -20]
char buf[0]	24	ldrb r0, [fp, -24]	strb r0, [fp, -24]
char buf[1]	23	ldrb r0, [fp, -23]	strb r0, [fp, -23]
char buf[2]	22	ldrb r0, [fp, -22]	strb r0, [fp,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



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

x

Best Practice: Assembler Generated FP Distance Table



FP Distance Table one For each function

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

pushed reg fp distance

```
.equ    FP_OFF,     12
```

Prior allocation distance

variable size in bytes

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

1. For each stack variable create a .equ symbol whose value is the distance in bytes from the FP after the prologue
2. After the last variable add a name PAD for the size of the frame padding (if any). if no padding, PAD will be set to the same value as the variable above it
3. The value of the symbol is an expression that calculates the distance from the FP based on the distance of the variable above it on the stack. The first variable will use SP_OFF as the starting distance

   .equ VAR, size_of var + variable_padding + previous_var_symbol *// previous_var_symbol distance of the var above*
4. Calculate the size of the local variable area that needs to be added to the sp in bytes

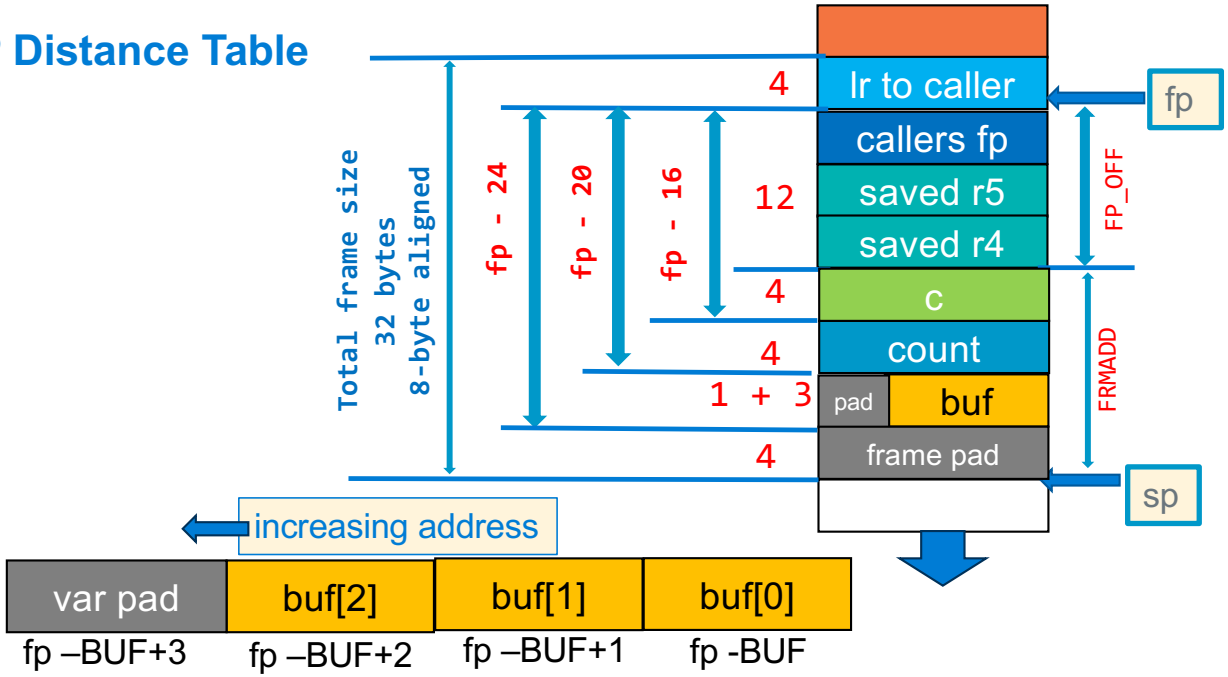
   FRMADD = distance PAD minus distance of the SP to the FP (FP_OFF) after the prologue push

x

Best Practice: Assembler Generated FP Distance Table

FP Distance Table For each function

```
.type   main, %function
.global main
.equ    FP_OFF,     12
.equ    C,          4 + FP_OFF
.equ    COUNT,      4 + C
.equ    BUF,        4 + COUNT
.equ    PAD,        4 + BUF
.equ    FRMADD,     PAD - FP_OFF
// FRMADD =  28 - 12 = 16
```



