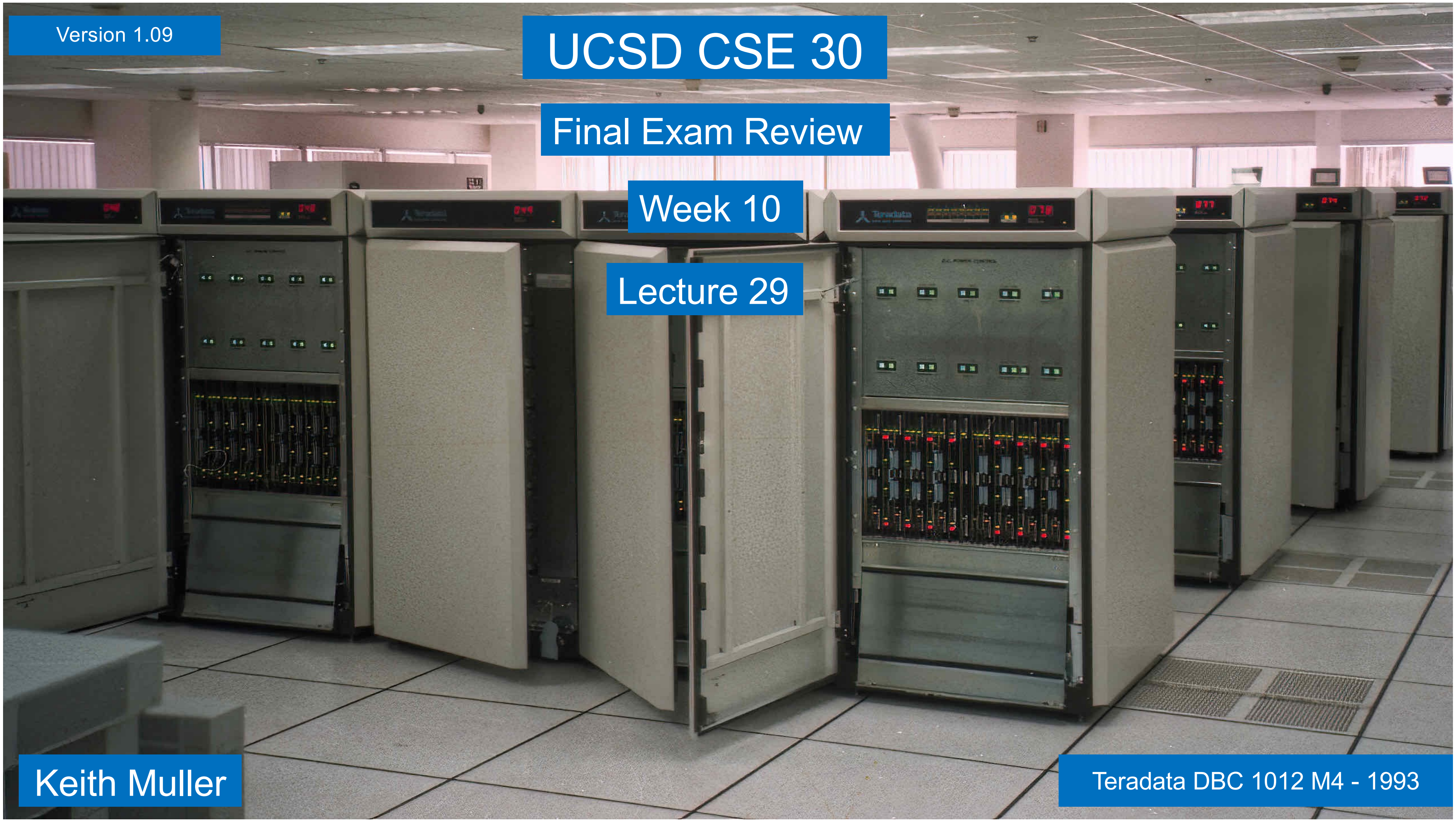
Version 1.09

UCSD CSE 30

Final Exam Review

Week 10

Lecture 29



Keith Muller

Teradata DBC 1012 M4 - 1993

Exam Logistics

- **Make sure you study the most recent versions of the slides!**
- **The final exam will be as scheduled Thursday June 9 11:30 AM – 2:29 PM**
- **The final will be in two rooms**
  - **The Jeannie**
  - **Mosaic 0113**
- We will be assigning students across the two rooms to keep students spread out (we should be under 50% occupancy for each room).
- **The room/seat will be e-mailed to you on Wed June 8.**
  - If you do not receive your assignment (or you forget) , no worries, we will seat you at the exam.
  - Just find me or one of the proctors for help. I will be outside of Jeannie prior to the exam.
- **The exam is no electronic devices** (please leave them at home or turned OFF).
  - Exam questions are being designed to focus on concepts and to minimize the potential for math errors).

Exam Logistics

- Bring pencil(s) and a good eraser
- The exam is mostly multiple choice (fill in a bubble) with a few fill in the blanks
- The exam is open notes. To keep things fair for all students, notes are defined to be:
- **Paper size (one of):**
  - US Standard 8 1/2 inch x 11 inch paper
  - A4 (210 x 297 mm)

  US standard 9 inch x 12 inch paper
- **Page limits**
  - Hand-written (by your hand not printed): 20 sheets of paper (both sides - total of 40 sides)
  - Printed: 10 sheets of paper (both sides - total of 20 sides) - including lecture slides
  - If you have a combination of printed and hand-written sheets:
    - each printed sheet is equal to two handwritten sheets.
- We will provide the arm instruction list (green card), with the exam and a C precedence chart

Help During Final Week

- Edstem/email – I will answer questions as time permits (it may take a couple of hours during the day until I get the final finished and printed)
  - edstem is preferred
- Tuesday Zoom office hours 4-5:30PM
- Check Canvas calendar for other office hours

Exam Logistics

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C Library Function API : Simple Character I/O

Operation	Usage Examples
Write a char	`int status; int c;` `status = putchar(c);  /* Writes to screen stdout */`
Read a char	`int c;` `c = getchar();  /* Reads from keyboard stdin */`

```
#include <stdio.h>  // import the API declarations
```

`int putchar(int c);`

- writes c (converted to a char) **to** `stdout`
- returns either: c on success *OR* EOF (a macro often defined as -1) on failure
- see man 3 putchar

`int getchar(void);`

- returns the next input character (if present) **converted to an int** read **from** `stdin`
- see man 3 getchar

- Both functions return an int because they must be able to return both valid chars **and** indicate the **EOF condition – see later slides** (-1 is not a valid char)

x

Memory Review: Organized in Units of Bytes

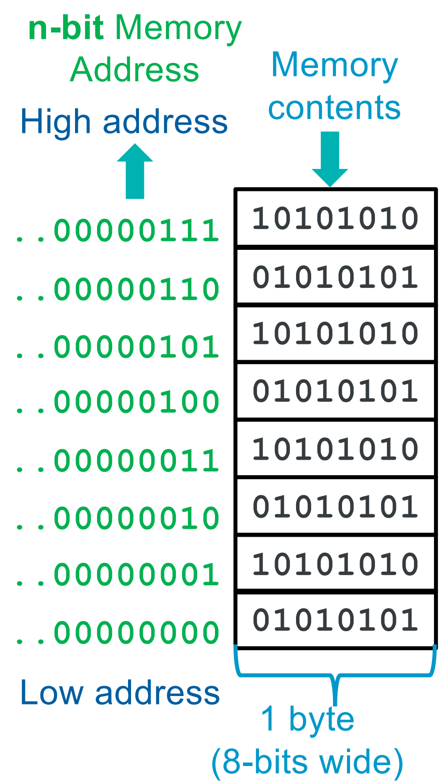
- One bit (digit) of storage (in memory) has two possible **states**: 0 or 1
- Memory is organized into a **fixed unit** of 8 bits, called a **byte**

MSB
Most Significant Bit

Bit position in Byte							
7	6	5	4	3	2	1	0
0	0	1	0	0	0	0	0
Content of each bit							

LSB
(Least Significant Bit)

- Conceptually, memory is a single, **large array** of **bytes**, **where each byte** has a unique *address (byte addressable memory)*
- An address is an **unsigned** (positive #) *fixed-length* n-bit binary value
  - Range (domain) of possible addresses = *address space*
- Each byte in memory can be **individually accessed** and operated on given its **unique address**



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

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

sizeof() operator returns:

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])**

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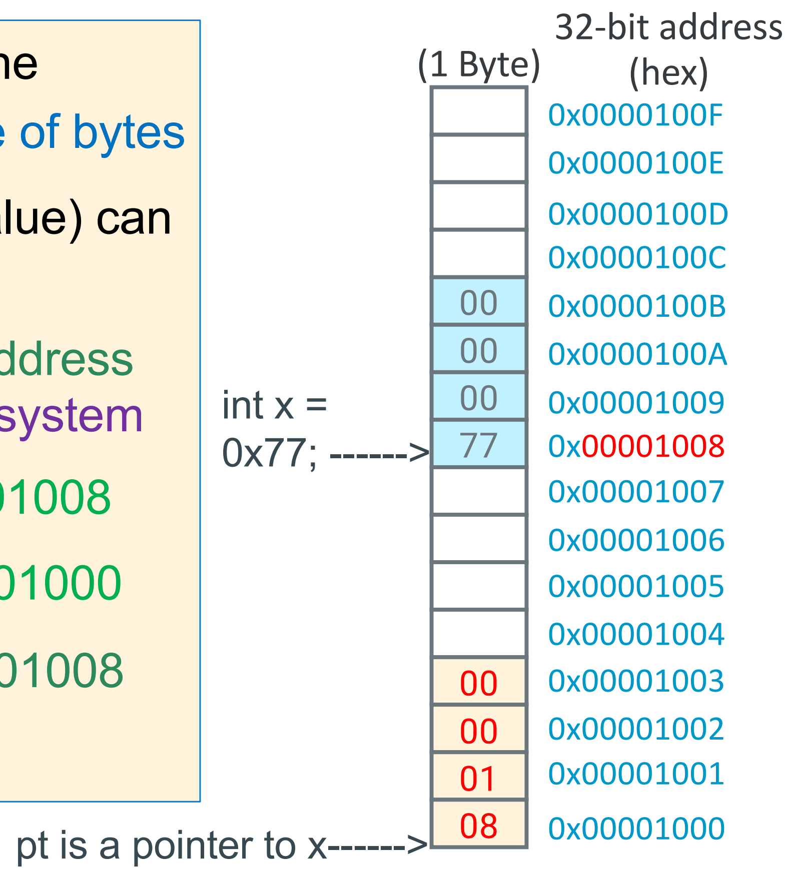
Address and Pointers

- 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 0x00001008
- The variable pt is at memory location 0x00001000
- The contents of pt is the address of x 0x00001008



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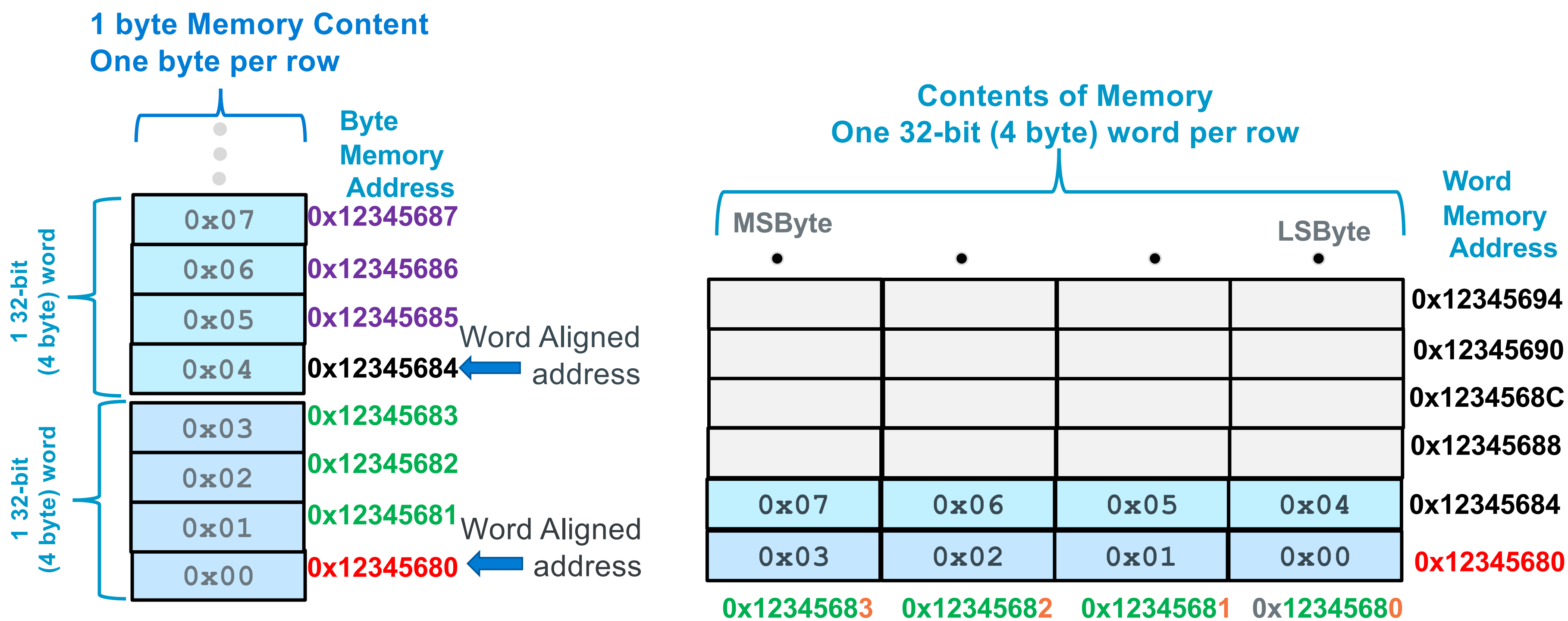
Byte Addressable Memory Shown as 32-bit words



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

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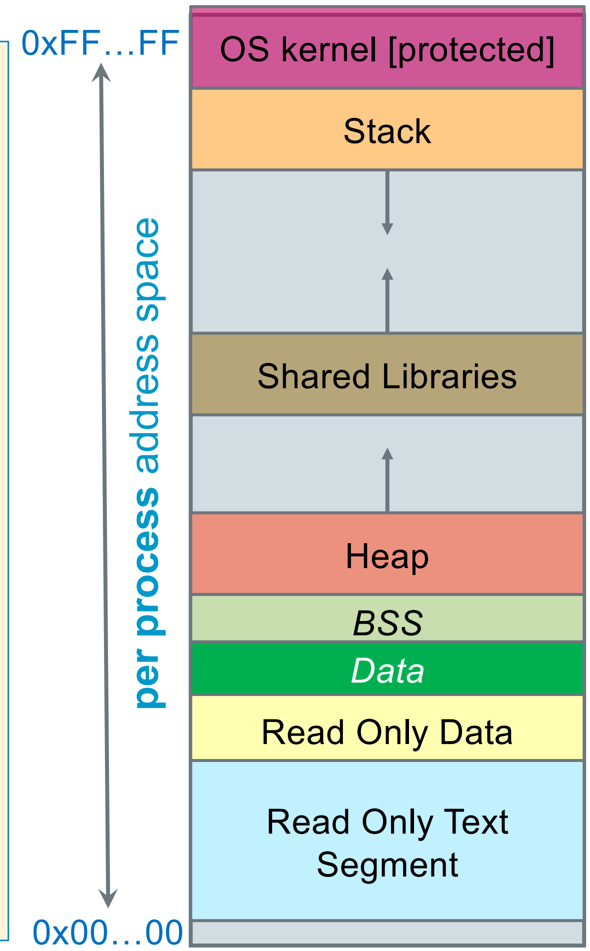
Process Memory Under Linux

- 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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Where Variables Reside in Memory

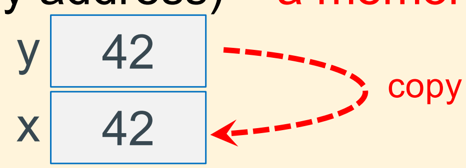
```
int global0 = 1;            // data segment
int global1[100];           // bss segment
static int global2;         // bss segment
int funcA(int b)            // text segment for code in funcA()
{                           // b may be in stack or a CPU register - later
    int x = 3;              // stack segment
    int s;                  // stack segment
    static int z;           // bss segment
    static int w = 1;      // data segment
    for (int j = 0; j < MAX; j++) {     // j in stack segment
        int w;              // stack segment
        printf("Hi\n");     // "Hi\n" literal is in read-only data
    }
/* …. rest of code …  */
```


x

Memory Addresses & Memory Content

- A **variable name** *(by itself)* in a C statement evaluates to either:
  - **Lvalue:** when on the left side (Lside or Left value) of the = sign is the address where it is stored in memory – a constant
  - **Rvalue:** on the right side (Rside or Right value) of an = sign is the contents or value stored in the variable (at its memory address) – a memory read

```
x = y;     // Lvalue = Rvalue
```



- **x** on left side (**Lside**) of the assignment operator = evaluates to:
  - The address of the memory assigned to the x – this is x's **Lvalue**
- **y** on right side (**Rside**) of the assignment operator = evaluates to:
  - READ the contents of the memory assigned to the variable y (type determines length) - this is y's **Rvalue**
- Read memory at y (**Rvalue**); write it to memory at x's address (**Lvalue**)

x

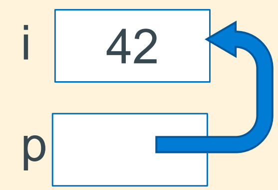
Introduction: Pointer Variables - 1

- In C, there is a *variable* ***type*** for **storing an address**: a ***pointer***
  - **Contents** of a pointer is an **unsigned** (0+ positive numbers) **memory address**
- When the **Rside** **of a variable** contains a **memory address**, (it **evaluates** to an **address**) the variable is called a **pointer variable**

```
type *name;  // defines a pointer; name contains address of a variable of type
```

- A pointer is defined by placing a ***star*** (or ***asterisk***) **(*)** ***before*** the identifier (name)
- You also must specify the type of variable to which the pointer points

```
int i = 42;
int *p = &i;  /* p "points at" i (assign address of i to p) */
```



- Recommended: be careful when defining multiple pointers on the same line:

`int *p1, p2;` is not the same as `int *p1, *p2;`

Use instead:

```
int *p1;
int *p2;
```


x

Introduction: Pointer Variables - 2

- **Pointers are <u>typed</u>**! Why?
  - Tells the compiler the size (sizeof()) of the data **you are pointing at** (number of bytes to access)
- A pointer definition:

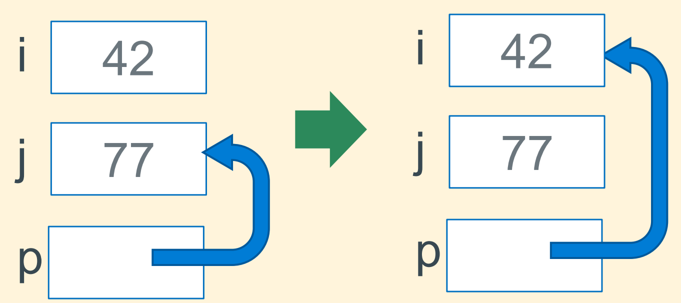
```c
int *p = &i;  /* p points at i (assign address i to p) */
```

- Is the same as writing the following definition and assignment statements

```c
int *p;      /* p is defined (not initialized) */
p = &i;      /* p points at i (assign address i to p */
```

- The * is part of the definition of p and is not part of the variable name
  - The name of the variable is simply p, not *p
- As with any variable, its value can be changed

```c
p = &j;     /* p now points at j */
p = &i;     /* p now points at i */
```



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Introduction: Address Operator: &

- Unary ***address operator*** (&) produces the **address** of where an identifier is in memory
- Requirement: **identifier must have a Lvalue**
  - Cannot be used with constants (e.g., 12) or expressions (e.g., x + y)
  - `&12` does not have an *Lvalue*, so &12 is **not** a legal expression
- How can I get an address on the **Rside**?
  - `&var` (any variable identifier or name)
  - **function_name** (name of a function, not func()); **&funct_name** is equivalent
  - **array_name** (name of the array like array_name[5]); &array_name is equivalent
- Example: this might print:

  *the **value** of g is: 42*

  *the **address** of g is: 0x71a0a0*

  (the address will vary)

```
int g = 42;
int main(void)
{
    printf("the value of g is: %d\n", g);
    printf("the address of g is: %p\n", &g);
}
```

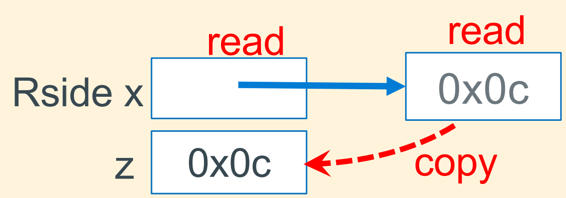
- *Tip*: The `printf()` format specifier to display an address/pointer (in hex) is "%p"

x

Introduction: Indirection Operator - 2

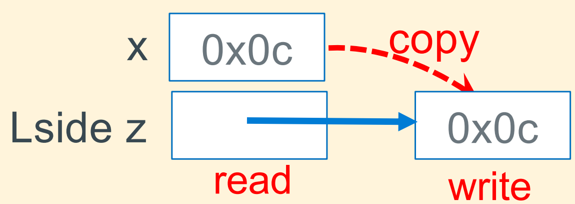
- * on the Rside: read the contents of the variable to get an address and then **read** and return the contents at that address (requires two reads of memory on the Rside)

```
z = *x; // copy the contents of memory pointed at by x to z
```



- * on the Lside: read the contents of the variable to get an address and then **write** the evaluation of the Rside expression to that address (requires one read of memory and one write of memory on the Lside)

```
*z = x; // copy the value of x to the memory pointed at by z
```



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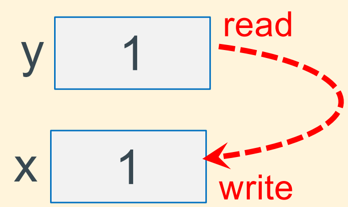
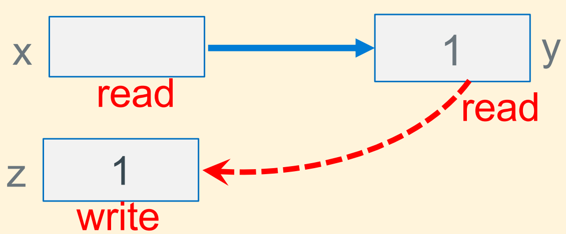
Introduction: Indirection Operator - 3

- Each * when used as a dereference operator in a statement (Lside and Rside) generates an <u>additional</u> read

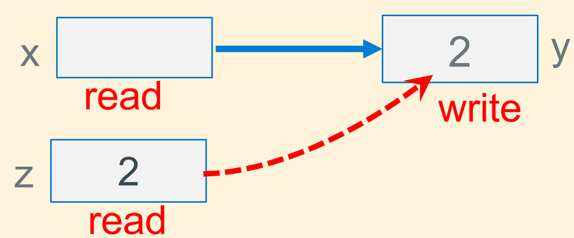
```
int x = 2, y = 1;
x = y;
```



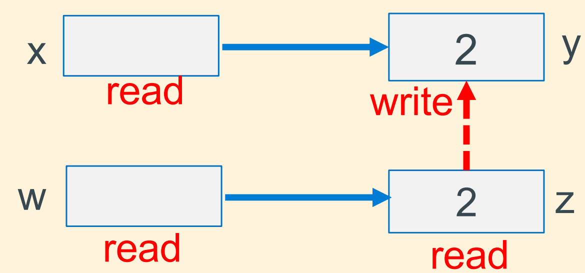

```
int z = 2, y = 1;
int *x = &y;
z = *x;
```




```
int z = 2, y = 1;
int *x = &y;
*x = z;
```




```
int z = 2, y = 1;
int *x = &y;
int *w = &z;
*x = *w;
```



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Recap: Lside, Rside, Lvalue, Rvalue

```
int x = 2, y = 1;
x = y;
```

Constant Var Name	Lvalue address	Rvalue Contents	
y	0x108	0x1	read
x	0x104	0x1	write

```
int z = 2, y = 1;
int *x = &y;
int *w = &z;
*x = *w;
```

```
*x on Lside is   0x10c
w  on Rside is   0x100
*w on Rside is   2
```

Constant Var Name	Lvalue address	Rvalue Contents	
x	0x10c	0x108	read
y	0x108	0x2	write
z	0x104	0x2	read
w	0x100	0x104	read

x

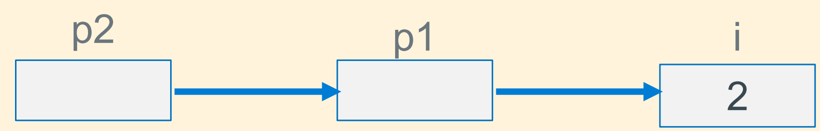
Pointer to Pointers (Double, Triple and … Indirection

- A pointer **cannot** point at itself, why?

```
int *p = &p; /* is not legal – type mismatch */
```

  - p is defined as (int *), a pointer to an int, **but**
  - the type of &p is (int **), a pointer to a pointer to an int
- Define a pointer to a pointer (p2 below)

```
int i = 2;
int *p1;
int **p2;
p1 = &i;
p2 = &p1;
printf("%d\n", **p2 * **p2);
```



number of * in the definition tells you how many reads it takes to get to the base type
reads = number of * + 1
e.g., int **p2 requires 3 reads to get to the int

- C allows any number of pointer indirections
  - more than three levels is very uncommon in real applications as it reduces readability and generates at lot of memory reads

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Function Output Parameters: Passing Pointers

- 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**
- Enables additional *values to be returned (besides the return)* from a function call

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

- With a pointer to x, inc() can change x in main()
  - This is called a *side-effect*
- inc() can also change the *value* of p, the copy, just like any other parameter

- 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

x

Arrays in C - 1

Definition: `type name[count]`

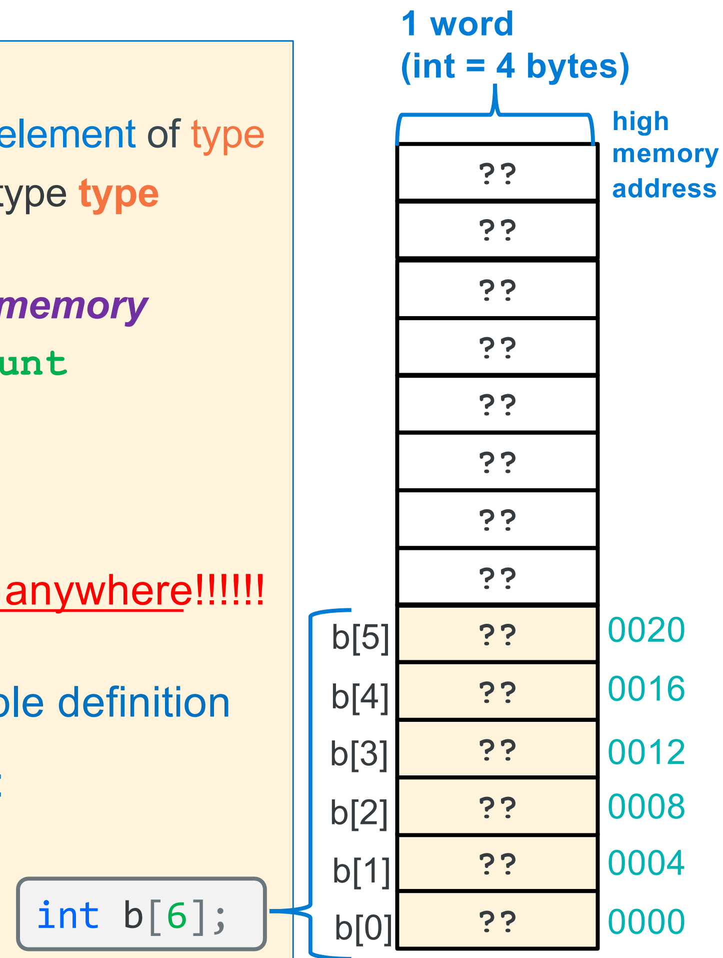
- ***"Compound"*** data type where each value in an array is an element of type
- Above allocates **name** with a *fixed* count array elements of type **type**
- **Arrays are indexed starting with 0**
- Allocates (`count * sizeof(type)`) bytes of ***contiguous memory***
- Common usage is to specify a compile-time constant for **`count`**

```
#define BSZ   6
int b[BSZ];
```

BSZ is a macro replaced by the C preprocessor before compilation starts

- **Size (bytes or element count) of an array** is not stored anywhere!!!!!!
  - **An array does not know its own size!**
  - **`sizeof(array)`** **only works** in **scope** of array variable definition
- automatic (only) variable-length arrays (sized at runtime):

```
/* VLA only in block scope - automatics */
int func (int n) {
    int scores[n];  // these are not widely used!
```



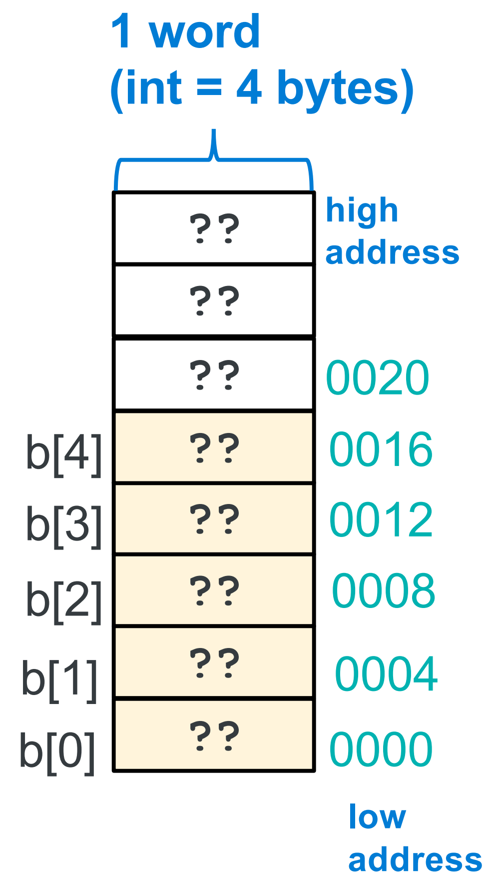
Arrays In C - 2

- `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[5];
int b[5];
```

- Array name (by itself with no [ ]) on the Rside evaluates to the address of the first element of the array
- Array **names are constants (like all variable names)** and cannot be assigned (cannot appear on the Lside by themself)

```
a = b;        // invalid does not copy the array
              // copy arrays element by element
```



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Arrays in C - 3

- Initialization: `type name[count] = {val0,…,valN};`
  - `{ }` *(optional)* initialization list can *only* be used at **time of definition**
  - If no `count` supplied, `count` is determined by compiler using the number of array initializers
  - `int block[20] = {}; //only works with constant size arrays`

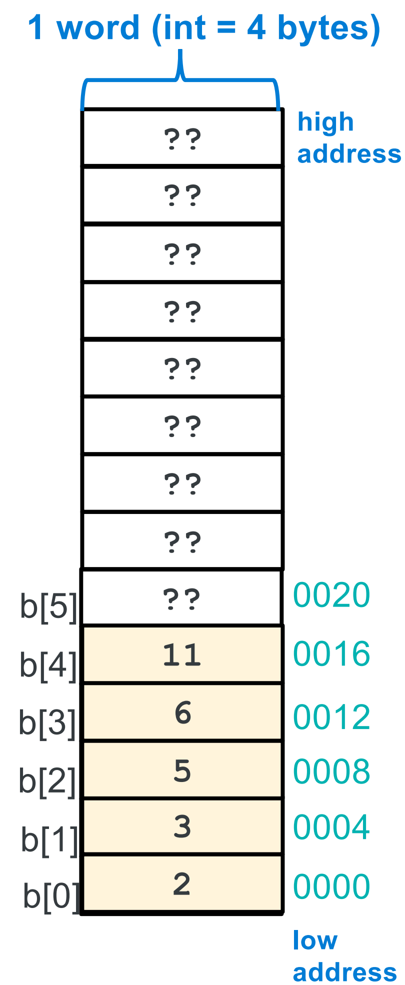
    no initialization values given; then elements are initialized to 0

    - defines an **array of 20 integers** each element filled with zeros
    - Performance comment: do not zero automatic arrays unless really needed!
  - When a **count** is given:
    - **extra** *initialization values* are **ignored**
    - **missing** *initialization values* are set to **zero**

```
int block[5] = {2, 3, 5, 6, 11, 13};
```

not needed and if used **may** truncate initialization list

6 initialization values given, **only 5 are used**



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So, How Big is My Array?

