

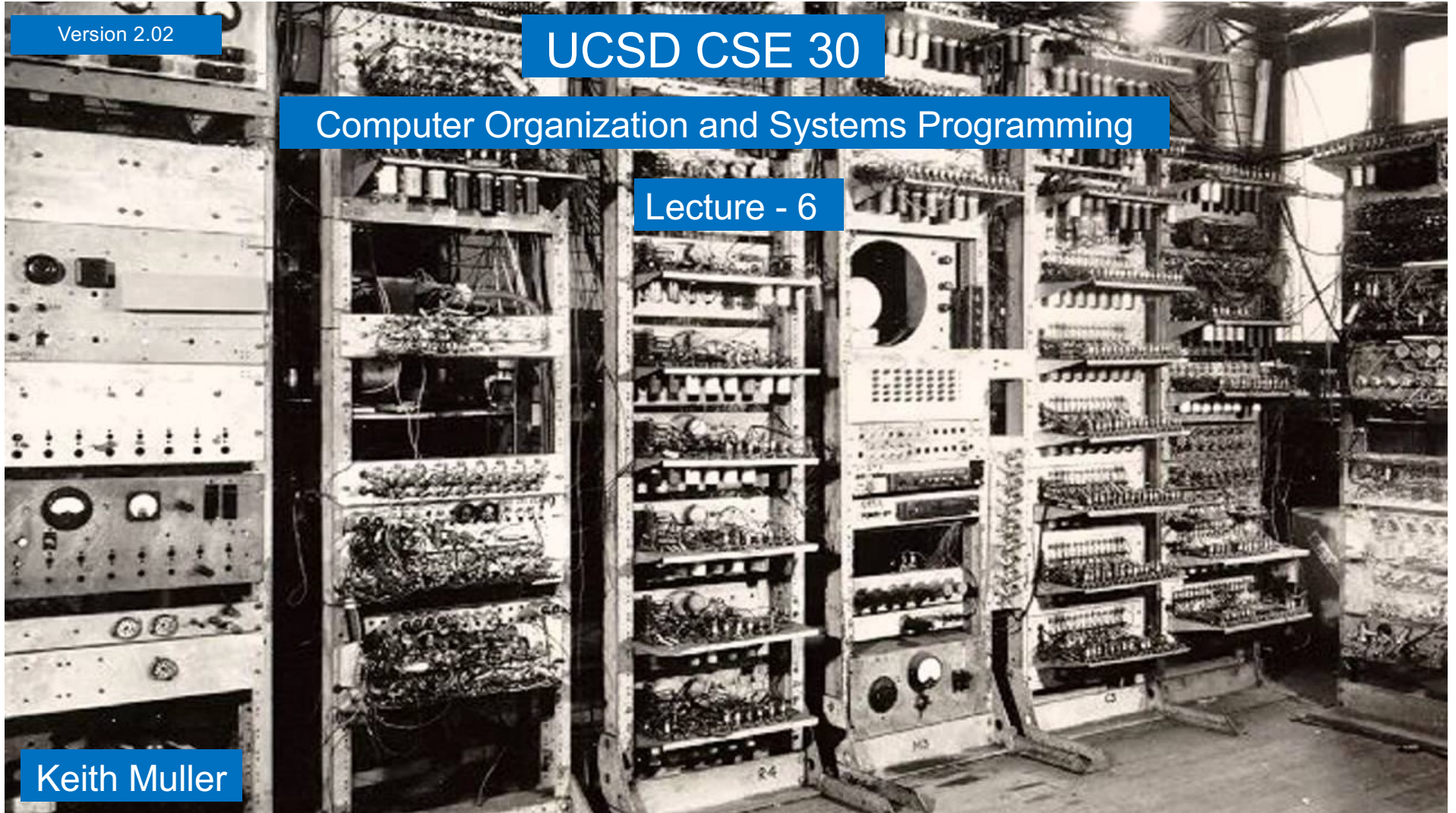
Version 2.02

UCSD CSE 30

Computer Organization and Systems Programming

Lecture - 6

Keith Muller

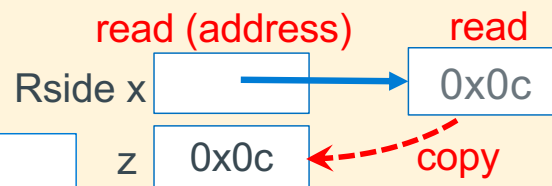


## Rside Indirection (or dereference) Operator: \*

- 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
```

Two reads here  
(1) read to get an address  
(2) read the address to get the value



## Rside Indirection (or dereference) Operator: \*

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

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

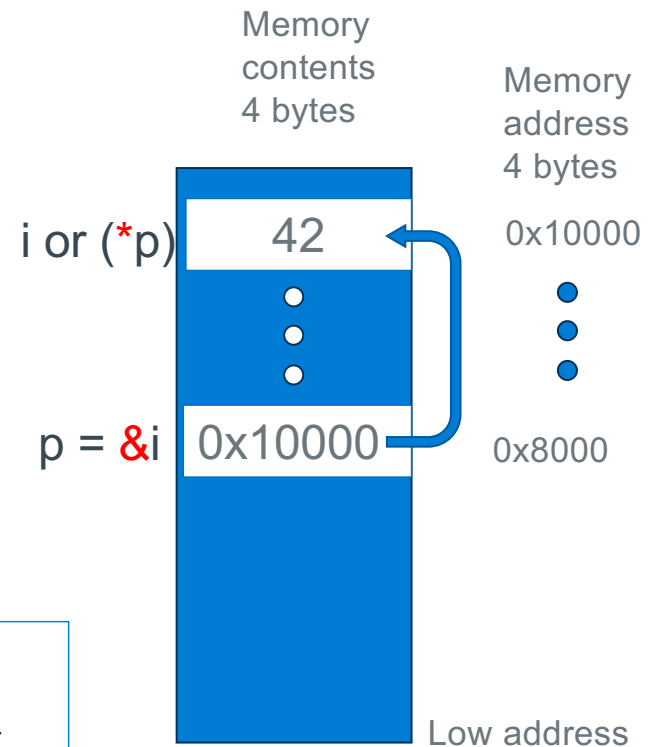
```
p = &i;
```

No reads here

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

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

Two reads here  
(1) read to get an address  
(2) read the address to get the value

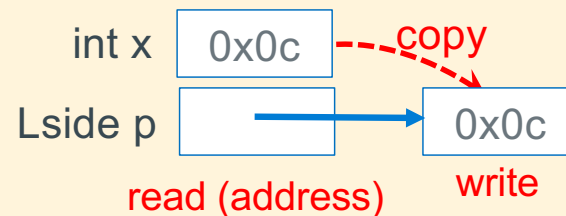


## Lside Indirection Operator

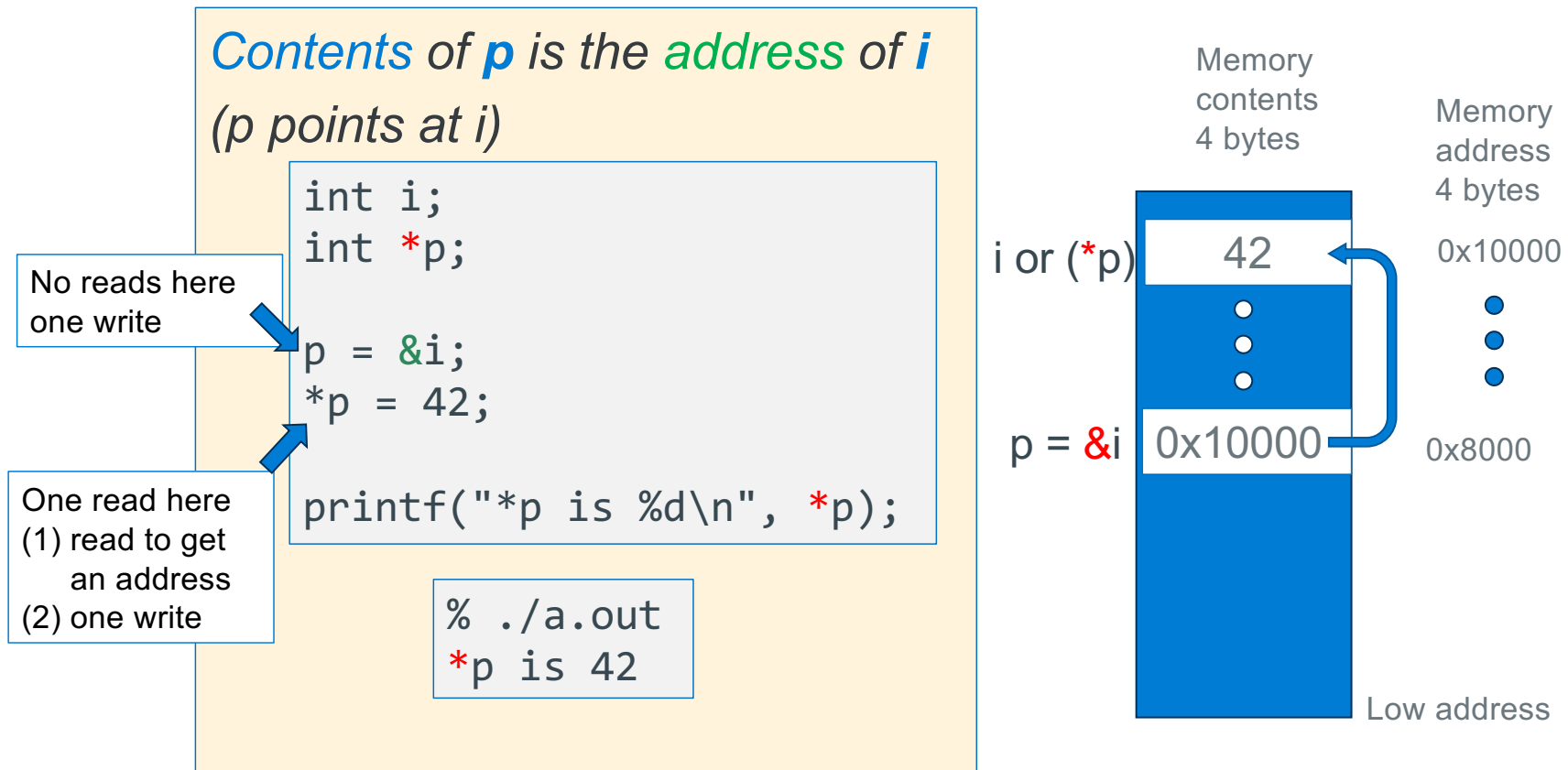
Performs the following steps when the **\*** is on the Lside:

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**)