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

x

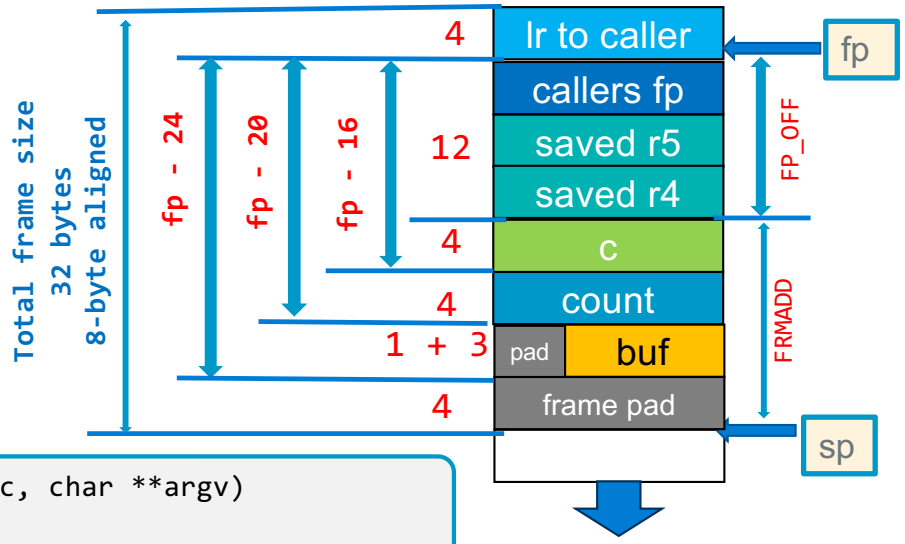
Initializing and Accessing Stack variables

```
    .section .rodata
.Lmess: .string "%d %d %s\n"
    .extern printf
```

```
main:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF
    add     sp, sp, -FRMADD
    // nothing to do for C
    mov     r2, 0
    str     r2, [fp, -COUNT]
    strb    r2, [fp, -BUF+2]
    mov     r2, 'h'
    strb    r2, [fp, -BUF]
    mov     r2, 'i'
    strb    r2, [fp, -BUF+1]

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

passes contents of stack var C and COUNT

passes address of a stack variable buf




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

pass stack address

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

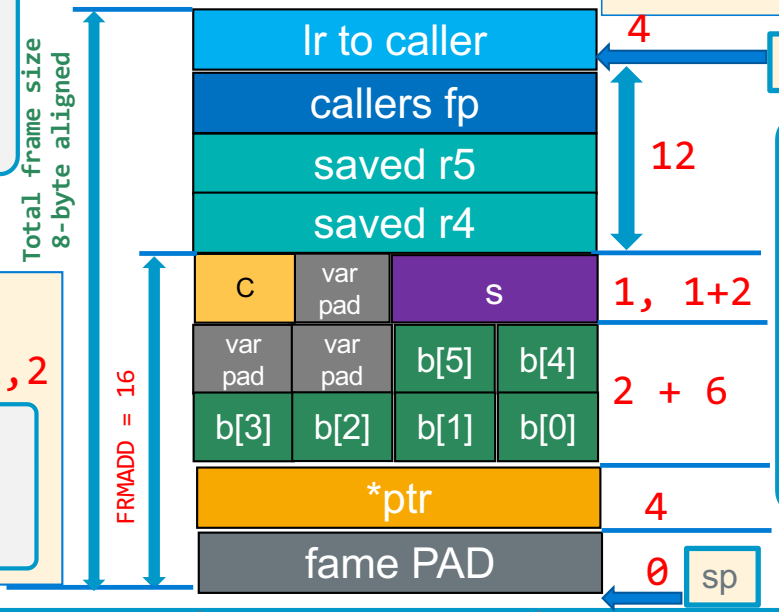
Variable	distance from fp	Address on Stack	Read variable	Write Variable
int c	C	add r0, fp, -C	ldr r0, [fp, -C]	str r0, [fp, -C]
int count	COUNT	add r0, fp, -COUNT	ldr r0, [fp, -COUNT]	str r0, [fp, -COUNT]
char buf[0]	BUF	add r0, fp, -BUF	ldrb r0, [fp, -BUF]	strb r0, [fp, -BUF]
char buf[1]	BUF-1	add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

x

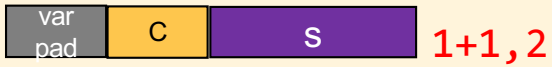
Stack Frame Design Practice

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

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



Alternative design




```
.equ    FP_OFF,     12
.equ    C,          2 + FP_OFF
.equ    S,          2 + C
…
```