```
// defining array with a fixed size use a #define to eliminate embedded "magic" numbers
#define SZ 6
int szblock[SZ];                    // manual: you specify the array has SZ elements
int indx; // use when SZ is defined

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

- Programmatically (and safely) determining the element count in a compiler calculated array

  `sizeof(array) / sizeof(of just one element in the array)`

  Remember: `sizeof(array)` **<u>only works</u>** in **scope** of the array variable definition

```
#include <stddef.h>
int block[] = {2, 3, 5, 6, 11, 13};      // automatic: compiler calculates array size
int cnt = (int)(sizeof(block) / sizeof(block[0]));       // in this case cnt = 6

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


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Pointer and Arrays - 1

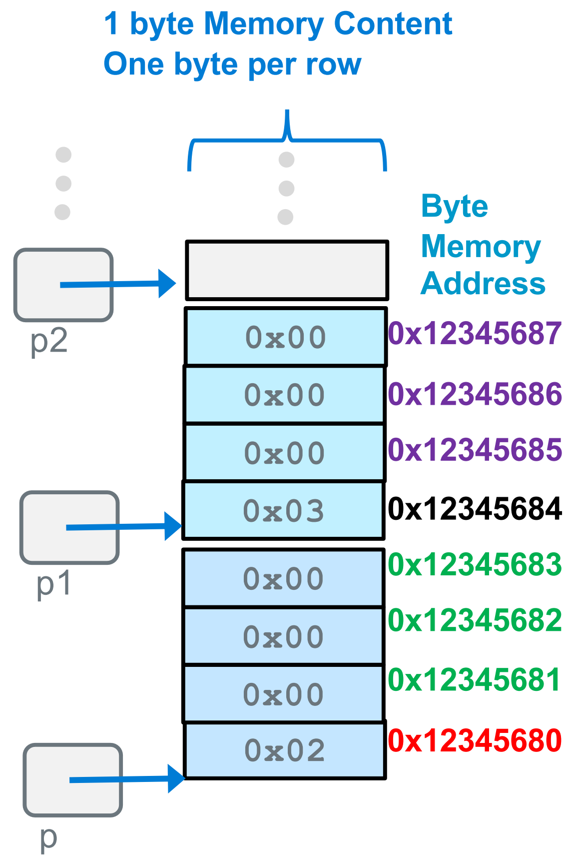
- A few slides back we stated: Array name (by itself) on the Rside evaluates to the address of the first element of the array

```
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 point at the first array element

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

*p = *p + 10;
*p1 = *p1 + 10;        // {12, 13, 5, 6, 11}
```



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Pointer and Arrays - 2

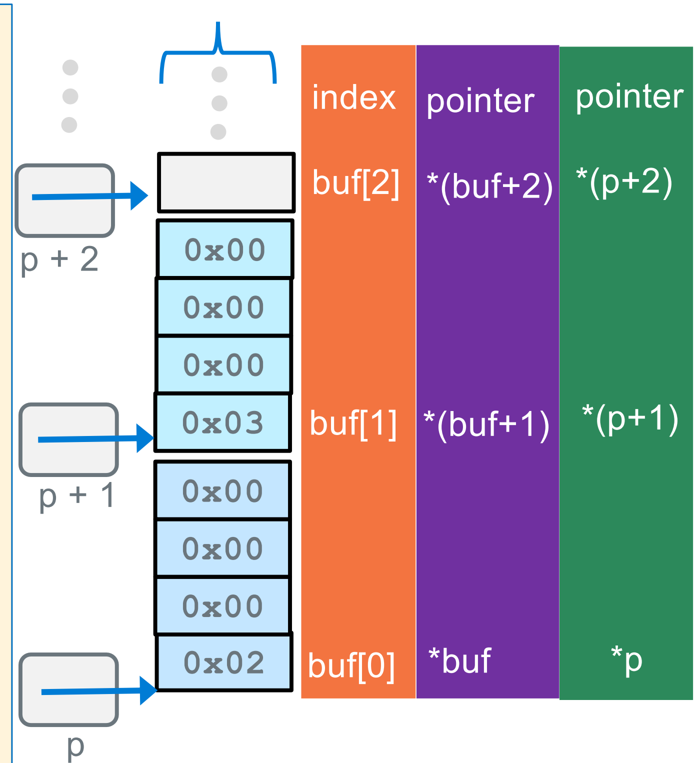
When p is a pointer, the actual value of (p+1) **depends on the type** that pointer p points at

- `(p+1)` adds `1 x sizeof(what p points at)` bytes to p
  - Comment: `++p` is equivalent to `p = p + 1`
- Using pointer arithmetic to find array elements:
  - Address of the second element `&buf[1]` is `(buf + 1)`
  - It can be referenced as `*(buf + 1)` **or** `buf[1]`

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

*p = *p + 10;
*(p + 1) = *(p + 1) + 10; // {12, 13, 5, 6, 11}
```

1 byte Memory Content
One byte per row



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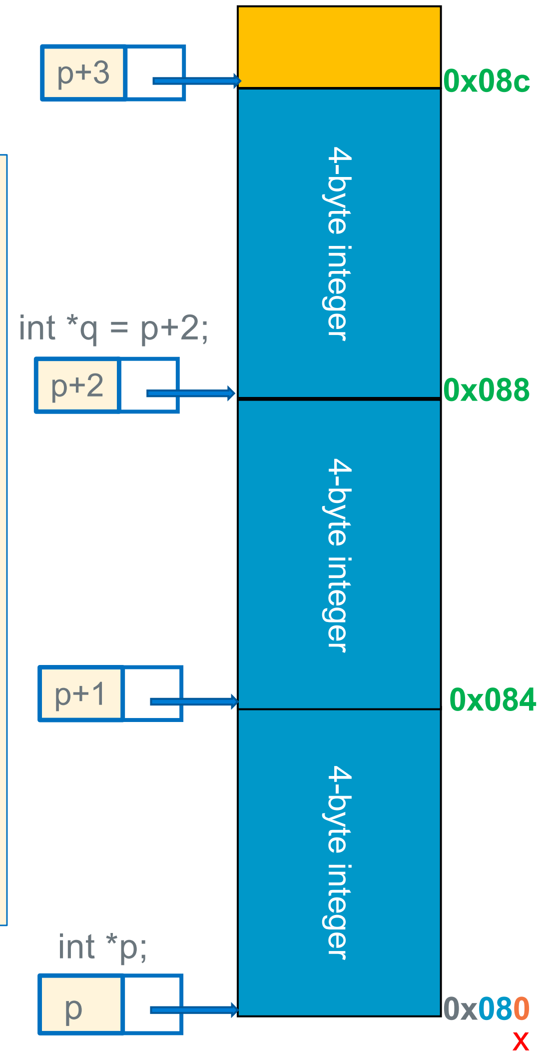
Pointer Arithmetic

- **You <u>cannot</u> add two pointers** *(what is the reason?)*
- A pointer q <u>can be subtracted</u> from another pointer p when the pointers are the same type – best done only within arrays!
- The value of **`(p-q)`** is the number of **elements between** the two pointers
  - Using memory address arithmetic (p and q Rside are both byte addresses):

```
distance in elements = (p - q)bytes/sizeof(*p)bytes

(p + 3) - p = 3 = (0x08c - 0x080)/4 = 3
```



Pointer Arithmetic Use With Arrays

```
char ray[4];
char *a = ray;
int x[2];
int *p = x;
int *q = &x[1];
```

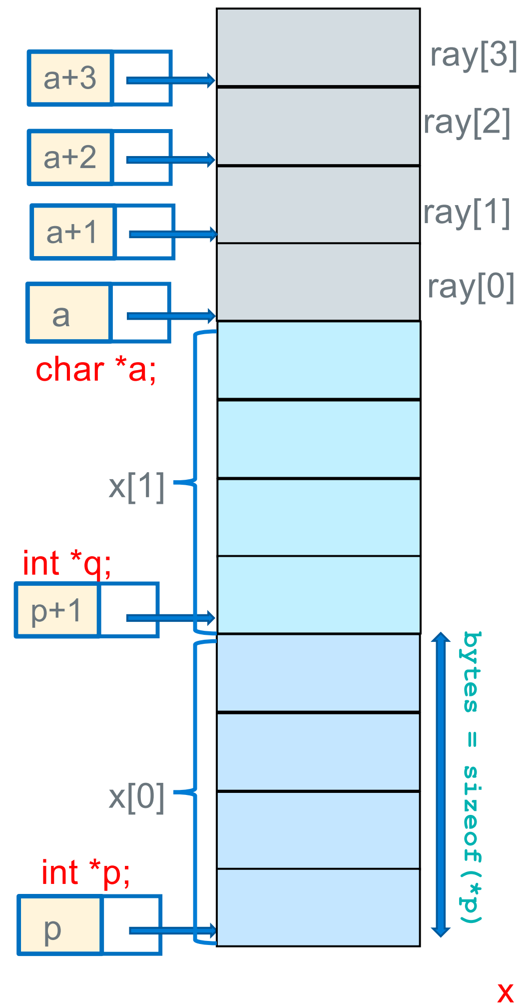
- Remember how ***`sizeof()`*** works:
  - `sizeof(p)` is the size of the **pointer**
  - `sizeof(*p)` evaluates to the size of **what p points at**
- Adding an integer i to a pointer p, the memory address computed by (p + i) in C is calculated with ***memory address arithmetic***

```
memory_address = p + (i × sizeof(*p))
```

- Subtracting an integer i from a pointer `(p - i)`

```
memory_address = p - (i × sizeof(*p))
```

- Number of element between two pointers p and q pointing at the same array
  - Caution: C only checks types, not if they are pointing at the same array



C Precedence and Pointers

- ++ -- pre and post increment combined with pointers will create code that is complex, hard to read and difficult to maintain, so be careful!
- My advice: Always Use () to improve readability

```
int array[] = {2, 5, 7, 9, 11, 13};
int *ptr = array;
int x;
```

```
x = 1 + (*ptr++)++; // yuck!!
```

2 1 3

```
/* Same as the one line above */
x = 1 + *ptr;    // x = 1 + *orig_ptr (2) = 3;

*ptr = *ptr + 1; //(*orig_ptr)++ is array[0]= 3;

ptr = 1 + ptr;   // ptr = &array[1] = points 5
```

Operator	Description	Precedence level	Associativity
( ) [ ] . -> ++ --	Parentheses: grouping or function call Brackets (array subscript) Dot operator (Member selection via object name) Arrow operator(Member selection via pointer) Postfix increment/decrement	1 highest	Left to Right
+ - ++ -- ! ~ * & (datatype) sizeof	Unary plus Unary minus Prefix increment/decrement Logical NOT One's complement Indirection Address (of operand) Type cast Determine size in bytes on this implementation	2	Right to Left
* / %	Multiplication Division Modulus	3	Left to Right
+ -	Addition Subtraction	4	Left to Right
<< >>	Left shift Right shift	5	Left to Right
< <= > >=	Less than Less than or equal to Greater than Greater than or equal to	6	Left to Right
== !=	Equal to Not equal to	7	Left to Right
&	Bitwise AND	8	Left to Right
^	Bitwise XOR	9	Left to Right
|	Bitwise OR	10	Left to Right
&&	Logical AND	11	Left to Right
||	Logical OR	12	Left to Right
?:	Conditional operator	13	Right to Left
= *= /= %= += -= &= ^= |= <<= >>=	Assignment operators	14	Right to Left
,	Comma operator	15	Left to Right

X

Returning Arrays; Array as an Output Parameter

This is very bad
you return the address
of an automatic variable

```
int *copyArray(int src[], int size)
{
  int i, dst[size];   // dynamic array

  for (i = 0; i < size; i++)
    dst[i] = src[i];
  return dst;  // no compiler error, but wrong!
}
```

- Option 1: Use an array either defined in the caller or valid in the caller's scope
  - Then pass a pointer to the array as an output parameter
- Option 2: use allocated storage: malloc()

```
#define SZ 5
…
int orig[SZ] = {9, 8, 1, 9, 5};
int copy[SZ];

copyArray(orig, copy, SZ);
…
```

```
void copyArray(int *src, int *dst, int size)
/* assumes dst array is same or larger */
{
  int *end = src + size;
  while (src < end)
    *dst++ = *src++;
}
```


X

C Strings - 1

- **C <u>does not</u>** 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 <u>when</u>** it is terminated by a '\0'
- **Length of a string** is the number of characters in it, <u>not including</u> the '\0'
- Strings in C are **<u>not</u>** 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 end

length of the string: number of char (= 5)

index	*0*	*1*	*2*	*3*	*4*	*5*
char	`'H'`	`'e'`	`'l'`	`'l'`	`'o'`	`'\0'`

length (size) of the array in number of char (= 6)

x

C Strings - 2

- **First** **`'\0'`** **<u>encountered</u> from the start of the string** always indicates the end of a string
- The **'\0' does not have to be** in the **last element in the space allocated to the array**
  - String length is always less than the size of the array it is contained in
- In the example below, the array buf contains <u>two strings</u>
  - One string starts at &(buf[0]) is "cat" with a string length of 3
  - The other string starts at &(b[4]) is "o" with a string length of 1
  - "o" has two bytes: 'o' and '\0'

string length: number of char (= 3)

string length: number of char (= 1)

index	*0*	*1*	*2*	*3*	*4*	*5*
buf	`'c'`	`'a'`	`'t'`	`'\0'`	`'o'`	`'\0'`
	`0x63`	`0x61`	`0x74`	`0x00`	`0x6f`	`0x00`

length (size) of the array in number of char (= 6)

x

String Literals (Read-Only) in Expressions

- When strings in quotations (*e.g.*, "string") are **part of** an **expression** (*i.e.*, *not* part of an *array initialization*) they are called ***string literals***

```
printf("literal\n");
printf("literal %s\n", "another literal");
```

- What is a ***string literal:***
  - Is a null-terminated string in a `const char array`
  - Located in the **read-only data** segment of memory
  - Is not assigned a variable name by the compiler, so it is only accessible by the location in memory where it is stored
- **String literals** are a type of ***anonymous variable***
  - Memory containing data without a name bound to them (only the address is known)
- Code above, the *string literal* in the printf()'s, are replaced with the starting address of the corresponding array (first or [0] element) when the code is compiled

x

Be Careful with C Strings and Arrays of Chars

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

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

```
char *mess2 = "Hello World";  // "Hello World" is a string literal
                              // mess2 is a pointer NOT an array!
*mess = 'h';                  // undefined in C, linux seg fault
mess2 = mess1;
```

- mess2 **pointer** to an **immutable** array with enough space to hold the string + '\0'
  - you **cannot change** array contents, but you can change what mess2 points at

```
char mess3[] = {'H','e','l','l','o',' ','W','o','r','l','d’\'};
```

- mess3 is an array but does not contain a '\0' SO IT IS NOT A VALID STRING

x

Copying Strings: Use the Sentinel; libc: strcpy(), strncpy()

- To copy an array, you must copy each character from source to destination array
- Watch overwrites: strcpy assumes the target array size is equal or larger than source array

index	*0*	*1*	*2*	*3*	*4*	*5*
char	'H'	'e'	'l'	'l'	'o'	'\0'

```
char str1[80];
strcpy(str1, "hello");
```

```
// strncpy adds a length limit on copy
char str1[6];
strncpy(str1, "hello", 5); // \0 not copied
str1[5] = '\0'; // make sure \0 terminated
```

```
char *strcpy(char *s0, char *s1)
{
    char *str = s0;

    if ((s0 == NULL) || (s1 == NULL))
       return NULL;
    while (*s0++ = *s1++)
       ;
    return str;
}
```

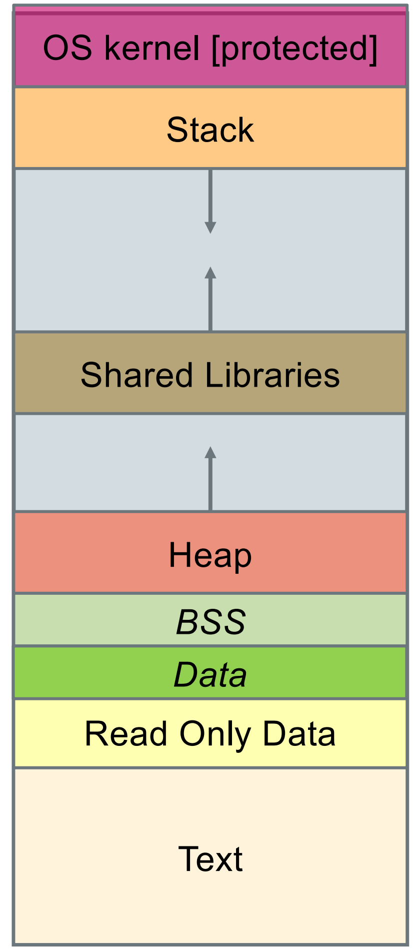
```
char *strncpy(char *s0, char *s1, int len)
{
    char *str = s0;
    if ((s0 == NULL) || (s1 == NULL))
       return NULL;

    while ((*s0++ = *s1++) && --len)
       ;
    return str;
}
```


X

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
`void *malloc(…)`	`size_t size`	no
`void *calloc(…)`	`size_t nmemb, size_t memsize`	yes
`void *realloc(…)`	`void *ptr, size_size`	no
`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 (not allowed in C, but allowed in gcc). The assignment to a typed pointer *"converts"* it from a void *
- **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

Heap Allocation Routine Summary

```c
void *malloc(size_t size);
void *calloc(size_t nmemb, size_t size);
void *realloc(void *ptr, size_t size);
char *strdup(char *s);
void free(void *ptr);
```

Heap **memory allocation** guarantee:

- `NULL` on failure, so check return value
- Memory is returned is contiguous
- it is not recycled unless you call free
- `realloc` preserves existing data
- `calloc` zero-initializes bytes, `malloc` and `realloc` do not

Undefined behavior occurs:

- If you overflow (i.e., you access beyond bytes allocated)
- If you use after `free`, or if `free` is called twice on a location
- If you `realloc`/`free` non-heap address

Use of Malloc

`void *malloc(size_t size)`

- Returns a pointer to a **contiguous** block of **`size`** bytes **of <u>uninitialized</u> 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

- **Always use** `sizeof()` it makes your **code more portable**

  `int *ptr = malloc(n * sizeof(*ptr));`

```
#include <stdlib.h>                  // need this for malloc() etc
    int col_cnt = 10;
    char *bufptr;
    /* ALWAYS CHECK THE RETURN VALUE FROM MALLOC!!!! */
    if ((bufptr = malloc(col_cnt * sizeof(*bufptr))) == NULL) {
        fprintf(stderr, "Unable to malloc memory");
        return NULL
    }
    return bufptr;
```


x

Calloc()

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

`calloc()` variant of **`malloc()`** but zeros out every byte of memory 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 allocation (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(col_cnt * sizeof(*bufptr))) == NULL) {
     fprintf(stderr, "Unable to malloc memory");
     return EXIT_FAILURE;
 }
 for (int j = 0; j < col_cnt; j++)
    *(bufptr + j) = 'a';                // fill each array element with 'a'
 free(bufptr);                          // returns memory to the heap
 bufptr = NULL;                         // set bufptr to NULL
```


x

Mis-Use of Free()

- Call **`free()`** only with only the same memory returned from the heap
  - It is NOT an error to pass **`free()`** a pointer to NULL
- 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()`, `realloc()`, `calloc()`**) may fail or seg fault

```
char *bytes = malloc(1024 * sizeof(*bytes));
char *ptr = "cse30";
          …
    /* some code */
    free(bytes + 5);        // not ok
    free(ptr);              /* not memory on the heap */
```

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


x

Heap Memory "Leaks"

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

```
void
leaky_memory (void)
{
    char *bytes = malloc(BLKSZ * sizeof(*bytes));
…
    /* code that never passes the pointer in bytes to anything */
    return;
}
```

- Your program is responsible for cleaning up any memory it allocates but no longer needs
  - 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
  - Make sure you free memory when you no longer need it
- Valgrind is a tool for finding memory leaks (not pre-installed in all linux distributions though!)

x

Dangling Pointers

- When a 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);
    return buff;
}
```

- `dangling_freed_heap()` type code often causes the allocators (**`malloc()`**and friends) to **seg fault**
  - Because it corrupts data structures the heap code uses to manage the memory pool

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
}
```

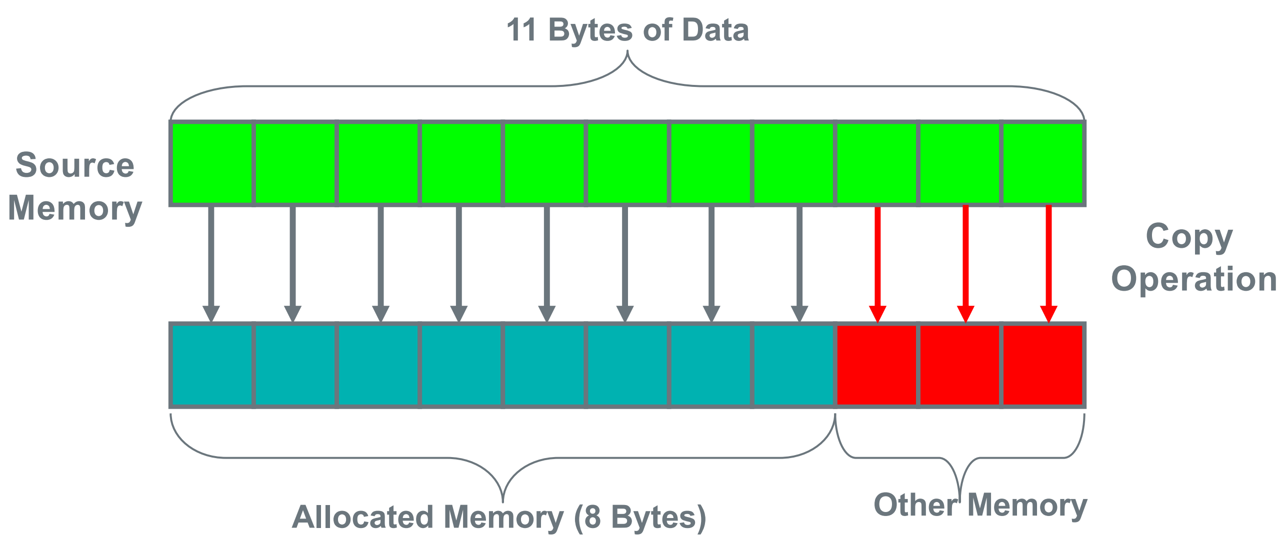
```
/*
 * this is ok to do
 * it is NOT a dangling
 * pointer
 */

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


x

string buffer overflow: common security flaw

- A buffer overflow occurs when data is written outside the boundaries of the memory allocated to target variable (or target buffer)
- **`strcpy()`** is a very *common source of buffer overrun security flaws*:
  - always ensure that the destination array is **large enough** (and don't forget the null terminator)
- **`strcpy()`** can cause problems when the ***destination*** and **source** regions ***overlap***



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Accessing members of a struct

- Like arrays, struct variables are aggregated contiguous objects in memory
- the . structure operator which *"selects"* the requested field or member

```
struct date {// defining struct type
    int month;
    int day; // members date struct
};
```

```
struct date bday; // struct instance
bday.month = 1;
bday.day = 24;
```

day	24
month	1

```
// shorter initializer syntax
struct date new_years_eve = {12, 31};
struct date final = {.day= 24, .month= 1};
```

- Now create a *pointer* to a struct

```
struct date *ptr = &bday;
```

- Two options to reference a member via a struct pointer (. is higher precedence than *):
- Use * and . operators: `(*ptr).month = 11;`
- Use -> operator for shorthand: `ptr->month = 11;`

x

Struct: Arrays and Dynamic Allocation

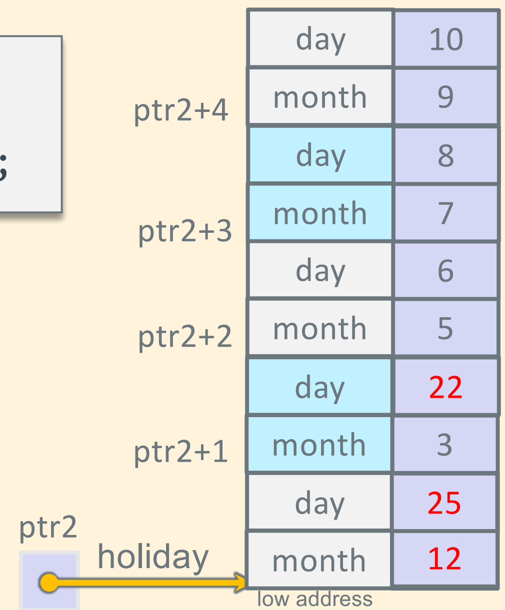
- Like any other type in C, you can create an array of structs

```
struct date holiday[] = {{1,2}, {3,4}, {5,6}, {7,8}, {9,10}};
int cnt = sizeof(holiday)/sizeof(*holiday);  // cnt = 5
```

- Allocate individual structs and arrays of structs using malloc()
  - Remember . is higher precedence than *:

```
#define HOLIDAY 5
struct date *pt1 = malloc(sizeof(*pt1));
struct date *pt2 = malloc(sizeof(*pt2) * HOLIDAY);
```

```
pt2->month = 12;
pt2->day = 25;
(pt2+1)->day = 22;   //or (*(pt2+1)).month
free(pt1);
pt1 = NULL;
free(pt2);
pt2 = NULL;
```



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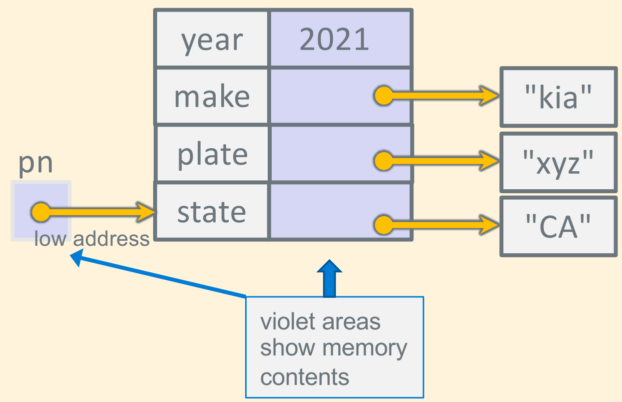
Struct Definition with Pointer Members

- You must allocate anything that is pointed at by a struct member independently (they are not part of the struct, only the pointers are)

```
struct vehicle {
  char *state;
  char *plate;
  char *make;
  int year;
};
struct vehicle name1;
pn = &name1;
```

```
name1.state = strdup("CA");
pn->plate = strdup("xyz");
pn->make = strdup("kia");
```



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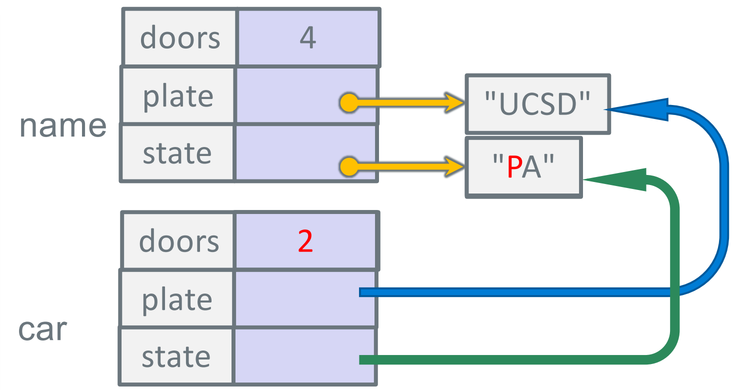
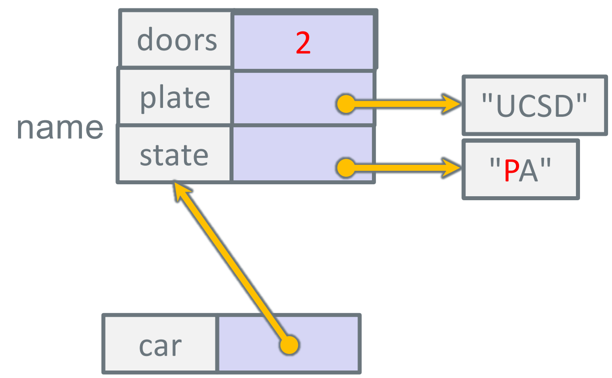
Struct as a Parameter to Functions

```
void change1(struct vehicle car)
{
    car.door = 2;
   *(car.state) = "P";
}
…
change1(name);
```




```
void change2(struct vehicle *car)
{
    car->door = 2;
   *(car->state) = "P";
}
…
change2(name);
```



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Review: Singly Linked Linked List - 1