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

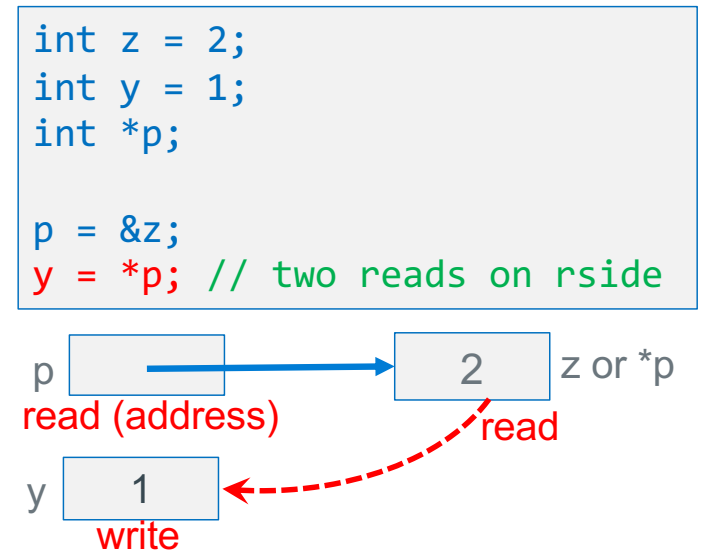
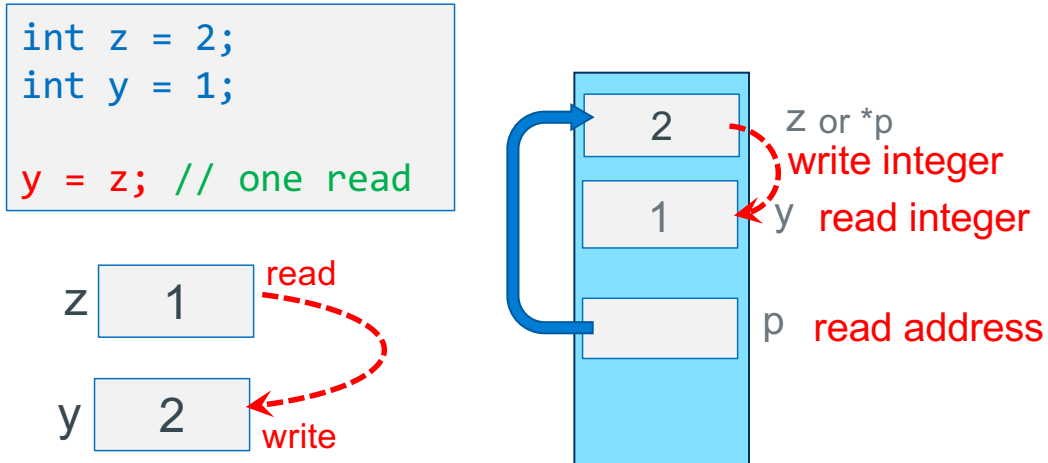


## Left Side Indirection (or dereference) Operator: \*



## Each use of a \* operator results in one additional read: Rside

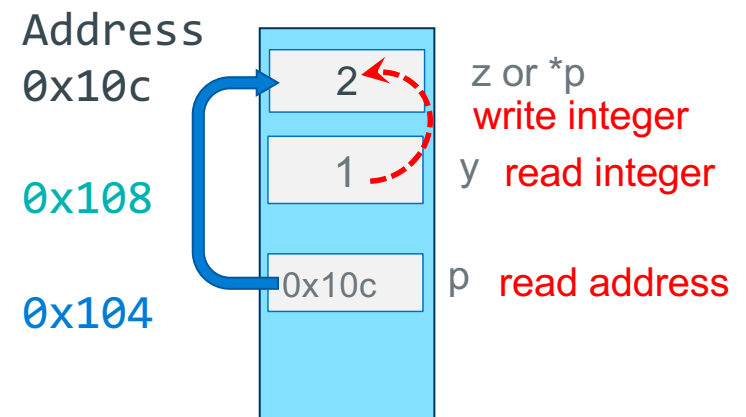
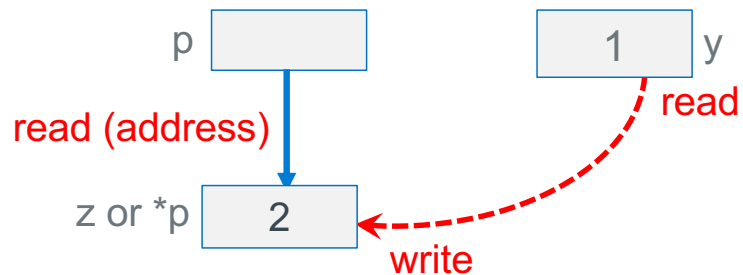
**RULE:** Each \* when used as a dereference operator in a **statement** (either **Lside** or **Rside**) it causes an additional read to be performed



Aside: `y = *(&z);` // same as `y = z`

## Each use of a \* operator results in one additional read: Lside

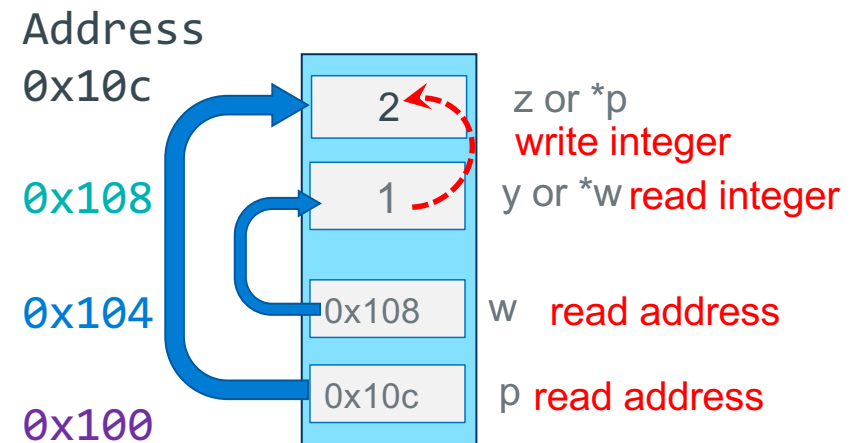
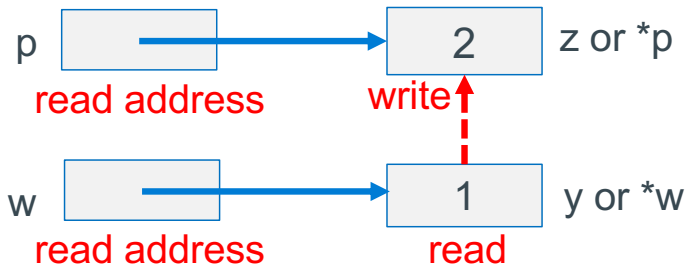
```
int z = 2;  
int y = 1;  
int *x;  
  
p = &z;  
*p = y;    // one read on lside
```



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

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

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





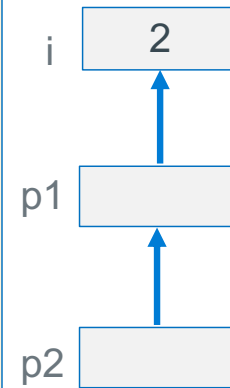
## Pointer to Pointers (Double Indirection)

- Define a pointer to a pointer (p2 below)