```
.equ    FP_OFF,     12
.equ    C,          1 + FP_OFF
.equ    S,          3 + C
.equ    B,          8 + S
.equ    PTR,        4 + B
.equ    PAD,        0 + PTR
.equ    FRMADD,     PAD – FP_OFF
// FRMADD =  28 - 12 = 16
```

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

x

Working with Pointers on the stack

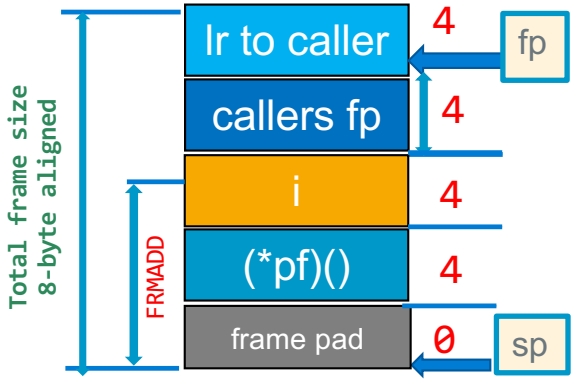
```
int sum(int j, int k)
{
    return j + k;
}
void testp(int j, int k, int (*func)(int, int), int *i)
{
    *i = func(j,k);
    return;
}
int main()
{
    int i;                    // NOTICE: i must be on stack as you pass the address!
    int (*pf)(int, int) = sum;  // pf could be in a register

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

Output Parameters (like i) you pass a pointer to them, **must be on the stack!**

x

Working with Pointers on the stack

```c
int main()
{
    int i; // NOTICE: i must be on stack as you pass the address!
    int (*pf)(int, int) = sum;  // pf could be in a register

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




```
    .section .rodata
.Lmess: .string "%d\n"
    .extern printf
    .text
    .global main
    .type   main, %function
    .equ    FP_OFF, 4
    .equ    I,      4 + FP_OFF
    .equ    PF,     4 + I
    .equ    PAD,    0 + PF
    .equ    FRMADD, PAD-FP_OFF
// FRMADD =  12 - 4 = 8
```

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

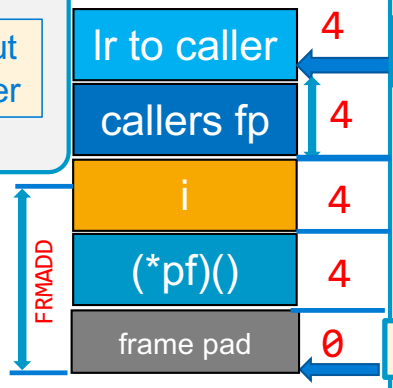
x

Working with Pointers on the stack

```
int main()
{
    int i;
    int (*pf)(int, int) = sum;

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

I is Output Parameter

```
    .section .rodata
.Lmess: .string "%d\n"
    .extern printf
    .text
    .global main
    .type   main, %function
    .equ    FP_OFF, 4
    .equ    I,      4 + FP_OFF
    .equ    PF,     4 + I
    .equ    PAD,    0 + PF
    .equ    FRMADD, PAD-FP_OFF
// FRMADD =  12 - 4 = 8
```



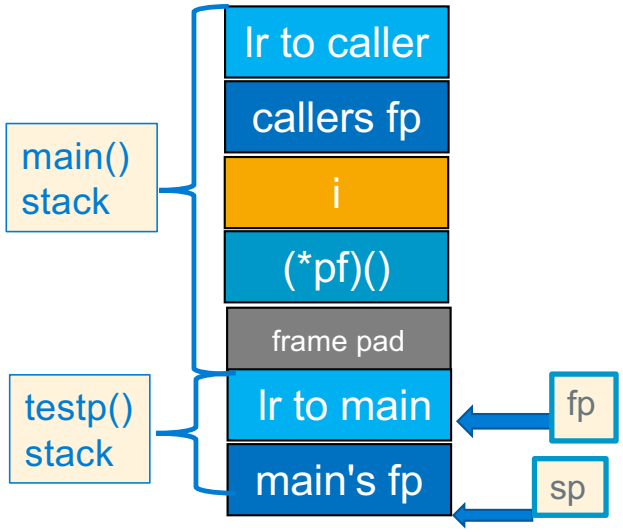

```
main:
    push    {fp, lr}
    add     fp, sp, FP_OFF
    add     sp, sp,-FRMADD

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

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

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

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

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

x

Working with Pointers on the stack

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



r0,r1,r2 already set

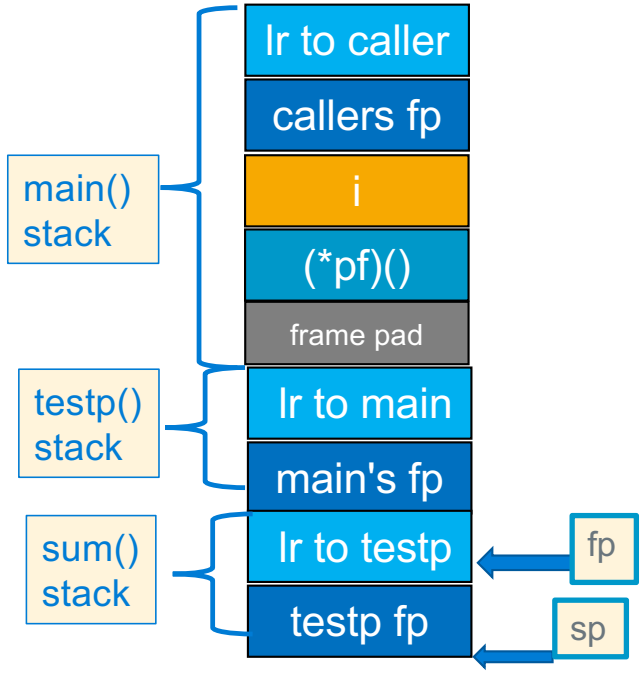
```
    .global testp
    .type   testp, %function
    .equ    FP_OFF, 12
testp:
    push    {r4, r5, fp, lr}
    add     fp, sp, FP_OFF