- Is a linear collection of nodes whose order is not specified by their relative location in memory, like an array
- Each node consists of a payload and a pointer to the next node in the list
  - The pointer in the last node in the list is NULL (or 0)
  - The head pointer points at the first node in the list (the head is not part of the list)
- Nodes are easy to insert and delete from any position without having to re-organize the entire data structure
- Advantages of a linked list:
  - Length can easily be changed (expand and contract) at execution time
  - Length does not need to be known in advance (like at compile time)
  - List can continue to expand while there is memory available

x

Linked List Using Self-Referential Structs

- A **self-referential struct** is a struct that has one or more members that are **pointers** to a **struct variable of the same type**

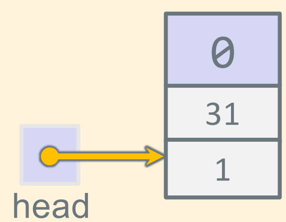
- Self-referential member
  - points to same type – itself

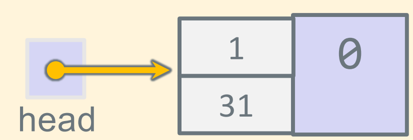
```
struct node {
  int data;
  struct node *next;
};
```

- There can be multiple struct members that make up the payload

```
struct node {
  int month;
  int day;
  struct node *next;
} x;
x.month = 1;
x.day = 31;
x.next = NULL;
```

```
struct node *head;  // head pointer
head = &x;
```





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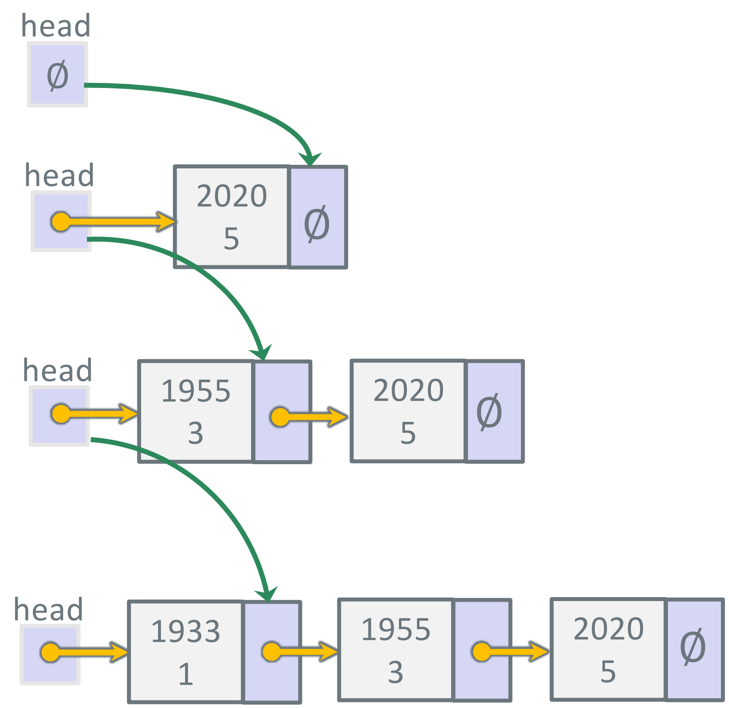
Creating a Node & Inserting it at the Front of the List

```
// create node; insert at front when passed head
struct node *creatNode(int data1, int data2,
       struct node *link)
{
    struct node *ptr = malloc(sizeof(*ptr));
    if (ptr != NULL) {
        ptr->data1 = data1;
        ptr->data2 = data2;
        ptr->next = link;
    }
    return ptr;
```

```
struct node *head = NULL; // insert at front
struct node *ptr;

if ((ptr = creatNode(2020, 5, head)) != NULL)
    head = ptr; // error handling not shown
if ((ptr = creatNode(1955, 3, head)) != NULL)
    head = ptr;
if ((ptr = creatNode(1933, 1, head)) != NULL)
    head = ptr;
```

```
struct node {
  int data1;
  int data2;
  struct node *next;
};
```



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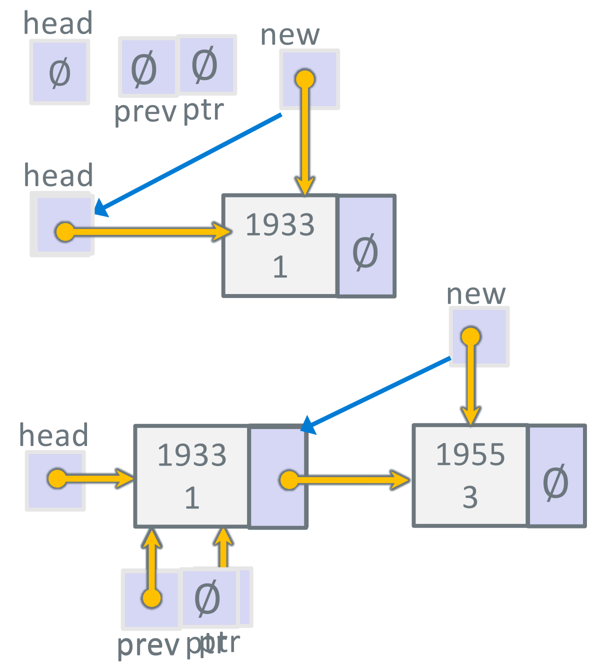
Creating a Node & Inserting it at the End of the List

```
struct node *
insertEnd(int data1, int data2,struct node *head)
{
    struct node *ptr = head;
    struct node *prev = head;
    struct node *new;

    if ((new = creatNode(data1, data2, NULL)) == NULL)
        return NULL;

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

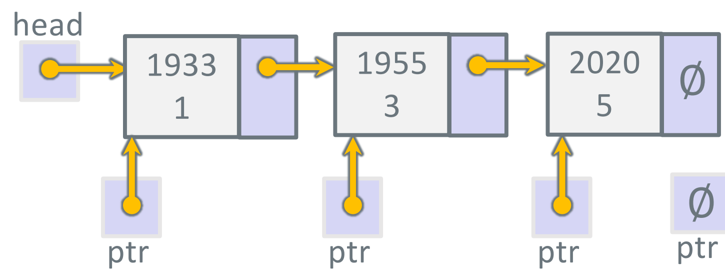



```
struct node *head = NULL;  // insert at end
struct node *ptr;
if ((ptr = insertEnd(1933, 1, head)) != NULL)
    head = ptr;
if ((ptr = insertEnd(1955, 3, head)) != NULL)
    head = ptr;
```


x

"Dumping" the Linked List

"walk the list from head to tail"




```
struct node *head;
struct node *ptr;
…
printf("\nDumping All Data\n");
ptr = head;
while (ptr != NULL) {
    printf("data1: %d data2: %d\n", ptr->data1, ptr->data2);
    ptr = ptr->next;
}
```

```
Dumping All Data
data1: 1933 data2: 1
data1: 1955 data2: 3
data1: 2020 data2: 5
```


x

Number Base Overview (as written in C)

- Decimal is base 10, Hexadecimal is base 16, and octal is base 8
- **Octal digits** have 8 values 0 – 7 (written in C as **0**0 – **0**7, careful **0**73 is octal = 59 in decimal)
- **Hex digits** have 16 values 0 - 9 a - f (written in C as 0x0 – 0xf)
- No standard prefix in C for binary (most use hex) – gcc (compiler) allows 0b prefix others might not

Hex digit Octal digit	0x0 00	0x1 01	0x2 02	0x3 03	0x4 04	0x5 05	0x6 06	0x7 07
Decimal value	0	1	2	3	4	5	6	7
Binary value	0b0000	0b0001	0b0010	0b0011	0b0100	0b0101	0b0110	0b0111

Hex digit Octal digit	0x8 010	0x9 011	0xa 012	0xb 013	0xc 014	0xd 015	0xe 016	0xf 017
Decimal value	8	9	10	11	12	13	14	15
Binary value	0b1000	0b1001	0b1010	0b1011	0b1100	0b1101	0b1110	0b1111

x

Hex to Binary (group 4 bits per digit from the right)

- Each Hex digit is 4 bits in base 2 $16^1 = 2^4$

$$0x\ \underbrace{f}_{1111}\ \underbrace{a}_{1010}\ \underbrace{5}_{0101}\ \underbrace{3}_{0011}$$

$\boxed{0b1111101001010011}$

binary start with a 0b in C

x

Octal to Binary (group 3 bits per digit from the right)

- One Octal digit is three binary digits $2^3 = 8^1$

01 7 5 1 2 3

1 111 101 001 010 011

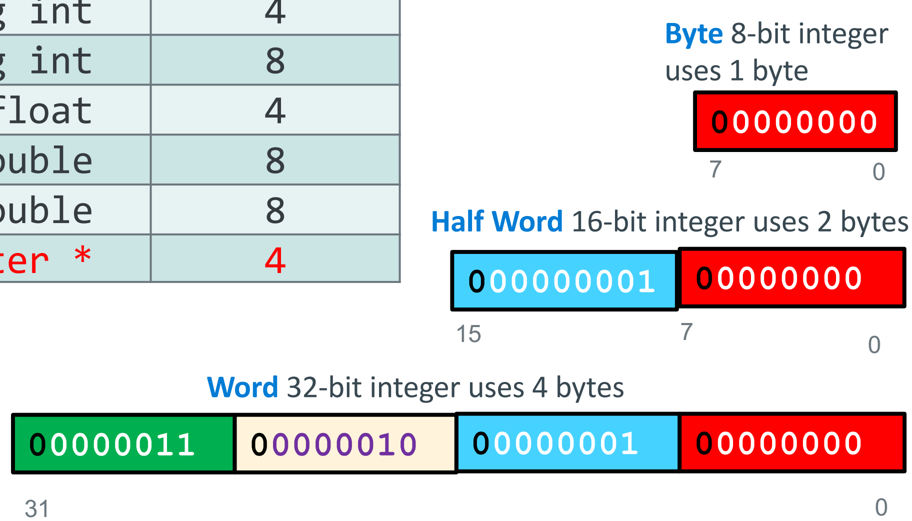
0b1111101001010011

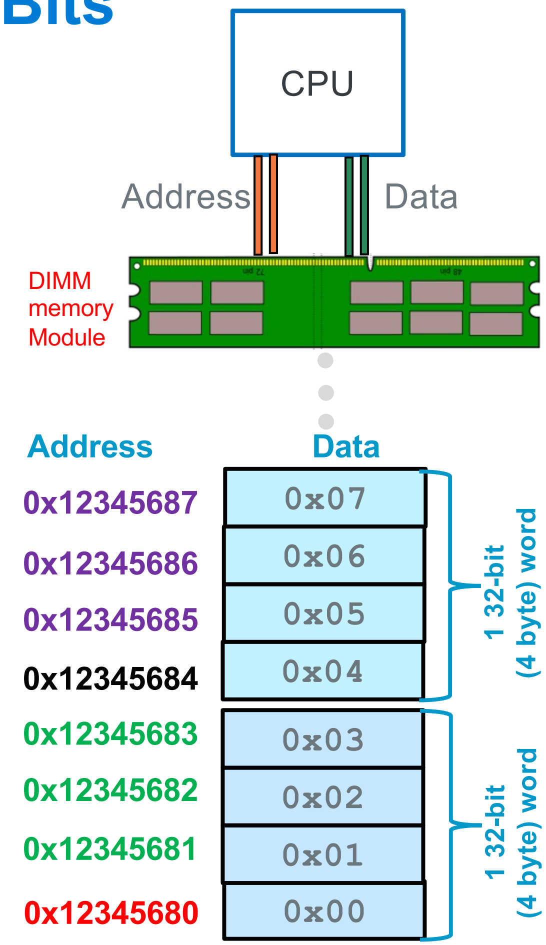
binary start with a 0b in C

x

Numbers Are Implemented with a Fixed # of Bits

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

Unsigned Decimal to Unsigned Binary Conversion

dividend 249	Quotient	Remainder	Bit Position
249/2	124	1	b0
124/2	62	0	b1
62/2	31	0	b2
31/2	15	1	b3
15/2	7	1	b4
7/2	3	1	b5
3/2	1	1	b6
1/2	0	1	b7

249(base 10) = $b_7\, b_6\, b_5\, b_4\, b_3\, b_2\, b_1 b_0 = 0b11111001$

11111001 = (1x128) + (1x64) + (1x32) + (1x16) + (1x8) + 1 = 249

x

Unsigned Binary to Unsigned Decimal Conversion

What is $\overset{b_7}{0}\ \overset{b_6}{1}\ \overset{b_5}{1}\ \overset{b_4}{0}\ \overset{b_3}{0}\ \overset{b_2}{1}\ \overset{b_1}{0}\ \overset{b_0}{1}_{(base\ 2)}$ in decimal (N)?

Product Shift Left	Addend	Bit Position	Product
0	+ 0	b7	0
2 x 0 = 0 (shift left)	+ 1	b6	1
2 x 1 = 2	+ 1	b5	3
2 x 3 = 6	+ 0	b4	6
2 x 6 = 12	+ 0	b3	12
2 x 12 = 24	+ 1	b2	25
2 x 25 = 50	+ 0	b1	50
2 x 50 = 100	+ 1	b0	101

$101_{(base\ 10)}$ = (1x64) + (1x32) + (1x4) + 1 (checking the conversion)

x

Unsigned Integers (positive numbers) with a Fixed # of Bits

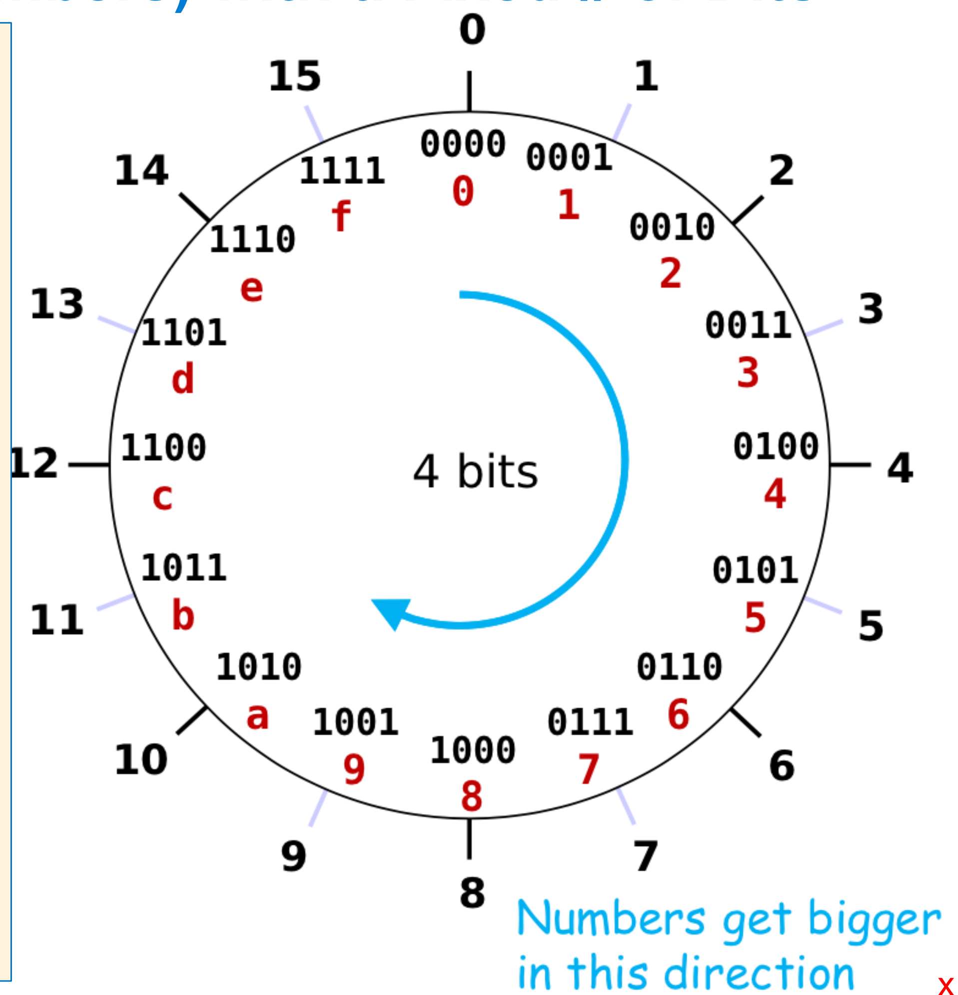
- Example 4 bits is 2^4 = 16 distinct values
- **Modular** (C operator: %) or clock math
  - Numbers start at 0 and “wrap around” after 15 and go back to 0
- Keep adding 1

  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

Unsigned Binary Number: Addition in **FIXED** 8 bits

Be Aware in Binary

1 + 1 = 10 base 10: (1 + 1 = 2)

1 + 1 + 1 = 11 base10: (1 + 1 + 1 = 3)

Carry Bit

carries	0	0	1	0	0	0	1	1		
		1	0	1	0	0	0	0	1	161
+		0	0	1	1	0	0	1	1	51
sum		1	1	0	1	0	1	0	0	212

Unsigned Binary Number: Subtraction in FIXED 8 bits

borrows										
	1	0	1	0	0	0	0	1		161
-	0	0	1	1	0	0	1	1	-	51
difference										

Be Aware in Binary

1 - 1 = 0

10 - 1 = 1 base 10: (2 – 1 = 1)

x

Unsigned Binary Number: Subtraction in **FIXED** 8 bits

borrows		10	10	10	10	10	10			
	0	1	0	1	1	1	0	1		161
-	0	0	1	1	0	0	1	1	-	51
difference	0	1	1	0	1	1	1	0		110

Be Aware in Binary

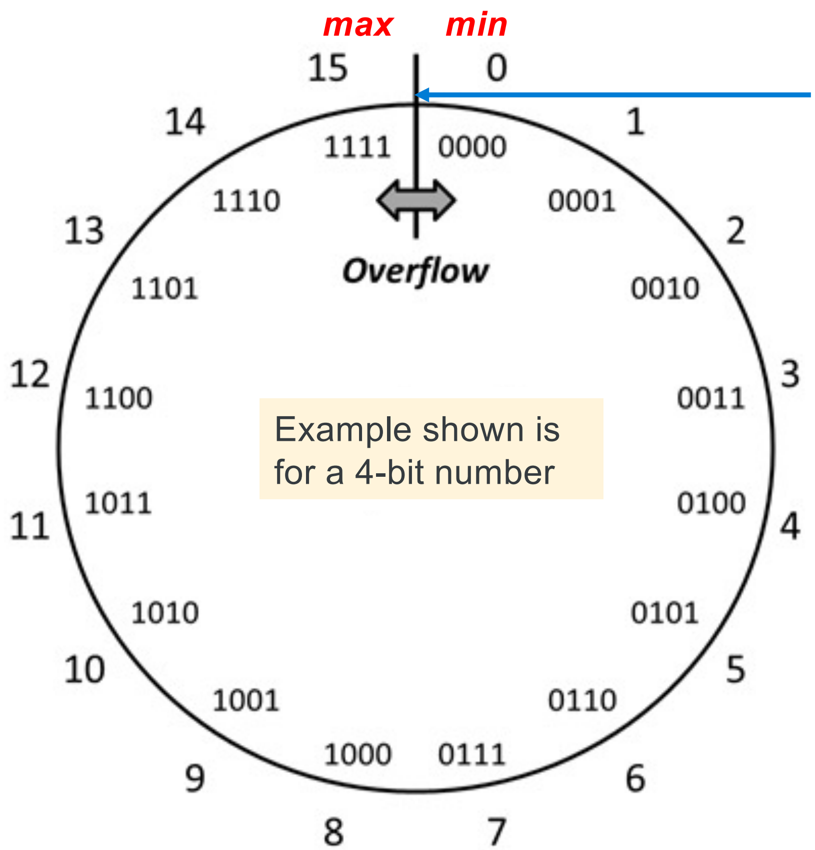
1 - 1 = 0

10 - 1 = 1 base 10: (2 – 1 = 1)

slide has powerpoint builds

x

Overflow: Going Past the Boundary Between max and min



Overflow: Occurs when an arithmetic result (from addition or subtraction for example) is is more than **min** or **max** limits

C (and Java) ignore overflow exceptions

- You end up with a bad value in your program and absolutely no warning or indication… happy debugging!….

x

Overflow: Unsigned Values 4-bit limit

Overflow: Occurs when an arithmetic result is **exceeds** the min or max limits

Addition Overflow: hardware drops carry

```
  15
+  2
----
  17
```

only 4 bits for numbers in this example

carry bit is always dropped from result

```
   1111
+  0010
-------
  10001
oops  1
```

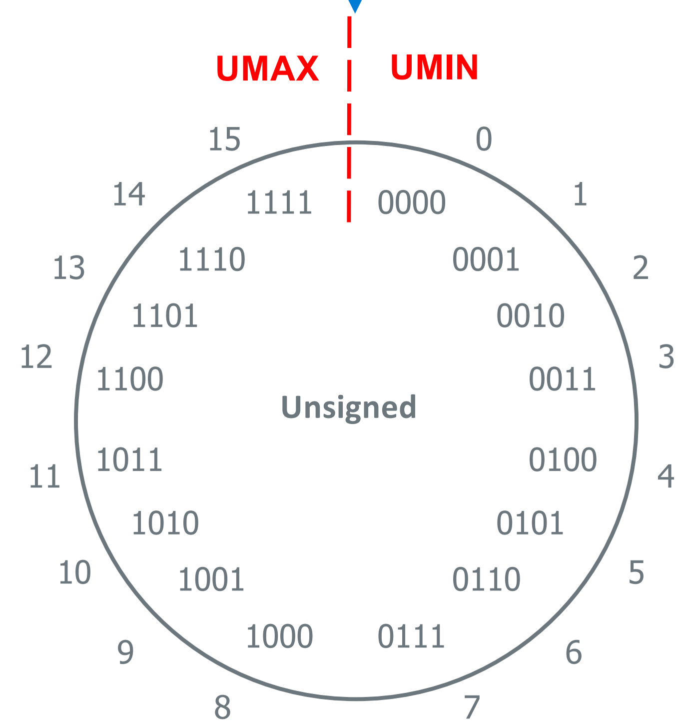
Subtraction Overflow: drops the borrow

```
   1
-  2
----
  -1
```

only 4 bits for numbers in this example

carry bit is always dropped from result

```
  10001
-  0010
-------
   1111
oops 15
```



x

Unsigned Integer Number Overflow: Addition in 8 bits

	Carry Bit								
carries	1	1	1	1	1	1	1	1	
		1	0	1	0	0	0	0	1	161
+		0	1	0	1	1	1	1	1	95
sum		0	0	0	0	0	0	0	0	256

only 8 bits for numbers in this example carry bit is always dropped from result

Rule: When Carry Bit != 0, overflow has occurred for unsigned integers!

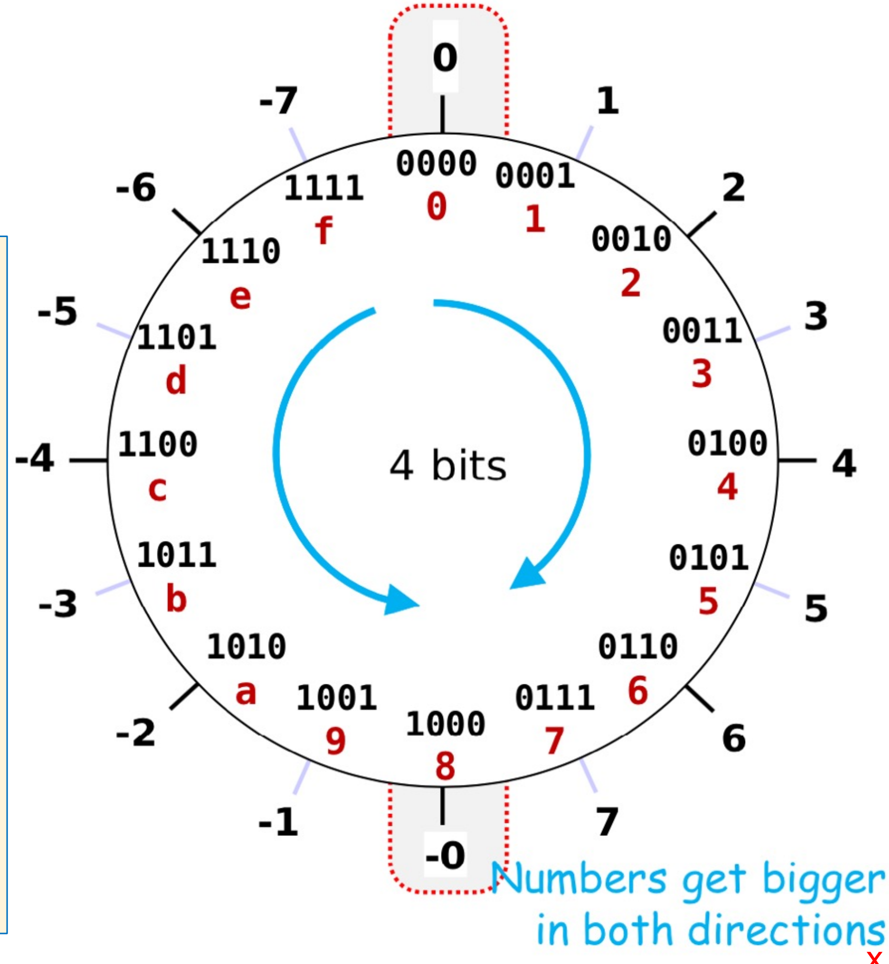
x

Negative Integer Numbers: Sign + Magnitude Method

- Use the Most Significant Bit as a sign bit
  - 0 as the MSB represents positive numbers
  - 1 as the MSB represents negative numbers
- Two (oops) representations for zero: 0000, 1000
- Tricky Math (must handle sign bit independently)

```
   4      0100        4      0100
 - 3    - 0011     + -3    + 1011
 ---    ------     ----    ------
   1      0001       -7      1111
           ✓                  ✗
```

- With Simple math, Positive and Negatives "*increment*" (+1) in the opposite directions!



Signed Magnitude Examples (Sign bit is always MSB)

$\underbrace{0}_{\text{positive}}\ \underbrace{110}_{6}$

$\underbrace{1}_{\text{negative}}\ \underbrace{011}_{3}$

Examples (4 bits):

1 000 = -0?	0 000 = 0?
1 001 = -1	0 001 = 1
1 010 = -2	0 010 = 2
1 011 = -3	0 011 = 3
1 100 = -4	0 100 = 4
1 101 = -5	0 101 = 5
1 110 = -6	0 110 = 6
1 111 = -7	0 111 = 7

$\underbrace{0}_{\text{positive}}\ \underbrace{0000000}_{0}$

$\underbrace{1}_{\text{negative}}\ \underbrace{0001100}_{12}$

Examples Using Hex notation (8 bits):

0x00 = 0b00000000 is positive, because the sign bit is 0

0x7F = 0b01111111 is positive (+127_{10})

0x85 = 0b10000101 is negative (-5_{10})

0x80 = 0b10000000 is negative… also zero

x

Excess Bias Encoding (As used in floating point numbers)

- Given a number in E bits, to divide the range in about 1/2 the following is used:

  excess N bias = $(2^{E-1} - 1)$ *(this is just one of many bias formulas)*

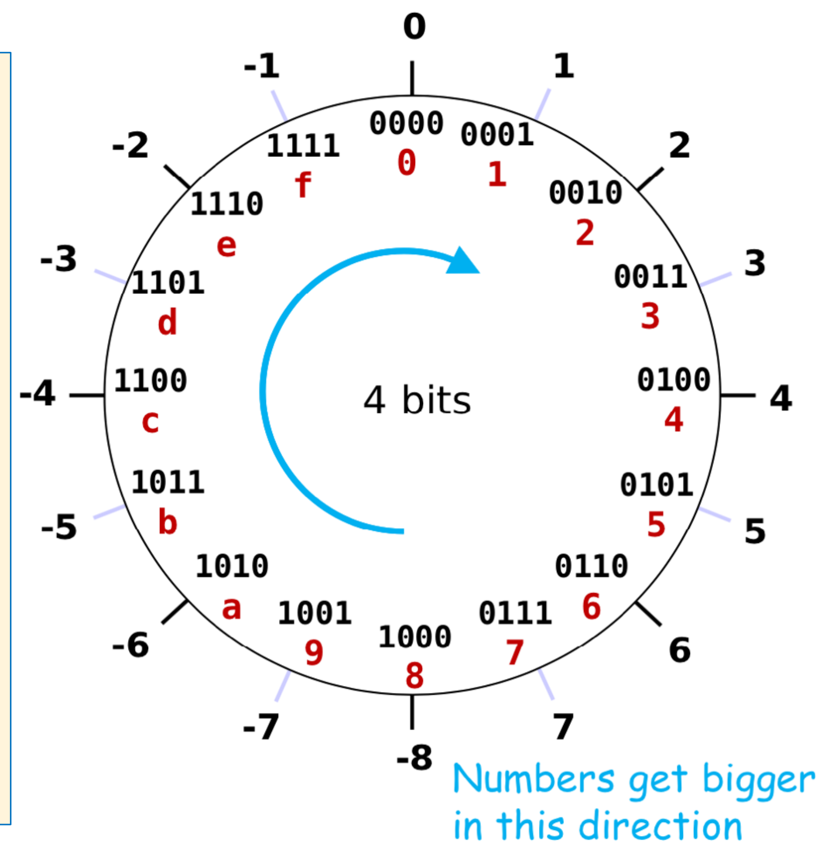
- **With this excess N Bias approach**: actual numbers range from most negative to most positive is: **-(bias) to bias+1**
- **So, for a number that is limited to** 4 bits (0 to 15 unsigned)
  - Then excess N bias = $2^{4-1} - 1 = 2^3 - 1$ = a bias of +7

actual	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8
bias	+7	+7	+7	+7	+7	+7	+7	+7	+7	+7	+7	+7	+7	+7	+7	+7
bias encoded	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

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 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

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

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

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

b_{n-1}	b_{n-2}	...	b_0

- 4-bit (w = 4) weight = -2^{4-1} = -2^3 = -8
  - 1010_2 **unsigned**:
    $1\mathrm{x}2^3 + 0\mathrm{x}2^2 + 1\mathrm{x}2^1 + 0\mathrm{x}2^0 =$ **10**
  - 1010_2 **two's complement**:
    $-1\mathrm{x}2^3 + 0\mathrm{x}2^2 + 1\mathrm{x}2^1 + 0\mathrm{x}2^0 = -8 + 2 =$ **–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

Summary: Min, Max Values: Unsigned and Two's Complement

Two's Complement → Unsigned for n bits

- **Unsigned Value Range**

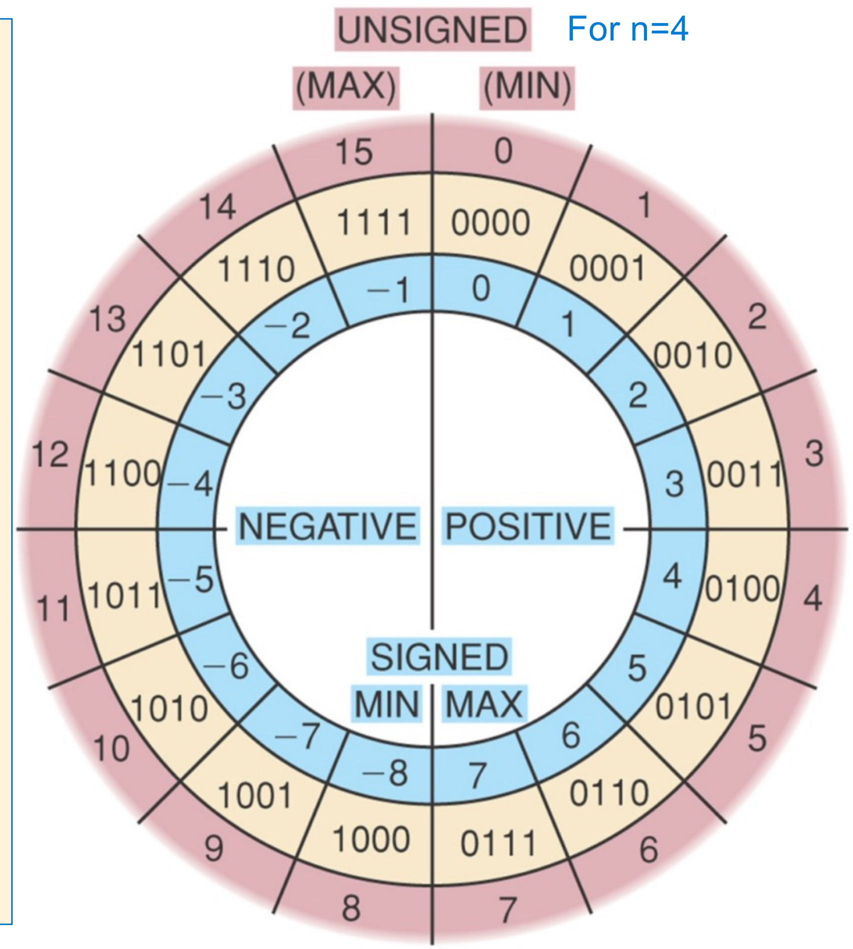
  UMin = `0b00…00`
  = 0

  UMax = `0b11…11`
  = $2^n - 1$

- **Two's Complement Range**

  SMin = `0b10…00`
  = -2^{n-1}

  SMax = `0b01…11`
  = $2^{n-1} - 1$



x

Negation Of a Two's Complement Number (Method 1)