```
int i = 2;
int *p1;
int **p2; // pointer to a pointer to an int

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

- C allows any number of pointer indirections
  - more than two levels is very uncommon in real applications as it reduces readability and generates a lot of memory reads
- RULE (important):** number of **\*** in the variable definition tells you how many **reads** it takes to get to the **base type**  
 $\text{\#reads to base type} = \text{number of } * \text{ (in the definition)} + 1$
- Example:  
`int **p2;` // requires 3 reads to get to the int

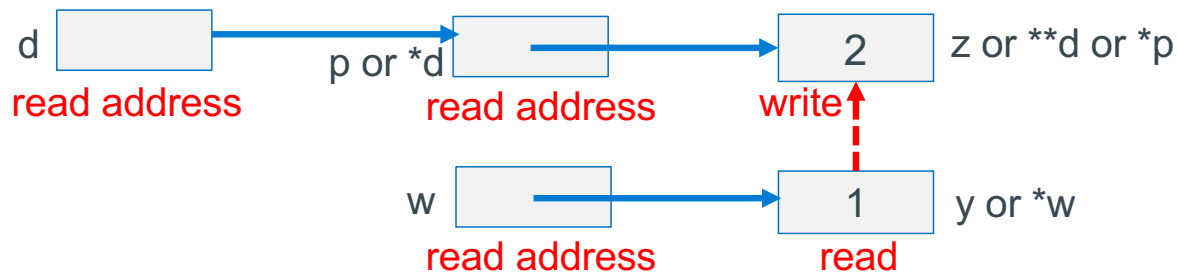
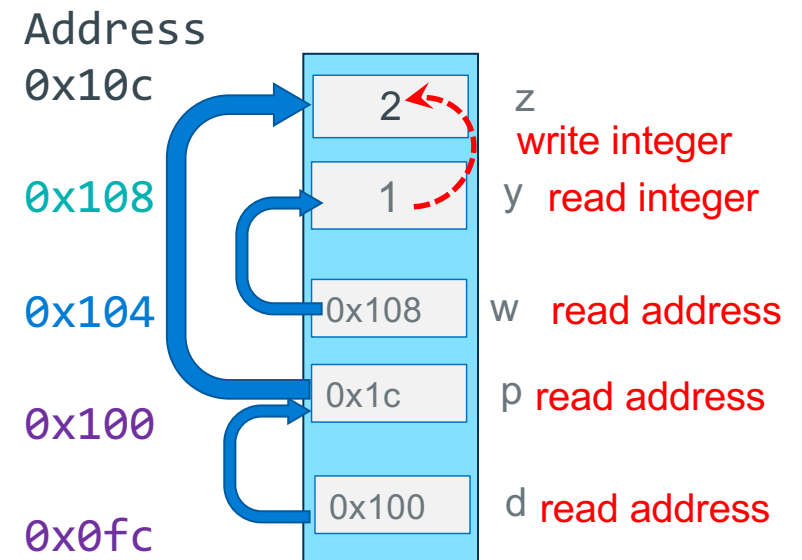


## Double Indirection: Lside

```

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

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



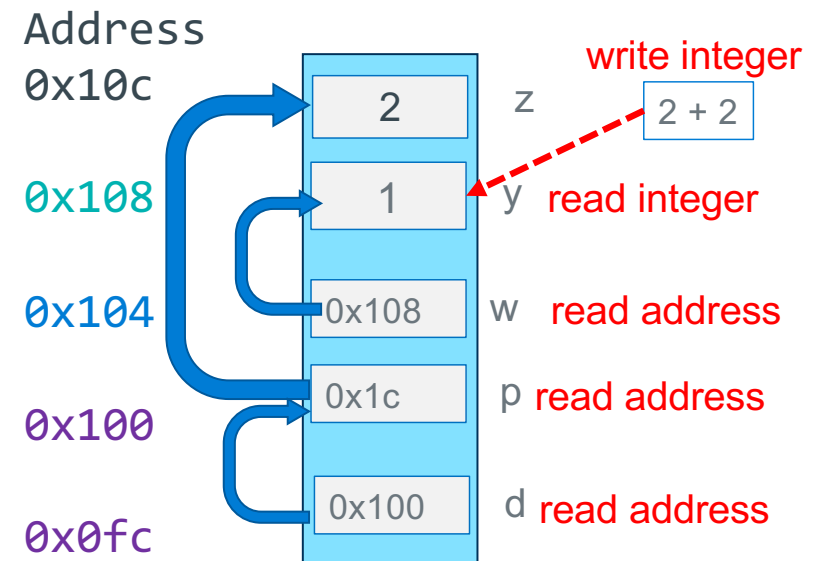
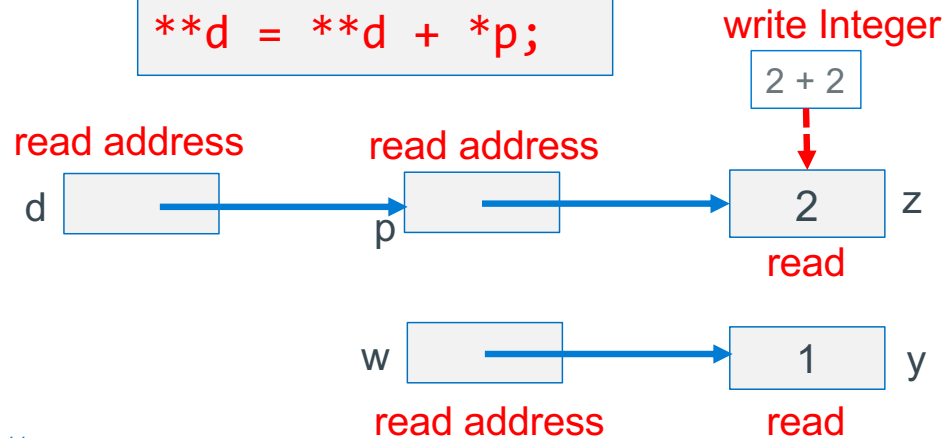
## Double Indirection: Rside

```

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

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

**d = **d + *p;
    
```



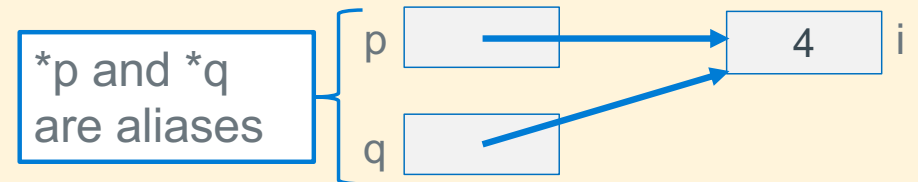
**Important Observation**  
`**d` on Lside is two reads  
`**d` on Rside is three reads

# 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)
- **Example:** 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;
int *q;

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



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

# Defining Arrays

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`

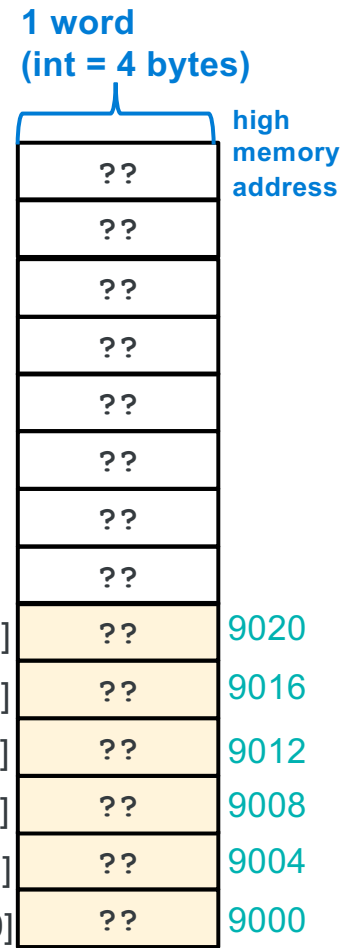
```
#define BSZ 6  
int b[BSZ];
```

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

- Array **names are constants** 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];
```