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

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


x

Working with Pointers on the stack

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

```
    .global sum
    .type   sum, %function
    .equ    FP_OFF, 4
sum:
    push    {fp, lr}
    add     fp, sp, FP_OFF

    add     r0, r0, r1

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

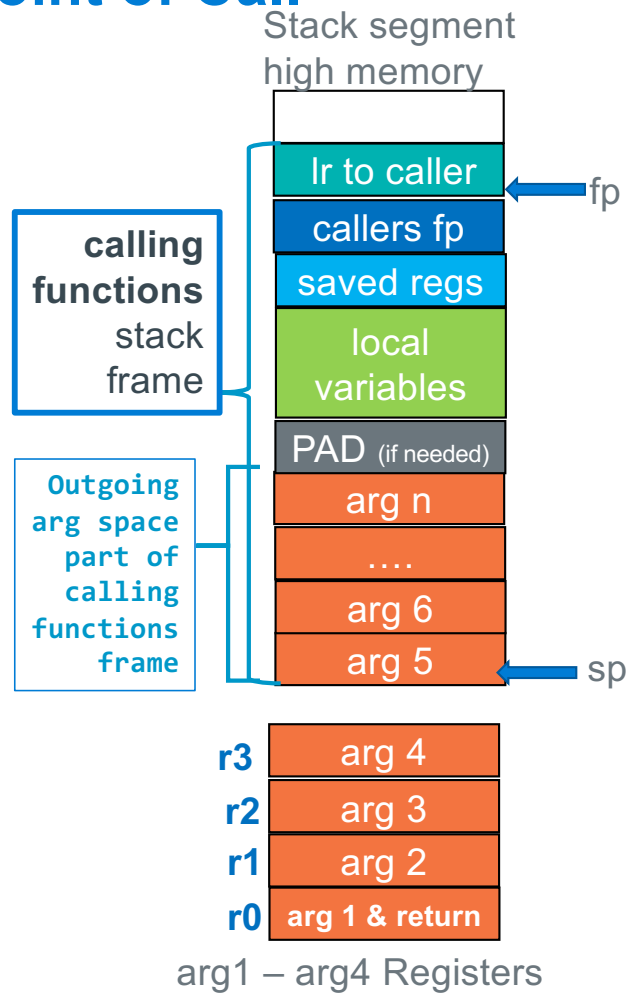


x

Passing More Than Four Arguments – At the point of Call

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

- **Approach: Increase stack frame size to include space for args# > 4**
  - Arg5 and above are in **caller's stack frame** at the **bottom of the stack**
- **Arg5** is always at the **bottom (at sp)**, arg6 and greater are above it
- **One arg value per slot!** – NO arrays across multiple slots
  - chars, shorts and ints are directly stored
  - Structs (not always), and arrays (always) are passed via a pointer
- Output parameters contain an address ***that points at*** the stack, BSS, data, or heap
- Prior to any function call (and obviously at the start of the called function):
  1. sp must point at arg5
  2. sp and therefore **arg5 must be at an 8-byte boundary**,
  3. **Add padding** to force arg5 alignment if needed is **placed above** the last **argument the called function is expecting**

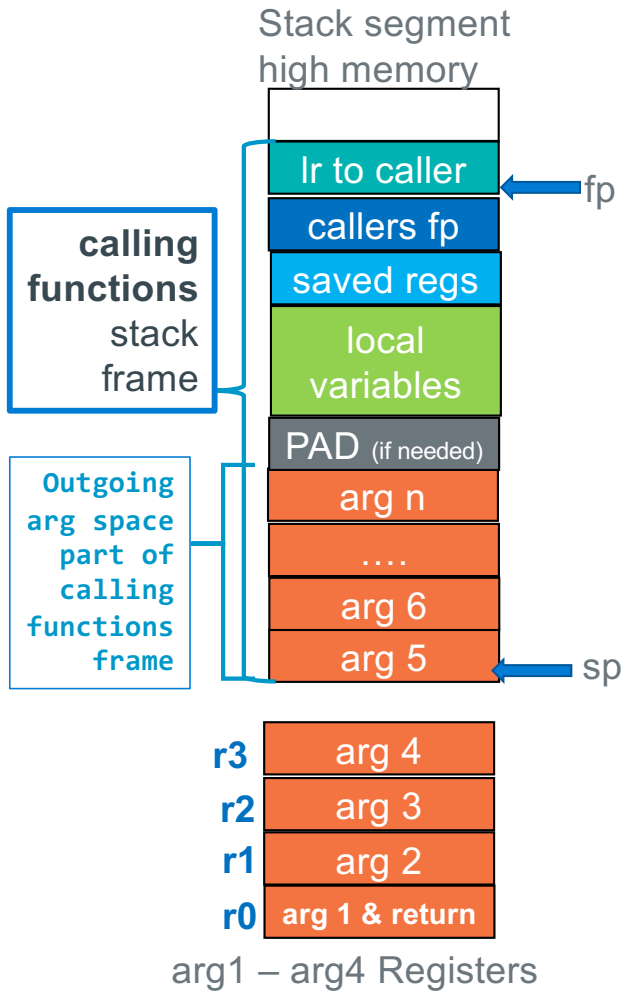