```
-x == ~x + 1;
```

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

```
    -7 = 1001
invert = 0110
add 1  +    1
     7   0111
```

```
 7 =       0111
-7 =    +  1001
(discard carry) 0000
```

```
     1 = 0001
invert = 1110
add 1  +    1
    -1   1111
```

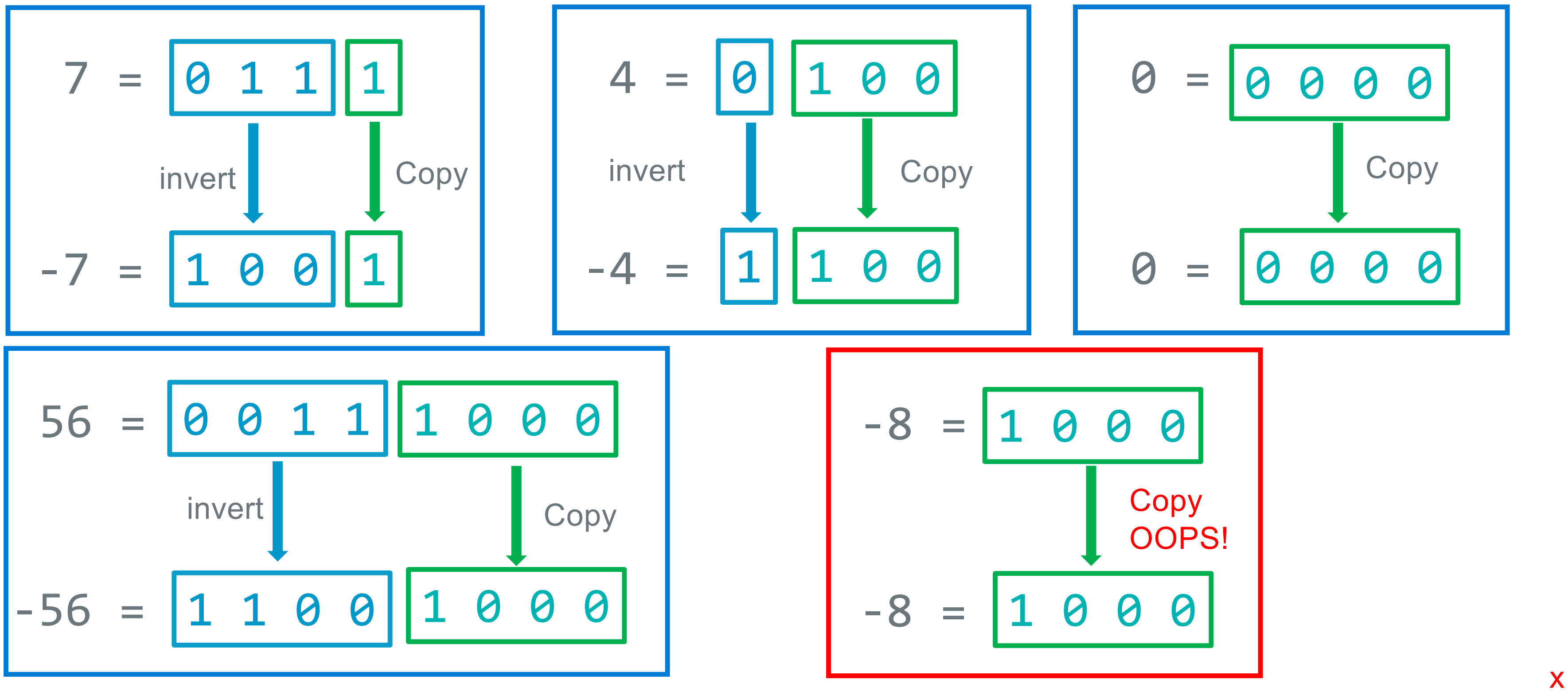
```
    -1 = 1111
invert = 0000
add 1  +    1
     1   0001
```

```
    -8 = 1000
invert = 0111
add 1  +    1
    -8   1000 oops!
```


x

Negation of a Two's Complement Number (Method 2)

1. **copy unchanged** right most bit containing a 1 and all the 0's to its right
2. Invert all the bits to the left of the right-most 1



Signed Decimal to Two's Complement Conversion

dividend -102	Quotient	Remainder	Bit Position
102/2	51	0	b0
51/2	25	1	b1
25/2	12	1	b2
12/2	6	0	b3
6/2	3	0	b4
3/2	1	1	b5
1/2	0	1	b6
0/2	0	0	b7

102(base 10) = $b_7\,b_6\,b_5\,b_4\,b_3\,b_2\,b_1 b_0 = 0b0110\ 0110$

Get the two complement of 01100110 is 10011010

x

Two's Complement to Signed Decimal Conversion - Positive

What is $\overset{b_7}{0}\ \overset{b_6}{1}\ \overset{b_5}{1}\ \overset{b_4}{0}\ \overset{b_3}{0}\ \overset{b_2}{1}\ \overset{b_1}{0}\ \overset{b_0}{1}_{(\text{base } 2)}$ in decimal (N)?

Signed Bit Bias	Bit	Bit Position	Bias
$-2^{W-1} = -2^{8-1} = -128$	x 0	b7	0
Product Shift Left	Addend	Bit Position	Product
2 x 0 = 0 (shift left)	+ 1	b6	1
2 x 1 = 2	+ 1	b5	3
2 x 3 = 6	+ 0	b4	6
2 x 6 = 12	+ 0	b3	12
2 x 12 = 24	+ 1	b2	25
2 x 25 = 50	+ 0	b1	50
2 x 50 = 100	+ 1	b0	SUM = 101
		Bias + SUM:	0 + 101 = 101

x

Two's Complement to Signed Decimal Conversion - Negative

What is $\overset{b_7}{1}\ \overset{b_6}{1}\ \overset{b_5}{1}\ \overset{b_4}{0}\ \overset{b_3}{0}\ \overset{b_2}{1}\ \overset{b_1}{0}\ \overset{b_0}{1}_{(\text{base } 2)}$ in decimal (N)?

Signed Bit Bias	Bit	Bit Position	Bias
$-2^{W-1} = -2^{8-1}$ = -128	x 1	b7	-128
Product Shift Left	Addend	Bit Position	Product
2 x 0 = 0 (shift left)	+ 1	b6	1
2 x 1 = 2	+ 1	b5	3
2 x 3 = 6	+ 0	b4	6
2 x 6 = 12	+ 0	b3	12
2 x 12 = 24	+ 1	b2	25
2 x 25 = 50	+ 0	b1	50
2 x 50 = 100	+ 1	b0	SUM = 101
		Bias + SUM:	-128 + 101 = -27

x

Two's Complement Addition and Subtraction

- **Addition:** just add the two number directly
- **Subtraction:** you can convert to addition: **difference = minuend – subtrahend**

  difference = minuend + 2's complement (subtrahend)

```
Cout
  0   0   0   0   0   0   1   1
    x = 0   1   0   1   0   0   1   1
    y = 0   0   0   0   1   0   1   1
    ---------------------------------
x + y = 0   1   0   1   1   1   1   0
```

```
    x = 0 1 0 1 0 0 1 1
    y = 0 0 0 0 1 0 1 1
    -------------------
  x-y = 0 1 0 0 1 0 0 0
```

2's complement first and then add

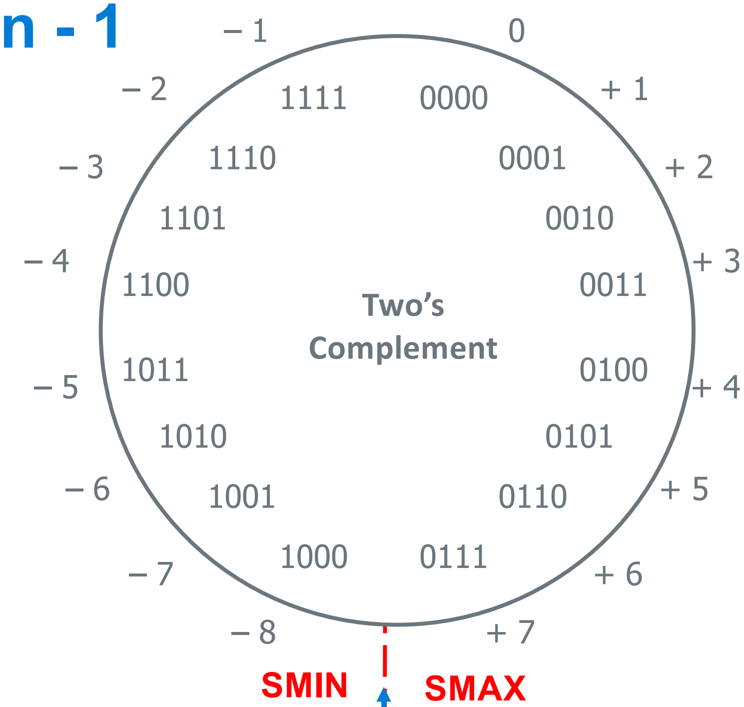
```
                 x = 0 1 0 1 0 0 1 1
            + (-y) = 1 1 1 1 0 1 0 1
                     ---------------
x - y = x +(-y)    = 0 1 0 0 1 0 0 0
```


x

Two's Complement Overflow Detection - 1

- When adding two positive numbers or two negative numbers
- **4-bit** Two's complement numbers (positive overflow)

```
Cout  Cin
 0     1    0    0
       0    1    0    1          5
  +    0    1    1    0          6
  ___________________________________
       1    0    1    1   -5   != 11
```



Overflow: Occurs when an arithmetic result is beyond the min or max limits

x

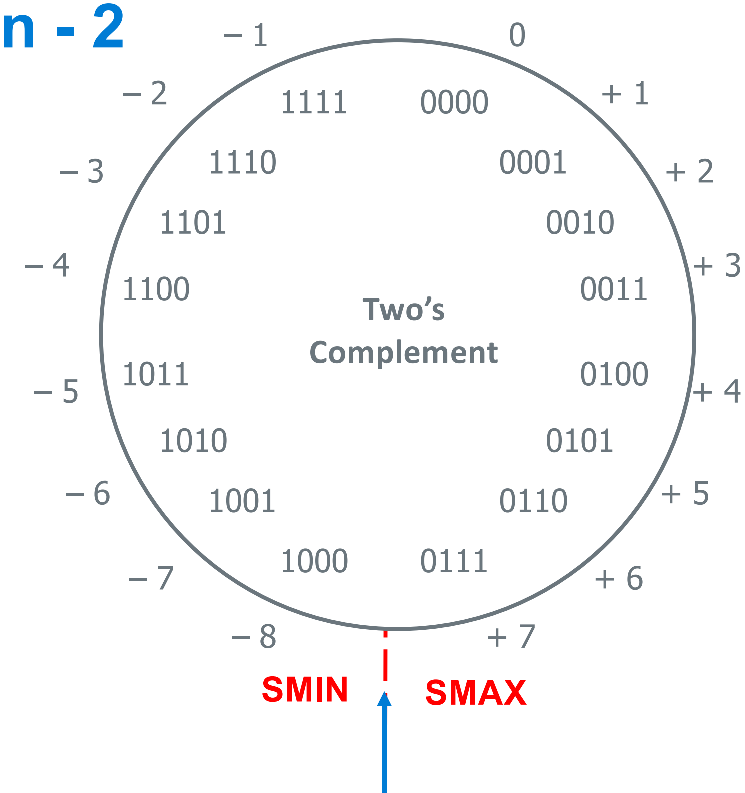
Two's Complement Overflow Detection - 2

- When adding two positive numbers or two negative numbers
- **4-bit** Two's complement numbers (negative overflow)

carry bit is dropped from result

```
Cout Cin
 1    0   1   1
      1   0   0   1          -7
    + 1   0   1   1          -5
    ---------------------------------
      0   1   0   0   +4   != -12
```

Result is correct **ONLY** when the **carry into** the sign bit position (MSB) equals the **carry out** of the sign bit position (MSB)



Overflow: Occurs when an arithmetic result is beyond the min or max limits

x

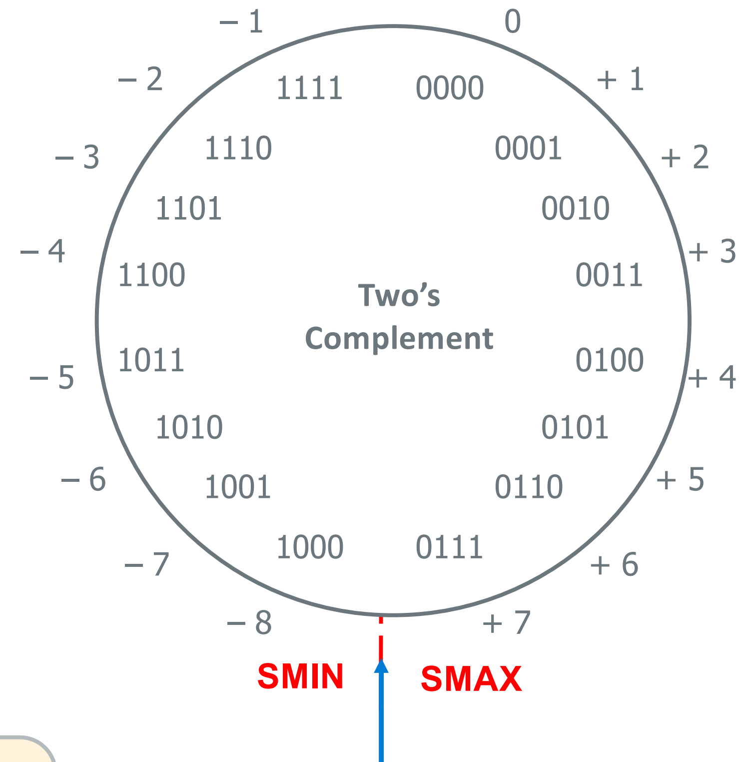
Two's Complement Alternative Overflow Detection

- **Addition:** (+) + (+) = (–) huh?

```
   6       0110
 + 3     + 0011
 ---     ------
   9       1001
      oops -7
```

- **Subtraction:** (–) + (–) = (+) huh?

```
 -7        1001
 - 3     + 1101
 ---     ------
 -10       0110
       oops 6
```



Another Way to look at it for signed numbers:
overflow occurs if
operands have same sign and result's sign is different

Overflow: Occurs when an arithmetic result is beyond the min or max limits

x

Summary: When Does Overflow Occur

Operand 1
+ Operand 2
Result

Operand 1 Sign	Operand 2 Sign	Is overflow Possible?
+	+	**YES**
–	–	**YES**
+	–	**NO**
–	+	**NO**

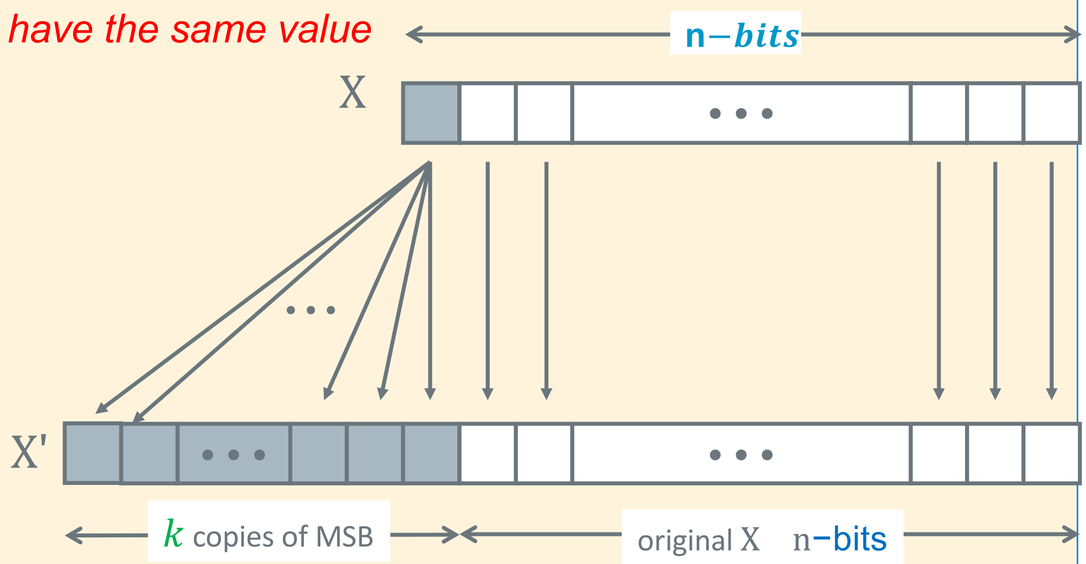
x

Sign Extension 2's complement number

- 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

x

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

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

```
    7     =     0111
extend to
8 bits
            00000111
Number is still 7
```

```
    1     =     0001
extend to
8 bits
            00000001
Number is still 1
```


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
```

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


x

Example: Two’s Complement Sign or bit Extension - 3

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

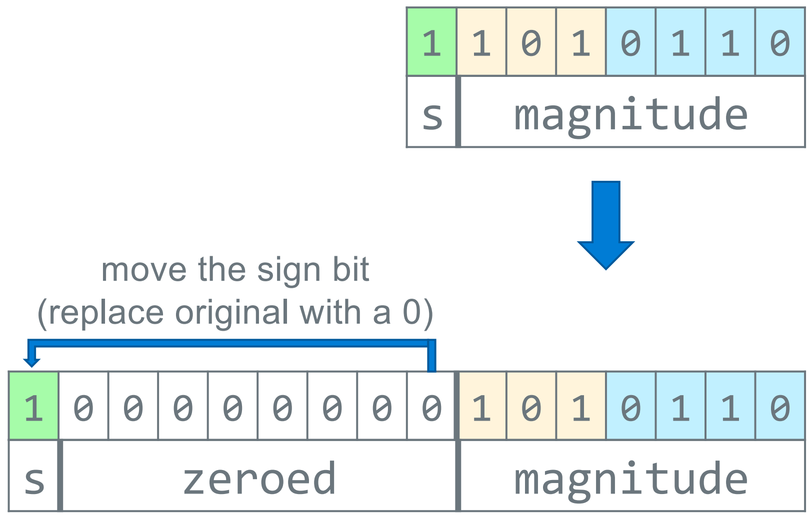
```
     1 = 0001

invert = 1110
add 1  +    1
    -1   1111
```

```
    -1     =         11111111
extend to
16 bits
           1111111111111111
```

```
    -1     =     1111
extend to
8 bits
             11111111
```

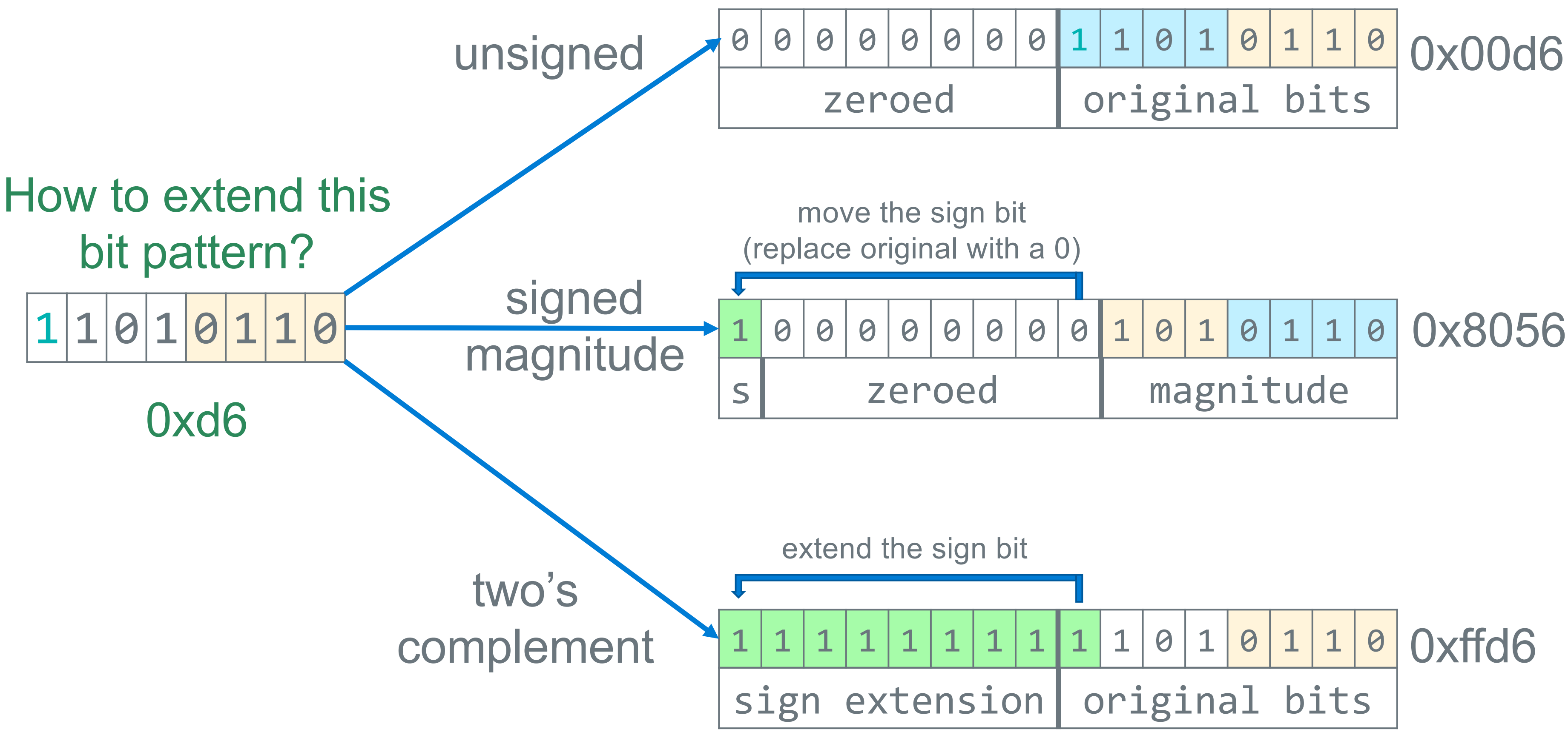
Sign Extension Signed Magnitude number

- Just move the sig bit and expand the magnitude with zeros to the left



x

Interpreting and extending with Different representations



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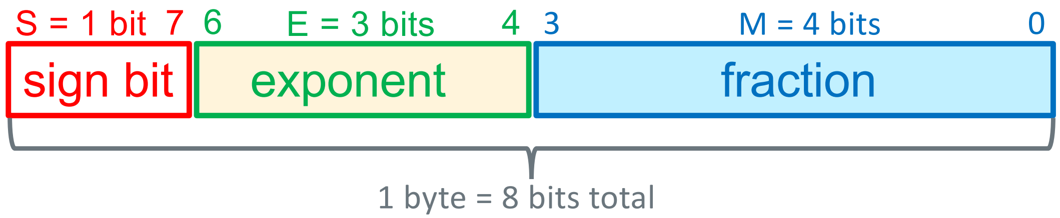
Floating Point Number in a Byte (Not A Real Format)



- **Mantissa encoding: = 1.[xxxx] encoded as an unsigned value**
- **Exponent encoding:** 3 bits encoded as an unsigned value using bias encoding
  - **Use the following variation of Bias encoding =** $(2^{E-1} - 1)$
  - 3 bits for the bias we have $2^{3-1} - 1 = 2^2 - 1$ = a bias of 3
  - **With a Bias of 3**: positive and negative numbers range: small to large is: 2^{-3} to 2^4

Actual	-3	-2	-1	0	1	2	3	4
Bias	+ 3	+ 3	+ 3	+ 3	+ 3	+ 3	+ 3	+3
Biased	0	1	2	3	4	5	6	7

x

Decimal to Float

Bias of 3

7	6 – 4	3 – 0
s	exponent (3 bits)	fraction (4 bits)

Binary	Decimal
2^{-2}	0.25
2^{-3}	0.125

Step 1: convert from base 10 to binary (absolute value)

$-0.375\text{(decimal)} = 0000.0110_{\text{base 2}}$

Step 2: Find out how many places to shift to get the number into the normalized 1.xxxx mantissa format

$0000.0110_2 = 1.1000 \times (2^{-2})_{\text{base 10}}$

exponent: -2_{10} + bias of $3_{10} = 1_{10} =$ 0b001 for the exponent (after adding the bias)

Step 3: Use as many digits as possible to the right of the decimal point in the fractional .xxxx part

1.1000

Step 4: Sign bit

positive sign bit is 0

negative sign bit is 1

s	exponent	fraction
1	0b001	0b1000
0x9		0x8

= 0x98

Float to Decimal

7	6 Bias of 3 4	3 0
s	exponent (3 bits)	fraction (4 bits)

Step 1: Break into binary fields

`0x45` =

0x4		0x5
s	exponent	fraction
0	0b100	0b0101

Step 2: Extract the unbiased exponent

$0b100 = 4_{\text{base } 10} - \text{bias of } 3_{10} = 1_{10}$ for the exponent (bias removed)

Step 3: Express the mantissa (restore the hidden bit)

`1.0101`

Step 4: Apply the **unbiased** exponent

$1.0101_{\text{base } 2} \times (2^{1})_{\text{base } 10} = 10.101$

Step 5: Convert to decimal

$10.101 = 2.625_{\text{base } 10}$

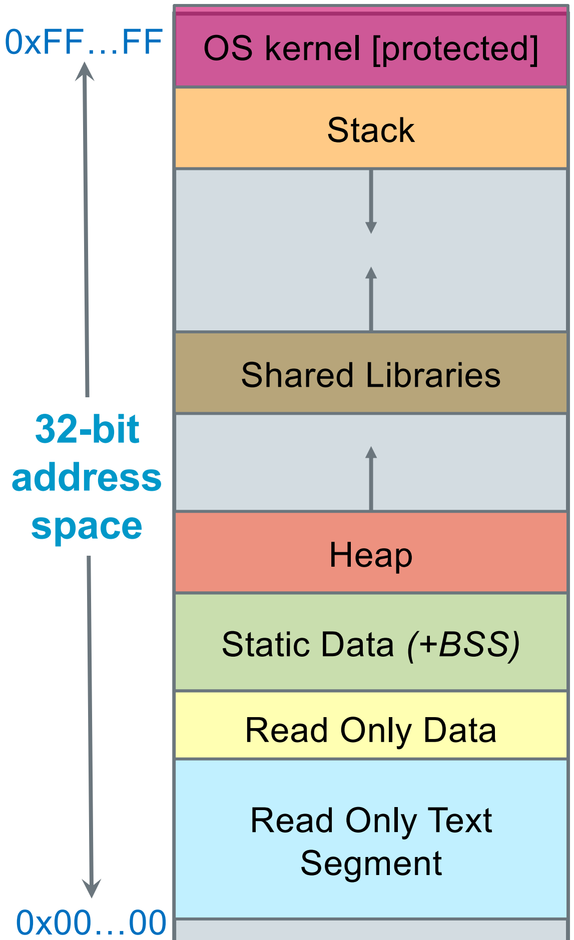
Step 6: Apply the Sign

$+\ 2.625_{\text{base } 10}$

Binary	Decimal
2^{-1}	0.5
2^{-2}	0.25
2^{-3}	0.125
2^{-4}	0.0625

x

Assembly and Machine Code



- Machine Language (or code): Set of instructions the CPU executes are encoded in memory using patterns of ones and zeros
- Assembly language is a symbolic version of the machine language
- Each assembly statement (called an **Instruction**), executes **exactly one** from a list of simple commands
  - Instructions describe operations (e.g., =, +, -, *)
- Each line of arm32 assembly code contains at most one instruction
- Assembler (gnu as) translates assembly to machine code

Memory Address	word (4-bytes) contents	Assembly Language
1040c:	e28db004	add fp, sp, 4
10410:	e59f0010	ldr r0, [pc, 16]
10414:	ebfffb3	bl 102e8 <printf>
10418:	e3a00000	mov r0, 0
1041c:	e24bd004	sub sp, fp, 4

Machine Code

high <- low bytes

x

Using Aarch32 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: dedicated hardware use (like r15 the pc) or special use when used with certain instructions (like r13 & r14)
- r15/pc is the program counter that contains the address of an instruction being executed (not exactly … later)