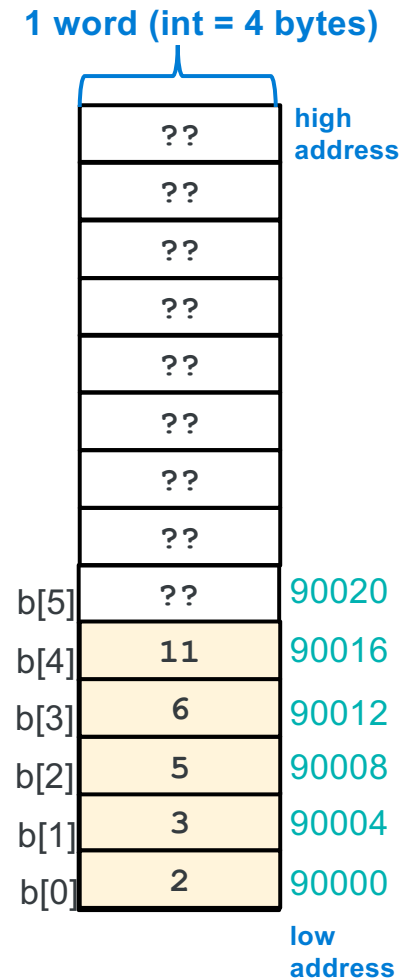
# Array Initialization

- 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**



X

# Accessing Arrays Using Indexing

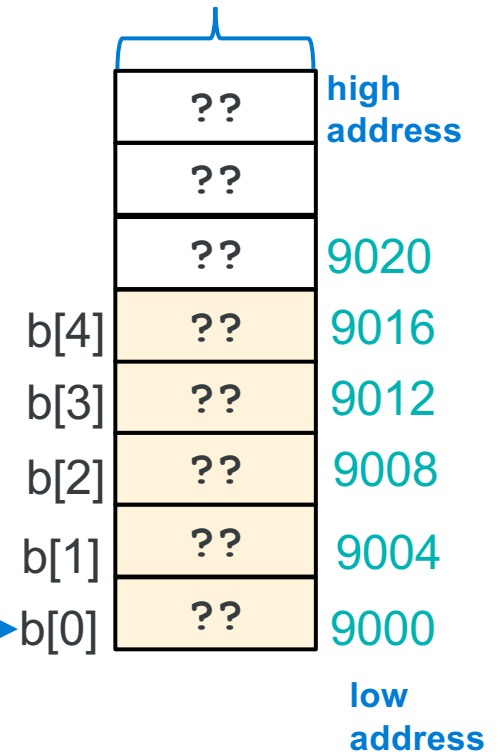
- **name** [**index**] selects the **index** element of the array
  - index **should be** unsigned
  - Elements range from: 0 to count – 1 ( int x[count]; )
- **name** [**index**] can be used as an **assignment target** or as a **value in an expression**
- **Array name** (by itself with no [ ]) on the **Rside** evaluates to the address of the first element of the array

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

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

p 9000

1 word  
(int = 4 bytes)



## How many elements are in an array?

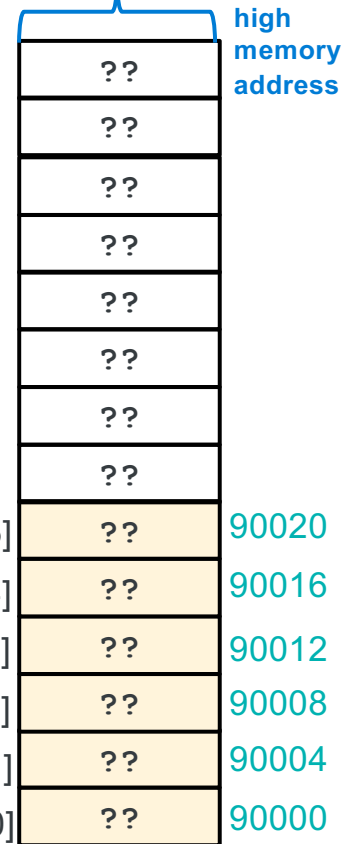
- The number of elements of space allocated to an array (called **element count**) and indirectly the total size in bytes of an array is not stored anywhere!!!!!!
- An **array name** is just the **address of the first element in a block of contiguous memory**
  - So an array does not know its own size!

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

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

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

1 word  
(int = 4 bytes)





## Determining Element Count: compile time calculation

- 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** where the array variable was defined

```
#include <stddef.h>
int main()
{
    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;
```

# Pointers and Arrays - 1

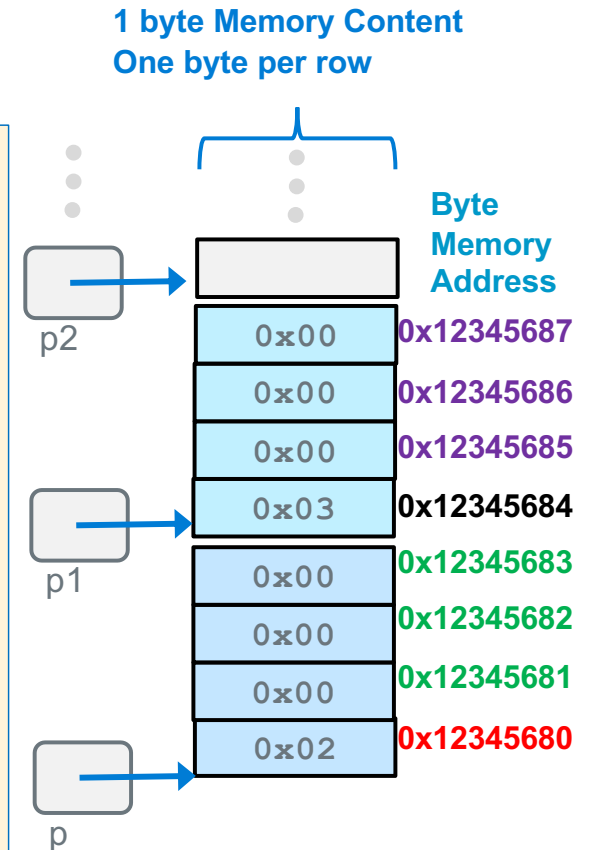
- A few slides back we stated: **Array name** (by itself) on the Rside evaluates to the **address of the first element of the array**

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

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

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

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



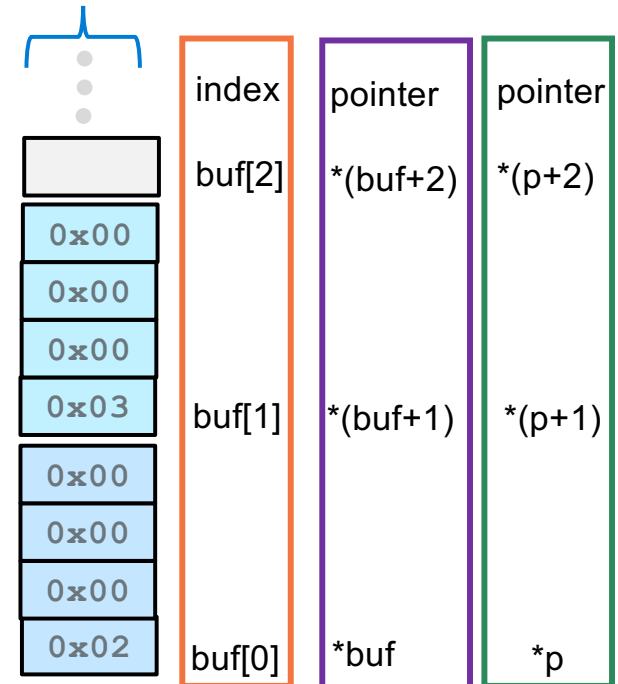
## Pointers and Arrays - 2

- When `p` is a pointer, the actual evaluation of the address:
  - `(p+1)` depends on the base type the 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]`

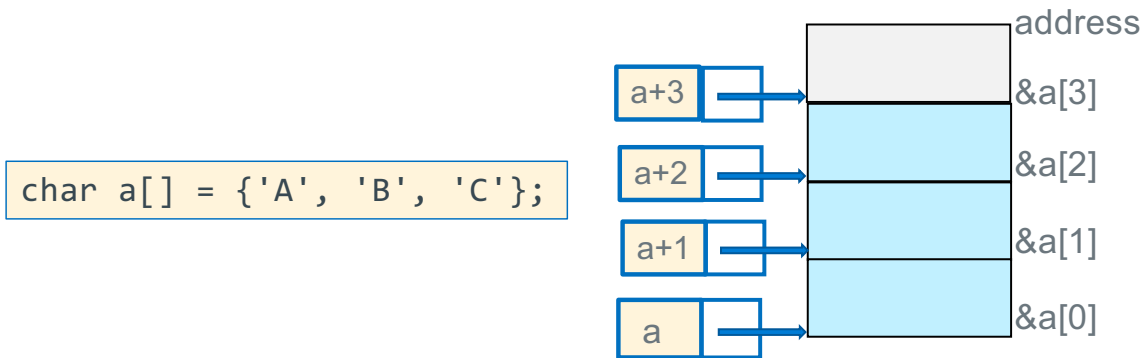
```
int buf[] = {2, 3, 5, 6, 11};
int *p;
p = buf;

*p = *buf + 10; // {12, 3, 5, 6, 11}
*(p + 1) = *(buf + 1) + 10; // {12, 13, 5, 6, 11}
```

