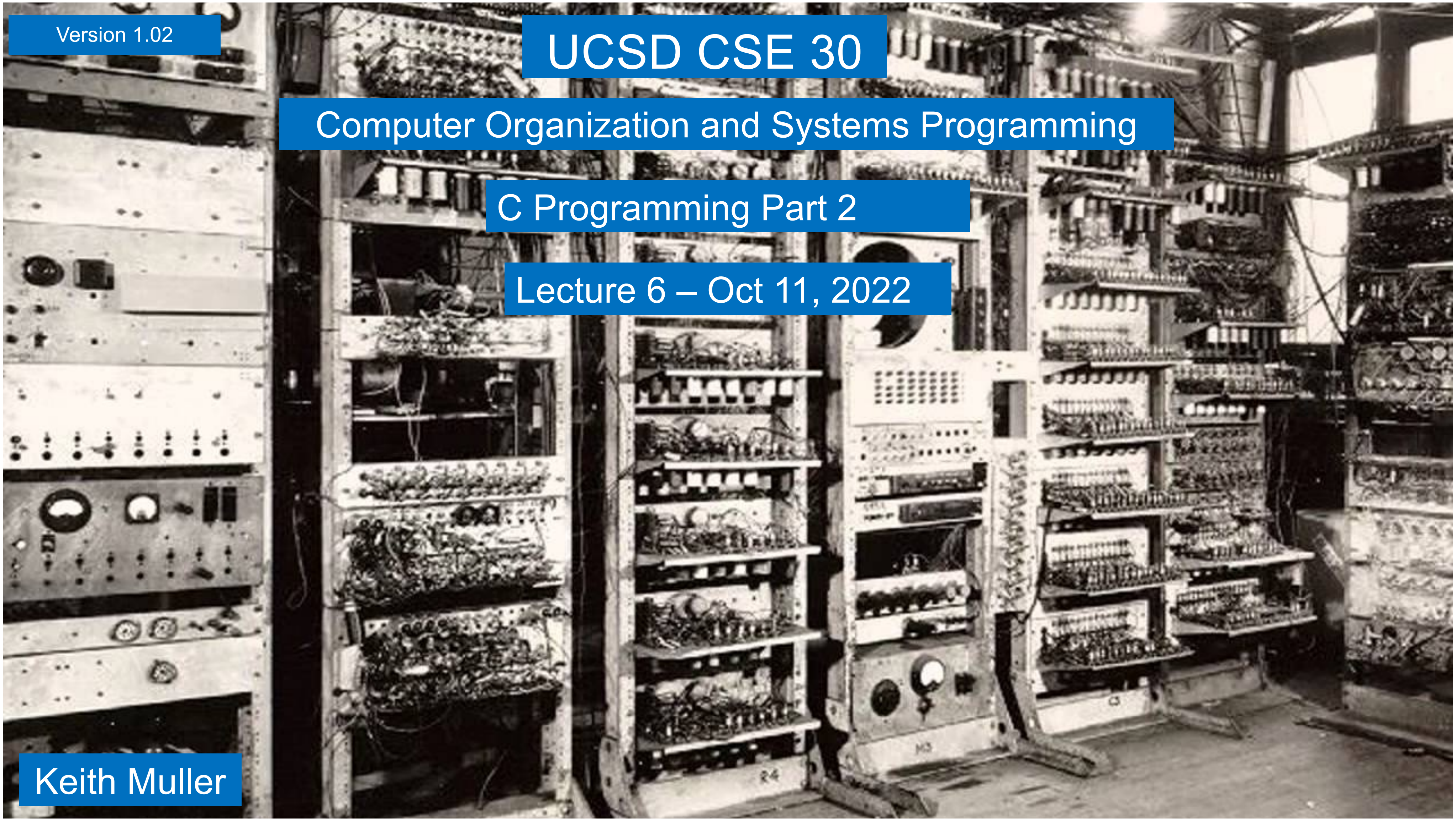


Version 1.02

UCSD CSE 30

Computer Organization and Systems Programming

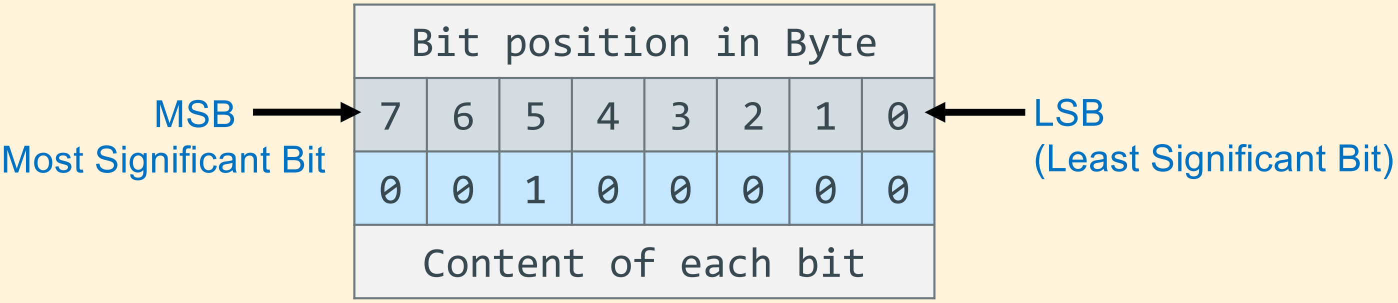
C Programming Part 2

Lecture 6 – Oct 11, 2022

Keith Muller

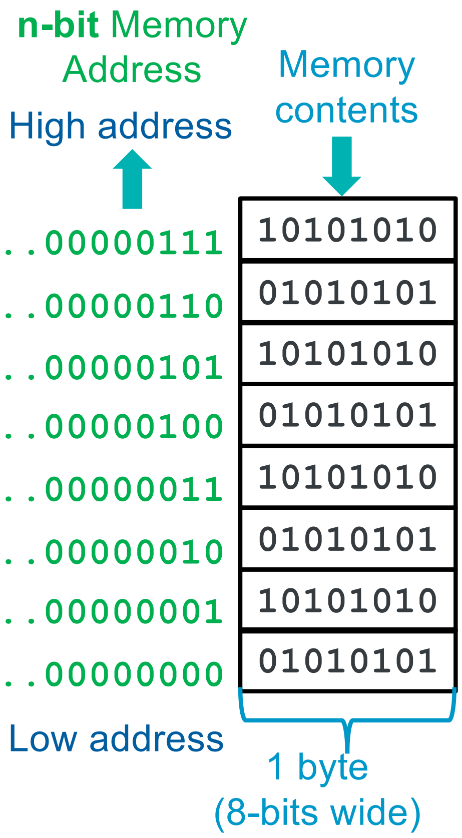
Memory Review: Organized in Units of Bytes

- 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**



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

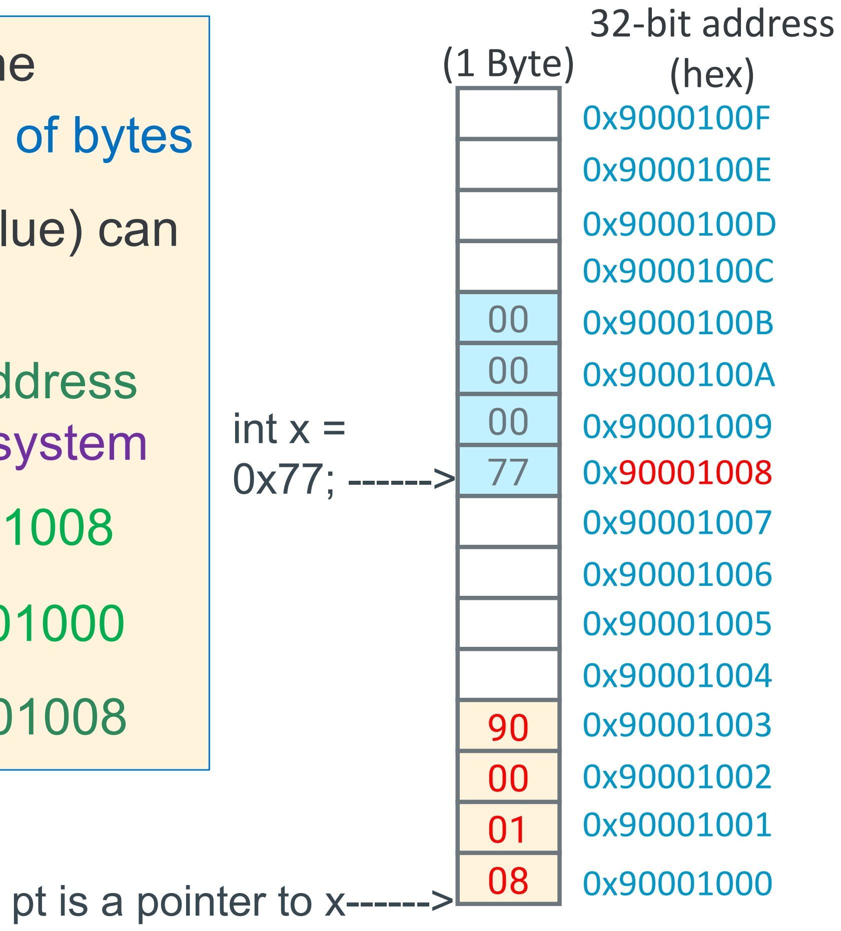


n-bit Memory Address	Memory contents
..00000111	10101010
..00000110	01010101
..00000101	10101010
..00000100	01010101
..00000011	10101010
..00000010	01010101
..00000001	10101010
..00000000	01010101

x

Address and Pointers

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



(1 Byte)	32-bit address (hex)
	0x9000100F
	0x9000100E
	0x9000100D
	0x9000100C
00	0x9000100B
00	0x9000100A
00	0x90001009
77	0x90001008
	0x90001007
	0x90001006
	0x90001005
	0x90001004
90	0x90001003
00	0x90001002
01	0x90001001
08	0x90001000

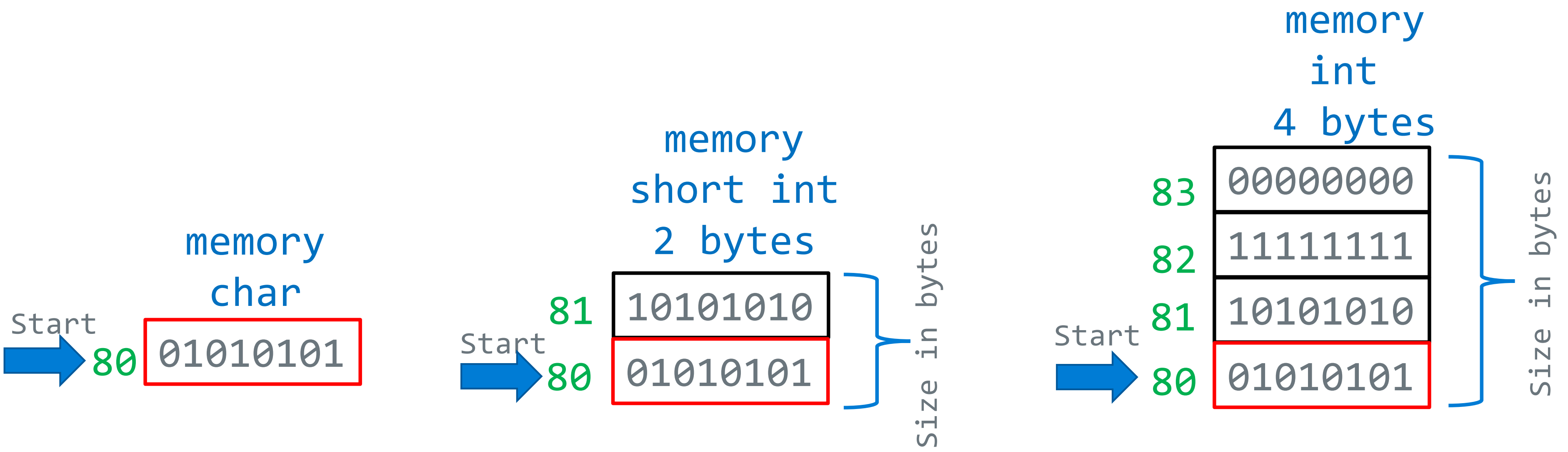
int x = 0x77; ------>

pt is a pointer to x------>

x

Variables in Memory: Size and Address

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



memory
char

Start
80 01010101

memory
short int
2 bytes

81 10101010
Start
80 01010101

Size in bytes

memory
int
4 bytes

83 00000000
82 11111111
81 10101010
Start
80 01010101

Size in bytes

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

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

sizeof() operator returns a value of type size_t:

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

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

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

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

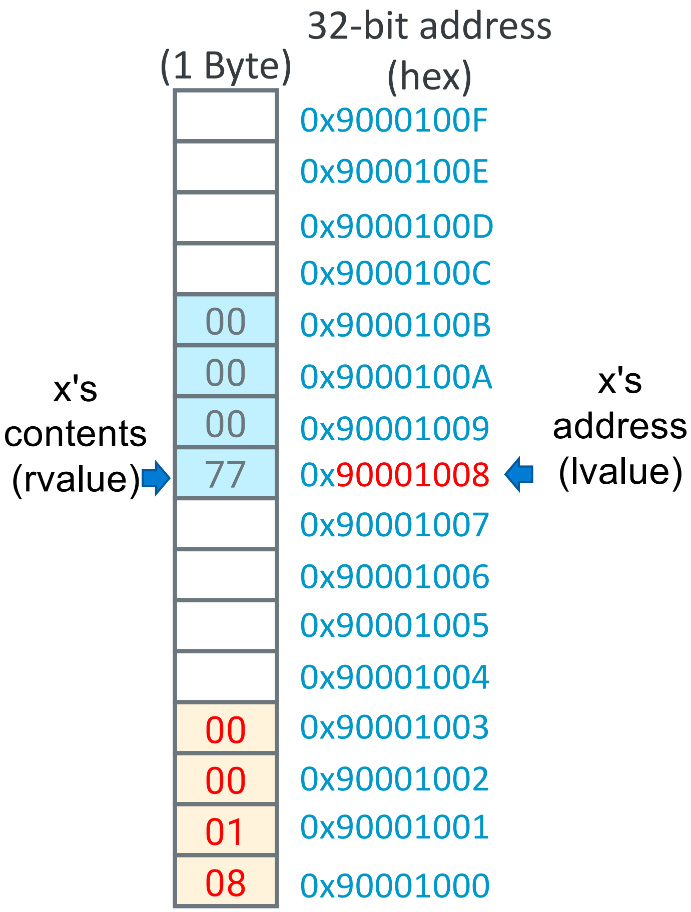
  - reads as:
    - number of bytes required to store **10 integers (an array of [10])**

Memory Addresses & Memory Content

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

Variable name 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
  - Address assigned to a variable cannot be changed at runtime
- **Rvalue:** when on the right side (Rside or Right value) of an = sign is the
  - contents or value stored in the variable (at its memory address)
  - requires a memory read to obtain



32-bit address (hex)

x's contents (rvalue)

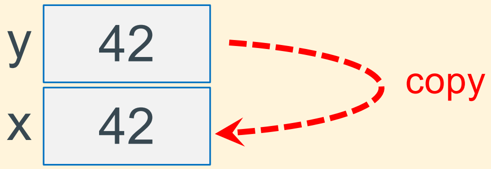
x's address (lvalue)

(1 Byte)	32-bit address (hex)
	0x9000100F
	0x9000100E
	0x9000100D
	0x9000100C
00	0x9000100B
00	0x9000100A
00	0x90001009
77	0x90001008
	0x90001007
	0x90001006
	0x90001005
	0x90001004
00	0x90001003
00	0x90001002
01	0x90001001
08	0x90001000

x

Memory Addresses & Memory Content

```
y = 42;

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 – number of bytes) - this is y's **Rvalue**
- So x = y; is:

  Read memory at y (**Rvalue**); write it to memory at x's address (**Lvalue**)

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 for use on the **Rside**? Three ways:
  - **&**`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

x

Introduction: Address Operator: &

- Unary ***address operator*** (&) produces the **address** of where an identifier is in memory

- Example: this might print:

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

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

  (the address will vary)

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

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

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**

- A pointer is defined by placing a ***star*** (or ***asterisk)*** **(*)** ***before*** the identifier (name)

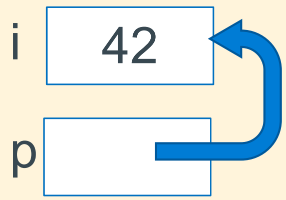
```
type *name;  // defines a pointer; name contains address of a variable of type
```

Introduction: Pointer Variables - 1

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

- 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;
```

Introduction: Pointer Variables - 2

- **Pointers are typed**! Why?
  - The compiler needs the size (sizeof()) of the data **you are pointing at** (number of bytes to access)
- A pointer definition:

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

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

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

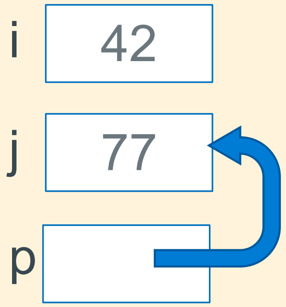
- The * is part of the definition of p and is not part of the variable name
  - The name of the variable is simply p, not *p
- C mostly ignores whitespace, so these three definitions are equivalent

```
int  *p = &i;      /* Style A */
int * p = &i;      /* Style B */
int*  p = &i;      /* Style C */
```

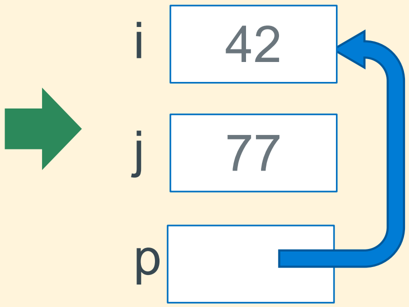
Introduction: Pointer Variables - 3

- As with any variable, its value can be changed

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



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



Introduction: Pointer Variables - 4

- Pointer variables all use the **same amount of memory** no matter what they point at

```
   int *iptr;
   char *cptr;

   printf("iptr(%u) cptr(%u)\n", sizeof(iptr), sizeof(cptr));
```

- Above prints on a 32-raspberry pi

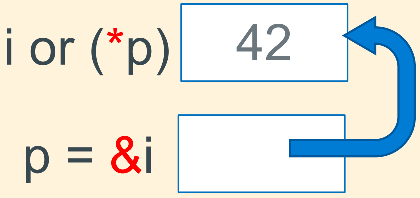
```
iptr(4) cptr(4)
```

x

Introduction: Indirection (or dereference) Operator: *

- The ***indirection operator*** (*) or the *dereference operator to a variable* is the **inverse** of the *address operator (&)*
- **address operator (&)** can be thought of as:

“get the address of this box”



i or (*p) 42

p = &i

- **indirection operator (*)** can be thought of as:

“follow the arrow to the next box and get its contents”

Introduction: Indirection (or dereference) Operator: *

*Contents of **p** is the address of **i** (p points at i)*

```
int i = 42;
int *p = &i;

printf("*p is %d\n", *p);
```

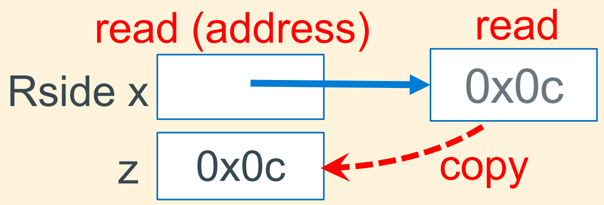
```
% ./a.out
*p is 42
```

Introduction: Indirection Operator Rside

- Performs the following steps when the * is on the Rside:

1. read the contents of the variable to get an address
2. **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
```



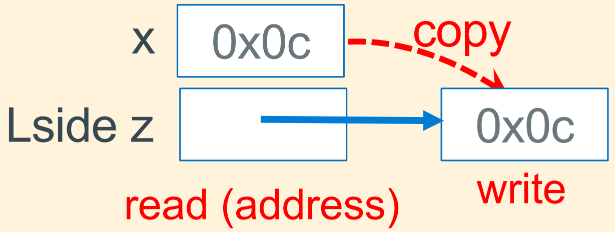
x

Introduction: Indirection Operator Lside

Performs the following steps when the * is on the Lside:

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

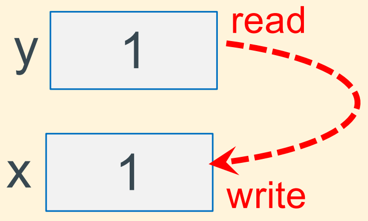
```
*z = x; // copy the value of x to the memory pointed at by z
```



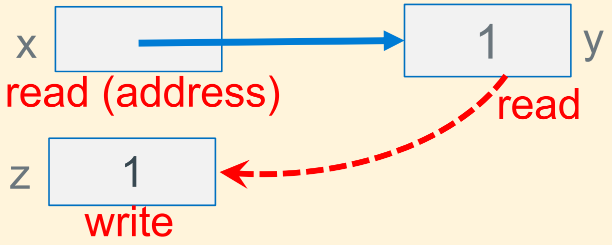
Each use of a * operator results in one additional read -1

Each * when used as a dereference operator in a statement (Lside and Rside) generates an additional read

```
int x = 2, y = 1;
x = y; // one read
```



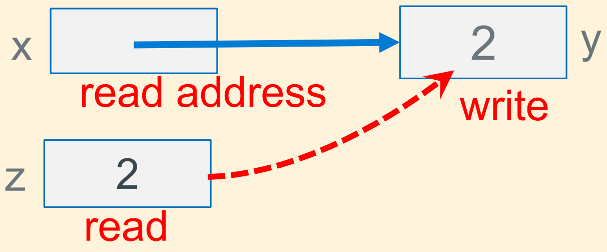
```
int z = 2, y = 1;
int *x = &y;
z = *x; // two reads
```



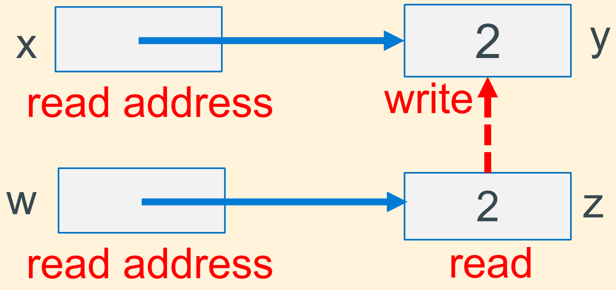
Each use of a * operator results in one additional read -2

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

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



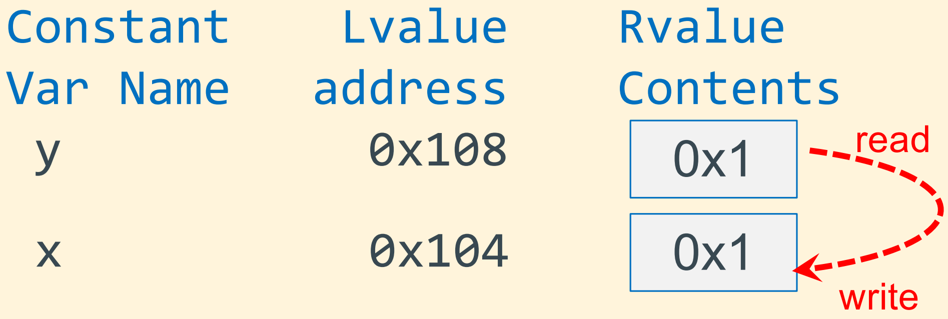
```
int z = 2, y = 1;
int *x = &y;
int *w = &z;
*x = *w;
```



x

Recap: Lside, Rside, Lvalue, Rvalue

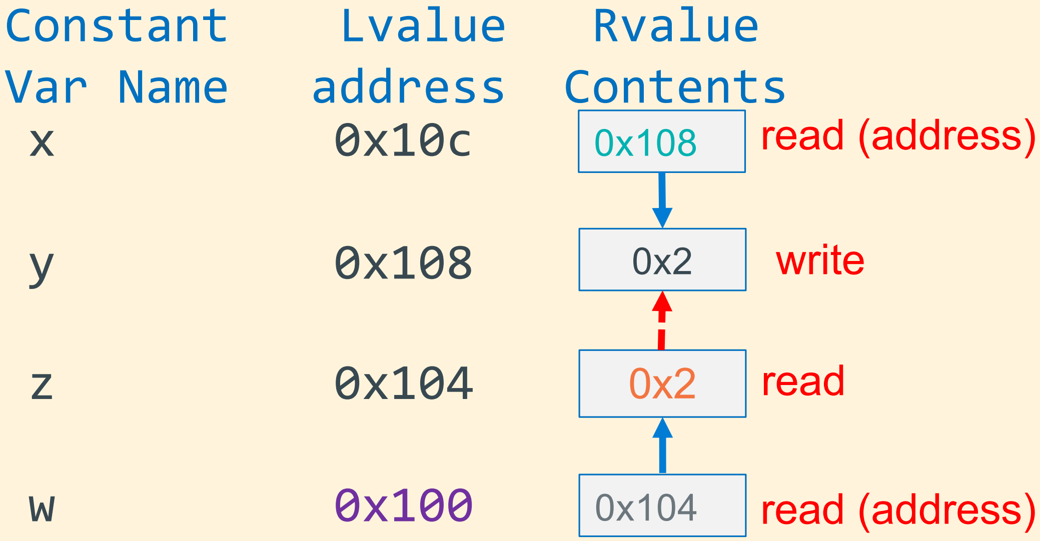
```
int x = 2, y = 1;
x = y;
```



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

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