Special Use Registers program counter	r15/pc
Special Use Registers function call implementation & long branching	r14/lr r13/sp r12/ip r11/fp
Preserved registers Called functions can't change	r10 r9 r8 r7 r6 r5 r4
Scratch Registers First 4 Function Parameters Function return value Called functions can change	r3 r2 r1 r0

Examples: Guards (Conditional Tests) and their Inverse

`Compare in C`	*"Inverse"* `Compare in C`
`==`	`!=`
`!=`	`==`
`>`	`<=`
`>=`	`<`
`<`	`>=`
`<=`	`>`

- Changing the conditional test (guard) to its inverse, allows you to swap the order of the blocks in an if else statement

x

cmp/cmm – Making Conditional Tests

cmp/cmm	Rn	rot4	imm8

operand 1 → Rn; Operand 2 constant → rot4, imm8

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

cmp/cmm	Rn	Rm

operand 1 → Rn; Operand 2 → Rm

```
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
```

Conditional Branch: Changing the Next Instruction to Execute

cond	b	imm24

Branch instruction

```
bsuffix .Llabel
```

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

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
BHS	Unsigned ≥ ("Higher or Same") or Carry Set	C = 1
BLO	Unsigned < ("Lower") or Carry Clear	C = 0
BHI	Unsigned > ("Higher")	C = 1 && Z = 0
BLS	Unsigned ≤ ("Lower or Same")	C = 0 || Z = 1
BMI	Minus/negative	N = 1
BPL	Plus - positive or zero (non-negative)	N = 0
BVS	Overflow	V = 1
BVC	No overflow	V = 0
B (BAL)	Always (unconditional)	

x

Conditional Branch: Changing the Next Instruction to Execute

```
        cmp    r3, r4
        beq   .Ldone
        blt   .Lelse
        // otherwise do the add
        add   r1, r2, 1
        b     .Ldone
.Lelse:
        sub   r0, r0, r1
.Ldone:
        mov   r3, r1
```

Condition	Meaning	Flag Checked
BEQ	Equal	Z = 1
BLT	Signed < ("Less Than")	N ≠ V
B	Always (unconditional)	

```
cmp    r3, r4 // r3 - r4
// if r3 == r4 sets Z = 1
// if r3 < r4 sets N and V; is N == V?
```

Two steps to do a Conditional Branch: Use a **cmp/cmm** instruction to set the condition bits

1. Follow the **cmp/cmm with one or more variants of the conditional branch instruction**
   Conditional branch instructions if evaluate to true (bases on the CC bits set) will go to the instruction with the branch label. Otherwise, it executes the instruction that follows
2. You can have one or more conditional branches after a single cmp/cmm

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 */
}
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 - 2

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

```
    cmp r0, 5
    beq .Lthen

    cmp r1, 3
    ble .Lelse
    // fall through
.Lthen:
    mov r2, r5 // true block
    // branch around else
    b .Lendif
.Lelse
    mov r5, r2 // false block
    // fall through
.Lendif:
```

If r0 == 5 true, then branch ***to*** the true block

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

x

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 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

pre-test loop guard

loop control variable

zero or more iterations

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

one or more iterations

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

post-test loop guard

x

Pre-Test Guards - While Loop

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

pre-test
loop guard

loop
iteration

inverted
test

```
.Lwhile:
    cmp r1, 10
    bge .Lendw
    // block
    add r1, r1, 1
    b .Lwhile
.Lendw:
    mov r2, r1
```

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

pre-test
loop guard

loop
iteration

```
.Lwhile:
    cmp r1, 10
    bge .Lendw
    cmp r2, r1
    beq .Lnext
    // block
.Lnext:
    add r1, r1, 1
    b .Lwhile
.Lendw:
    mov r2, r1
```


x

Post-Test Guards – Do While Loop

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

r2 = r1;
```

loop iteration

post-test loop guard

```
.Ldo:
    // block
    add r1, r1, 1
    cmp r1, 10
    blt .Ldo

    mov r2, r1
```

test is not inverted

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

r2 = r1;
```

loop iteration

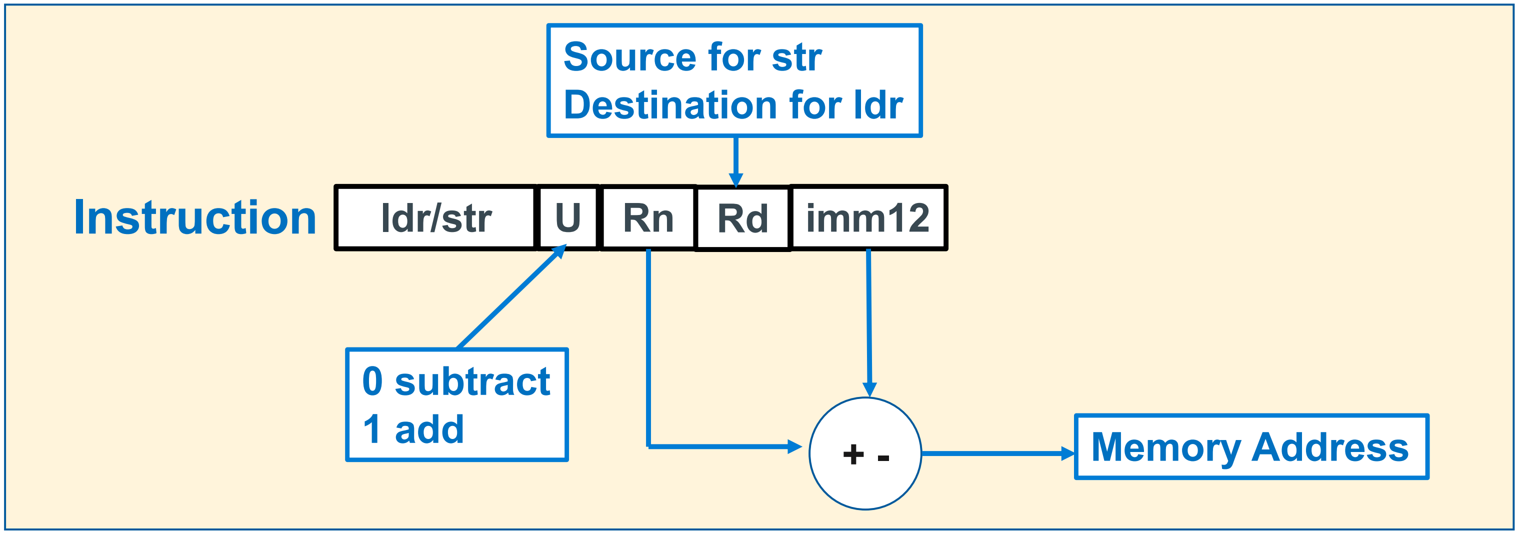
post-test loop guard

```
.Ldo:
    cmp r2, r1
    beq .Lnext
    // block
.Lnext
    add r1, r1, 1
    cmp r1, 10
    blt .Ldo

    move r2, r1
```


x

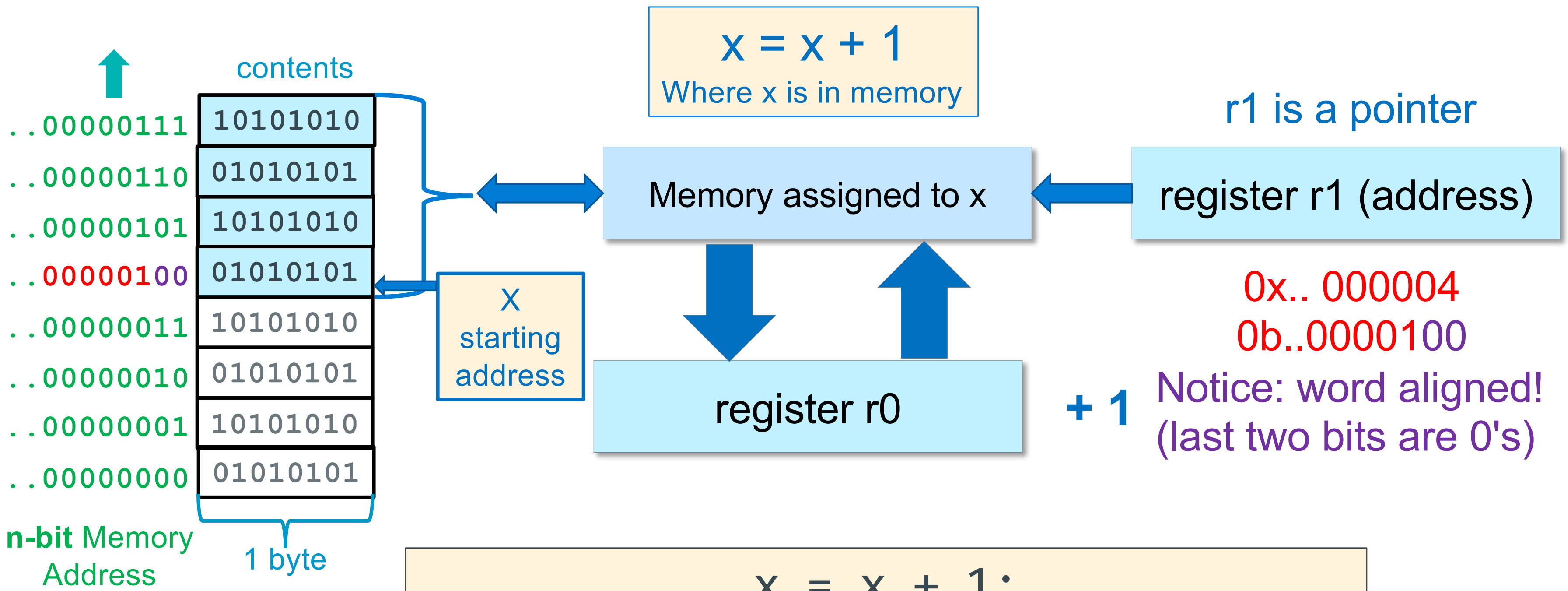
ldr/str Register Base and Register + Immediate Offset Addressing



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

x

Example Base Register Addressing Load – Modify – Store

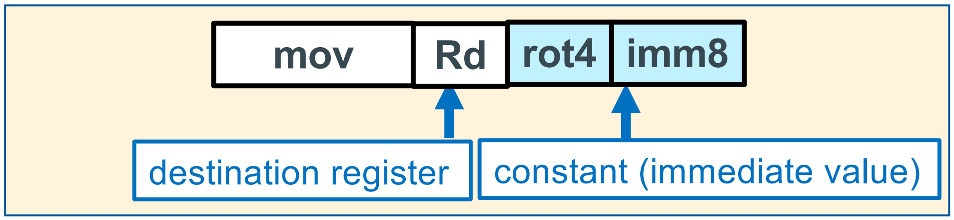



```
x = x + 1;
ldr r0, [r1]          // r0 = *r1 (read x)
add r0, r0, 1         // r0 = r0 + 1 (x++)
str r0, [r1]          // *r1 = r0 write x
```

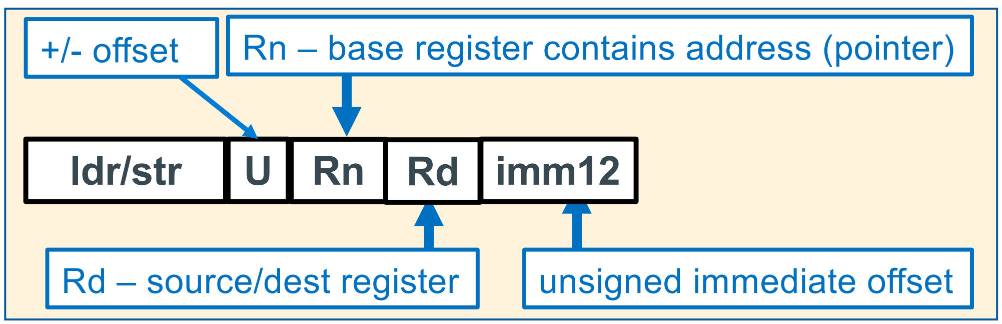

x

Review From Earlier week: How to Access Memory?

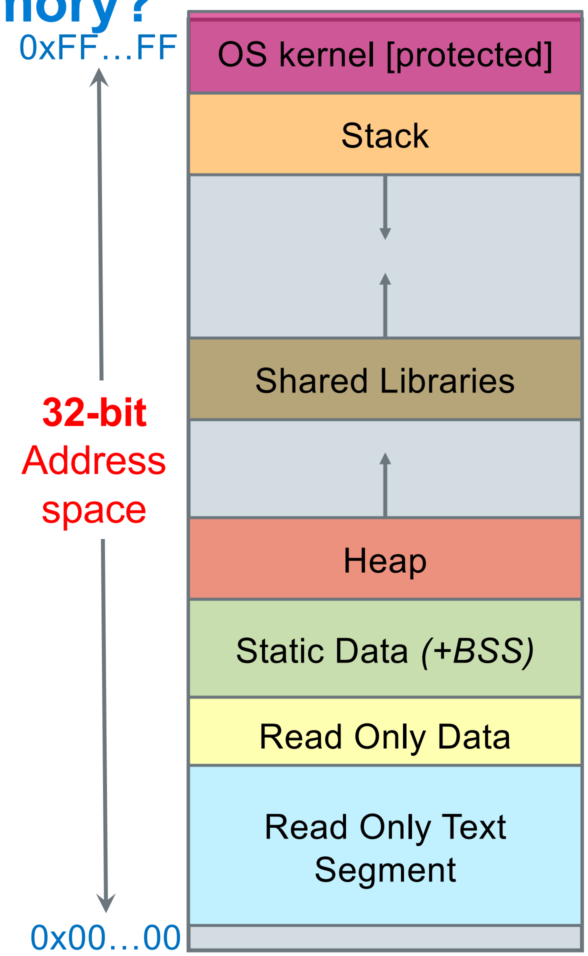
- Address space is 32 bits wide – POINTERS in registers



rot4/imm8 is too small



Even if you changed the instruction to reuse the base register bits (4 bits) + imm12 to get 16-bits, it is still too small!



x

How to Access variables in a Data Segment

```
ldr/str  Rd,  [Rn, +- imm12]
```

- How do you get the **address into the base register Rn** for a Labeled location in memory?
- Assembler **creates a table of pointers** in the **text segment** called the **literal table**
  - It is accessed using **the pc as the base register**
  - Each entry contains a **32-bit Label address**
- How to access this table to get a pointer:

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

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

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

assembly source file ex.S

```
        .bss
y:      .space 4

        .data
x:      .word 200

        .section .rodata
.Lmsg:  .string "Hello World"

        .text
        // function header
main:

        // load the contents into r2
        ldr r2, =x      // int *r2 = &x
        ldr r2, [r2]    // r2 = *r2;
        // &x was only needed once above

        // store the contents of r0
        ldr r1, =y      // r1 = &y
        str r0, [r1]    // y = r0
        // keeping &y in r1 above
…
```


x

Using ldr for immediate values to big for mov, add, sub, and, etc

- In data processing instructions, the field **imm8 + rotate 4 bits** is too small to store many numbers outside of the range of -256 to 255, how do you get larger immediate values into a register?

mov	Rd	rot4	imm8

fails → `mov r0, 1023`

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

replacement → `ldr r0, =1023`

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

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


x

Loading and Storing: Variations List

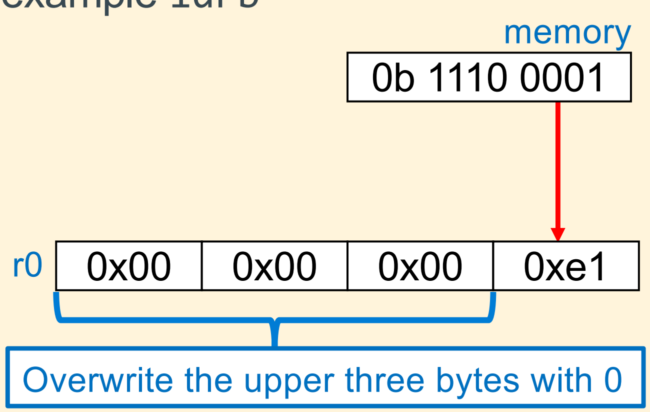
- Load and store have variations that move 8-bits, 16-bits and 32-bits
- Load into a register with less than 32-bits will set the upper bits not filled from memory differently depending on which variation of the load instruction is used
- Store will only select the lower 8-bit, lower 16-bits or all 32-bits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

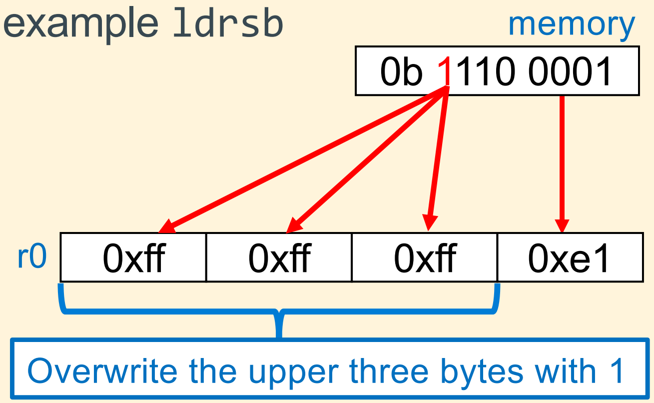
Instruction	Meaning	Sign Extension	Memory Address Requirement
`ldrsb`	load signed byte	sign extension	none (any byte)
`ldrb`	load unsigned byte	zero fill (extension)	none (any byte)
`ldrsh`	load signed halfword	sign extension	halfword (2-byte aligned)
`ldrh`	load unsigned halfword	zero fill (extension)	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 Variables < 32-Bits Wide

Unsigned	Signed (2's complement)
Zero-Extend: Add leading 0's	Sign-Extend: Replicate sign bit
example `ldrb`	example `ldrsb`



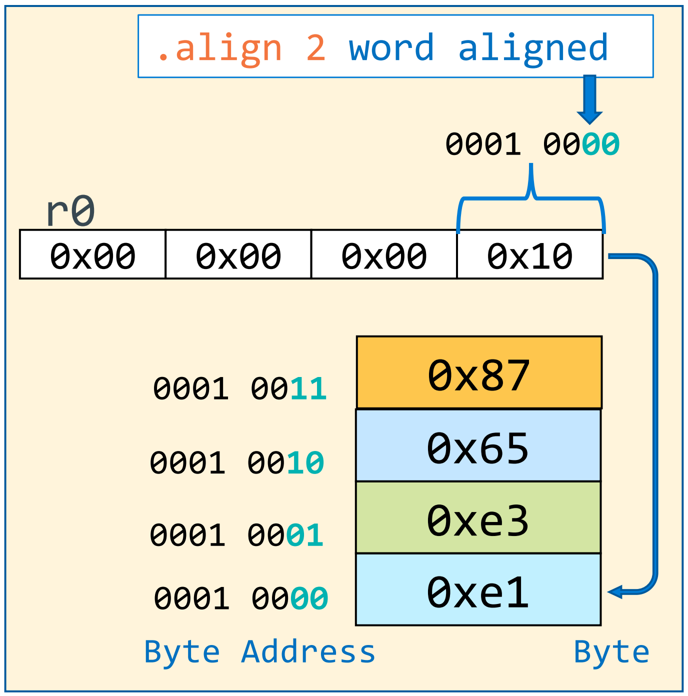


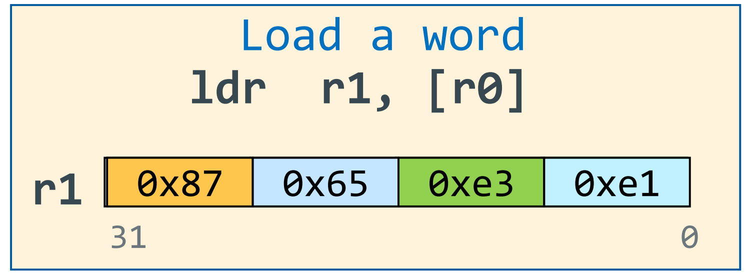
Instructions that zero-extend:
ldrb, ldrh

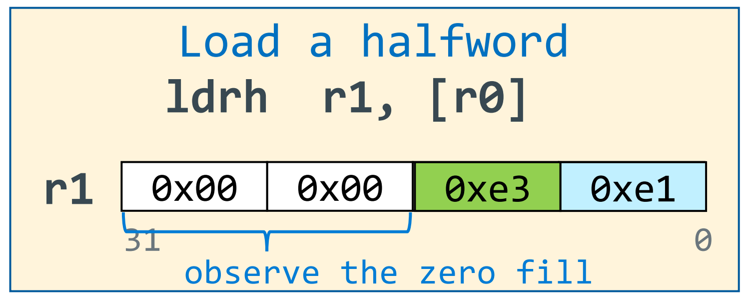
Instructions that sign-extend:
ldrsb, ldrsh