x

Passing More Than Four Arguments – At the point of Call

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

- **Called functions** have the **right to change stack args** just like they can change the register args!
  - Caller **must always assume all args** including ones on the stack are **changed by the caller**
- Calling function prior to making the call you must
  1. Evaluate first four args: place the resulting values in r0-r3
  2. Evaluate Arg 5 and greater and place the resulting values on the stack

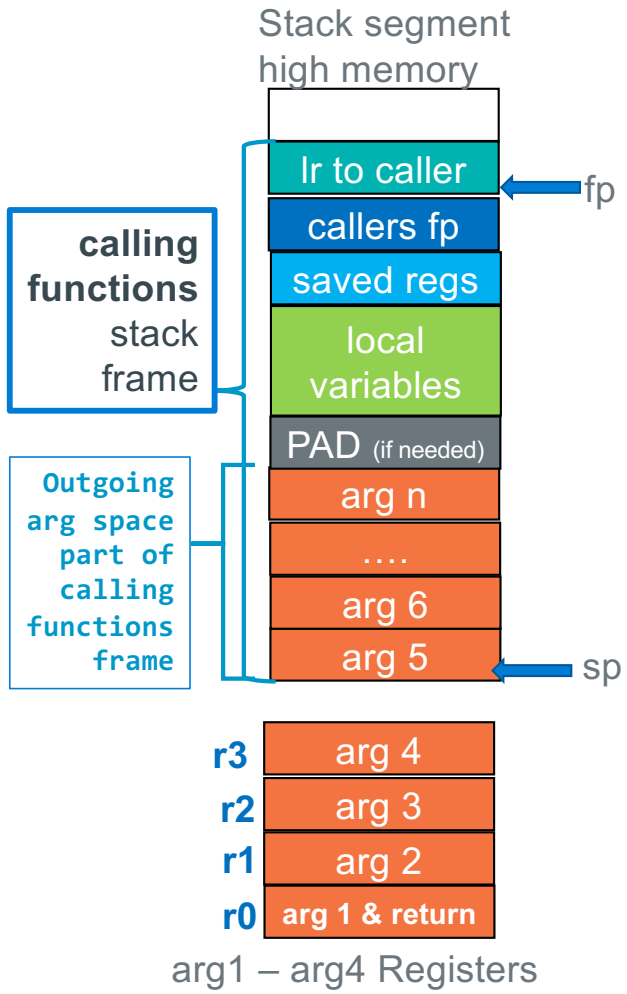


x

Passing More Than Four Arguments – At the point of Call

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

- **Approach**: Extend the stack frame to include enough space for stack arguments for the called function that has the greatest number of args
  1. Examine every function call in the body of a function
  2. Find the function call with greatest arg count, this determines space needed for outgoing args
  3. Add the greatest arg count space as needed to the frame layout
  4. Adjust PAD as required to keep the sp 8-byte aligned



x

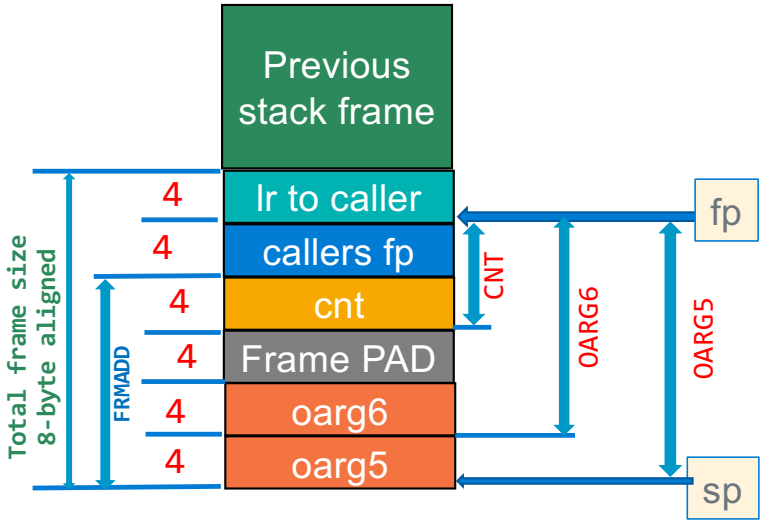
Calling Function Stack Frame: Pass ARG 5 and higher

Rules: At point of call

1. **OARG5 must be pointed at by sp**
2. **SP must be 8-byte aligned at function call**

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