```
*x on Lside is   0x108
 w on Rside is   0x100
*w on Rside is   2
```



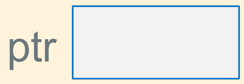
Constant Var Name	Lvalue address	Rvalue Contents
x	0x10c	0x108
y	0x108	0x2
z	0x104	0x2
w	0x100	0x104

x

Pointer Practice

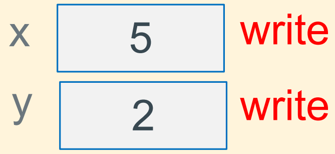
```
int *ptr;
```

Declares a variable, ptr, which is a pointer to (*it* contains the address of) an int in memory



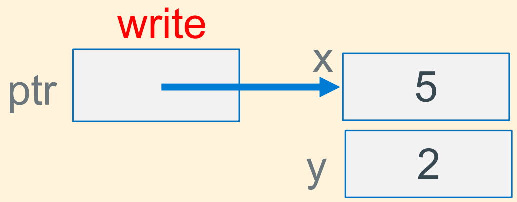
```
int x = 5;

int y = 2;
```

Declares two variables, x and y, that contain ints, and *initializes* them to 5 and 2, respectively



```
ptr = &x;
```

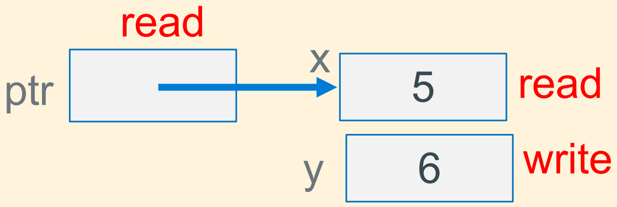
Sets ptr to contain the address of x ("ptr points to x")



```
y = 1 + *ptr;
```

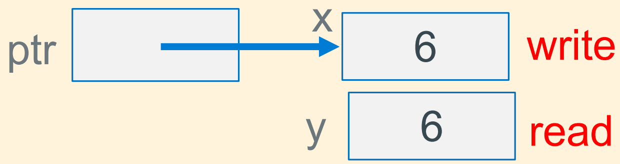
"Dereference ptr"

Sets y to "1 plus the value stored at the address held by ptr. Because ptr points to x, this is equivalent to y = 1 + x;



```
x = *(&y);
```

Sets x = y; The * and & cancel each other. get the address of y and then get the contents pointed by that address



x

The NULL Constant and Pointers

- **NULL is a constant** that **evaluates to zero (0)**
- You assign a pointer variable to contain NULL to indicate that the pointer does not point at anything
- A pointer variable with a value of NULL is called a “NULL pointer” (invalid address!)
- Memory location 0 (address is 0) is not a valid memory address in any C program
- Dereferencing NULL at runtime will cause a program fault (segmentation fault)!

```
p = NULL;
i = *p;               /* segmentation fault! */
*(int *)900000 = 25;  /* cast 900000 to a pointer */
                      /* if writeable address space, it works */
                      /* that memory location just changed */
```

Using the NULL Pointer

- Many functions return NULL to indicate an error has occurred

```
/* these are all equivalent */
int *p = NULL;
int *p = (int *)0;   // cast 0 to a pointer type
int *p = (void *)0;  // automatically gets converted to the correct type
```

- NULL is considered “false” when used in a Boolean context
  - **Remember: false expressions** in C are defined to be zero *or* NULL
- The following two are equivalent (the second one is preferred for readability):

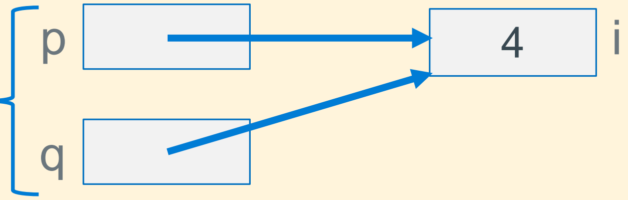
```
if (p) ...
if (p != NULL) ...
```

What is Aliasing?

- Two or more variables are aliases of each other when they all reference the same memory (so different names, same memory location)
- When one pointer is copied to another pointer it *creates an* ***alias***
- ***Side effect***: Changing one variables value (content) changes the value for other variables
  - Multiple variables all read and write the **same** memory location
  - Aliases occur either by accident (coding errors) or deliberate (careful: readability)

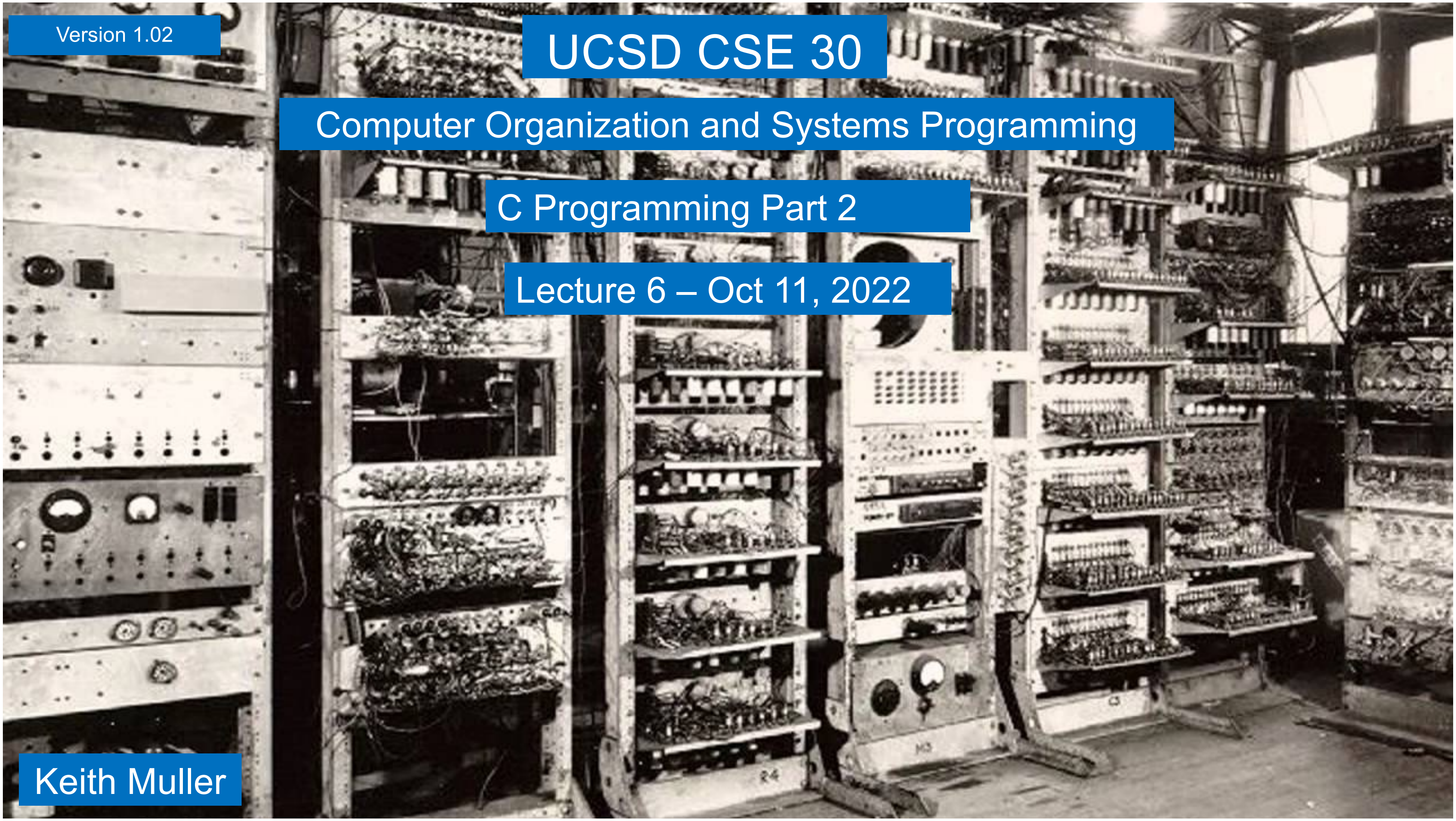
```
int i = 5;
int *p = &i;
int *q;

q = p;   // *p & *q are aliases
*q = 4;  // changes i
```

*p and *q are aliases



Result *p, *q and i all have the value of 4

x



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UCSD CSE 30

Computer Organization and Systems Programming

C Programming Part 2

Lecture 6 – Oct 11, 2022

Keith Muller

Defining Arrays - 1

Definition: `type name[count]`

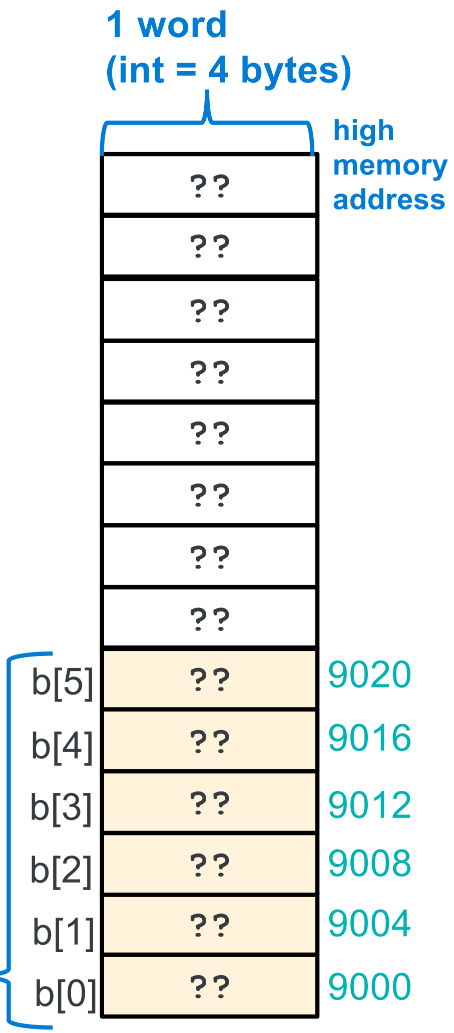
- ***"Compound"*** data type where each value in an array is an element of type
- Allocates **name** with a *fixed* count array elements of type **type**
- Allocates (`count * sizeof(type)`) bytes of ***contiguous memory***
- Common usage is to specify a compile-time constant for **`count`**

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

BSZ is a macro replaced by the C preprocessor at compile time

- Array **names are constants (like all variable names)** and cannot be assigned (the name cannot appear on the Lside by itself)

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



```
int b[6];
```

x

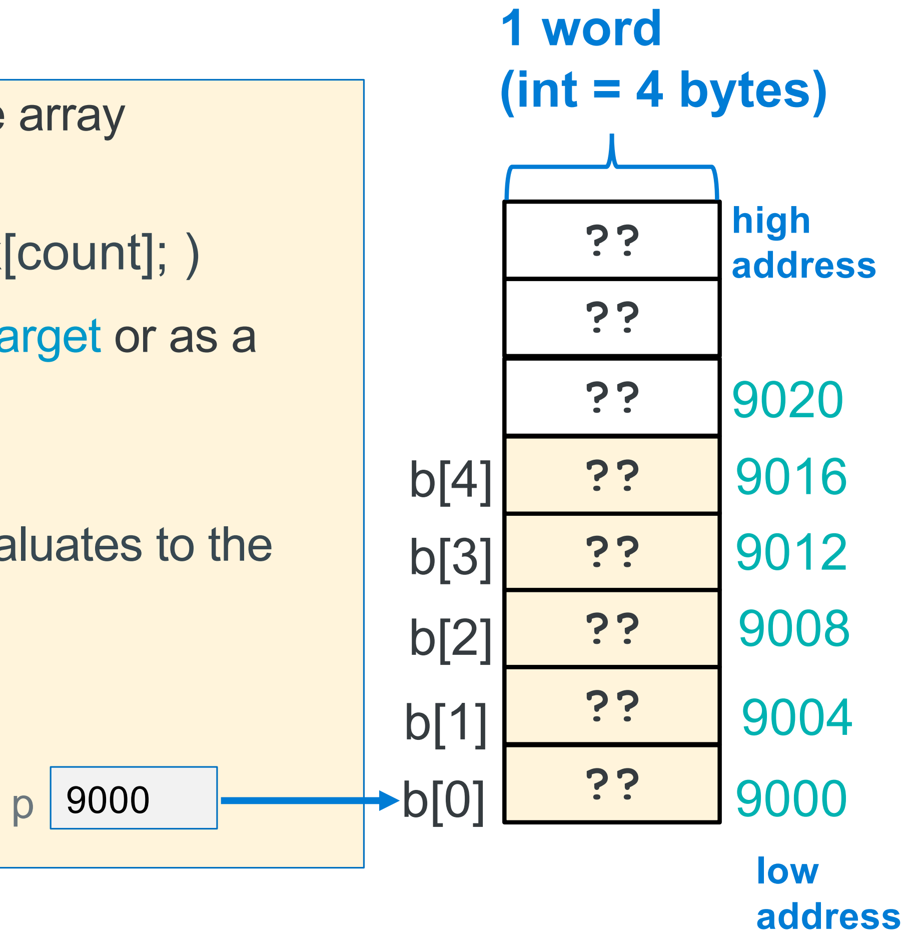
Accessing Arrays Using Indexing

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