1 byte Memory Content  
One byte per row



## Pointer Arithmetic In Use – C's Performance Focus



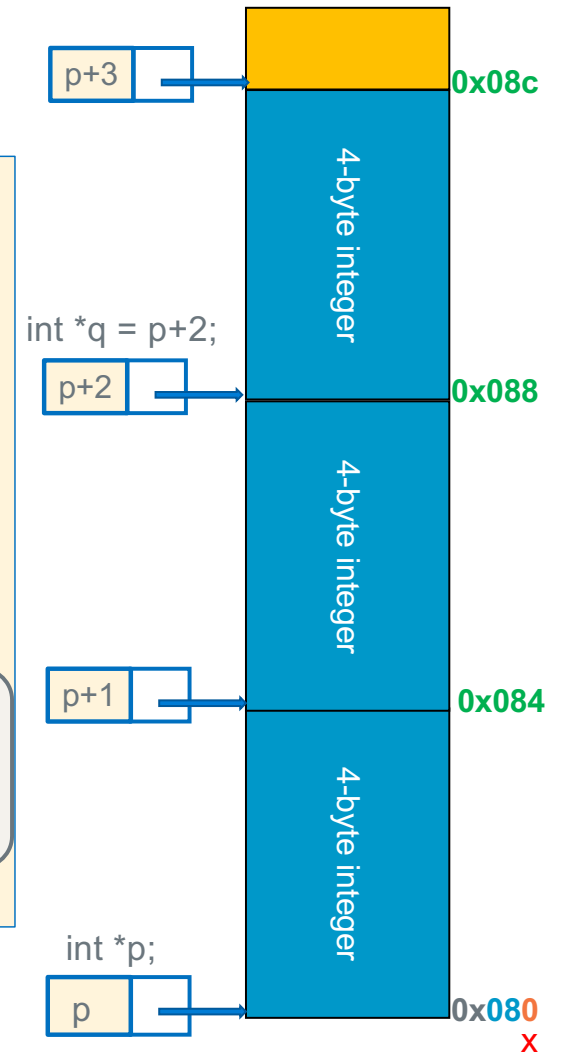
- **Alert!**: C performance focus does not perform any array “bounds checking”
- **Performance by Design**: bound checking slows down execution of a properly written program
- **Example**: array `a` of length `i`, C does not verify that `a[j]` or `*(a + j)` is valid (does not check:  $0 \leq j < i$ )
  - 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

# 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* are both **byte addresses**):

distance in elements =  $(p - q) / \text{sizeof}(*p)$

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



## Pointer Comparisons

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

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

```
int numb[] = {9, 8, 1, 9, 5};
int *end;
int *a;
end = numb + (int) (sizeof(numb)/sizeof(*numb));
a = numb;
while (a < end) // compares two pointers (address)
    /* rest of code including doing an a++ */
```

- 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

## Using Pointers to Traverse an array

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

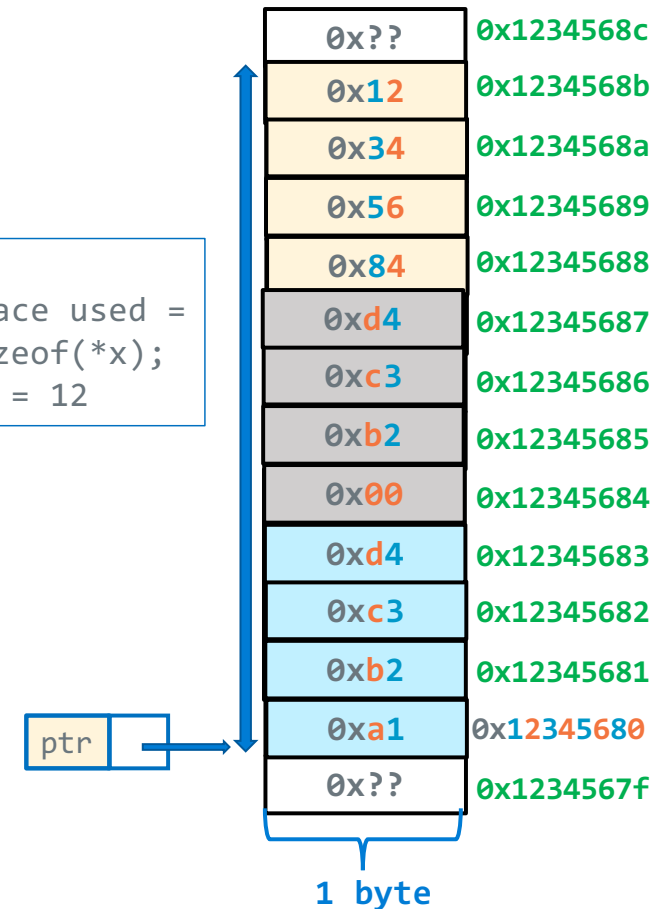
for (int j = 0; j < cnt; j++)
    printf("%#x\n", x[j]);
}
```

```
cnt = 3;
actual space used =
cnt * sizeof(*x);
= 12
```

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

for (int j = 0; j < cnt; j++)
    printf("%#x\n", *(ptr + j));
}
```

Brute force translation to pointers



## Fast Ways to Traverse an Array: Use a Limit Pointer

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

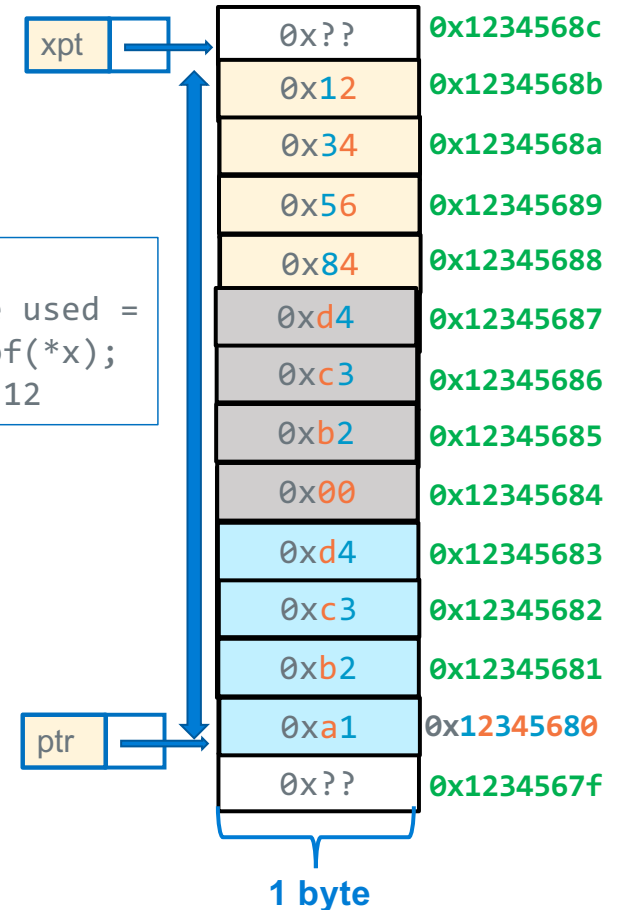
```
int *ptr;
int *xptr;
ptr = x; //or &x[0]
xptr = ptr + cnt;
```

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

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

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

cnt = 3;  
actual space used =  
cnt \* sizeof(\*x);  
= 12





## C Precedence and Pointers

- ++ -- pre and post increment combined with pointers can create code that is complex, hard to read and difficult to maintain
- Use () to help readability

Operator	Description	Associativity
() [] . -> ++ --	Parentheses or function call Brackets or array subscript Dot or Member selection operator Arrow operator Postfix increment/decrement	left to right
++ -- + - ! ~ (type) * & sizeof	Prefix increment/decrement Unary plus and minus not operator and bitwise complement type cast Indirection or dereference operator Address of operator Determine size in bytes	right to left
* / %	Multiplication, division and modulus	left to right
+ -	Addition and subtraction	left to right
<< >>	Bitwise left shift and right shift	left to right
< <= > >=	relational less than/less than equal to relational greater than/greater than or equal to	left to right
== !=	Relational equal to or not equal to	left to right
&&	Bitwise AND	left to right
^	Bitwise exclusive OR	left to right
	Bitwise inclusive OR	left to right
&&	Logical AND	left to right
	Logical OR	left to right
? :	Ternary operator	right to left
= += -= *= /= %= &= ^=  = <<= >>=	Assignment operator Addition/subtraction assignment Multiplication/division assignment Modulus and bitwise assignment Bitwise exclusive/inclusive OR assignment	right to left
,	comma operator	left to right

common	With Parentheses	Meaning
*p++	*(p++)	(1)The Rvalue is the object that p points at (2)increment pointer p to next element ++ is higher than *
(*p)++		(1)Rvalue is the object that p points at (2)increment the object
*++p	*(++p)	(1)Increment pointer p first to the next element (2)Rvalue is the object that the incremented pointer points at
++*p	++(*p)	Rvalue is the incremented value of the object that p points at