```
.equ    FP_OFF,4
.equ    CNT,            4 + FP_OFF      // int cnt
.equ    PAD,            4 + CNT         // added as needed
.equ    OARG6,          4 + PAD         // 4 bytes
.equ    OARG5,          4 + OARG6       // 4 bytes
.equ    FRMADD          OARG5 - FP_OFF
// FRMADD =  20 - 4 = 16
```



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

x

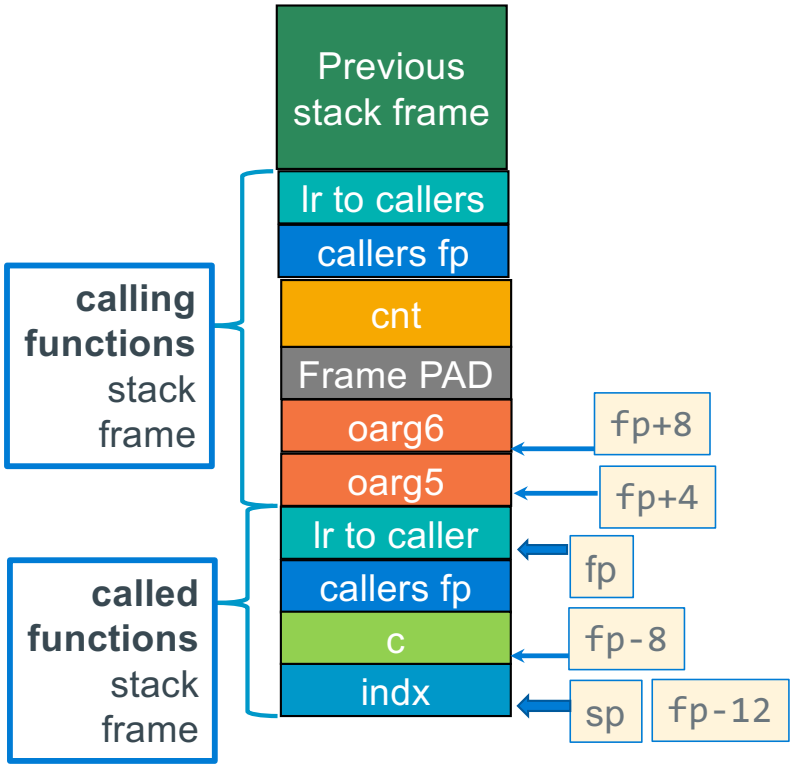
Called Function: Retrieving Args From the Stack

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

- At function start and before the push{} the sp is at an 8-byte boundary
- **Args > 4 in caller's stack frame and arg 5 always starts at fp+4**
  - Additional args are higher up the stack, with one “slot” every 4-bytes

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

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



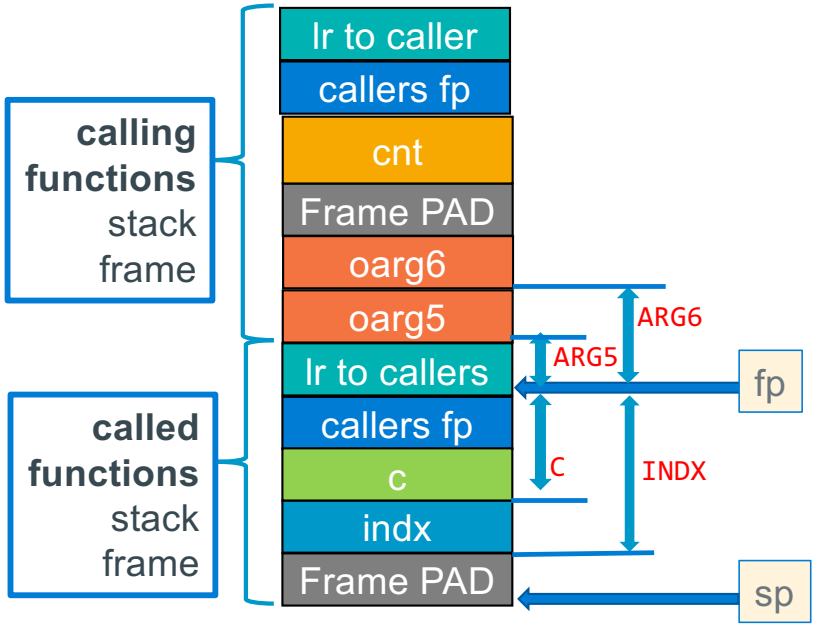
Rule:
Called functions always access stack args using a **positive offset to the fp**

x

Called Function: Retrieving Args From the Stack