```
int a[5];
int b[5];
```

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

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



Array Initialization

- 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

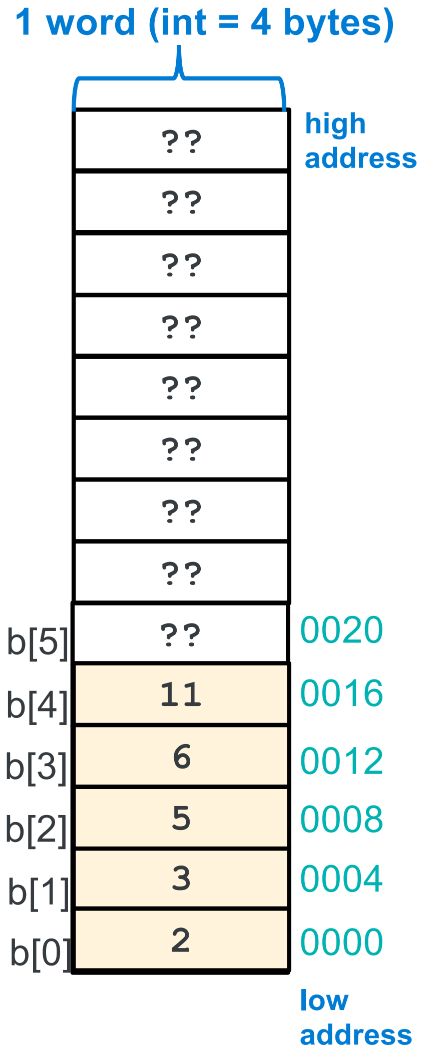
no initialization values given; then elements are initialized to 0

  - `int block[20] = {}; //only works with constant size arrays`
    - 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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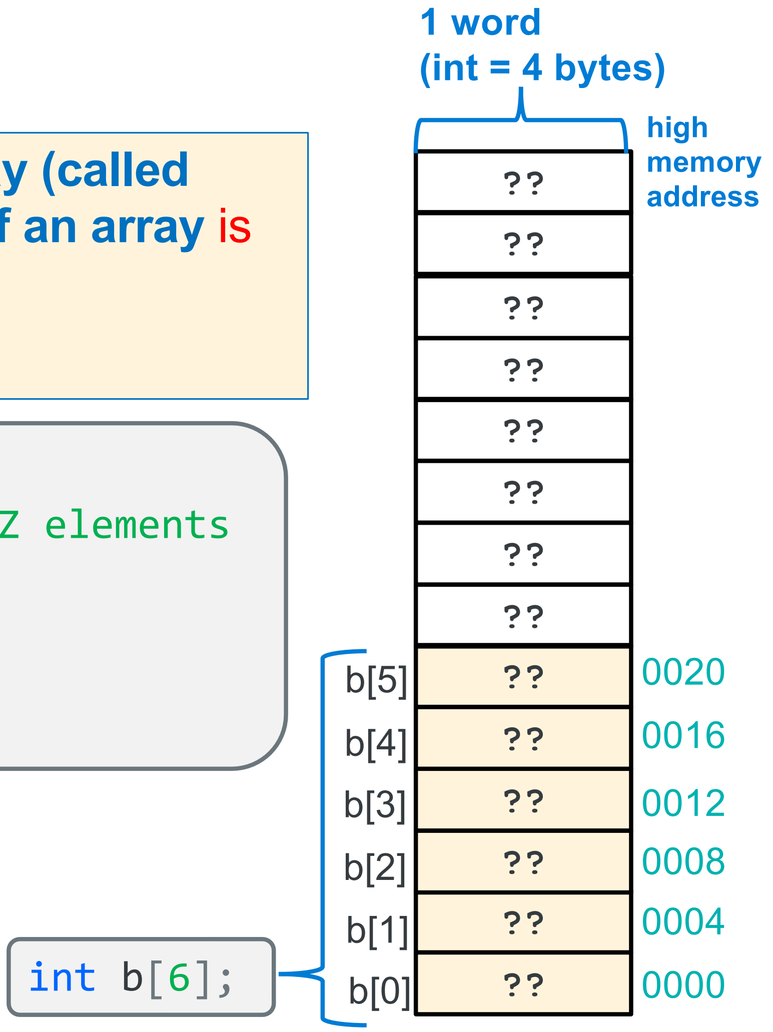
How many elements are in an array?

- The number of elements of space allocated to an array (called element count) and indirectly the total size in bytes of an array is not stored anywhere!!!!!!
  - An array does not know its own size!

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

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



	1 word (int = 4 bytes)	
	??	high memory address
	??	
	??	
	??	
	??	
	??	
	??	
	??	
b[5]	??	0020
b[4]	??	0016
b[3]	??	0012
b[2]	??	0008
b[1]	??	0004
b[0]	??	0000

```
int b[6];
```

x

Determining Element Count for a compiler calculated array

- Programmatically determining the element count in a compiler calculated array

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

- `sizeof(array)` **only works** when used in the SAME **scope** as where the array variable was defined

```
#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

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

Pointer and Arrays - 1

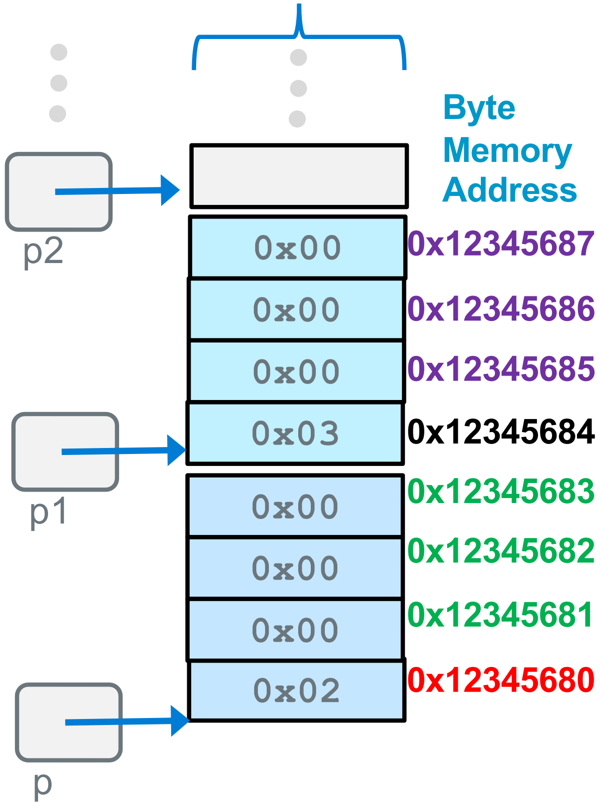
- A few slides back we stated: Array name (by itself) on the Rside evaluates to the address of the first element of the array

```
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 evaluate*** to the address of the first array element

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

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

1 byte Memory Content
One byte per row



Byte Memory Address

0x00	0x12345687
0x00	0x12345686
0x00	0x12345685
0x03	0x12345684
0x00	0x12345683
0x00	0x12345682
0x00	0x12345681
0x02	0x12345680

x

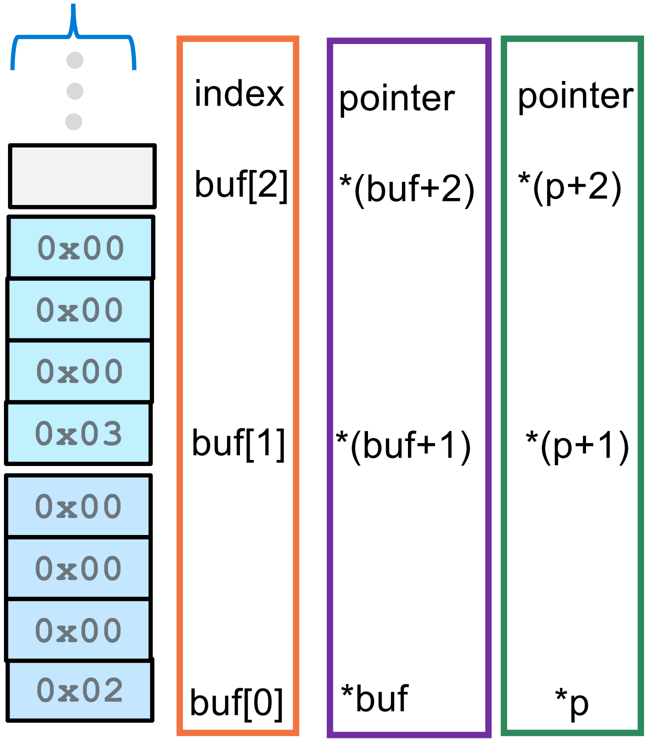
Pointer and Arrays - 2

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
  - **++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}
```

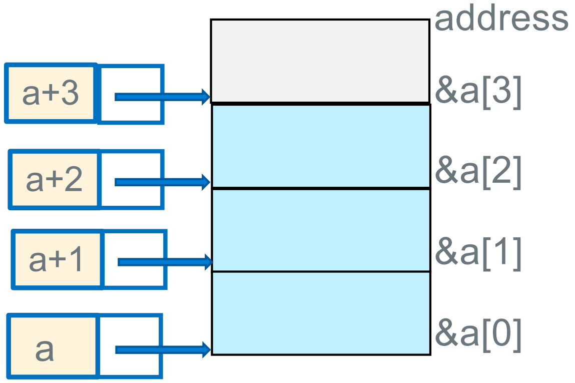
1 byte Memory Content
One byte per row



x

Pointer Arithmetic In Use – C's Performance Focus

```
char a[] = {'A', 'B', 'C'};
```



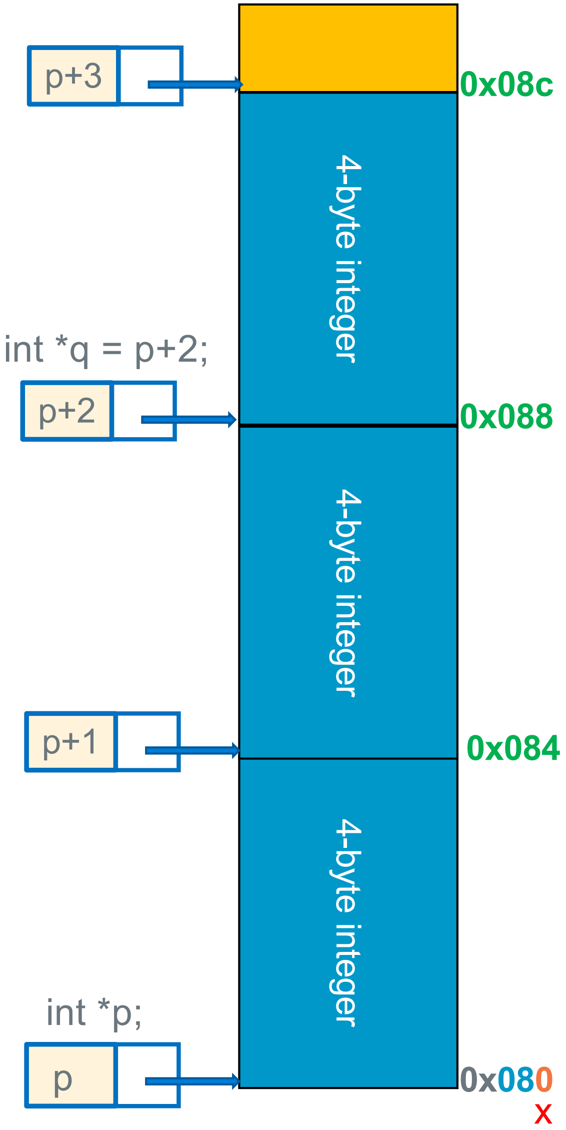
- **Alert!:** C performance focus **does not** perform any array “bounds checking”
- **Performance by Design**: *bound checking **slows down execution** of a properly written program*
- Example: array **a** of length i, C **does not verify** that **a[j] or *(a + j)** is valid (does not check: 0 ≤ j < i)
  - C simply *“translates”* and accesses the memory specified from: **`a[j]`** to be **`*(a + j)`** which may be *outside the bounds* of the array
  - OS only ***"faults"*** for an incorrect access to memory (read-only or not assigned to your process)
    - It does not fault for out of bound indexes or out of scope
- **lack of bound checking** is a common source of **errors** and **bugs** and is a common criticism of C

x

Pointer Arithmetic

- **You cannot add two pointers** *(what is the reason?)*
- A pointer q can be subtracted 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) / sizeof(*p)