## Example of a hard-to-understand pointer statement

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

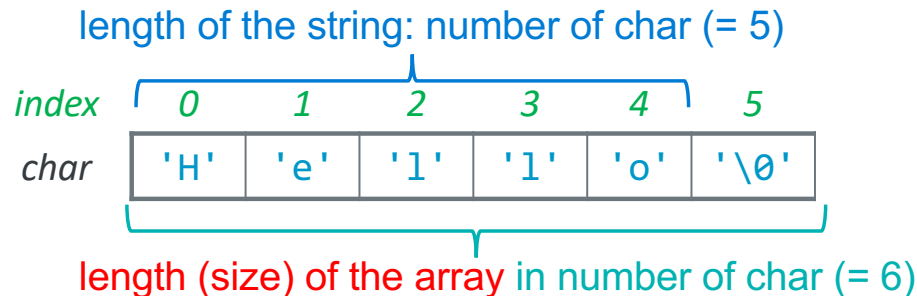
```
x = 1 + (*ptr++)++; // yuck!!
```

common	Alternate	Meaning
*p++	*(p++)	The Rvalue is the object that p points at; then increment pointer p to next element
(*p)++		The Rvalue is the object that p points at; then increment the object
++p	*(++p)	Increment pointer p first to the next element; the Rvalue is the object that the incremented pointer points at
++*p	++(*p)	The Rvalue is the incremented value of the object that p points at

```
/* Same as the one line above */  
x = 1 + *ptr;           // x = 1 + *ptr (2) = 3;  
  
*ptr = *ptr + 1;        // (*ptr)++ is array[0]= 2 + 1;  
  
ptr = 1 + ptr;          // ptr = &array[1] = now points at 5
```

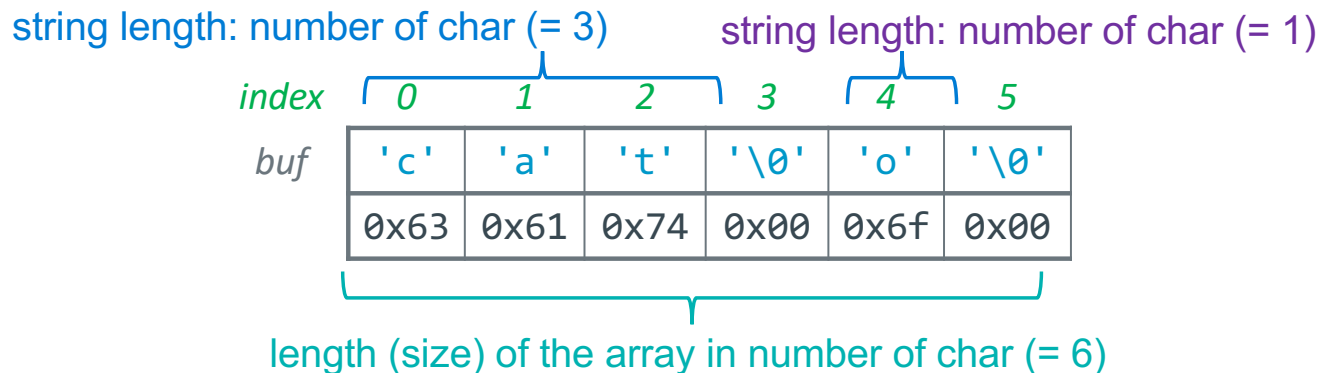
# C Strings - 1

- 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



## C Strings - 2

- First '`\0`' encountered 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 two strings
  - 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`



## 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";
char c[] = {'c', 'a', 't', '\0', 'a', 'b'};
char empty[] = "";
```

*// compiler calculates size, adds '\0'*  
*// array size 6, string length 3*  
*// empty string - contains '\0'*  
*// string length = 0*

## 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)

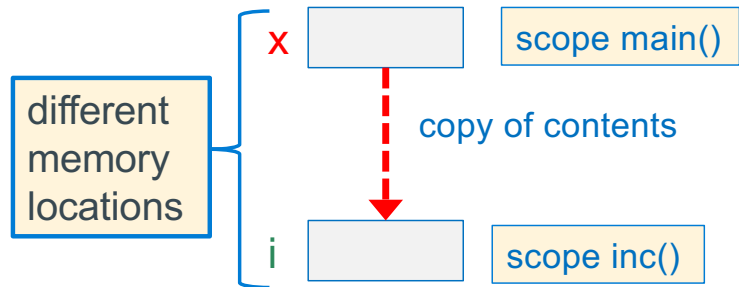
- What **Called** Function Does
  - Passed Parameters are used like local variables
  - **Modifying** the **passed parameter** in the **function** is **allowed** just like a **local variable**
  - So, writing to the parameter, **only** **changes** the **copy**
- The **return value** from a function in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

## 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

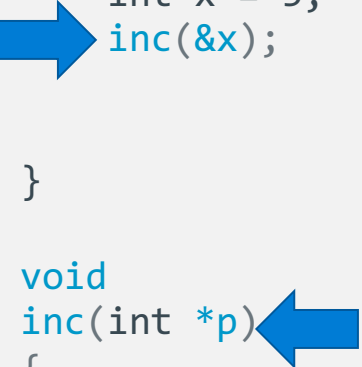


- when `inc(x)` is called, a copy of `x` is made to another memory location
  - `inc()` cannot change the variable `x` since `inc()` does not have the address of `x`, it is local to `main()` so, 5 is printed
- The `inc()` function is free to change its copy of the argument (just like any local variable)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

## Output Parameters (Mimics Call by Reference)

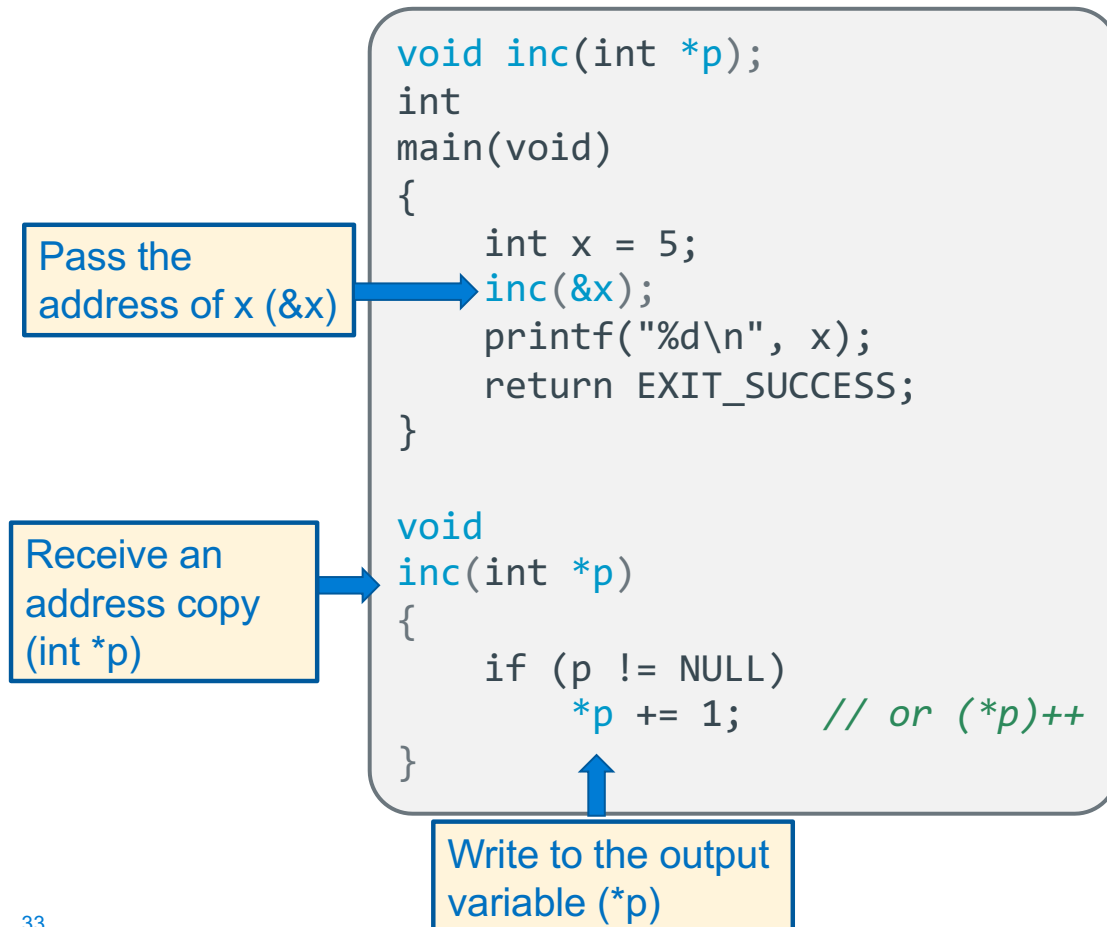
- Passing a pointer parameter with the intent that the called function will use the address it to store values for use by the calling function, then pointer parameter is called an **output parameter**
- To pass the address of a variable x use the **address operator** (&x) or the contents of a pointer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

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



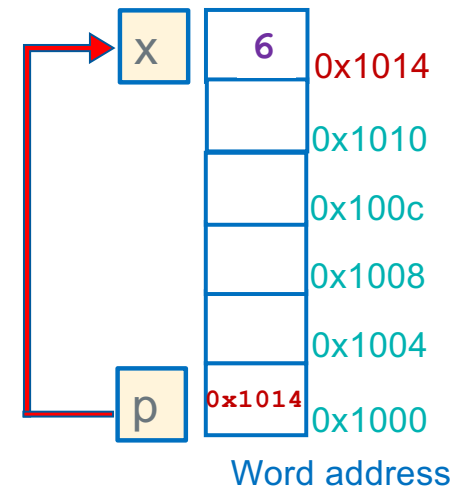


## Example Using Output Parameters



### At the Call to inc() in main()

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



### With a pointer to X,

inc() can change x in main()  
this is called a side effect

p just like any other local variable

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

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

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

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

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

### IMPORTANT:

See the size difference 20 in `main()` in `passa()` is 4 bytes (size of a pointer)

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

## 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

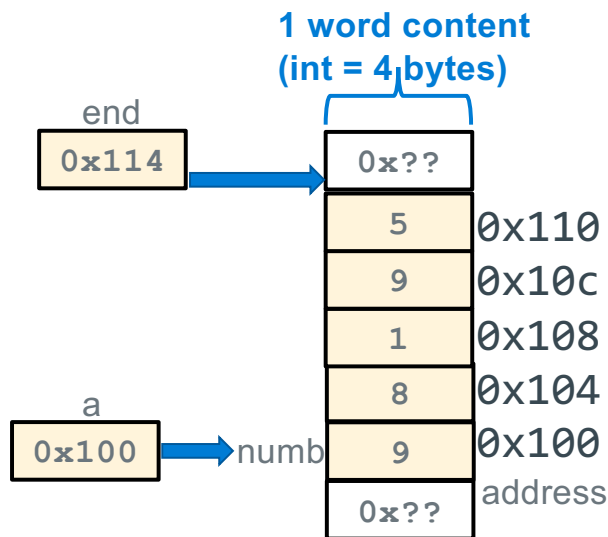
## Two ways to pass array size

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 sum = 0;
    int *end;
    end = a + size;

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

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

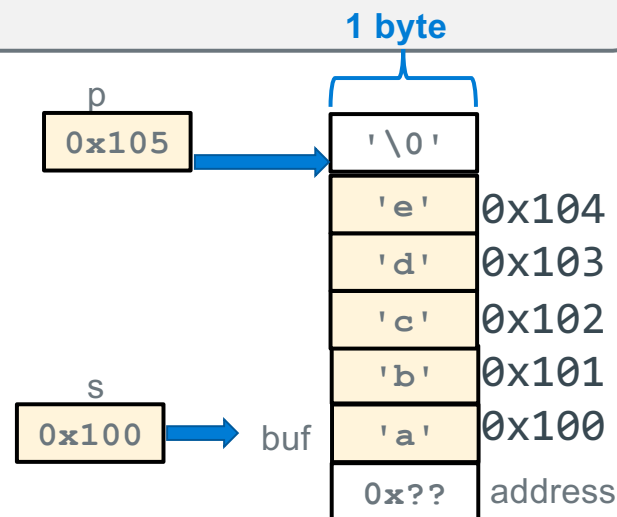
## Arrays As Parameters, Approach 2: Use a sentinel element

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

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