```
.equ    FP_OFF,     4
.equ    C,          4 + FP_OFF
.equ    INDX,       4 + C
.equ    PAD,        0 + INDX
.equ    FRMADD,     PAD - FP_OFF
// below are distances into the caller's stack frame
.equ    ARG6,       8
.equ    ARG5,       4
```

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



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

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

Observe the positive offsets

x

Example: Passing Stack Args, Calling Function

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

void
testp(int j, int k, int l, int m, int (*func)(int, int), int *i)
{
    *i = func(j,k) + func(l, m);  // notice two func() calls

    return;
}

int main()
{
    int i;  // NOTICE: i must be on stack as you pass the address!
    int (*pf)(int, int) = sum; // pf could be in a register

    testp(1, 2, 3, 4, pf, &i);
    printf("%d\n", i);

    return EXIT_SUCCESS;
}
```

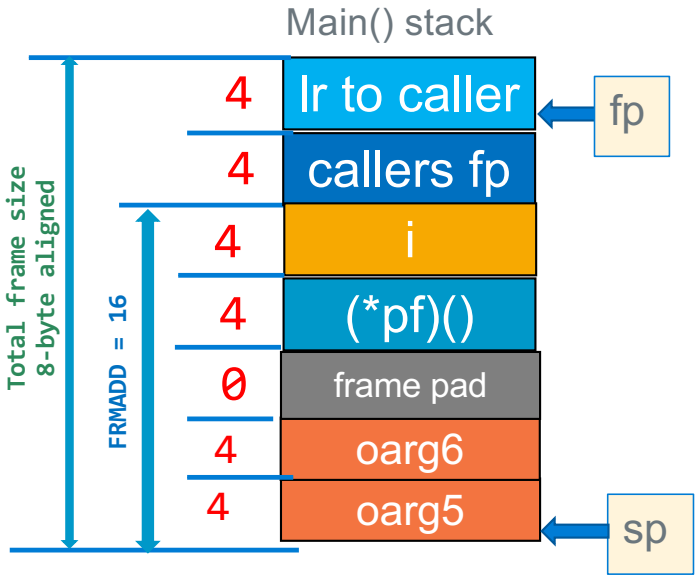
arg1 arg2 arg3 arg4 arg5 arg6

x

Example: Passing Stack Args, Calling Function

```
int main()
{
    int i;  // NOTICE: i must be on stack as you pass the address!
    int (*pf)(int, int) = sum; // pf could be in a register

    testp(1, 2, 3, 4, pf, &i);
    printf("%d\n", i);
    return EXIT_SUCCESS;
}
```

```
    .equ    FP_OFF, 4
    .equ    I,      4 + FP_OFF
    .equ    PF,     4 + I
    .equ    PAD,    0 + PF
    .equ    OARG6,  4 + PAD
    .equ    OARG5   4 + OARG6
    .equ    FRMADD, OARG5 – FP_OFF
// FRMADD =  20 - 4 = 16
```

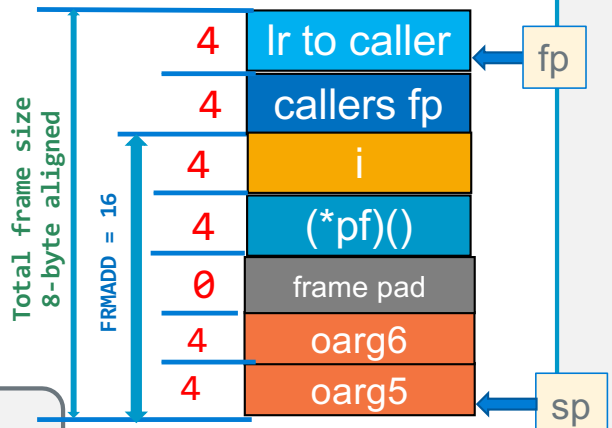


Variable or Argument	distance from fp	Address on Stack	Read variable	Write Variable
int i	I	add r0, fp, -I	ldr r0, [fp, -I]	str r0, [fp, -I]
int (*pf)()	PF	add r0, fp, -PF	ldr r0, [fp, -PF]	str r0, [fp, -PF]
int oarg6	OARG6	add r0, fp, -OARG6	ldr r0, [fp, -OARG6]	str r0, [fp, -OARG6]
int oarg5	OARG5	add r0, fp, -OARG5	ldr r0, [fp, -OARG5]	str r0, [fp, -OARG5]