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

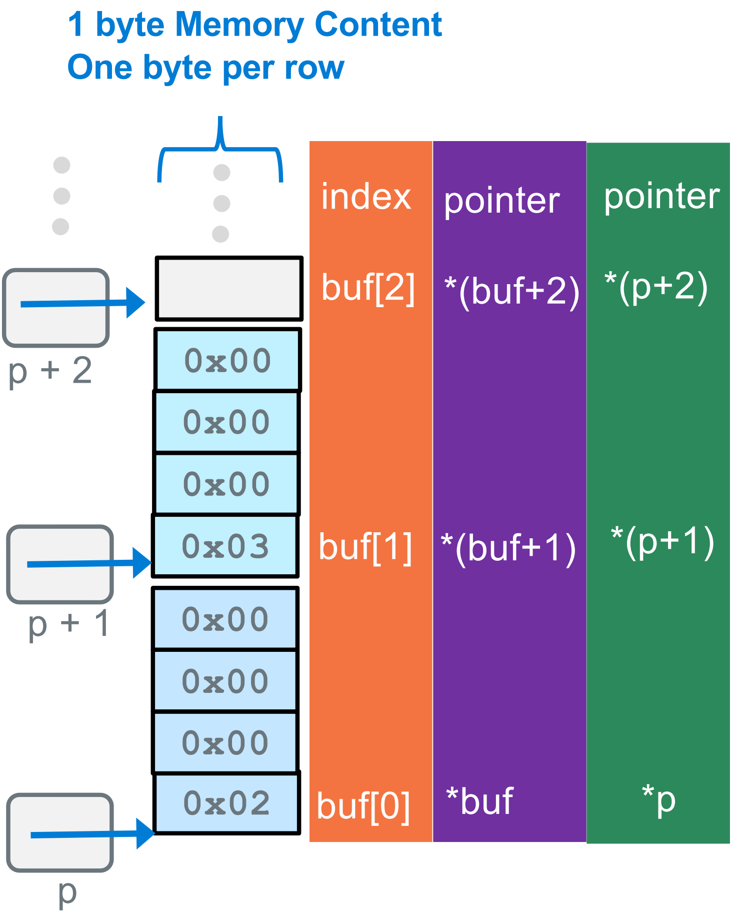


Pointer and Arrays - 2

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}
```



x

Pointer Comparisons

- Pointers (**same type**) can be compared with the comparison operators:

  `<, <=, ==, !=, >=, >`

```
int numb[] = {9, 8, 1, 9, 5};
int *end = numb + (int) (sizeof(numb)/sizeof(*numb));
int *a = numb;

while (a < end)  // compares two pointers (address)
      /* rest of code */
```

- Invalid, Undefined, or **risky** pointer arithmetic (some examples)
  - Add, multiply, divide on two pointers
  - Subtract two pointers of different types or pointing at different arrays
  - Compare two pointers of different types
  - Subtract a pointer from an integer

Fast Ways to "Walk" an Array: Use a Limit Pointer

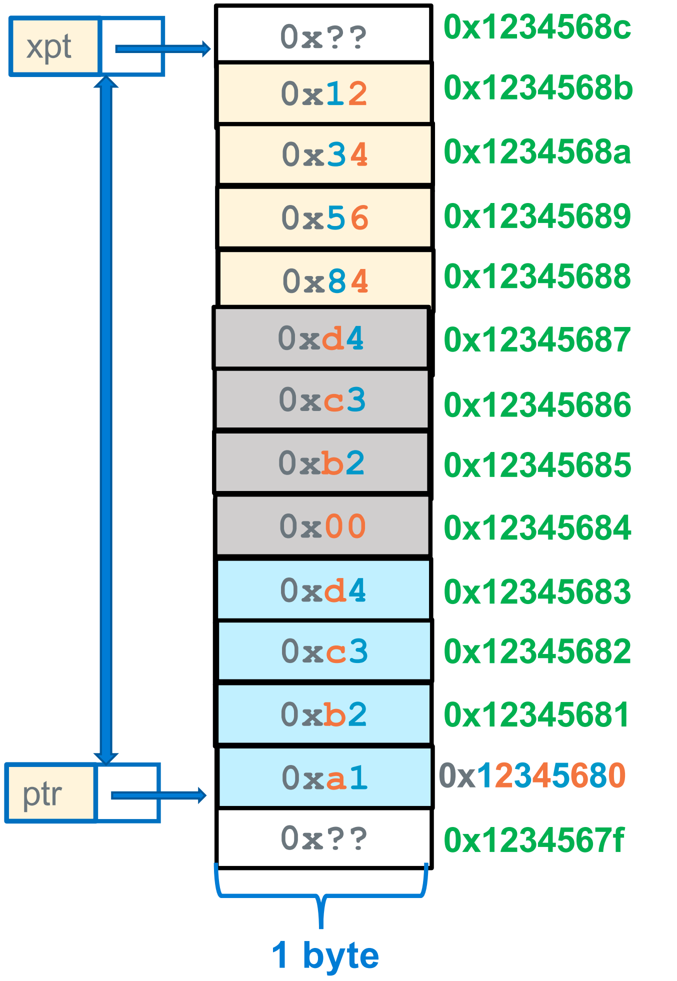
```
int x[] = {0xd4c3b2a1, 0xd4c3b200, 0x12345684};
int cnt = (int)(sizeof(x) / sizeof(*x));


int *ptr = x; //or &x[0]
```

xpt is a loop **limit pointer** points 1 element past the end of the array

```
cnt   = 3;
bytes = cnt * sizeof(*x);
      = 12
```

```
int *xpt = ptr + cnt;

while (ptr < xpt) {
    printf("%#x\n", *ptr);
    ptr++;
}
```

```
 % ./a.out
0xd4c3b2a1
0xd4c3b200
0x12345684
```

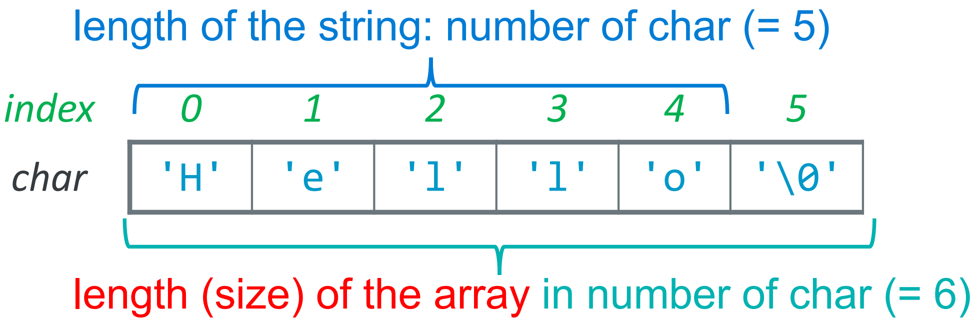


0x??	0x1234568c
0x12	0x1234568b
0x34	0x1234568a
0x56	0x12345689
0x84	0x12345688
0xd4	0x12345687
0xc3	0x12345686
0xb2	0x12345685
0x00	0x12345684
0xd4	0x12345683
0xc3	0x12345682
0xb2	0x12345681
0xa1	0x12345680
0x??	0x1234567f

x

C Strings - 1

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



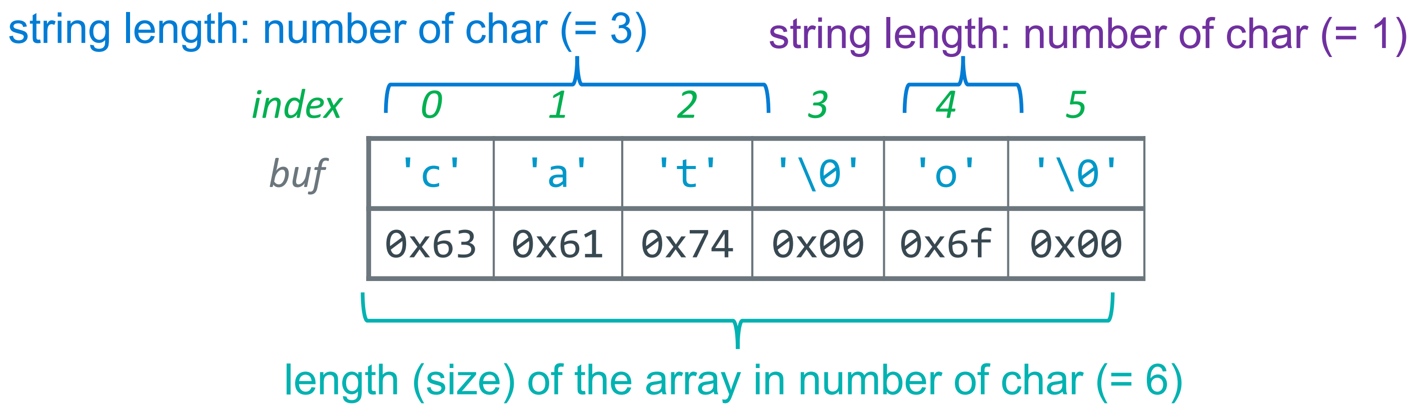
length of the string: number of char (= 5)

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

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

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**
  - But, 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

Defining Strings: Initialization

- When you combine the automatic length definition for arrays with double quote(") **initialization**
  - Compiler automatically adds the null terminator '\0' for you

```
char a[4] = {'c', 'a', 't', '\0'};
char b[] = "cat";                           // compiler calculates size, adds '\0'
char c[] = {'c', 'a', 't', '\0', 'a, 'b'};  // array size 6, string length 3
char empty[] = "";                          // empty string – contains '\0'
                                            // string length = 0
```

x

Defining Strings: Initialization Equivalents

- Following definitions create **equivalent** 4-character arrays
  - These are all strings as they all include a null ('\0') terminator

```
char a[4] = {'c', 'a', 't', '\0'};
char b[4] = {'c', 'a', 't', 0};
char c[4] = {'c', 'a', 't'};      // missing initial value defaults to 0
char d[4] = { 99, 97, 116, 0};    // 99 = 'c', 97 = 'a', 116 = 't'
char e[4] = "cat";
char f[4] = "cat\0";              // literal has 5 chars; array f string
                                 // length is 3
```

When a double quoted string is used in an expression, it has a different meaning (next slide)

Background: Different Ways to Pass Parameters

- **Call-by-reference (or pass by reference)**
  - Parameter in the called function is an ***alias*** (references the same memory location) for the supplied argument
  - Modifying the parameter modifies the calling argument

Call-by-value (or pass by value) (C)

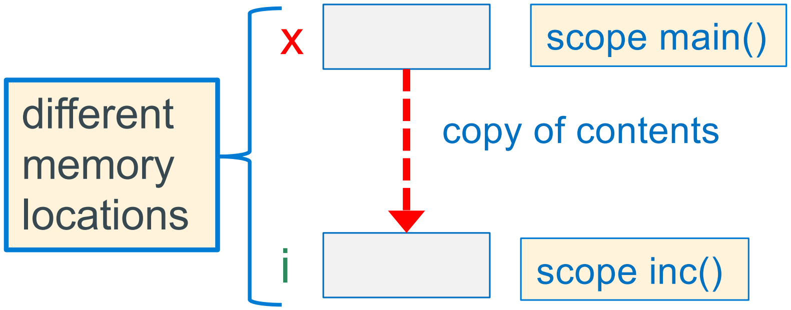
  - What **Called** Function Does
    - Passed Parameters are used like local variables
    - Modifying the passed parameter in the function is allowed just like a local variable
    - So, writing to the parameter, ***only*** changes the ***copy***
- The return value from a function in C is **by value**

x

Passing Parameters – Call by Value Example