```
/* Assumes parameter is a terminated string */
int strlen(char *s)
{
    char *p = s;
    if (p == NULL)
        return 0;
    while (*p++)
        ;
    return (p - s - 1);
}
```



## Reference: Some String Routines in libc (#include <string.h>)

Function	Description
<code>strlen(<i>str</i>)</code>	returns the # of chars in a C string (before null-terminating character).
<code>strcmp(<i>str1</i>, <i>str2</i>)</code> , <code>strncmp(<i>str1</i>, <i>str2</i>, <i>n</i>)</code>	compares two strings; returns 0 if identical, <0 if <b><i>str1</i></b> comes before <b><i>str2</i></b> in alphabet, >0 if <b><i>str1</i></b> comes after <b><i>str2</i></b> in alphabet. <b><i>strncmp</i></b> stops comparing after at most <b><i>n</i></b> characters.
<code>strchr(<i>str</i>, <i>ch</i>)</code> <code>strrchr(<i>str</i>, <i>ch</i>)</code>	character search: returns a pointer to the first occurrence of <b><i>ch</i></b> in <b><i>str</i></b> , or <b><i>NULL</i></b> if <b><i>ch</i></b> was not found in <b><i>str</i></b> . <code>strrchr</code> find the last occurrence.
<code>strstr(<i>haystack</i>, <i>needle</i>)</code>	string search: returns a pointer to the start of the first occurrence of <b><i>needle</i></b> in <b><i>haystack</i></b> , or <b><i>NULL</i></b> if <b><i>needle</i></b> was not found in <b><i>haystack</i></b> .
<code>strcpy(<i>dst</i>, <i>src</i>)</code> , <code>strncpy(<i>dst</i>, <i>src</i>, <i>n</i>)</code>	copies characters in <b><i>src</i></b> to <b><i>dst</i></b> , including null-terminating character. Assumes enough space in <b><i>dst</i></b> . Strings must not overlap. <b><i>strncpy</i></b> stops after at most <b><i>n</i></b> chars, and <u>does not</u> add null-terminating char.
<code>strcat(<i>dst</i>, <i>src</i>)</code> , <code>strncat(<i>dst</i>, <i>src</i>, <i>n</i>)</code>	concatenate <b><i>src</i></b> onto the end of <b><i>dst</i></b> . <b><i>strncat</i></b> stops concatenating after at most <b><i>n</i></b> characters. <u>Always</u> adds a null-terminating character.
<code>strspn(<i>str</i>, <i>accept</i>)</code> , <code>strcspn(<i>str</i>, <i>reject</i>)</code>	<b><i>strspn</i></b> returns the length of the initial part of <b><i>str</i></b> which contains <u>only</u> characters in <b><i>accept</i></b> . <b><i>strcspn</i></b> returns the length of the initial part of <b><i>str</i></b> which does <u>not</u> contain any characters in <b><i>reject</i></b> .

## Do not overuse strlen()

- C string library function `strlen()` calculates string length **at runtime**
- **Do not overuse `strlen()`, as it walks the array each time called**

```
int count_e(char *s) //  $O(n^2)$  !!!  
{  
    int count = 0;  
    if (s == NULL)  
        return 0;  
    for (int j = 0; j < strlen(s); j++) {  
        if (s[j] == 'e')  
            count++;  
    }  
    return count;  
}
```



```
int count_e(char *s) //  $O(n)$  !!!  
{  
    int count = 0;  
    if (s == NULL)  
        return 0;  
    while (*s) {  
        if (*s++ == 'e')  
            count++;  
    }  
    return count;  
}
```

## 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) ...
```

## Simple String IO - Reading

Task	Example Function Calls
Read a string	<pre>#include &lt;stdio.h&gt;  char *strptr; char myStr[BFSZ];  strpstr = fgets(myStr, BFSZ, stdin);</pre> <div>must pass the size of the array so fgets() knows how much space there is</div>

`char *fgets(char array[ ], int size, FILE *stream)`

- `char *` is a pointer (address) to an array of char
- reads in at most **one less than size** characters from **stream** and stores them into **array**
- Reading stops after an **EOF** or a newline '\n'
  - If a newline ('\n') is read, it is stored into the buffer
  - **A terminating null byte ('\0') is always stored after the last character in the buffer**

t	h	i	s		i	s		a		s		t	r	i	n	g	\n	\0
---	---	---	---	--	---	---	--	---	--	---	--	---	---	---	---	---	----	----

- Returns a **NULL at end of file** (or a read failure), otherwise a pointer to array (pointers later...)
- See `man 3 fgets`

## Returning a Pointer

```
char *next(char *ptr)
{
    if (ptr == NULL)
        return NULL;

    while ((*ptr != '\0') && (*ptr != ','))
        ptr++;

    if (*ptr == ',')
        return ++ptr;
    return NULL;
}
```

```
#include <stdlib.h>
#include <stdio.h>
#define BUFSZ 512
char *next(char *);

int main()
{
    char buf[BUFSZ];
    char *ptr;

    while (fgets(buf, BUFSZ, stdin) != NULL) {
        printf("buf: %s\n", buf);

        if ((ptr = next(buf)) != NULL)
            printf("after: %s\n", ptr);
        else
            printf("no comma found\n");
    }
    return EXIT_SUCCESS;
}
```

## 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:
  - Address of a **passed parameter copy** as the caller may or will deallocate it after the call
  - 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
}
```

## Copying Strings: Use the Sentinel; libc: strncpy()

<i>index</i>	0	1	2	3	4	5
<i>char</i>	'H'	'e'	'l'	'l'	'o'	'\0'