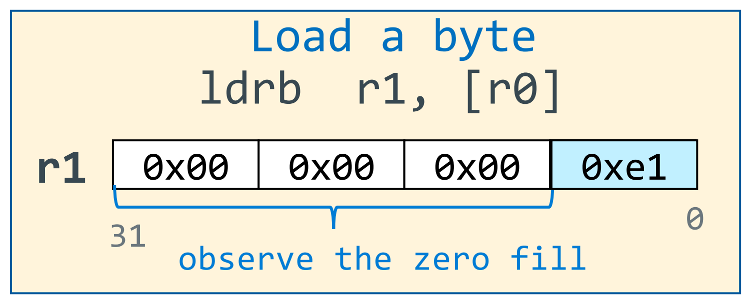
x

Load a Byte, Half-word, Word



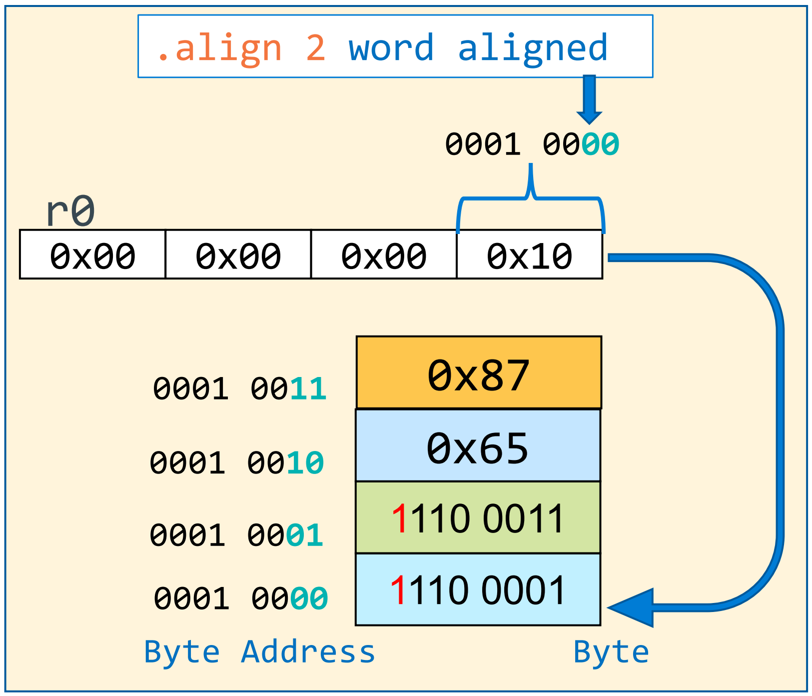


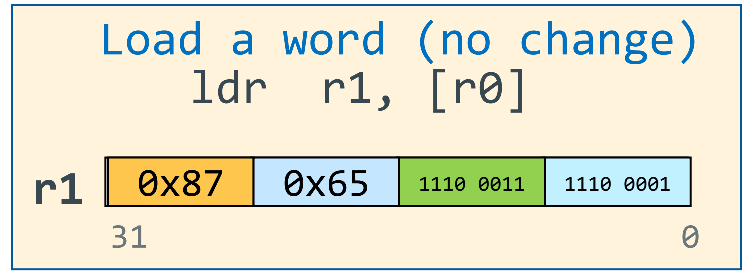


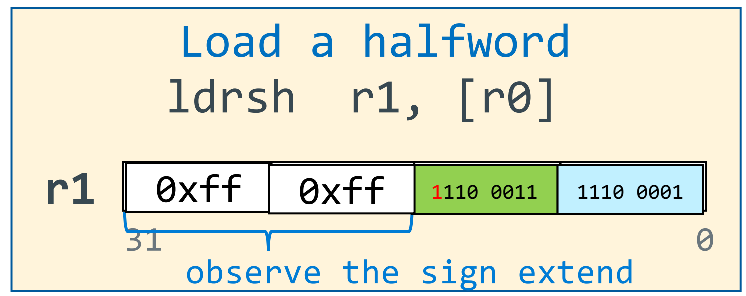


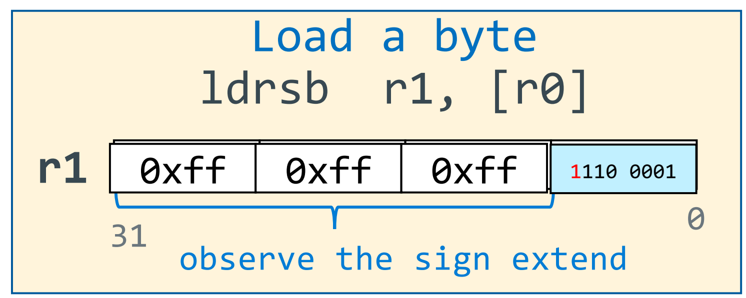
x

Signed Load a Byte, Half-word, Word

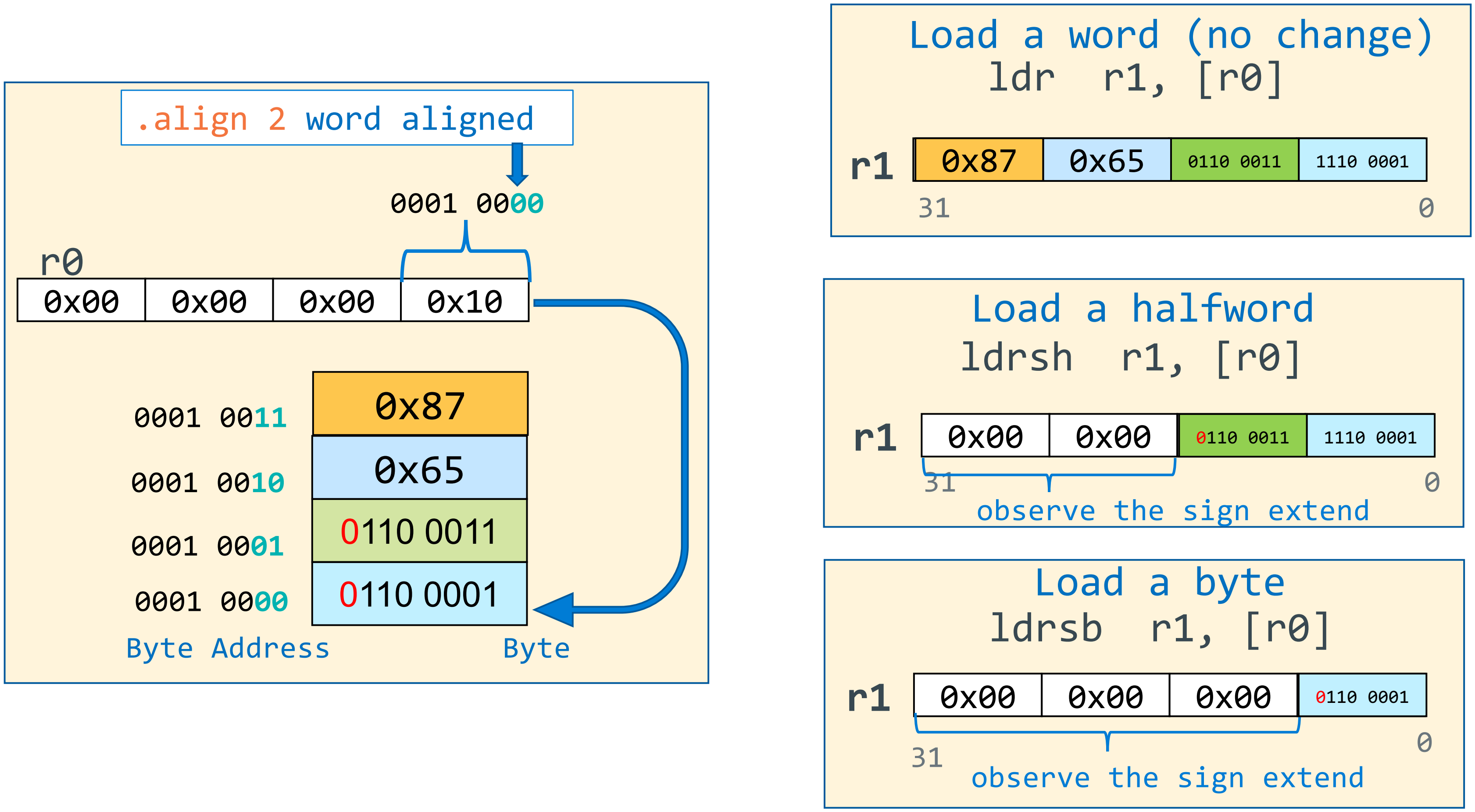






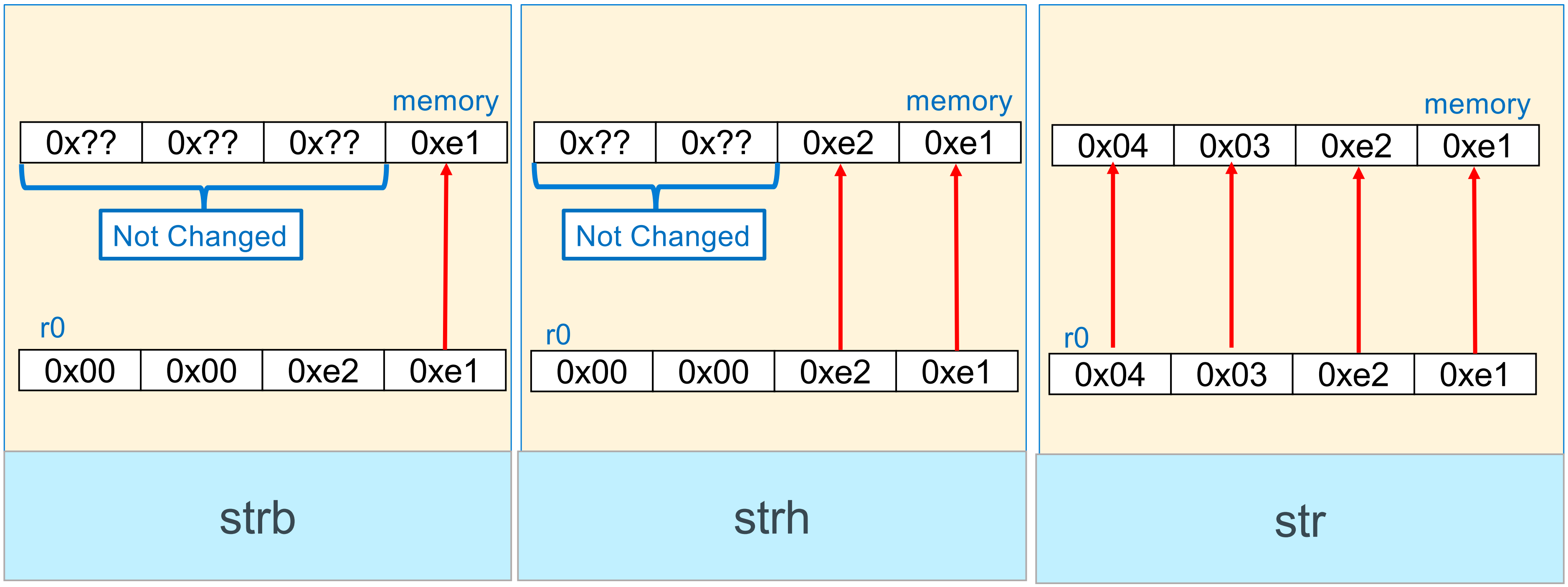


Signed Load a Byte, Half-word, Word



x

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



x

Store a Byte, Half-word, Word

initial value in r0

0x20	0x00	0x00	0x00

Store a byte

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

	31			0
r1	0x87	0x65	0xe3	0xe1

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

observe other bytes NOT altered

Store a halfword

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

	31			0
r1	0x87	0x65	0xe3	0xe1

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

Store a word

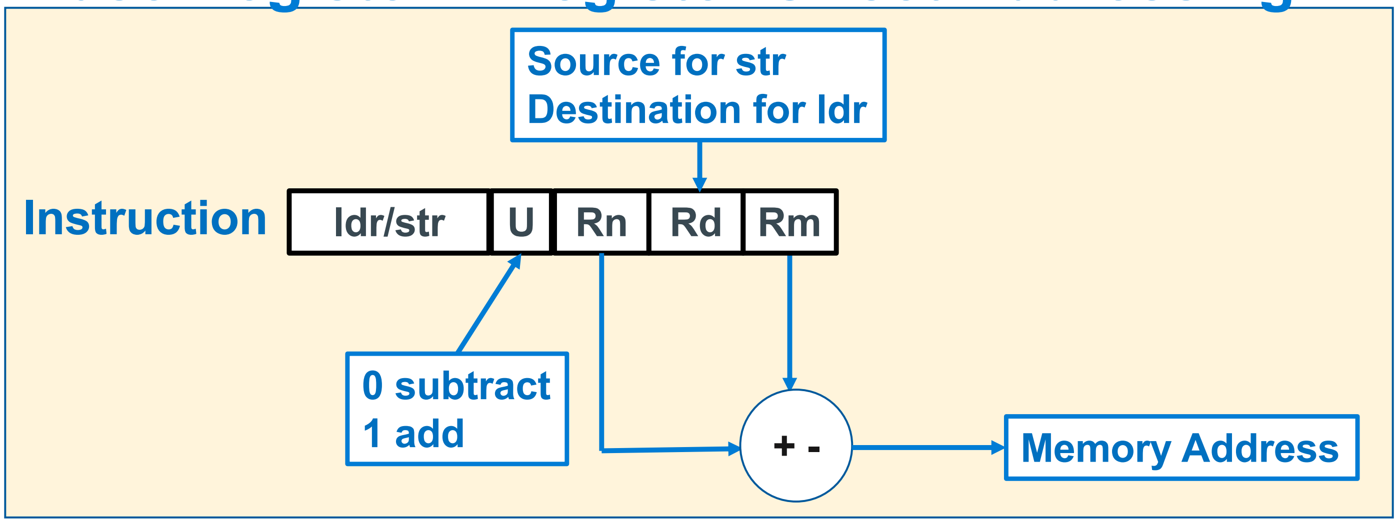
```
str  r1, [r0]
```

	31			0
r1	0x87	0x65	0xe3	0xe1

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

x

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]`

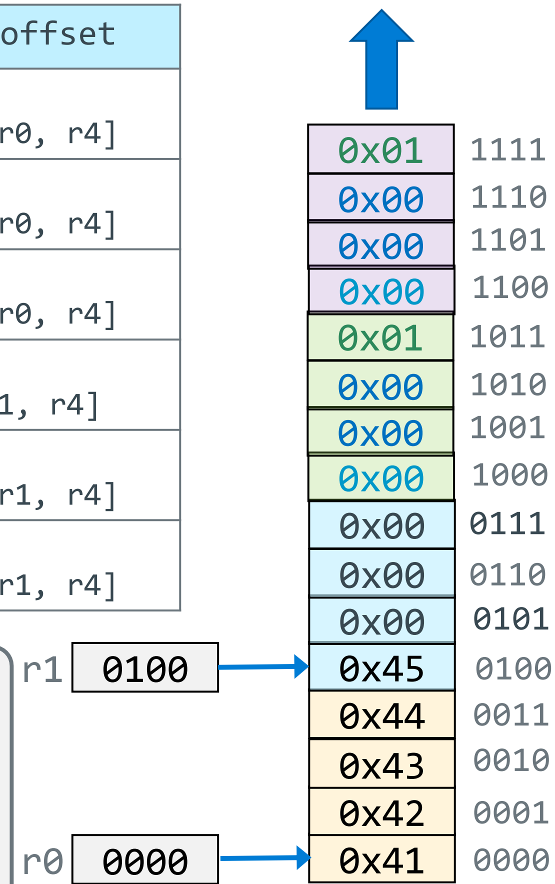
X

Array addressing with ldr/str

Array element	Base addressing	Immediate offset	register offset
ch[0]	ldrb r2, [r0]	ldrb r2, [r0, 0]	mov r4, 0 ldrb r2, [r0, r4]
ch[1]	add r0, r0, 1 ldrb r2, [r0]	ldrb r2, [r0, 1]	mov r4, 1 ldrb r2, [r0, r4]
ch[2]	add r0, r0, 2 ldrb r2, [r0]	ldrb r2, [r0, 2]	mov r4, 2 ldrb r2, [r0, r4]
x[0]	ldr r2, [r1]	ldr r2, [r1, 0]	mov r4, 0 ldr r2, [r1, r4]
x[1]	add r1, r1, 4 ldrb r2, [r1]	ldrb r2, [r1, 4]	mov r4, 4 ldrb r2, [r1, r4]
x[2]	add r1, r1, 8 ldrb r2, [r0]	ldrb r2, [r1, 8]	mov r4, 8 ldrb r2, [r1, r4]

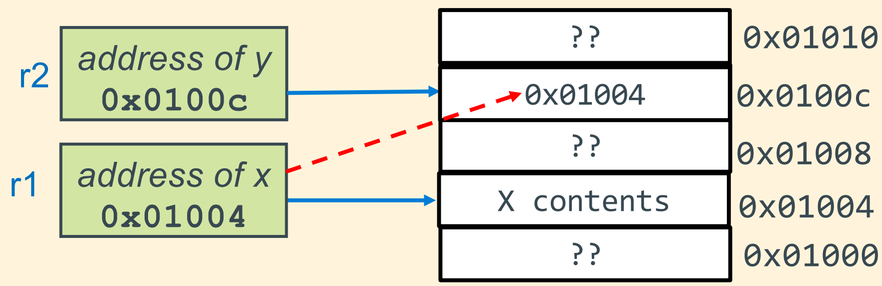
table rows are independent instructions

```
        .data
ch:     .byte 0x41, 0x42, 0x43, 0x44
x:      .word 0x00000045
        .word 0x01000000
        .word 0x01020304
        .text
         ldr    r0, =ch
         ldr    r1, =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
```

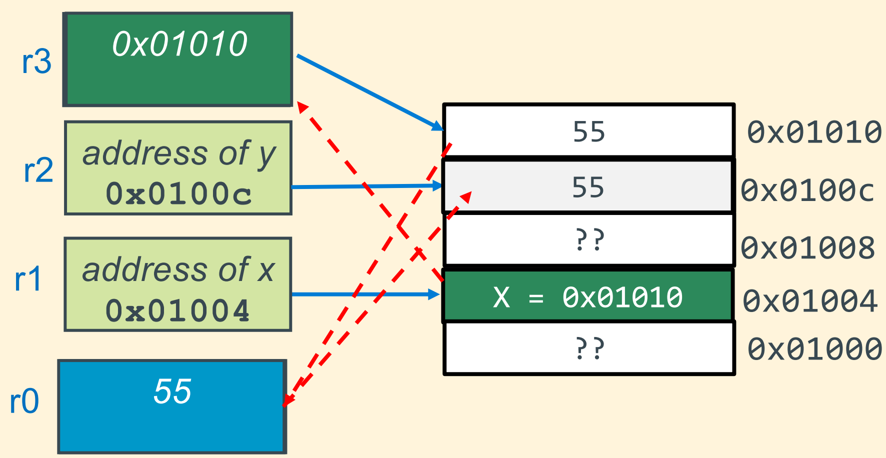

x

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
```

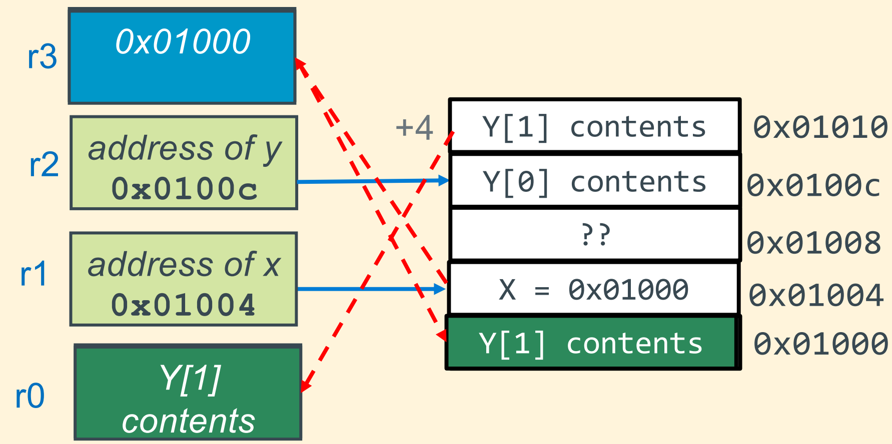

x

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

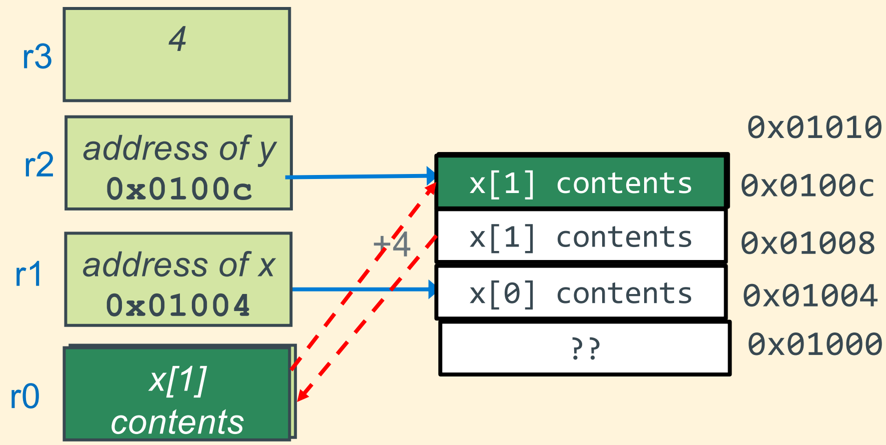
ldr/str practice - 4

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

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

Function Calls, Parameters and Locals: Requirements

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

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

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

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

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

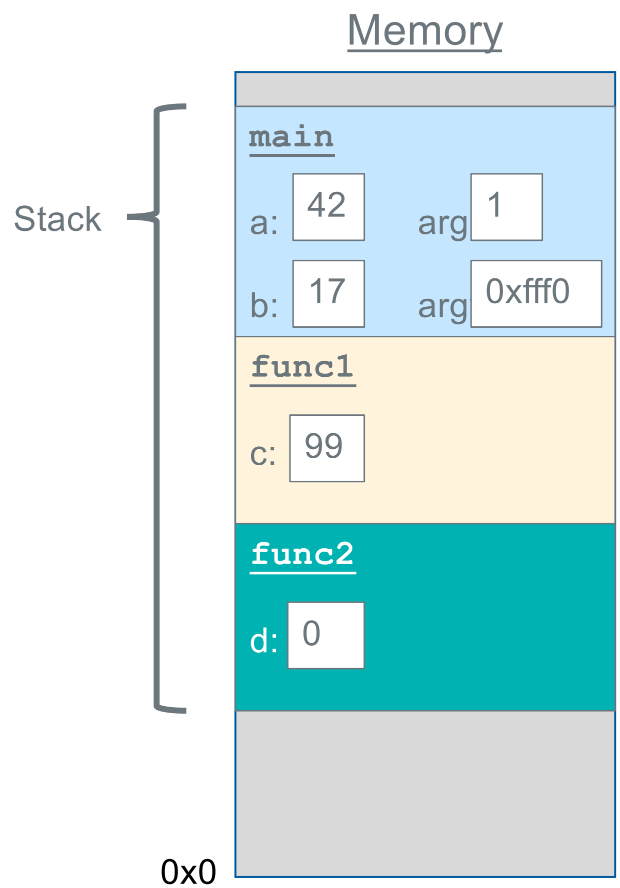
x

The Stack

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

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

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

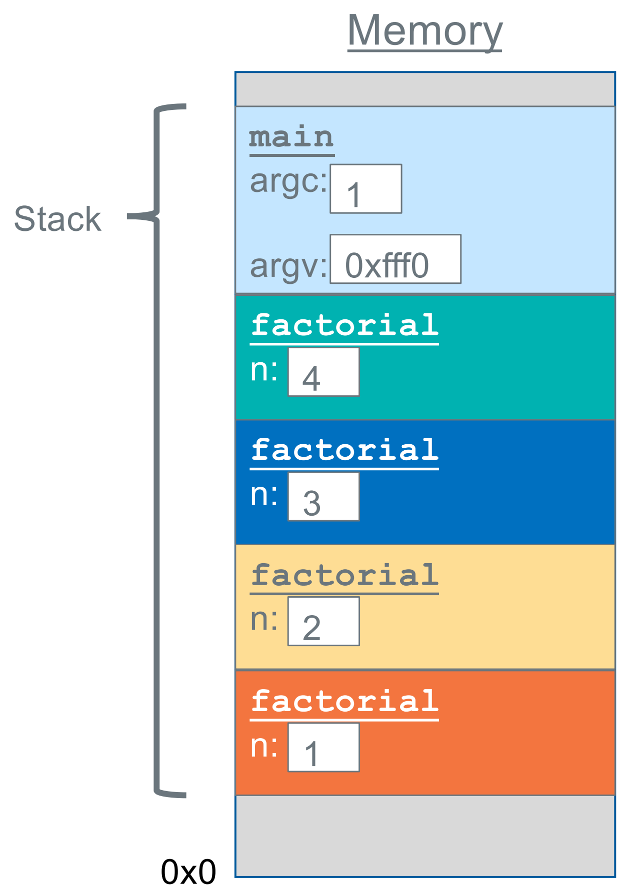


The Stack

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

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

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



Support For Function Calls and Function Call Return - 1

bl	imm24

Branch with Link (function call) instruction

```
bl label
```

- Function call to the instruction with the address `label` (no local labels for functions)
  - imm24 number of instructions from pc+8
- label **any function label** in the current file, or any function label that is defined as .global in any file that it is linked to
- BL **saves** the address of the instruction **immediately** following the **bl** instruction **in register lr** (link register is also known as r14)
- **The contents of the link register is the return address to the calling function**

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

```
main:
  •
bl  f1  ------>  f1:
  •               •
```

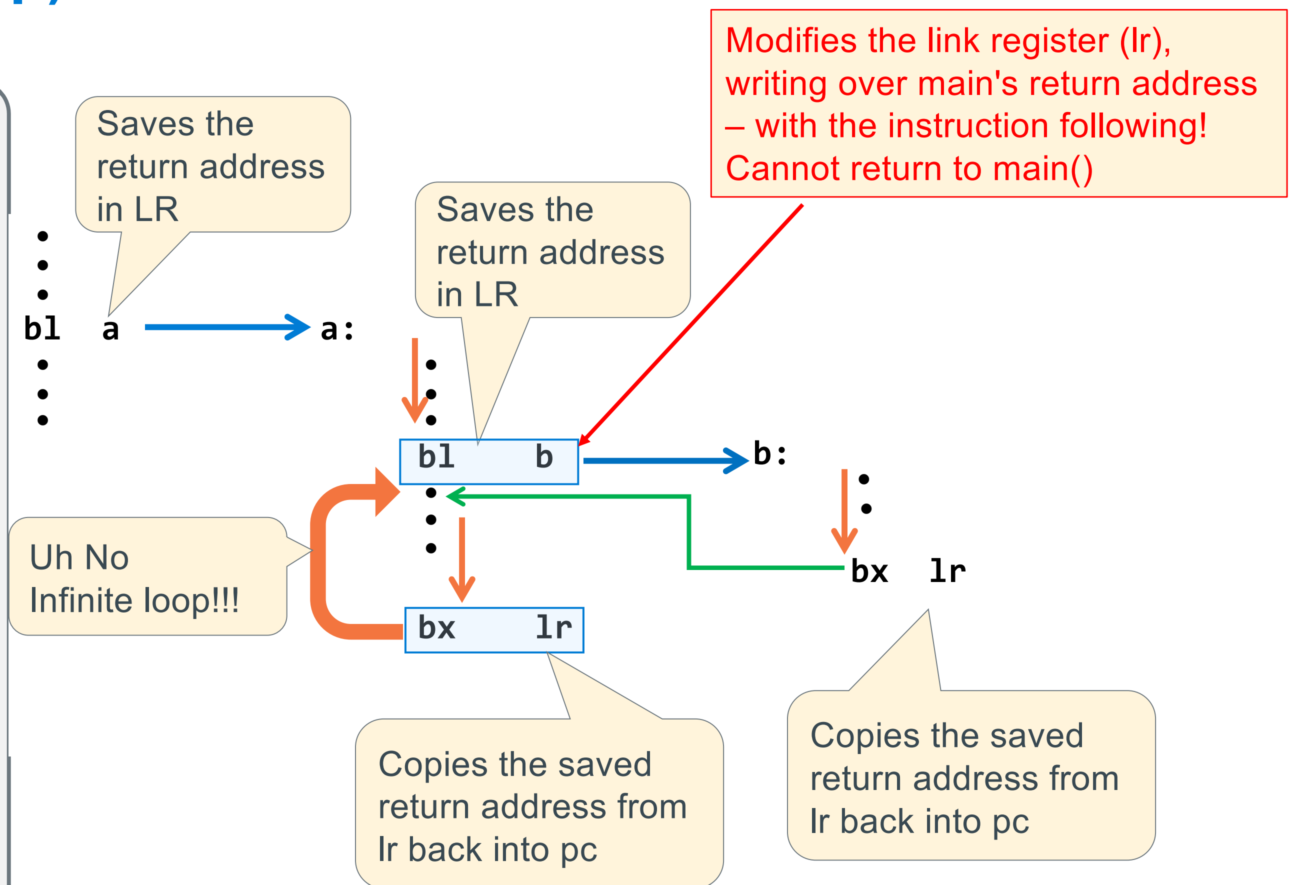

x

Preserving lr (and fp): The Foundation of a stack frame

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

int a(void)
{
    b();
    /* other code */
    return 0;
}

int b(void)
{
    /* other code */
    return 0;
}
```



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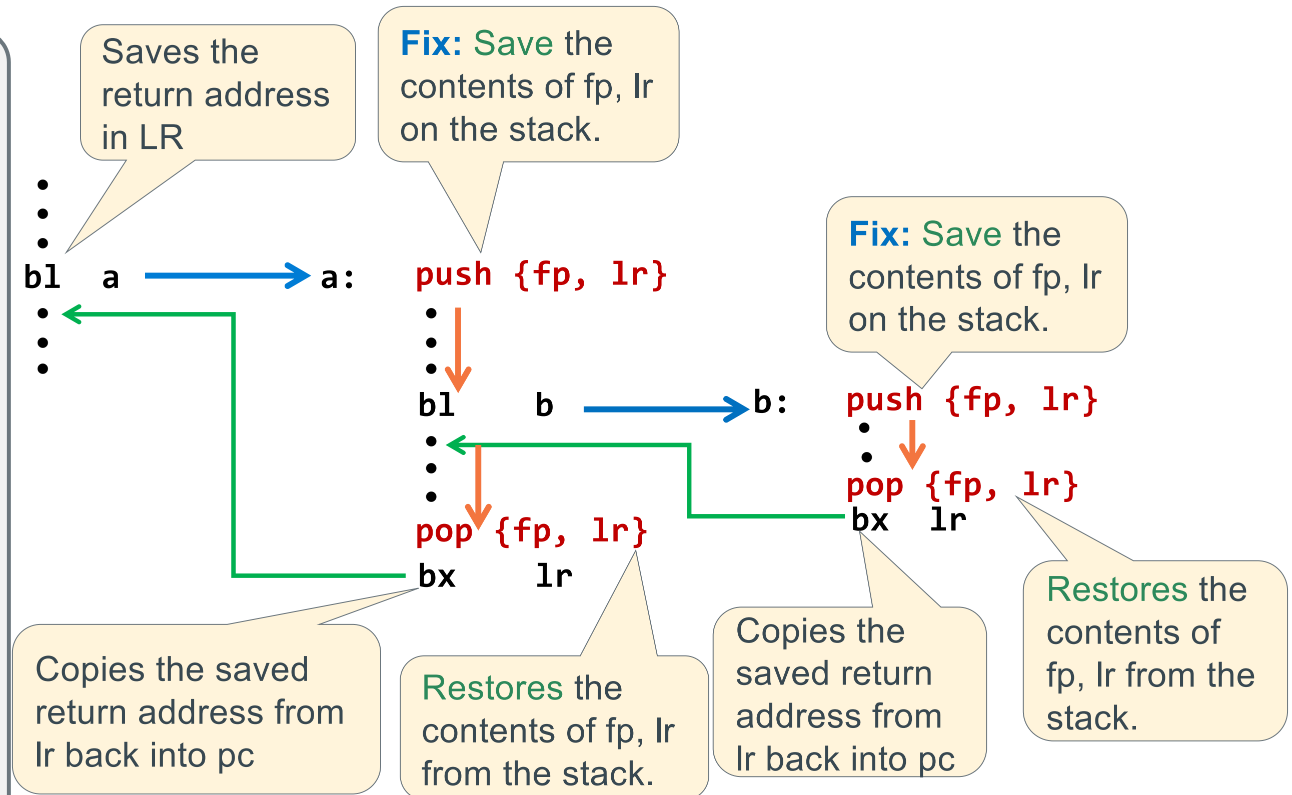
Preserving lr (and fp): The Foundation of a stack frame