```
int main(void)
{
    int x = 5;
    inc(x);                // makes a copy of x
    printf("%d\n", x); // 5 or 6 ?
}

void inc(int i)        // i is local to inc
{
    ++i;
}
```

if this was an expression like inc(x+1) it evaluates and stores the result in the memory allocated for the copy



- when `inc(x)` is called, a copy of x is made to another memory location
  - `inc()` cannot change the variable x since `inc()` does not have the address of x, it is local to `main()` so, 5 is printed
- The `inc()` function is free to change it's copy of the argument (just like any local variable) remember it does NOT change the parameter in `main()`

x

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

How to Implement Output Parameters

- To pass the address of a variable x use the **address operator** (&x) **or** the contents of a pointer variable that points at x
- To be receive an address in the called function, define the corresponding parameter type to be a pointer
  - It is common to describe this method as: “pass a pointer to x”

```
void inc(int *p);  // inc() is passed an address
…
inc(&x);             // pass the address of a variable to inc()
```

- Be careful when passing and using pointers
  - When you have the address of a memory location you are in effect over-riding (or by-passing) scope protections for accessing variables

x

Example Using Output Parameters

```
void inc(int *p);
int
main(void)
{
    int x = 5;
    inc(&x);
    printf("%d\n", x);
    return EXIT_SUCCESS;
}

void
inc(int *p)
{
    if (p != NULL)
        *p += 1;          // or (*p)++
}
```

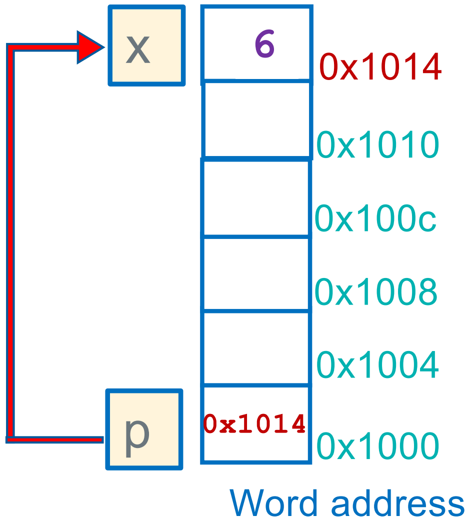
Pass the address of x (&x)

Receive an address copy (int *p)

Write to the output variable (*p)

At the Call to inc() in main()

1. Allocate space for p
2. Copy x's address into p



x

Arrays As Parameters: What is the size of the array?

- It’s tricky to use arrays as parameters, as **they are passed as pointers to the start of the array**
  - In C, **Arrays do not know their own size** and at runtime there is no “bounds” checking on indexes

```
int sumAll(int a[]);

int main(void)
{
  int numb[] = {9, 8, 1, 9, 5};
  int sum = sumAll(numb);

  return EXIT_SUCCESS;
}

int sumAll(int a[])
{
  int i, sum = 0;
  int sz = (int) (sizeof(a)/sizeof(*a));
  for (i = 0; i < sz; i++) // this does not work
      sum += a[i];
  }
}
```

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

“inside” the body of sumAll(), the question is:
how big is that array? all I have is a POINTER to the first element…..
sz is a 1 on 32 bit arm

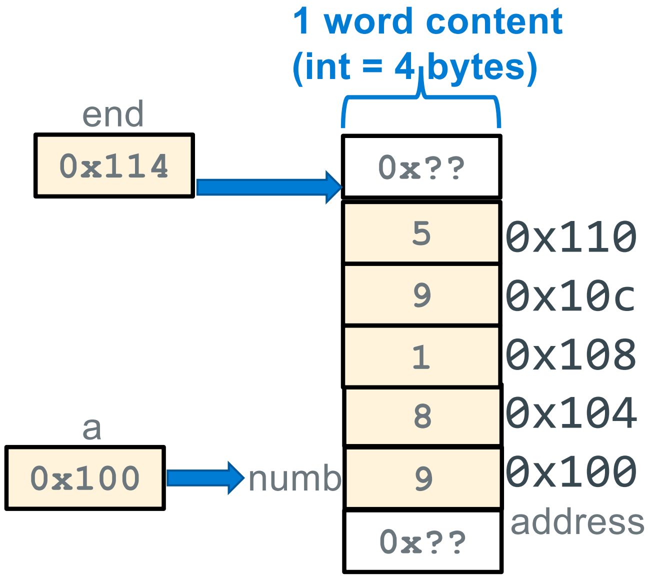
Arrays As Parameters, Approach 1: Pass the size

Two ways to pass array size

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

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

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

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



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

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

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

  for (int i= 0; i < size; i++)
      sum += a[i]; // *(a + i)
  return sum;
}
```

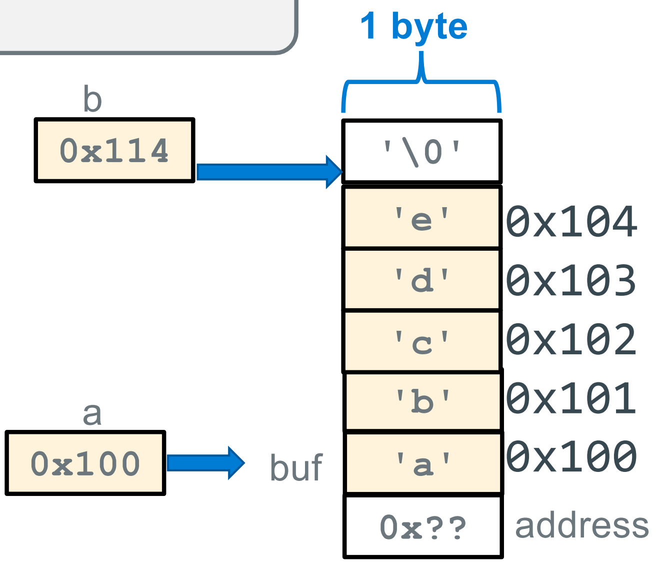
x

Arrays As Parameters, Approach 2: Use a sentinel element

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

```
int my_strlen(char *a);
int main(void)
{
  char buf[] = {'a', 'b', 'c', 'd', 'e', '\0'}; // string

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

```
int strlen(char *a)
{
  char *b = a;

  if (a == NULL)  // check for NULL pointer
    return 0;
  while (*b++ != '\0')
      ;
  return (b - a - 1);
}
```



1 byte

'\0'	
'e'	0x104
'd'	0x103
'c'	0x102
'b'	0x101
'a'	0x100
0x??	address

2D Array of Char (where elements may contain strings)

- 2D array of chars (where rows may include strings)
- Each row has the same fixed number of memory allocated
- All the rows are the same length regardless of the actual string length)
- The column size must be large enough for the longest string

high memory

```
char aos2d[3][22] = {"my", "two dimensional", "char array"};
```

aos2d[2]	c	h	a	r		a	r	r	a	y	'\0'											
aos2d[1]	t	w	o		d	i	m	e	n	s	i	o	n	a	l		a	r	r	a	y	'\0'
aos2d[0]	m	y	'\0'																			

low memory

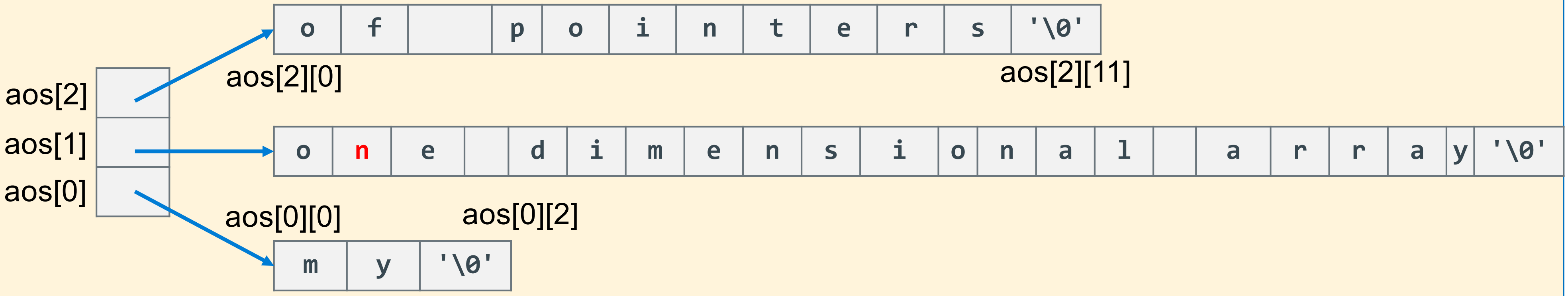
high memory

```
#define ROWS 3
char aos[ROWS][22] = { "my", "two dimensional", "char array"};
char (*ptc)[22] = aos;  // ptr points at a row of 22 chars

for (int i = 0; i < ROWS; i++)
    printf("%s\n", *(ptc + i));
```

x

Pointer Array to Strings (This is NOT a 2D array)

- 2D char arrays are an inefficient way to store strings (wastes memory) unless all the strings are similar lengths, so 2D char arrays *are rarely used* with string elements
- **An array of pointers** is common for strings as *"rows"* can very in length

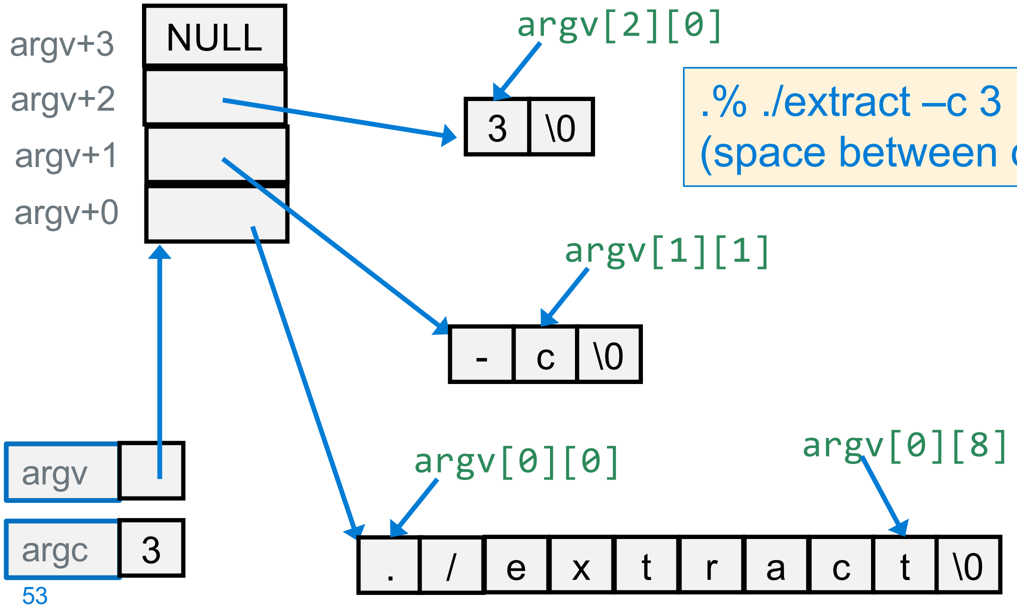

o f p o i n t e r s '\0'
aos[2][0]
aos[2][11]
aos[2]
aos[1]
aos[0]
o n e d i m e n s i o n a l a r r a y '\0'
aos[0][0]
aos[0][2]
m y '\0'

- `aos` is an array of pointers; each pointer points at a character array (also a string here)
- Not a 2D array, but any char can be accessed as if it was in a 2D array of chars
  - When I was learning, this was the most confusing syntax aspects of C!

main() Command line arguments: argc, argv

- Arguments are passed to main() as a pointer to an array of pointers `(**argv or *argv[])`

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

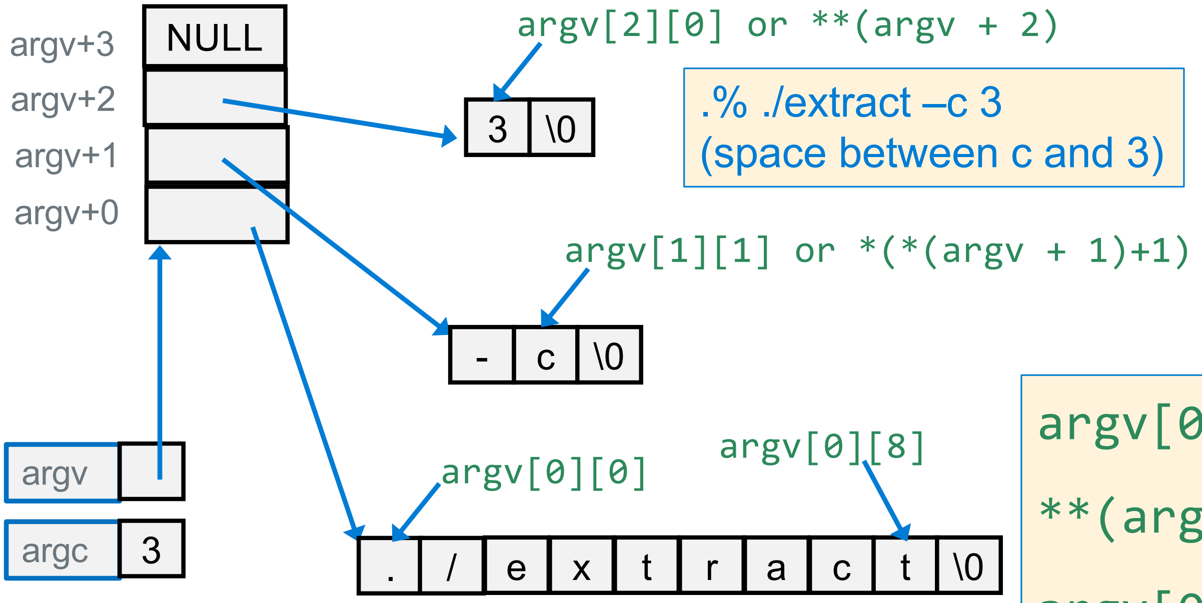


.% ./extract –c 3
(space between c and 3)