x

Example: Passing Stack Args, Calling Function

```
int main()
{
    int i;
    int (*pf)(int, int) = sum;

    testp(1, 2, 3, 4, pf, &i);
    printf("%d\n", i);
    return EXIT_SUCCESS;
}
```




```
main:
    push    {fp, lr}
    add     fp, sp, FP_OFF
    add     sp, sp,-FRMADD

    ldr     r0, =sum        // get func address
    str     r0, [fp, -PF]   // store sum in var pf

    add     r0, fp, -I      // get address of I
    str     r0, [fp,-OARG6] // arg 6: store address of I

    ldr     r0, [fp, -PF]   // get PF from stack
    str     r0, [fp,-OARG5] // arg 5: store sum() address

    mov     r0, 1           // arg 1: 1
    mov     r1, 2           // arg 2: 2
    mov     r2, 3           // arg 3: 3
    mov     r3, 4           // arg 4: 4

    bl      testp

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

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

```
    .section .rodata
.Lmess: .string "%d\n"
// other stuff not shown
    .equ    FP_OFF, 4
    .equ    I,      4 + FP_OFF
    .equ    PF,     4 + I
    .equ    PAD,    0 + PF
    .equ    OARG6,  4 + PAD
    .equ    OARG5   4 + OARG6
    .equ    FRMADD, OARG5 - FP_OFF
// FRMADD =  20 - 4 = 16
```

Variable or Argument	distance from fp	Address on Stack	Read variable	Write Variable
int i	I	add r0, fp, -I	ldr r0, [fp, -I]	str r0, [fp, -I]
int (*pf)()	PF	add r0, fp, -PF	ldr r0, [fp, -PF]	str r0, [fp, -PF]
int oarg6	OARG6	add r0, fp, -OARG6	ldr r0, [fp, -OARG6]	str r0, [fp, -OARG6]
int oarg5	OARG5	add r0, fp, -OARG5	ldr r0, [fp, -OARG5]	str r0, [fp, -OARG5]

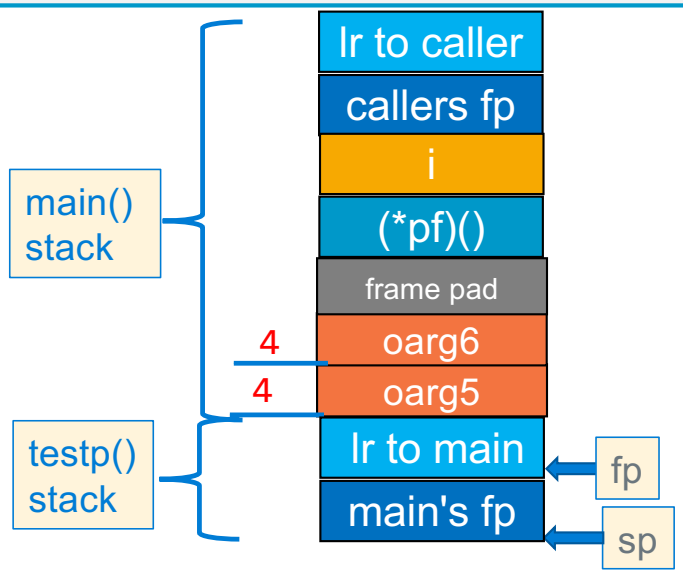
x

Example: Passing Stack Args, Called Function

arg1 arg2 arg3 arg4 arg5 arg6

```
void
testp(int j, int k, int l, int m, int (*func)(int, int), int *i)
{
    *i = func(j, k) + func(l, m);

    return;
}
```

short circuit: make this call first




```
    .equ    FP_OFF, 20
    .equ    ARG6,   8
    .equ    ARG5,   4
testp:
    push    {r4-r7, fp, lr}
    add     fp, sp, FP_OFF

    mov     r4, r2          // save l
    mov     r5, r3          // save m
    ldr     r6, [fp, ARG5]  // load func
    ldr     r7, [fp, ARG6]  // load i
    blx     r6              // r0 = func(j, k)

    mov     r1, r5          // arg 2 saved m
    mov     r5, r0          // save func return value
    mov     r0, r4          // arg 1 saved l
    blx     r6              // r0 = func(l, m)
    add     r0, r0, r5      // func(l,m) + func(j,k)
    str     r0, [r7]        // store sum to *i

    sub     sp, fp, FP_OFF
    pop     {r4-r7, fp, lr}
    bx      lr
```

Argument	distance	Address on Stack	Read variable	Write Variable
int *i	ARG6	add r0, fp, ARG6	ldr r0, [fp, ARG6]	str r0, [fp, ARG6]
int (*pf)()	ARG5	add r0, fp, ARG5	ldr r0, [fp, ARG5]	str r0, [fp, ARG5]

x