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

int a(void)
{
    b();
    /* other code */
    return 0;
}

int b(void)
{
    /* other code */
    return 0;
}
```



The frame pointer is used to find variables on the stack – later

x

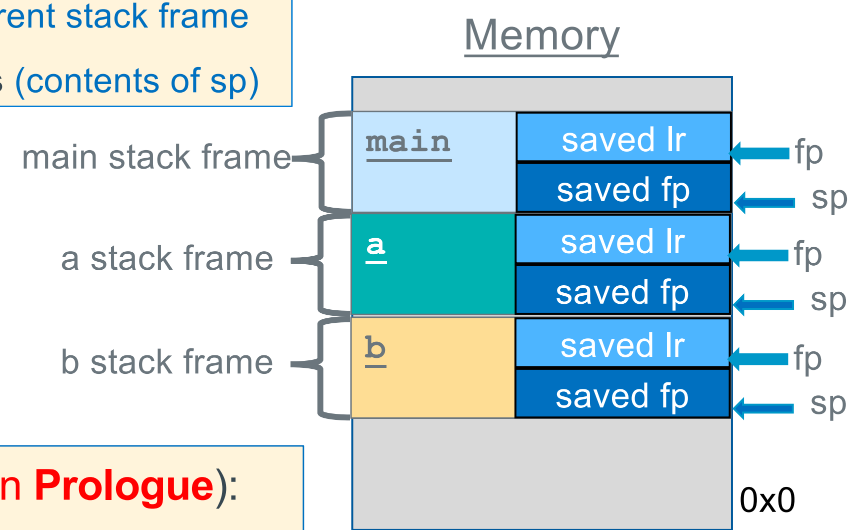
Minimal Stack Frame (Arm Arch32 Procedure Call Standards)

Requirements

- `sp` points at top element in the stack (lowest byte address)
- `fp` points at the `lr` copy stored in the current stack frame
- **Stack frames align to 8-byte addresses** (contents of sp)

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

- Function entry (Function **Prologue**):
  1. creates the frame (subtracts from sp)
  2. saves values
- Function return (Function **Epilogue**):
  1. restores values
  2. removes the frame (adds to sp)



We will see how the fp is used in a few slides

x

Review Return Value and Passing Parameters to Functions

(Four parameters or less)

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

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

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

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

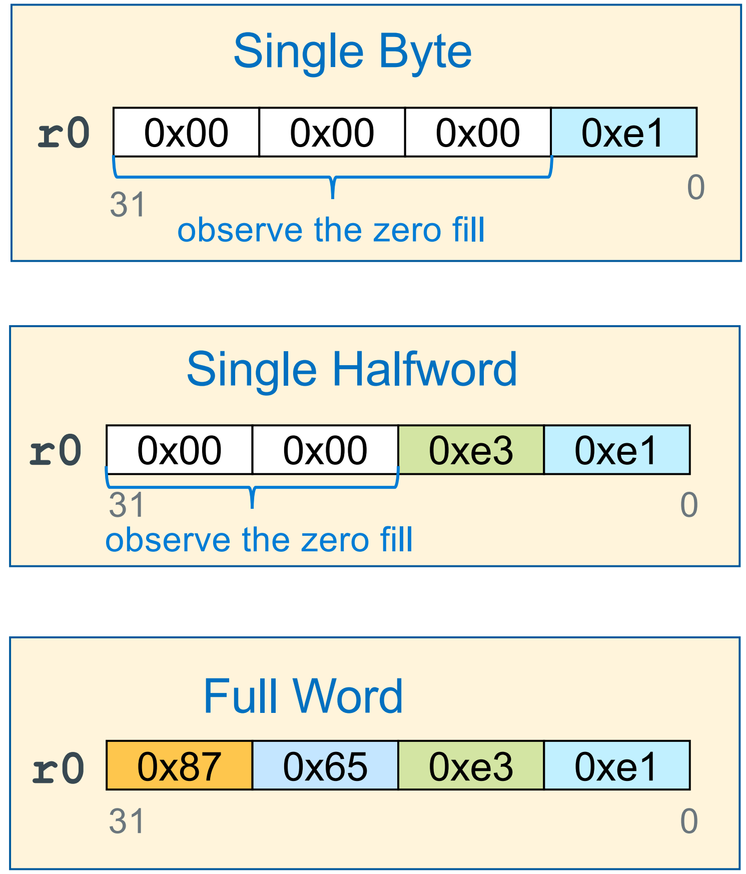
- Each **parameter and return value is limited to data that can fit in 4 bytes or less**
- You receive up to the first four parameters in these four registers
- You copy up to the first four parameters into these four registers before calling a function
- For parameter values using more than 4 bytes,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

X

Argument and Return Value Requirements

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

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



Preserved Registers: Protocols for Use

Register	***Function Call Use***	***Function Body Use***	***Save before use Restore before return***
r4-r10		contents preserved across function calls	Yes
r7	os system call number	contents preserved across function calls	Yes

- **Function Call Spec**:

  Preserved registers **will not be changed** by any function you call

- **Interpretation**: 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

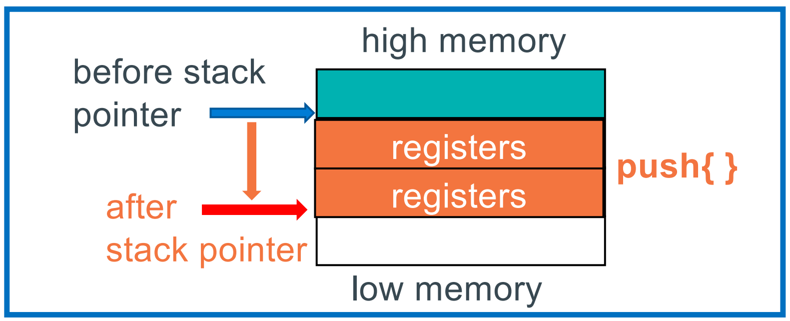
If the function wants to use a preserved register it must:

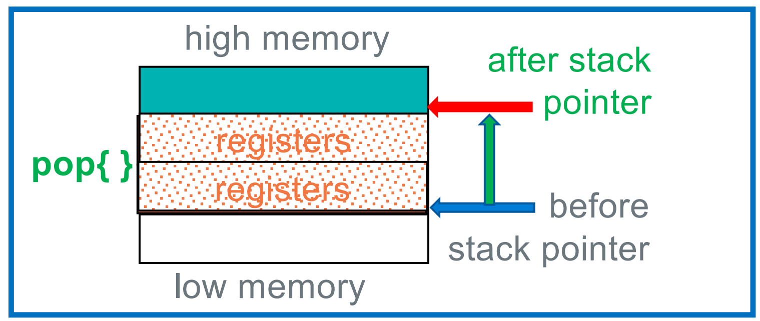
1. *Save* the value contained in the register at function entry
2. Use the register in the body of the function
3. *Restore* the original saved value to the register at function exit (before returning to the caller)

x

Preserving and Restoring Registers on the Stack
Used at Function entry and exit

Operation	*Pseudo Instruction (Use in CSE30)*	ARM instruction (reference only)	*Operation*
Push registers onto stack Function entry	push *{reg list}*	`stmfd sp!, {reg list}`	`sp ← sp – 4 × #registers` `Copy registers to mem[sp]`
Pop registers from stack Function Exit	pop *{reg list}*	`ldmfd sp!, {reg list}`	`Copy mem[sp] to registers,` `sp ← sp + 4 × #registers`





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Preserving and Restoring Registers on the Stack
Function entry and Function exit

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

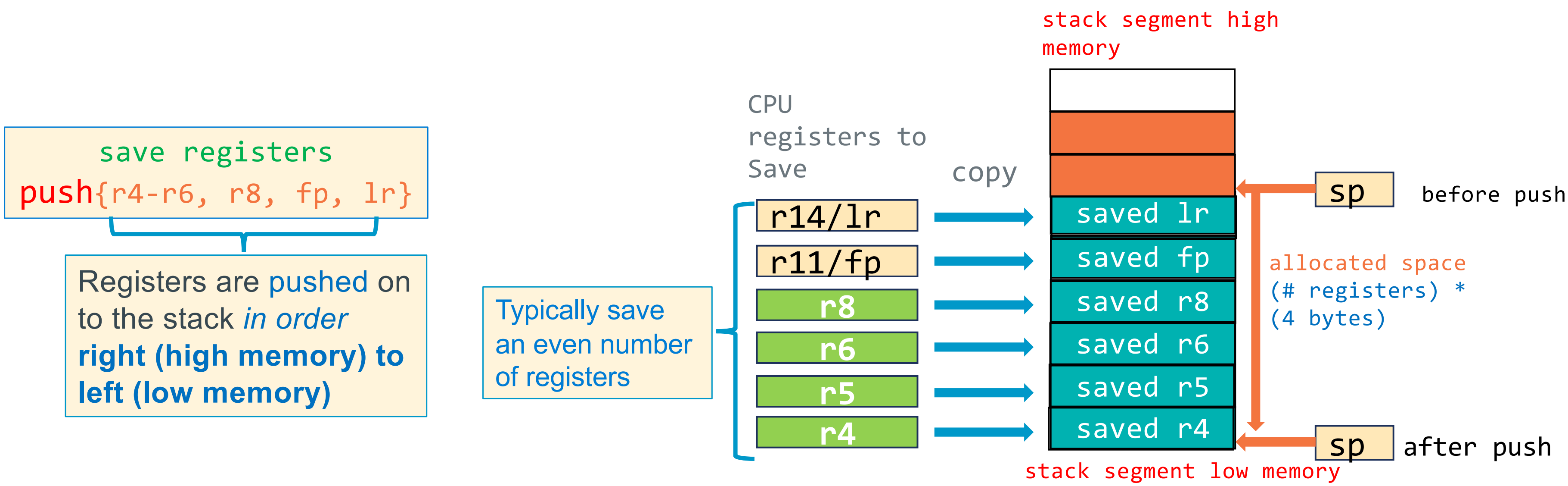
- Where **`{reg list}`** is a **list of registers** in numerically increasing order

  example: `push {r4-r10, fp, lr}`

- Registers cannot be: (1) duplicated in the list, nor be (2) listed out of numeric order
- Register ranges can be specified `{r4, r5, r8-r11, fp, lr}`

x

push: Multiple Register Save



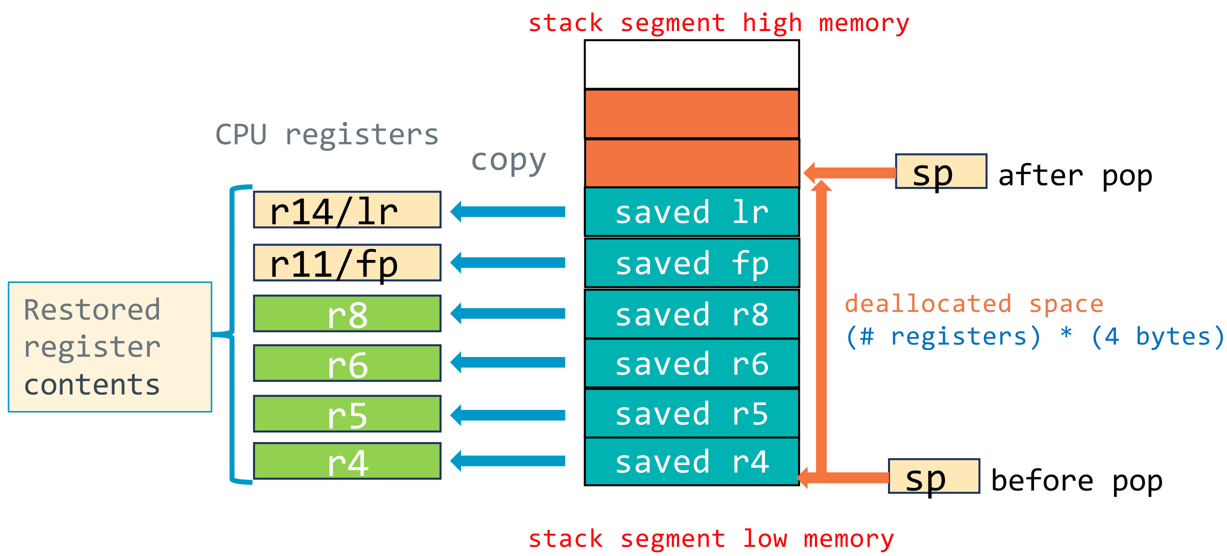
- `push` copies the contents of the `{reg list}` to stack segment memory
- `push` **Also** subtracts (# of registers saved) * (4 bytes) from the `sp` to *allocate* space on the stack
  - sp = sp – (# registers_saved * 4)

x

pop: Multiple Register Restore

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

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



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

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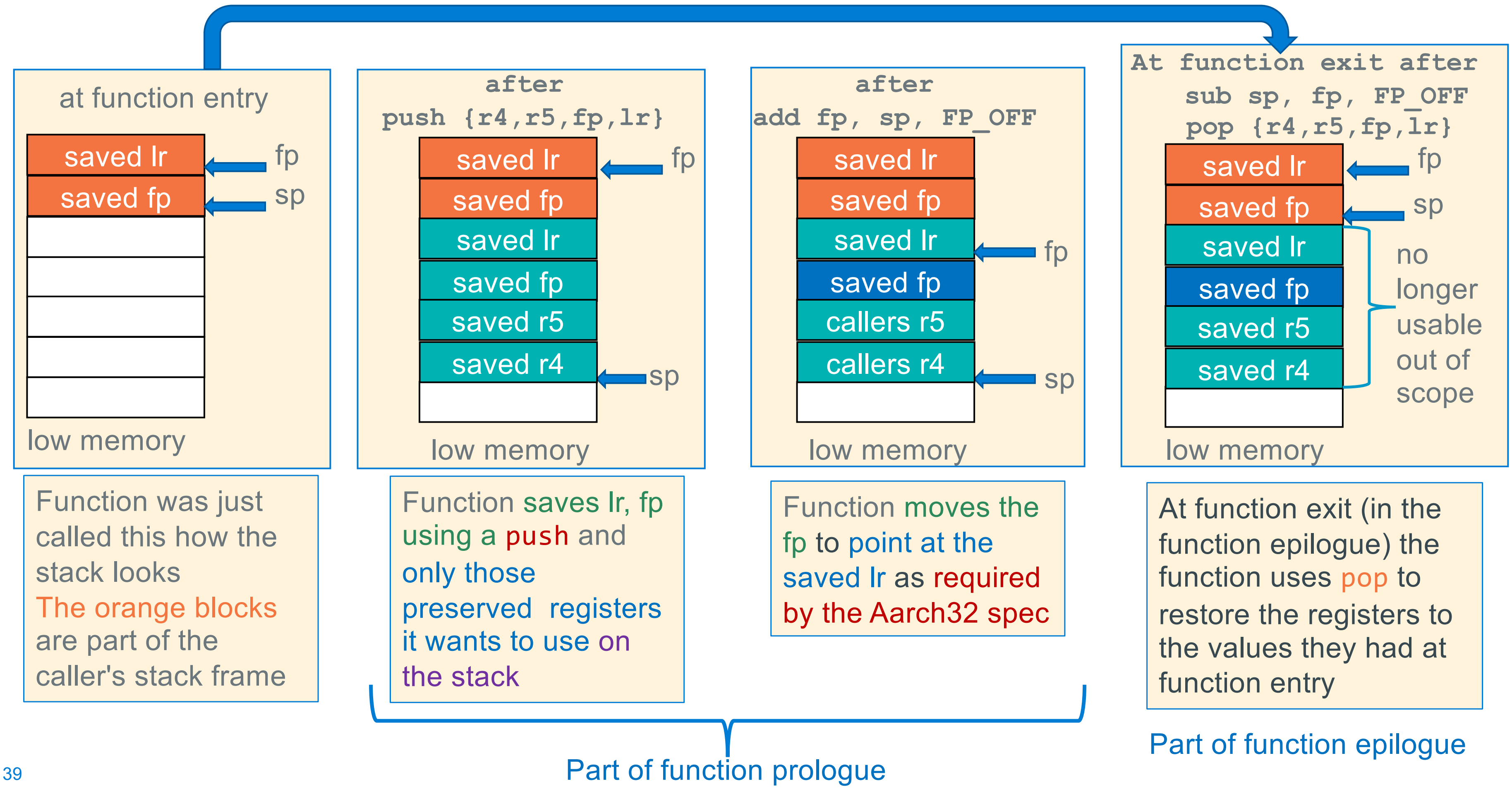
Saving/Restoring Preserved Registers At Function entry/exit



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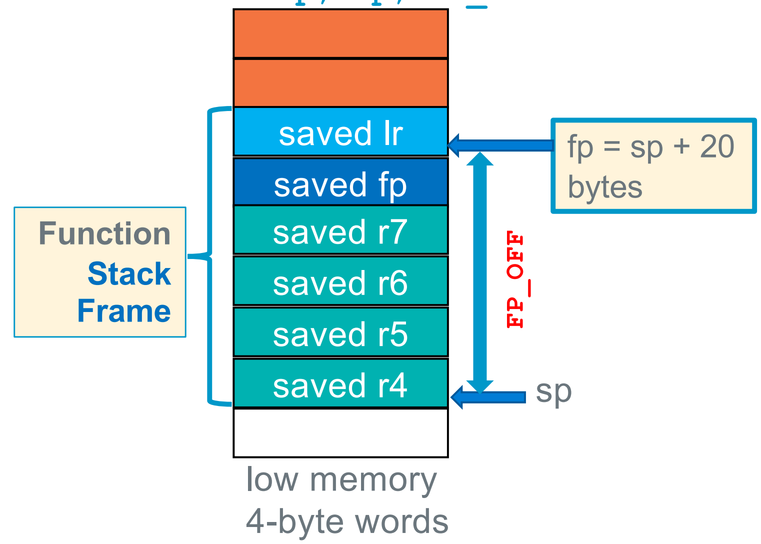
Setting FP_OFF: Distance from FP to SP

```
    // 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
```

always at top of function saves regs and **sets fp**

always at bottom of function **restores regs including the sp**

after push {r4-r7,fp,lr}
add fp, sp, FP_OFF



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

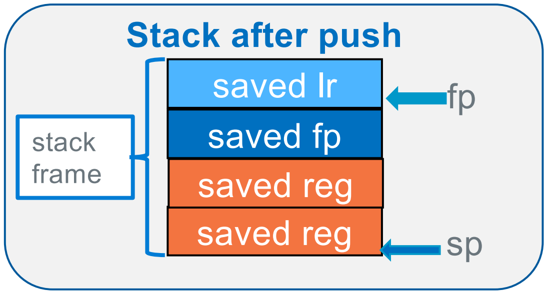
```
FP_OFF = (#regs - 1)*4 // -1 is lr offset from sp

Where # regs = #preserved + lr + fp
```

Means Caution, odd number of regs!

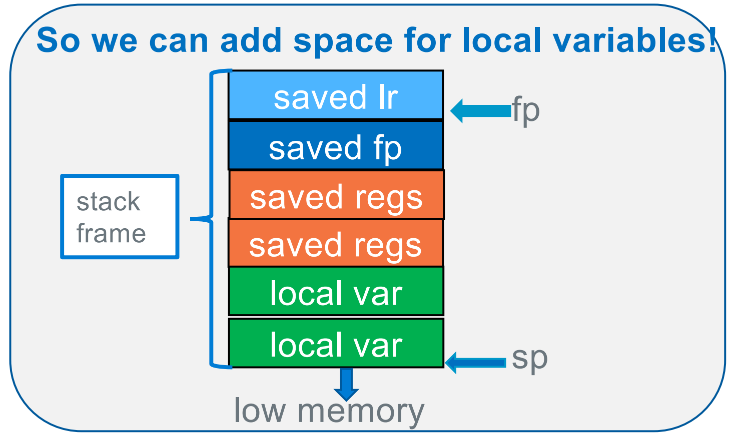
x

Why is there a `sub, fp, FP_OFF ?`




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

- As you will see, we will move the sp to allocate space on the stack for local variables and parameters, so for the pop to restore the registers correctly:
- `sp` must point at the last saved preserved register put on the stack bay the save register operation: the `push`




```
    .equ    FRMSZ, 8
    push    {fp, lr}
    add     fp, sp, FP_OFF
    sub     sp, sp, FRMSZ
// your code

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

    bx      lr  // func return
```

- force the **`sp`** (using the **`fp`**) to contain the same address it had after the push operation
  `sub sp, fp, FP_OFF`

x

Variable Alignment on Stack

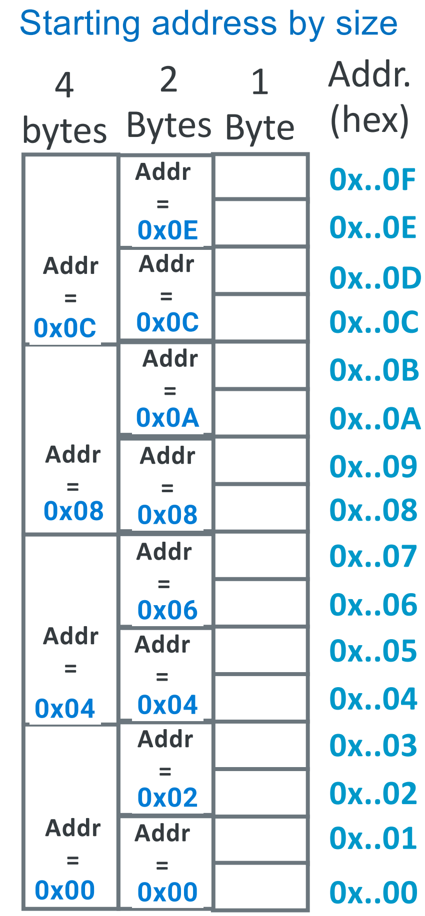
integer/pointer: 4 bytes

short: 2 bytes

char: 1

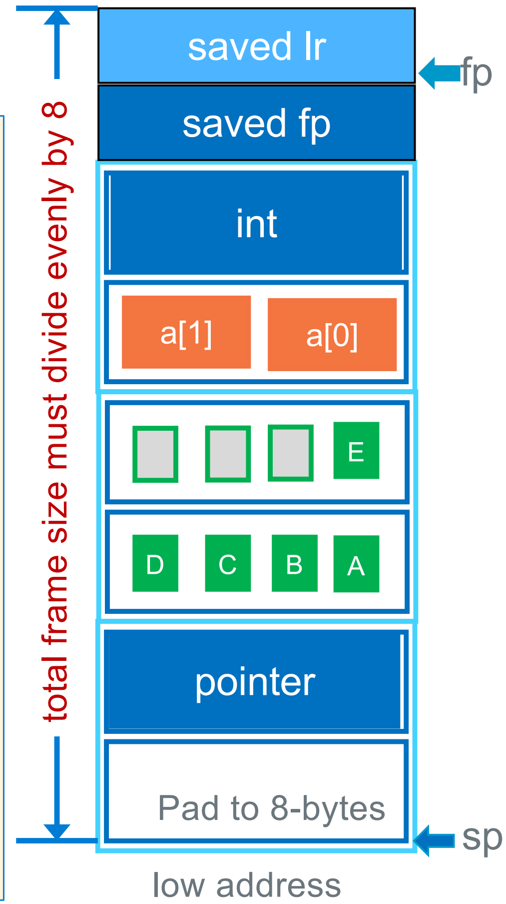
Variable Type/Size	Address ends in
`8-bit char -1 byte`	`0b..0 or 0b..1`
`16-bit int -2 bytes`	`0b..0`
`32-bit int -4 bytes`	`0b..00`
`32-bit pointer -4 bytes`	`0b..00`

- Starting address alignment requirements for local variables stored on the stack is just like static variables
- sp must be aligned to 8-bytes at function entry & exit
  - contents of sp always ends in `0b..000` at function entry
- Approach we will take (also what compilers often do): allocate all the local variable space as part of the function prologue
  - Aside: You cannot use .align as assembly directives are for fixed address



Overview: Stack Frame Alignment Rules

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



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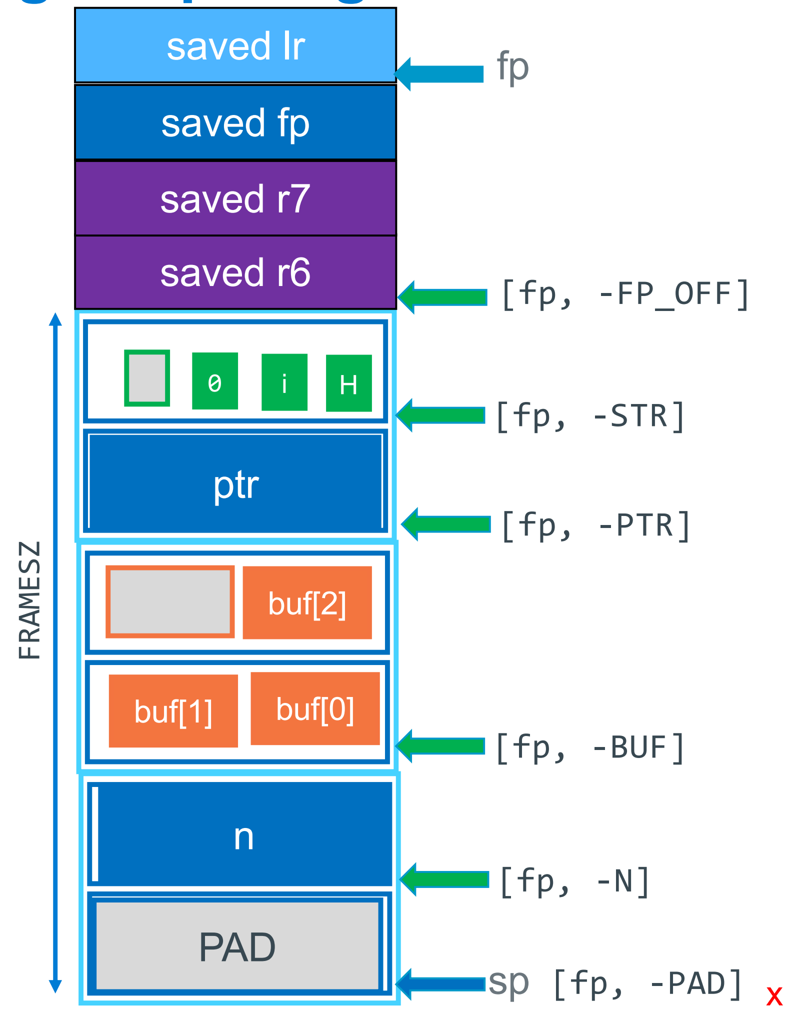
Stack Frame Design – Step 4 Modifying the prologue

Distance Offsets from fp

```
        .equ   FP_OFF,        12  // local base
           // NAME,           SIZE + prev_name
        .equ   STR,           4 + FP_OFF
        .equ   PTR,           4 + STR
        .equ   BUF,           8 + PTR
        .equ   N,             4 + BUF
        .equ   PAD,           4 + N
        .equ   FRAMESZ        PAD - FP_OFF
```

```
main:
   push    {r6, r7, fp, lr}
   add     fp, sp, FP_OFF
   sub     sp, sp, FRAMESZ // add for locals
   // no change to epilogue
```

variable	arm ldr/str statement examples
n	ldr/str r0, [fp, -N]
buf[1]	ldrh/strh r0, [fp, -BUF + 2]
&(str[0])	sub r0, fp, STR

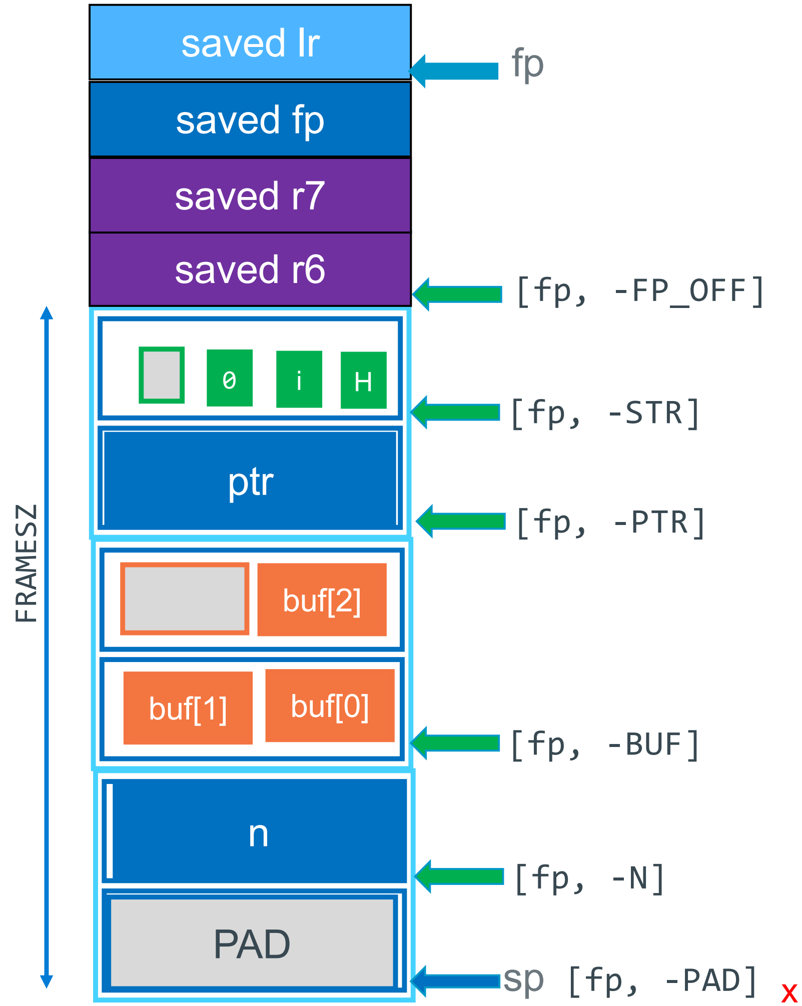


Stack Frame Design – Step 5 Initialize the variables

```
char str[] = "Hi";
char *ptr = str;
short buf[3];
// other code
int n = 0;
// other code
```

Used in PA5

```
main:
        push    {r6, r7, fp, lr}
        add     fp, sp, FP_OFF
        sub     sp, sp, FRAMESZ
        sub     r6, fp, STR      // &(str[0])
        str     r6, [fp, -PTR]
        mov     r6, 'H'
        strb    r6, [fp, -STR]
        mov     r6, 'i'
        strb    r6, [fp, -STR+1]
        mov     r6, 0
        strb    r6, [fp, -STR+2]
       // other code
        mov     r6, 0
        str     r6, [fp, -N]
```

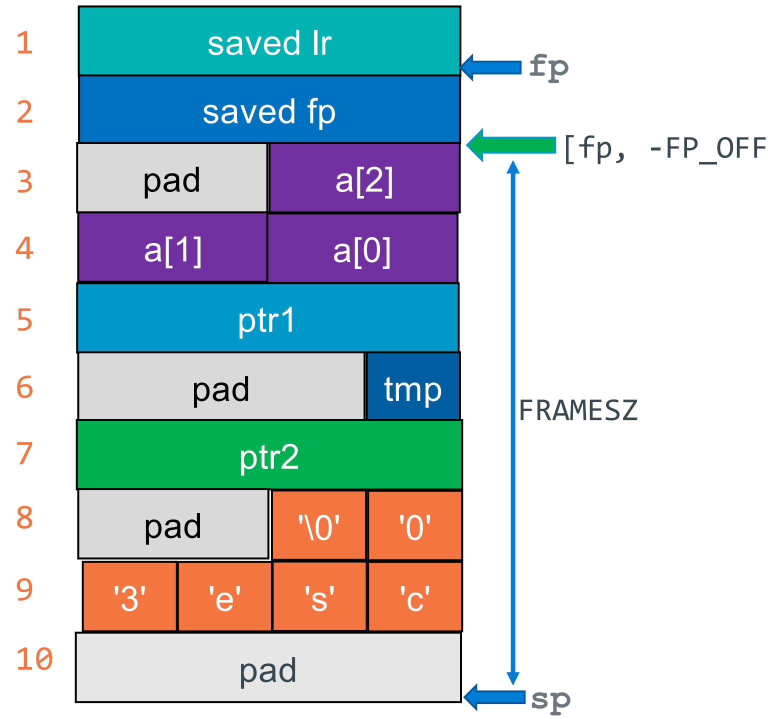


Local Variables: Stack Frame Design Practice

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

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

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



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

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

x

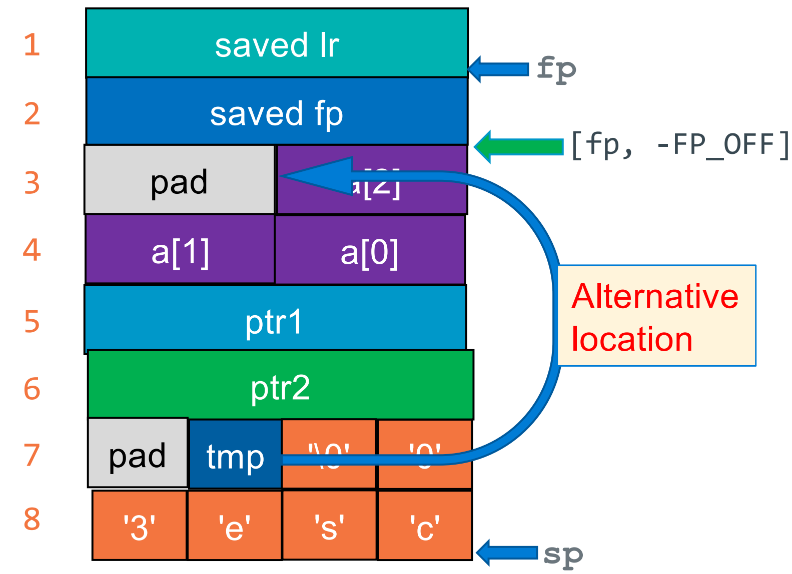
Local Variables: Stack Frame Design Reordering

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

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

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

size change

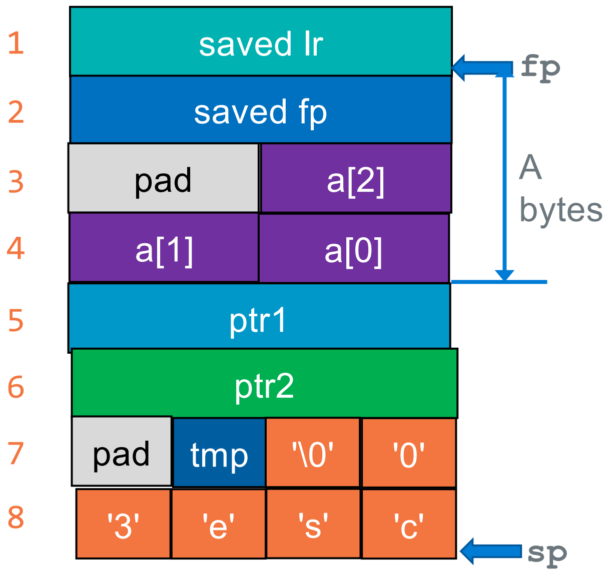


When writing real code, you do not have to put all locals on the stack

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

x

Entire source file



	Evaluated into r0
`&(a[1])`	`sub  r0, fp, A - 2`
`&(a[1])`	`add  r0, fp, -A + 2`
`&(nm[1])`	`add  r0, fp, -NM + 1`
`ptr2`	`add  r0, fp, -PTR2`

```
        .arch armv6
        .arm
        .fpu vfp
        .syntax unified
         // globals etc here
        .text
        .type      doit, %function
        .global    doit
        .equ       EXIT_SUCCESS, 0
        .equ       FP_OFF,   4  // Local base
        .equ       A,        8 + FP_OFF
        .equ       PTR1,     4 + A
        .equ       PTR2,     4 + PTR1
        .equ       TMP,      2 + PTR2
        .equ       NM,       6 + TMP
        .equ       PAD,      0 + NM
        .equ       FRAMESZ   PAD - FP_OFF
doit:
        push    {fp, lr}
        add     fp, sp, FP_OFF
        sub     sp, sp, FRAMESZ
        // doit() code goes here
        mov     r0, EXIT_SUCCESS

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

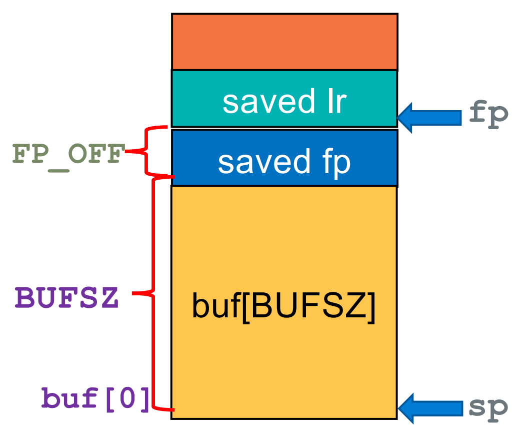
```
With large frames you may
need to use ldr if the
immediate value FRAMESZ
does not fit in imm8 (r3
is not a parameter in this
example)
ldr     r3, =FRAMESZ
sub     sp, sp, r3
```

Passing an Output Parameter

```
#define BUFSZ 256
int main(void)
{
  char buf[BUFSZ];
  if (fgets(buf, BUFSZ, stdin) != NULL)
    printf("%s", buf);
  return EXIT_SUCCESS;
}
```

char *fgets(char *s, int size, FILE *stream);

returns *s or NULL   r0,   r1,   r2




```
if the immediate value
of BUF does not fit in
imm8
ldr     r0, =BUF
sub     r0, fp, r0

if the immediate value
of BUFSZ does not fit in
imm8
ldr     r1, =BUFSZ
```

```
        .extern printf
        .extern fgets
        .extern stdin
        .section .rodata
.Lpfstr .string  "%s"
        .text
        // function header stuff not shown
        .equ    BUFSZ,      256
        .equ    FP_OFF,     4
        .equ    BUF,        BUFSZ + FP_OFF
        .equ    FRAMESZ,    BUF - FP_OFF
main:
        push    {fp, lr}
        add     fp, sp, FP_OFF
        sub     sp, sp, FRAMESZ
        sub     r0, fp, BUF
        mov     r1, BUFSZ
        ldr     r2, =stdin
        ldr     r2, [r2]
        bl      fgets
        cmp     r0, NULL
        beq     .Ldone
        mov     r1, r0
        ldr     r0, =.Lpfstr
        bl      printf
.Ldone: // rest of file not shown
```

stdin is a global variable pointer *FILE

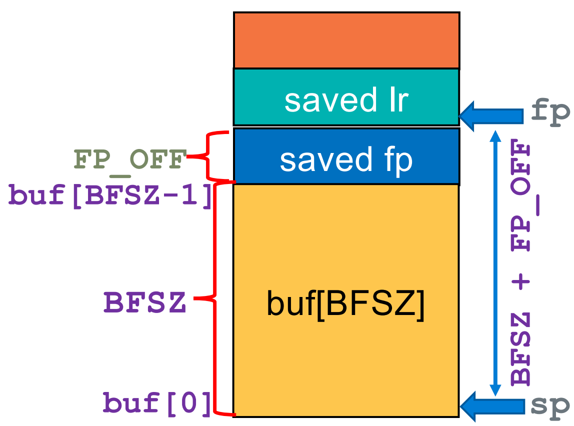
```
r0 = &(buf[0]);
r1 = BUFSZ;
r2 = stdin
```