```
printf("%s\n", *(argv+0));
printf("%s\n", *(argv+1));
printf("%s\n", *(argv+2));
```

x

main() Command line arguments: argc, argv

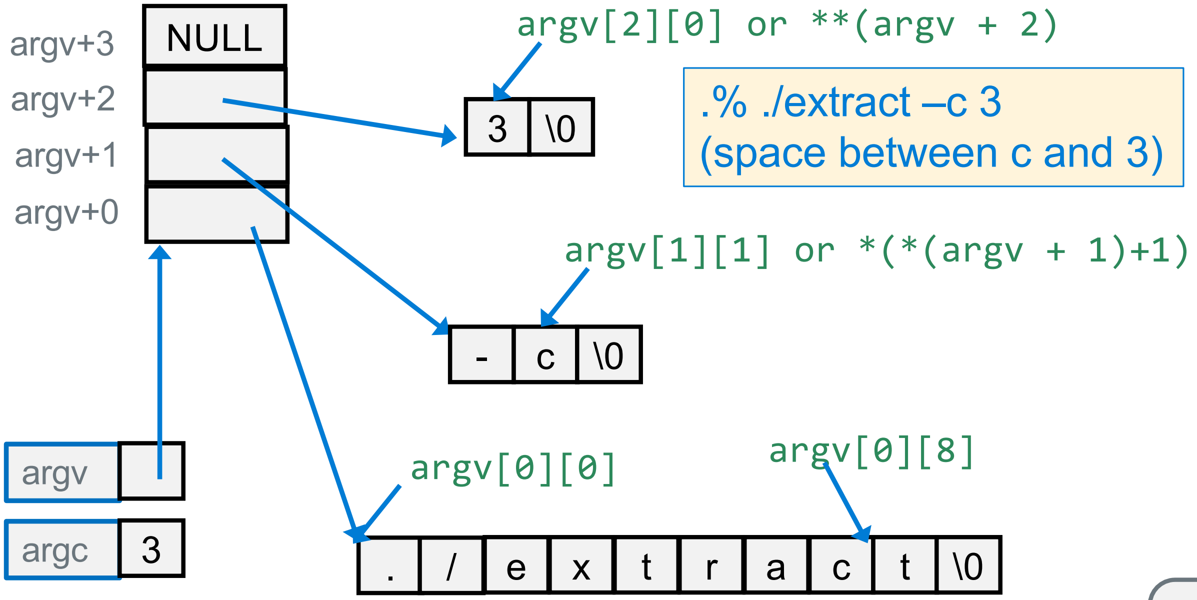


.% ./extract –c 3
(space between c and 3)

```
argv[0][0] equiv to **(argv+0)

**(argv+0) equiv **argv

argv[0][8] equiv *(*argv + 8)


char *pt = *argv;

*pt equiv to **(argv+0)

*(pt+8) equiv to *(*argv + 8)
```

x

main() Command line arguments: argc, argv



.% ./extract –c 3
(space between c and 3)

```
argv[0][0] equiv to **(argv+0)
**(argv+0) equiv **argv
argv[0][8] equiv *(*argv + 8)

char *pt = *argv;
*pt equiv to **(argv+0)
*(pt+8) equiv to *(*argv + 8)
```

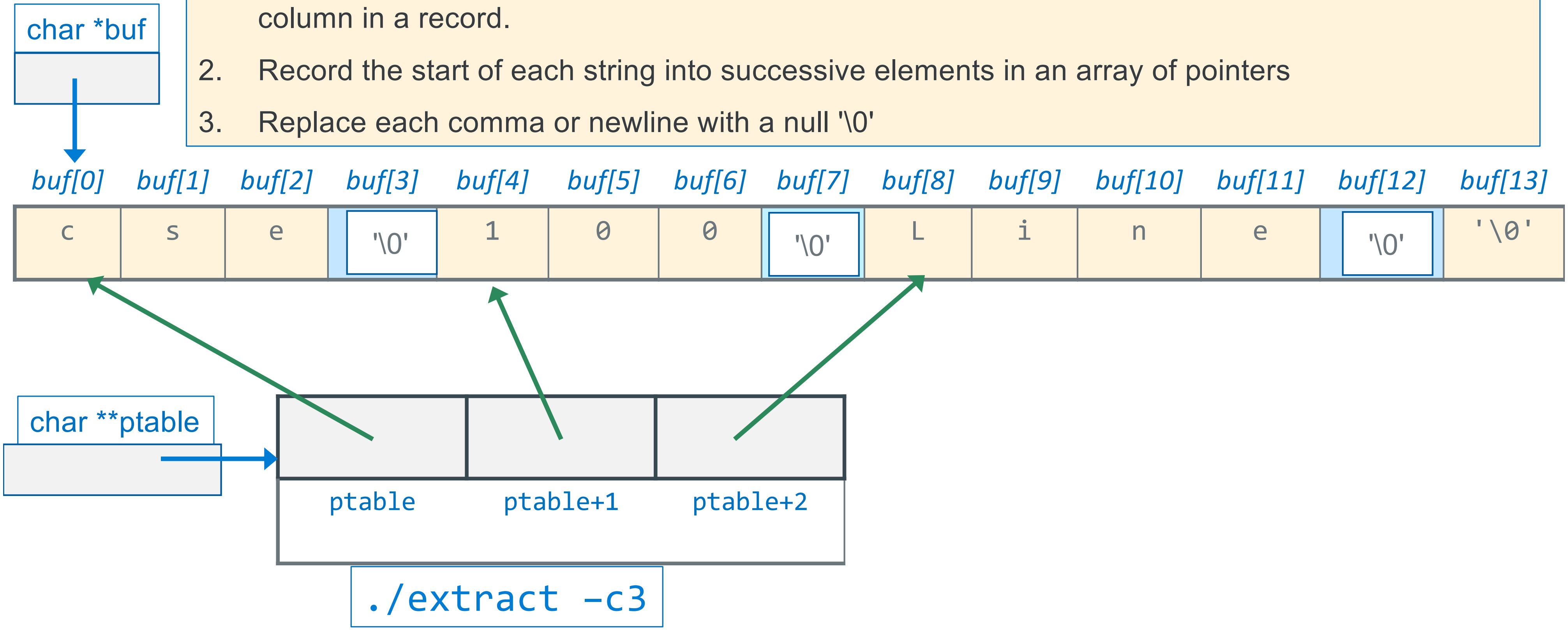
```
int main(int argc, char *argv[])
{
    for (int i = 0; argv[i] != NULL; i++) {
        for (int j = 0; argv[i][j] != '\0'; j++)
           putchar(argv[i][j]);
       putchar('\n');
    }
    return EXIT_SUCCESS;
}
```

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

x

PA4: Creating a 2D Array of Mutable String Pointers

1. Break a string of comma separated words into individual strings without copying. Do This by walking the string until you see an either a comma , or a newline \n. Each points at a field or column in a record.
2. Record the start of each string into successive elements in an array of pointers
3. Replace each comma or newline with a null '\0'



char *buf

buf[0]	*buf[1]*	*buf[2]*	*buf[3]*	*buf[4]*	*buf[5]*	*buf[6]*	*buf[7]*	*buf[8]*	*buf[9]*	*buf[10]*	*buf[11]*	*buf[12]*	*buf[13]*
c	s	e	'\0'	1	0	0	'\0'	L	i	n	e	'\0'	'\0'

char **ptable

ptable	ptable+1	ptable+2

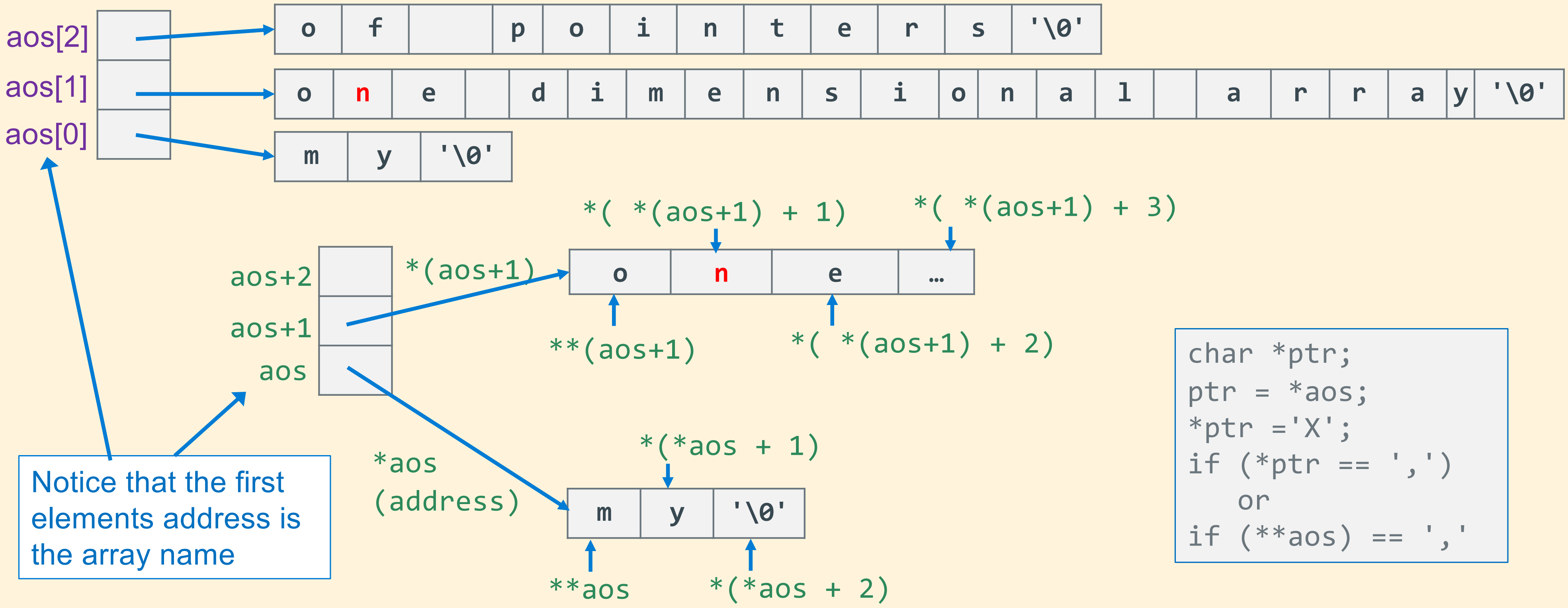
```
./extract -c3
```

Review: Pointer Array to Strings

aos+2 is not shown due to space limits on the slide

How to access: aos[1][1] is *(*(aos + 1) + 1) which contains 'n'

its address is (*(aos + 1) + 1)



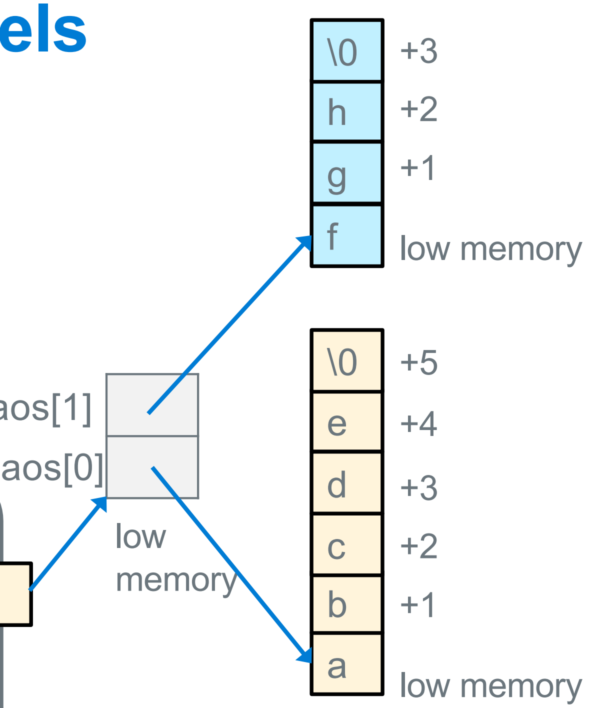
Notice that the first elements address is the array name

```
char *ptr;
ptr = *aos;
*ptr ='X';
if (*ptr == ',')
   or
if (**aos) == ','
```

Pointer Array to Mutable Strings and Sentinels

- Make an array of pointers to mutable strings requires using a cast to an array (char [ ])
- Add a NULL sentinel at the end to indicate the end of the array

```
char *aos[] = {
   (char []) {"abcde"},
   (char []) {"fgh"},
   (char *)  {NULL}
};
char **ptc = aos;
```



```
printf("%c\n", *(*(aos + 1) + 1));

while (*ptc != NULL) {
    printf("%s\n", *ptc);     // prints string

    for (int j = 0; *(*ptc + j); j++)
        putchar(*(*ptc + j)); // char in string

    putchar('\n');
    ptc++;
}
```

```
%./a.out
g
abcde
abcde
fgh
fgh
```

x

Comparing stings

- Characters can be easily compared (c1 < c2) as they are numbers, so the **character order** is determined by the ASCII values assigned to each character
  - 65 = A 66 = B 67 = C 68 = D 69 = E 70 = F 71 = G, and so on.
- Example: the following strings are in lexicographical (alphabetical) order:

  "" "a" "az" "c" "cab" "cabin" "cat" "catastrophe"

- Compare two strings lexicographically (i.e., comparing ASCII values), subtract one from the other

Return Value	Comparison
< 0	s1 < s2
> 0	s1 > s2
= 0	s1 == s2

```
int strcmp(char *s1, char *s2)
{
     while (*s1 == *s2) {
          if ((*s1 == '\0') && (*s2 == '\0'))
               break;
          s1++;
          s2++;
    }
    return *s1 - *s2;  // character difference
}
```

Slides For PA4

strtol() and strtoul() examples of passing a pointer to a pointer

```
long int strtol(const char *str, char **endptr, int base);

unsigned long int strtoul(const char *str, char **endptr, int base);
```

reruns the string converted to a long or unsigned long

str pointer to the string to convert

endptr pass the address of a variable that is a char pointer (output variable)

base: number base of the integral value

- **Example**: string is to contain just positive numbers >= 0 (in ascii) with no extra stuff
- If the string is not valid, then
  - `*endptr != '\0'` then string contains more than just numbers (bad input)
  - `*endptr` stores the address of the first invalid character found in the buffer pointed (`str`)
- How to use endptr when it does not contain NULL:
  - If there are other conversion errors (you can read the man page) then errno != 0
  - When conversion is ok, `errno` is unaltered (always clear it before calling these routines)

strtol() and strtoul() examples of passing a pointer to a pointer

```
#include <stdlib.h>
#include <errno.h>
char *endptr;
char buf[] = "33";  // test buffer string
int number;

errno = 0; // set errno to 0 (zero) before each call
number = (int)strtol(buf, &endptr, 10)
// check if the string was a proper number
// *entpr should be at the end of the string == '\0'

if ((*endptr != '\0') || (errno != 0)) {
   // handle the error
}
printf("%d\n", number);
```

Extra Slides

C Precedence and Pointers

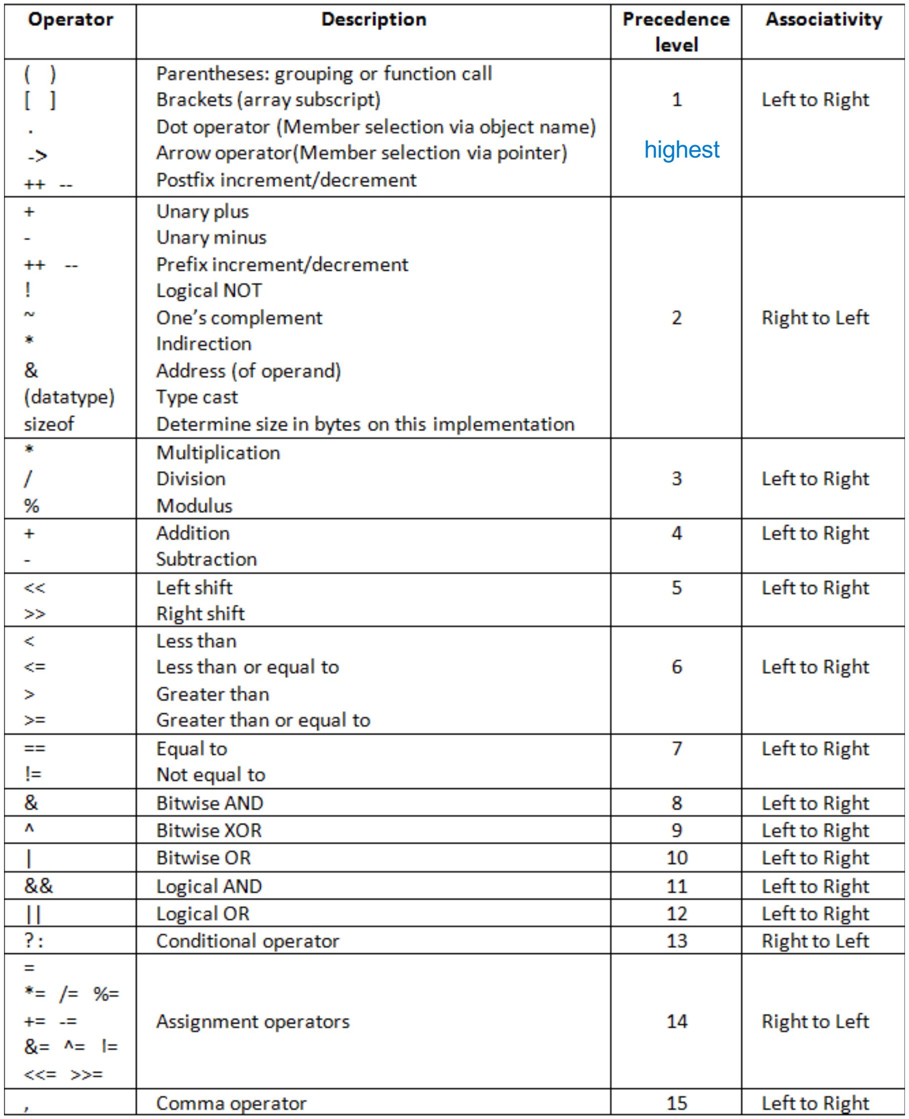
- ++ -- pre and post increment combined with pointers will create code that is complex, hard to read and difficult to maintain, so be careful!
- My advice: Always Use () to improve readability

```
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

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)
- 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

String Literals, Mutable and Immutable arrays

```
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!
```

- In the example above, "Hello World" is immutable string literal (array)
  - "Hello World" is not associated with a variable name; anonymous variable
  - "Hello World" has space to hold the string + ’\0’
  - "Hello World" is read only (immutable) and cannot be modified at runtime
- mess2 is a **pointer** to an **immutable** array with space to hold the string + ’\0’

Be Careful with C Strings and Arrays of Chars

mess2 **pointer** to an **immutable** array with space to hold the string + ’\0’

- you **cannot change** array contents, but you can change what mess2 points at

```
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;                // where mess2 points can be changed
```

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

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

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;
}
```

2D Arrays

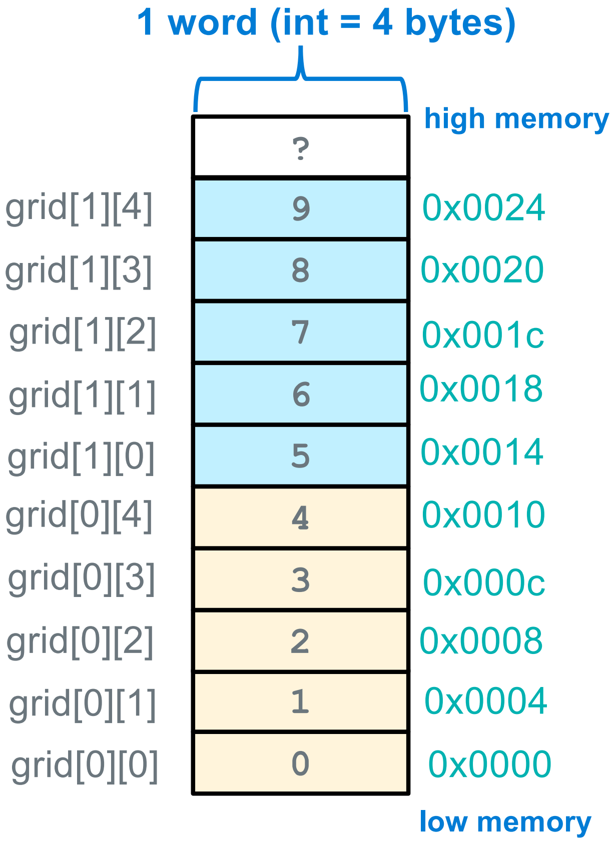
- Generic (uniform) 2D array format:

```
type name[rows][cols] = {{values},…,{values}};
```

  - allocates a single, contiguous block of memory
  - The array is organized in ***row-major*** *format*

```
// a 2-row, 3-column array of char
char matrix[2][3];

// a 2-row, 5-column (row length) array of ints
// Must specify row length, compiler counts rows

int grid[][5] = {
  {0, 1, 2, 3, 4},
  {5, 6, 7, 8, 9}
};

grid[1][2] using pointers is *( *(grid + 1) + 2)
```

[1][0]	[1][1]	[1][2]	[1][3]	[1][4]
[0][0]	[0][1]	[0][2]	[0][3]	[0][4]



	?	
grid[1][4]	9	0x0024
grid[1][3]	8	0x0020
grid[1][2]	7	0x001c
grid[1][1]	6	0x0018
grid[1][0]	5	0x0014
grid[0][4]	4	0x0010
grid[0][3]	3	0x000c
grid[0][2]	2	0x0008
grid[0][1]	1	0x0004
grid[0][0]	0	0x0000

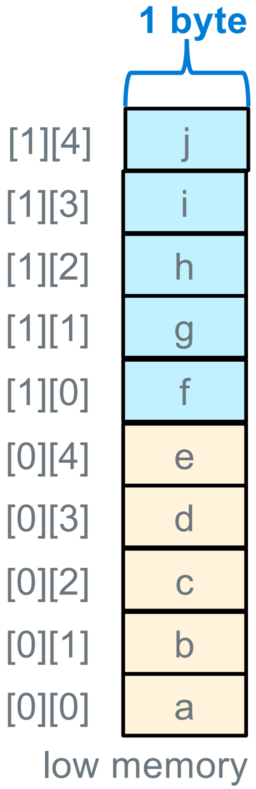
x

2D Array Access

```c
#define LEN 6
int main(void)
{
    char a[][LEN] = {"abcde","fghij"};

    for (int i = 0; i < sizeof(a)/(sizeof(a[0][0]) * LEN); i++) {
        for (int j = 0; j < LEN; j++)
            putchar(a[i][j]);
         putchar('\n');
    }
    return EXIT_SUCCESS;
}
```

must supply ROW length (number of cols)

```
%./a.out
abcde
fghij
```



1 byte

[1][4] j
[1][3] i
[1][2] h
[1][1] g
[1][0] f
[0][4] e
[0][3] d
[0][2] c
[0][1] b
[0][0] a

low memory

```c
char *ptc = &a[0][0]; // pointer to a char!
putchar( *(ptc + (i * sizeof(a[0][0]) * LEN) + j) );
```

2D Array of Char (elements may contain strings)

- 2D array of chars (where rows may include strings) - Mutable
- Each row is the same fixed size of memory
- So, all the rows are the same length regardless of the actual string length
- The column size must be large enough for the longest string

high memory

```
char aos2d[3][22] = {"my", "two dimensional", "char array"};
```

aos2d[2]	c	h	a	r		a	r	r	a	y	'\0'	0	0	0	0	0	0	0	0	0	0	0
aos2d[1]	t	w	o		d	i	m	e	n	s	i	o	n	a	l		a	r	r	a	y	'\0'
aos2d[0]	m	y	'\0'	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

low memory

high memory

```
#define ROWS 3
char aos[ROWS][22] = { "my", "two dimensional", "char array"};
char (*ptc)[22] = aos;  // ptr points at a row of 22 chars

for (int i = 0; i < ROWS; i++)
    printf("%s\n", *(ptc + i) );
```

x