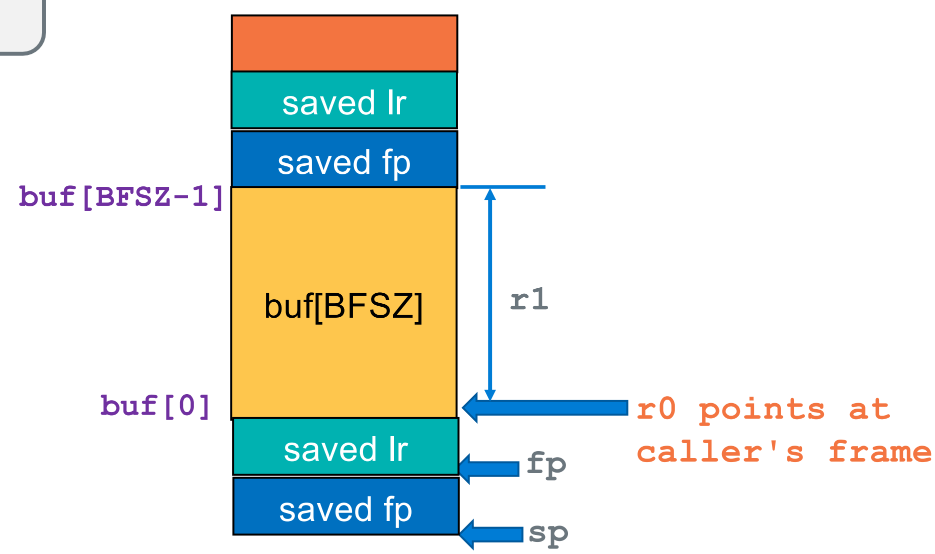

x

Writing Functions: Receiving an Output Parameter - 1

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

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

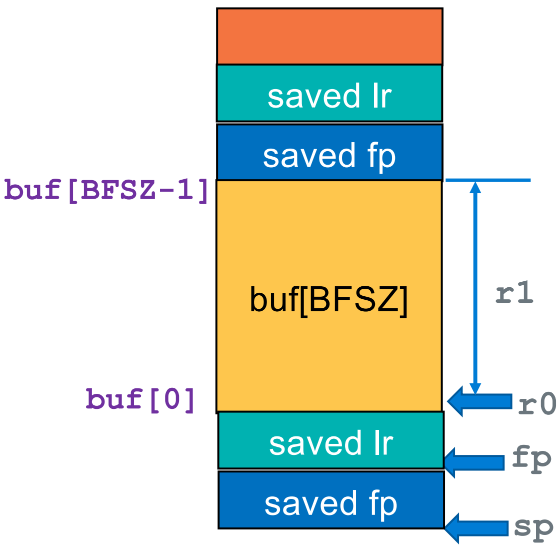




x

Writing Function: Receiving an Output Parameter - 2

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



Using r1 for endptr

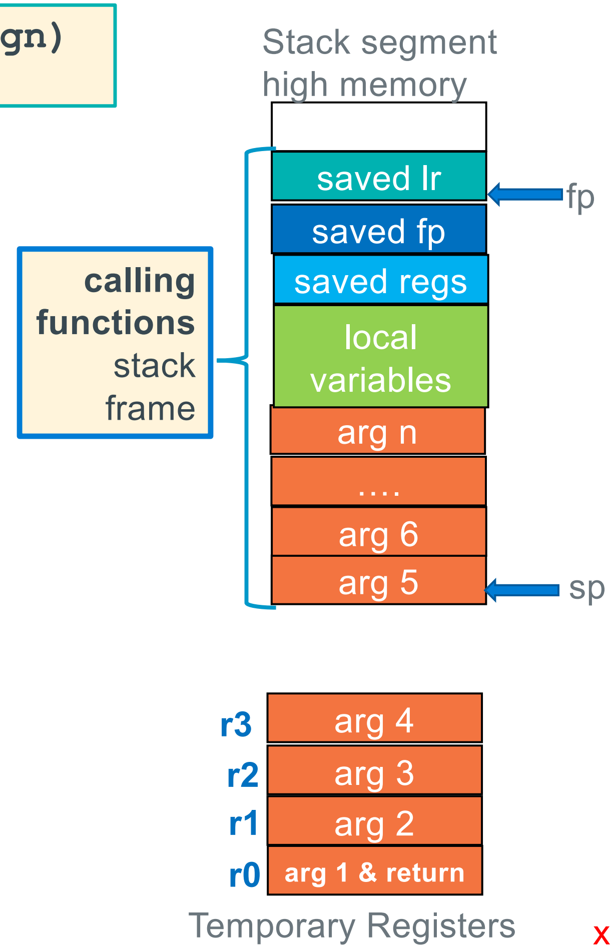
```
fillbuf:
    push    {fp, lr}        // stack frame
    add     fp, sp, FP_OFF  // set fp to base

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

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

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


x

Passing More Than Four Arguments - 1

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

- Each argument is a value that must fit in 32-bits
- **Args > 4 are in the caller's stack frame and arg 5 always starts at fp+4**
  - At the function call (bl) sp points at arg5
  - Additional args are higher up the stack, with one argument "slot" every 4-bytes
- Called functions have the right to change stack args just like they can change the register args!
- Caller must assume all args including ones on the stack are changed by the caller



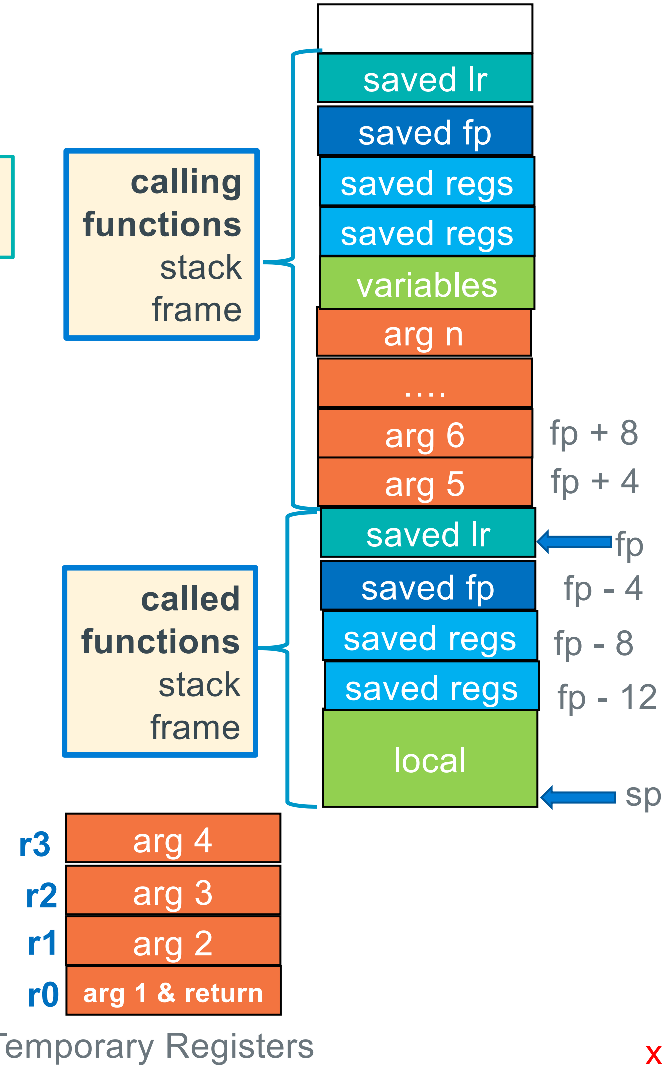
x

Passing More Than Four Arguments - 2

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

- **Addressing rules**
  - Adding to fp to get arg address in caller's frame
  - Subtracting from fp are addresses in called frame
- Why does it work this way?
- This "algorithm" for finding args was designed to enable languages to have variable argument count functions like:

```
printf("conversion list", arg0, … argn);
```



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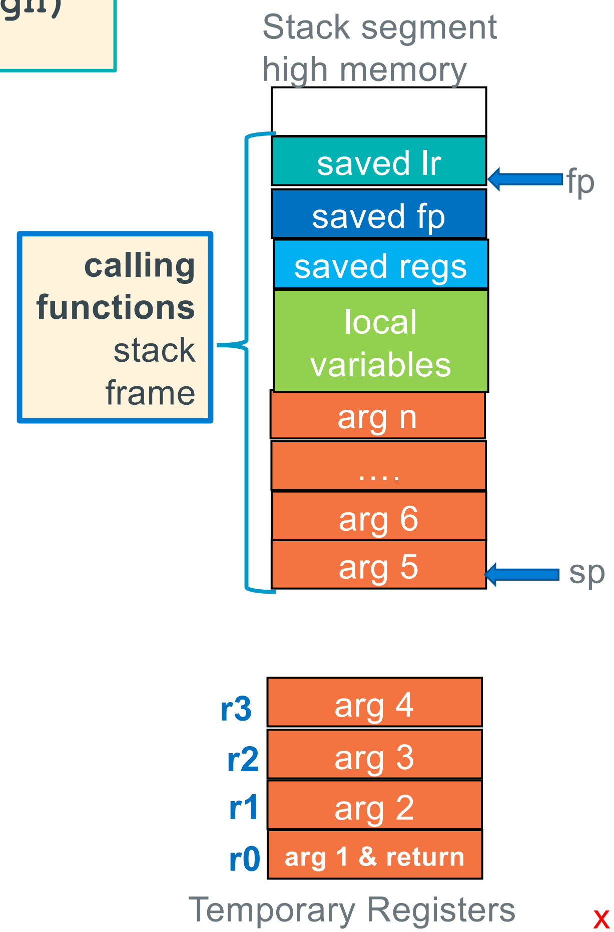
Passing More Than Four Arguments – Calling Function

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

- Calling function prior to making the call
  1. Evaluate first four args: place resulting values in r0-r3
  2. Arg 5 and greater are evaluated
  3. Store Arg 5 and greater parameter values on the stack
- **One arg value per slot!** – NO arrays in a slot
- chars, shorts and ints are directly stored
- Structs (not always), arrays are passed via a pointer
- **Pointers** passed as output parameters usually contain an address ***that points at*** the stack, BSS, data, or heap



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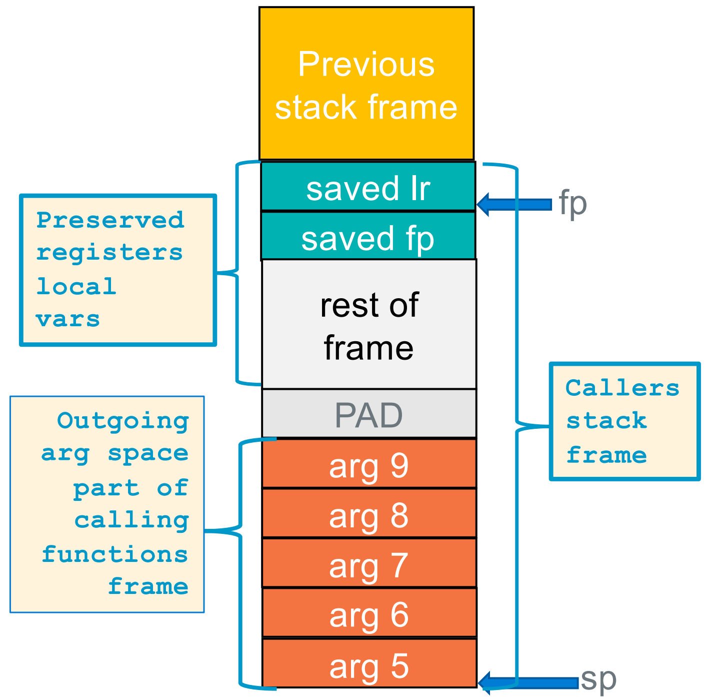
Calling Function: Allocating Stack Parameter Space

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

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

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

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



Rules: At point of call
1. **arg5 must be pointed at by sp**
2. **SP must be 8-byte aligned**

x

Passing More than Four Args – Six Arg Example

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

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

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

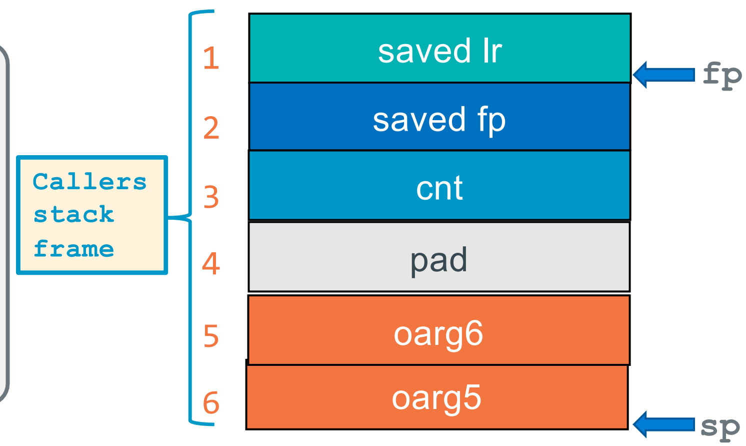
```
int
sixsum(int a1, int a2, int a3, int a4, int a5, int a6)
{
    return a1 + a2 + a3 + a4 + a5 + a6;
}
```


x

Calling Function > 4 Args - 1

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

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



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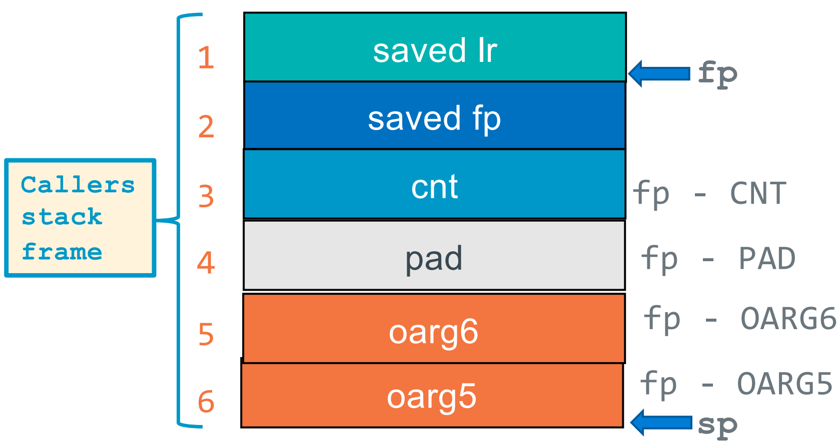
Calling Function > 4 Args - 2

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

```
.equ   FP_OFF,        4
.equ   CNT,           4 + FP_OFF
.equ   PAD,           4 + CNT
.equ   OARG6,         4 + PAD
.equ   OARG5,         4 + OARG6
.equ   FRAMESZ        OARG5 – FP_OFF
```




```
main:
    push    {fp, lr}
    add     fp, sp, FP_OFF
    sub     sp, sp, FRAMESZ

    mov     r0, 6
    str     r0, [fp, -OARG6]
    mov     r0, 5
    str     r0, [fp, -OARG5]
    mov     r3, 4
    mov     r2, 3
    mov     r1, 2
    mov     r0, 1
    bl      sixsum
    str     r0, [fp, -CNT]
    mov     r1, r0
    ldr     r0, =.Lpfstr
    bl      printf

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

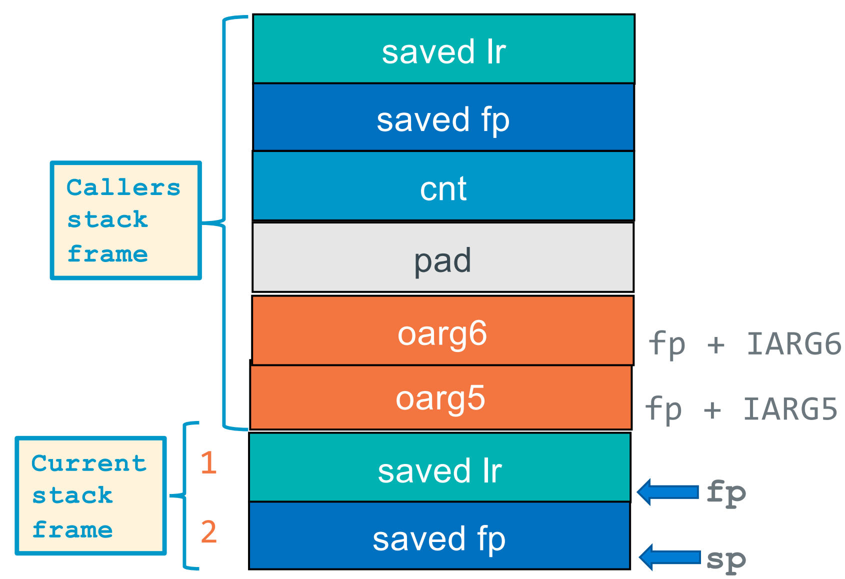

x

Called Function > 4 Args

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

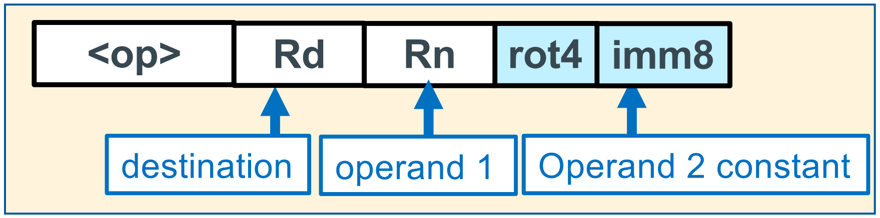
```
.equ   IARG6,        8 // offset into caller's frame
.equ   IARG5,        4 // offset into caller's frame
.equ   FP_OFF,       4 // local base
```

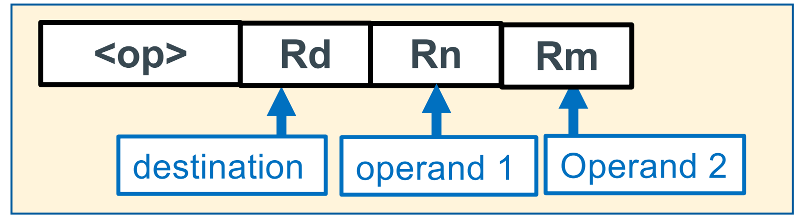
```
sixsum:
        push    {fp, lr}
        add     fp, sp, FP_OFF
        add     r0, r0, r1
        add     r0, r0, r2
        add     r0, r0, r3
        ldr     r1, [fp, IARG5]
        add     r0, r0, r1
        ldr     r1, [fp, IARG6]
        add     r0, r0, r1
        sub     sp, fp, FP_OFF
        pop     {fp, lr}
        bx      lr
```



X

Bitwise Instructions





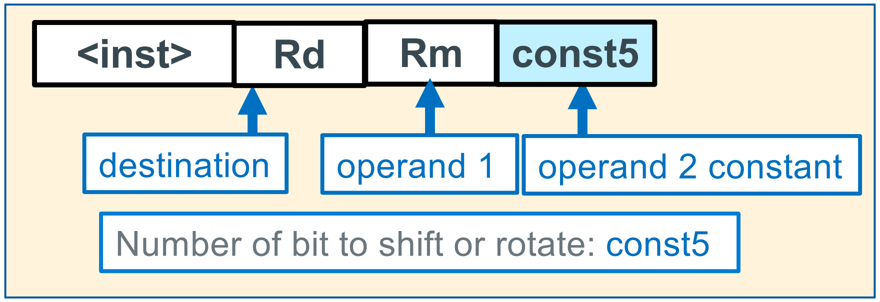

```
<op>  Rd,  Rn, constant   // Rd = Rn <op> constant
<op>  Rd,  constant       // Rd = Rd <op> constant
<op>  Rd,  Rn,  Rm        // Rd = Rn <op> Rm
```

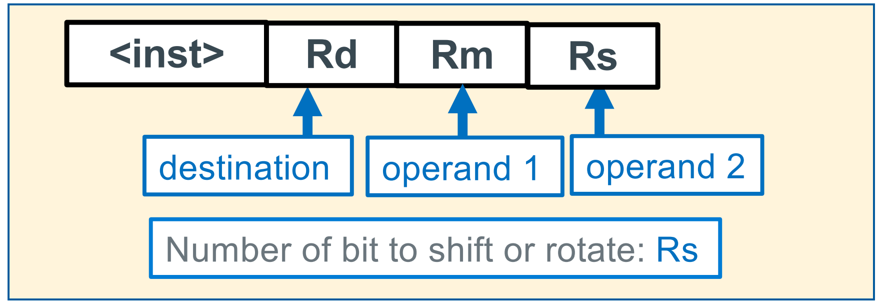
Bytes: 0 <= imm8 <= 255 + values from "rotating" rot 4 bits

Bitwise <op> description	*<op> Syntax*	*Operation*
Bitwise **AND**	`and` R_d, R_n, Op2	$R_d \leftarrow R_n$ & Op2
Bit Clear each bit in Op2 that is a 1, the same bit in R_d, is cleared	`bic` R_d, R_n, Op2	$R_d \leftarrow R_n$ & ~Op2
Bitwise **OR**	`orr` R_d, R_n, Op2	$R_d \leftarrow R_n$ | Op2
Exclusive **OR**	`eor` R_d, R_n, Op2	$R_d \leftarrow R_n$ ^ Op2

x

Shift and Rotate Instructions





Instruction	*Syntax*	*Operation*	*Notes*	*Diagram*
Logical Shift Left	LSL R_d, R_m, *const5* LSL R_d, R_m, R_s	$R_d \leftarrow R_m$ << *const5* $R_d \leftarrow R_m$ << R_s	Zero fills shift: 0 - 31	
Logical Shift Right	LSR R_d, R_m, *const5* LSR R_d, R_m, R_s	$R_d \leftarrow R_m$ >> *const5* $R_d \leftarrow R_m$ >> R_s	Zero fills shift: 1 - 32	
Arithmetic Shift Right	ASR R_d, R_m, *const5* ASR R_d, R_m, R_s	$R_d \leftarrow R_m$ >> *const5* $R_d \leftarrow R_m$ >> R_s	Sign extends shift: 1 - 32	
Rotate Right	ROR R_d, R_m, *const5* ROR R_d, R_m, R_s	$R_d \leftarrow R_m$ ror *const5* $R_d \leftarrow R_m$ ror R_s	right rotate rot: 0 - 31	

x

Bit Masks: Masking - 1

- Bit masks access/modify specific bits in memory
- Masking act of applying a mask to a value
- `or:` 0 passes bit unchanged, 1 sets bit to 1
- `eor:` 0 passes bit unchanged, 1 inverts the bit
- `bic:` 0 passes bit unchanged, 1 clears it
- `and:` 0 clears the bit, 1 passes bit unchanged

mask force lower 16 bits to 1 "**mask on**" operation

```
orr  r1, r2, r3
DATA: r2 0xab ab ab 77
MASK: r3 0x00 00 ff ff lower half to 1
RSLT: r1 0xab ab ff ff
```

mask to invert the lower 8-bits "**bit toggle**" operation

```
eor  r1, r2, r3
DATA: r2 0xab ab ab 77
MASK: r3 0x00 00 00 ff flip LSB bits
RSLT: r1 0xab ab ab 88


MASK: r3 0x00 00 00 ff apply a 2nd time
RSLT: r1 0xab ab ab 77 original value!
```

x

Bit Masks: Masking - 2

mask to **extract top 8 bits** of r2 into r1

```
and  r1, r2, r3
DATA: r2 0xab ab ab 77
MASK: r3 0xff 00 00 00
RSLT: r1 0xab 00 00 00
```

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

```
and  r1, r2, r3
DATA: r2 0xab ab ab 77
MASK: r3 0x00 00 00 01 is bit 0 set?
RSLT: r1 0x00 00 00 01 (0 if not set)
```

mask to force lower 8 bits to 0 "**mask off**" operation

```
and  r1, r2, r3
DATA: r2 0xab ab ab 77
MASK: r3 0xff ff ff 00 clear LSB
RSLT: r1 0xab ab ab 00
```

clear bit 5 to a 0 without changing the other bits

```
bic  r1, r2, r3
DATA: r2 0xab ab ab 77
MASK: r3 0x00 00 00 20 clear bit 5 (0010)
RSLT: r1 0xab ab ab 57
```


x

Bit Masks: Masking - 3

mask to get **1's complement** operation

(like mvn)

```
eor   r1, r2, r3
DATA: r2 0xab ab ab 77
MASK: r3 0xff ff ff ff
RSLT: r1 0x54 54 54 88
```

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

```
mask = 2^k  - 1 so for mod 2, mask = 2 -1 = 1
and   r1, r2, r3
DATA: r2 0xab ab ab 77
MASK: r3 0x00 00 00 01 (mod 2 even or odd)
RSLT: r1 0x00 00 00 01 (odd)
```

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

```
mask = 2^k -1 so for mod 16, mask = 16 -1 = 15
and   r1, r2, r3
DATA: r2 0xab ab ab 77
MASK: r3 0x00 00 00 0f (mod 16)
RSLT: r1 0xab 00 00 07 (if 0: divisible by)
```


x

Masking Summary

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

selects this field when used with and

0 0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1 1	0 0 0 0 0 0 0 0 0 0 0 0 0 0	selection mask

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

clears this field when used with and

1 1 1 1 1 1 1 1 1	0 0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	clear a field mask

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

0 0 0 0 0 0 0 0 0	*source*	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

lsl to get this edge into msb

lsr to get this edge into lsb

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

0 0 0 0 0 0 0 0 0	*source*	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Keep these bits	0 0 0 0 0 0 0 0 0	Keep these bits

x

Inserting Bitfields – Combining Isolated Source and Cleared Destination

isolated source

31 … 24	23 … 16	15 … 0	
all zero's	*source*	*all zero's*	r2
0 0 0 0 0 0 0 0	1 0 1 0 1 0 1 0	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	r2

field cleared in destination

31 … 24	23 … 16	15 … 0	
do not change	*all zeros*	*do not change*	r1
1 0 1 0 1 0 1 0	0 0 0 0 0 0 0 0	1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0	r1

inserted field

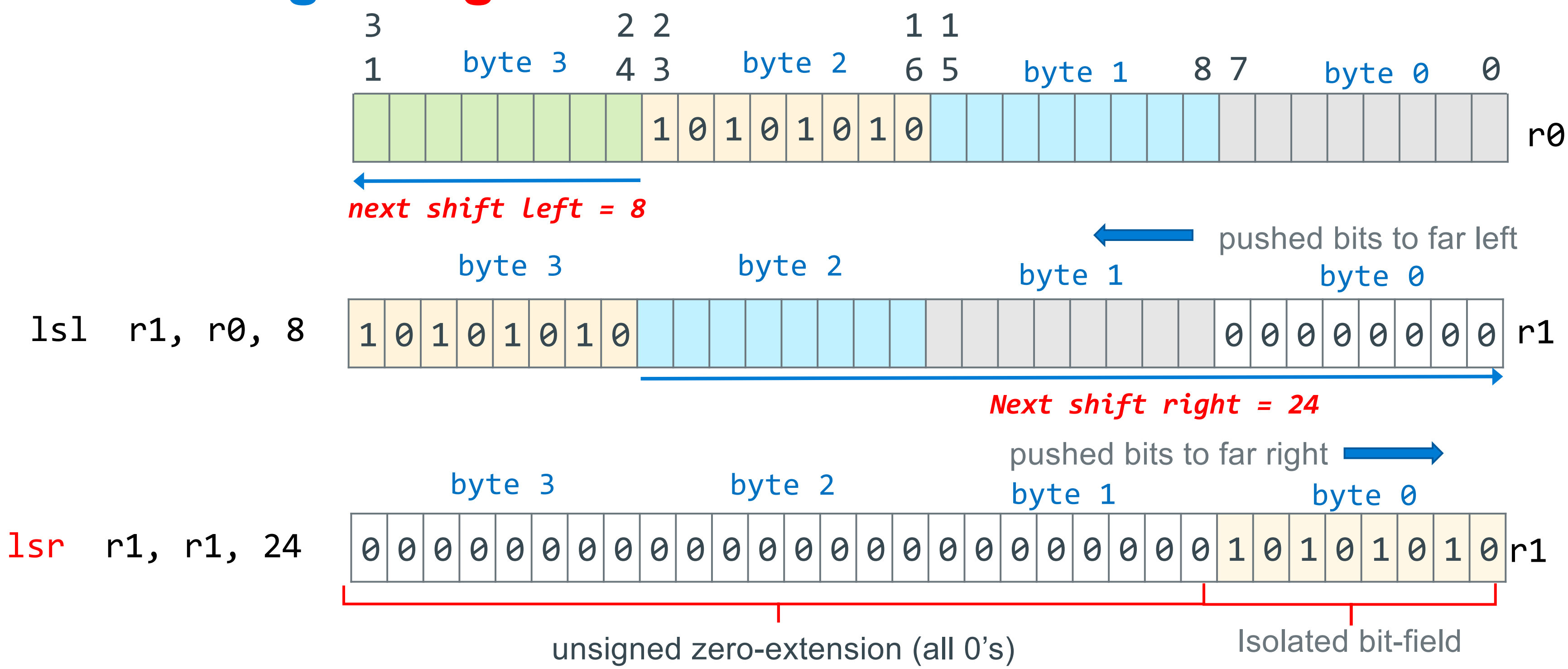
```
orr    r1, r1, r0
```

31 … 24	23 … 16	15 … 0	
1 0 1 0 1 0 1 0	1 0 1 0 1 0 1 0	1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0	r1

x

Isolating **Unsigned** Bitfields

Hint: Useful for PA5



- You can use ror to move the field to the desired location
- Alternative: If you can create an immediate value mask with a data operation like: movn, mov, add, or sub that is often faster

x