```
// strncpy adds a length limit on copy
char str1[6];
int cnt = (int)(sizeof(str1) / sizeof(str1[0]));

strncpy(str1, "hello", cnt); // \0 copied
strncpy(str1, "hello", cnt - 1); // \0 not copied
```

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

    while ((*s0++ = *s1++) && --len) //watch short circuit
        here
        ;
    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}  
};
```

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

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

1 word (int = 4 bytes)

	?	high memory
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
		low memory

## 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 - 1

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

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

`mess1[]` Hello World\0

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

```
char *mess2 = "Hello World"; // "Hello World" read only string literal  
// mess2 is a pointer NOT an array!
```

`mess2` → Hello World\0 ← read only string literal

- `mess3` is a **pointer** to a mutable array

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

using the cast `(char [])`  
makes it mutable

`mess3` → Hello World\0 ← mutable string

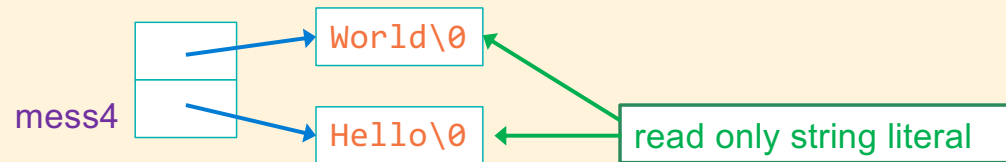


## String Literals, Mutable and Immutable arrays - 2

- `mess4` is an array of pointers to immutable arrays

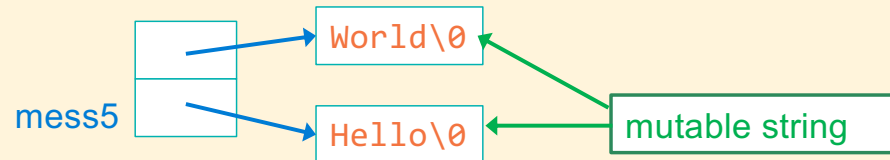
```
char *mess4[] = {"Hello","World"}; // immutable string  
*(*mess4 + 1) = '\0'; // bus error
```

Bus error: writing  
read only memory  
Seg fault: writing  
unallocated memory



- `mess5` is an array of pointers to mutable arrays

```
char *mess5[] = { (char []){"Hello"}, (char []){"World"}};  
*(*mess5 + 1) = '\0'; // OK!
```



## 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

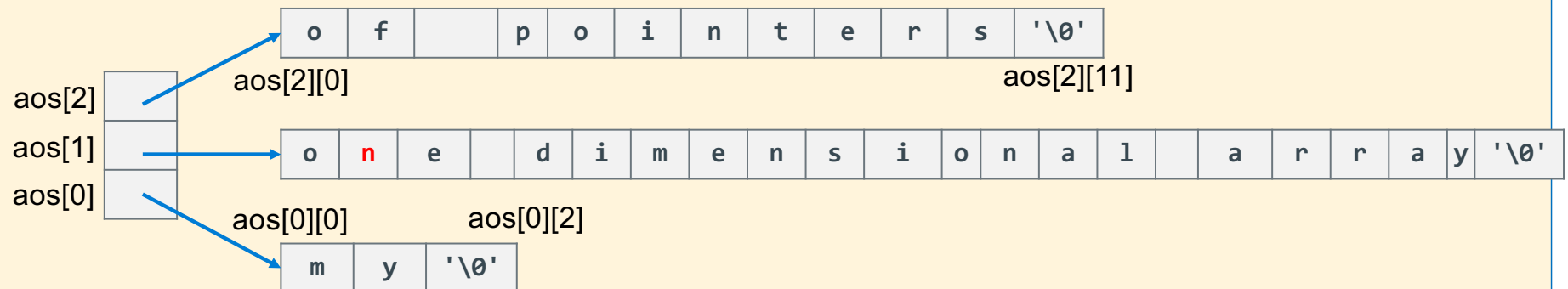
```
#define ROWS 3
char aos[ROWS][22] = { "my", "two dimensional", "char array"};
char (*ptc)[22] = aos; // ptr points at a row of 22 chars

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

high memory

## 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 vary in length
- `char *aos[3];`



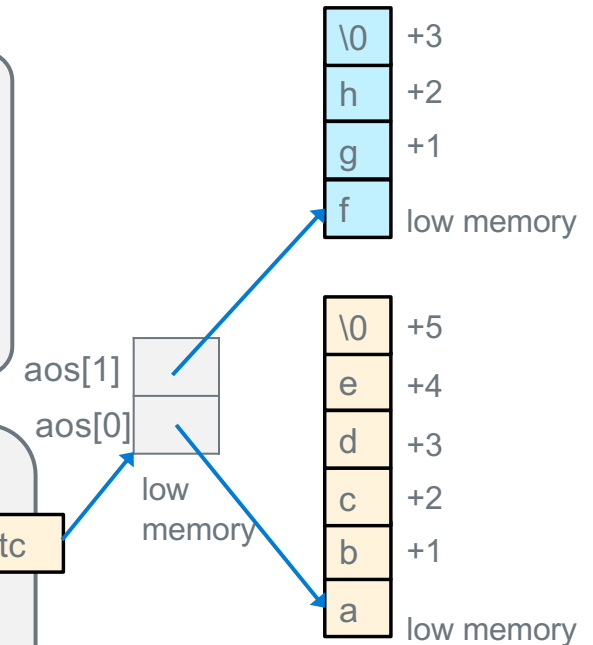
- `aos` is an **array of pointers**; each pointer points at a **character array (also a string here)**
- **Not a 2D array**, but any char can be accessed as if it was in a 2D array of chars
  - When I was learning, this was the most confusing syntax aspects of C

## Pointer Array to Mutable Strings

- 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++;  
}
```

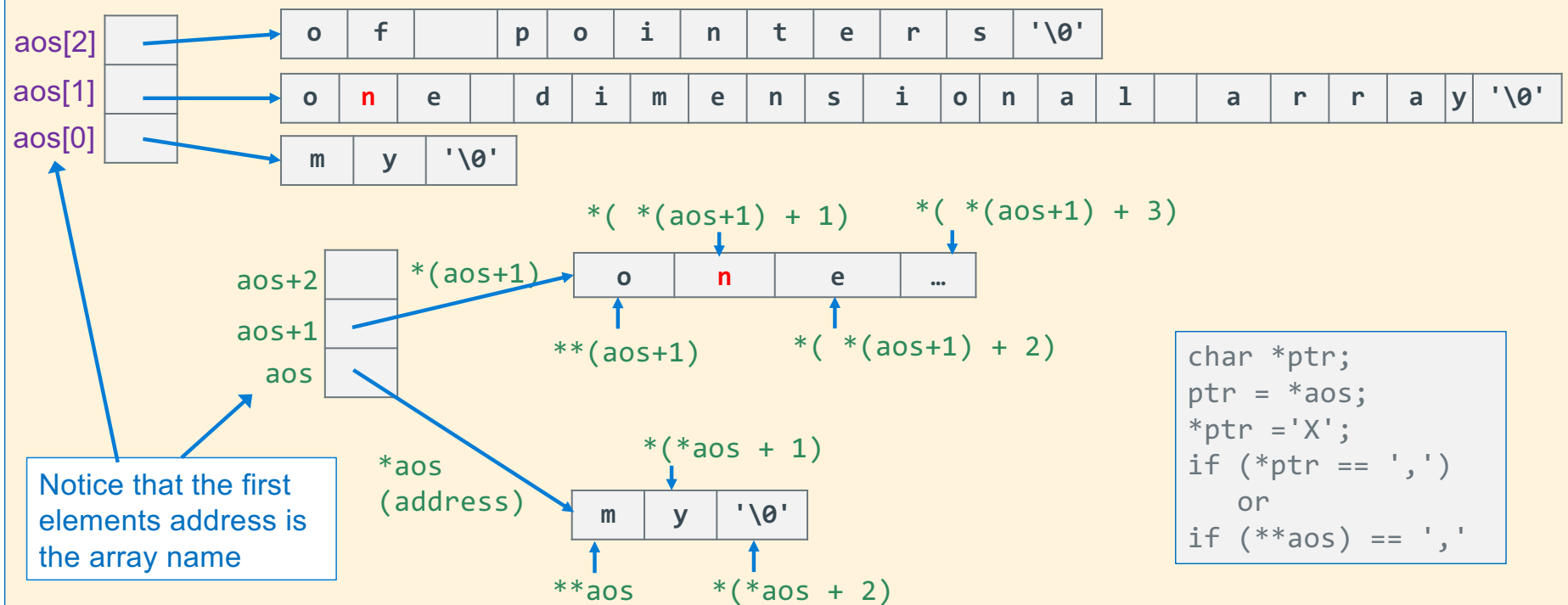


```
%./a.out  
g  
abcde  
abcde  
fgh  
fgh
```

# Pointer Array to Strings

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

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

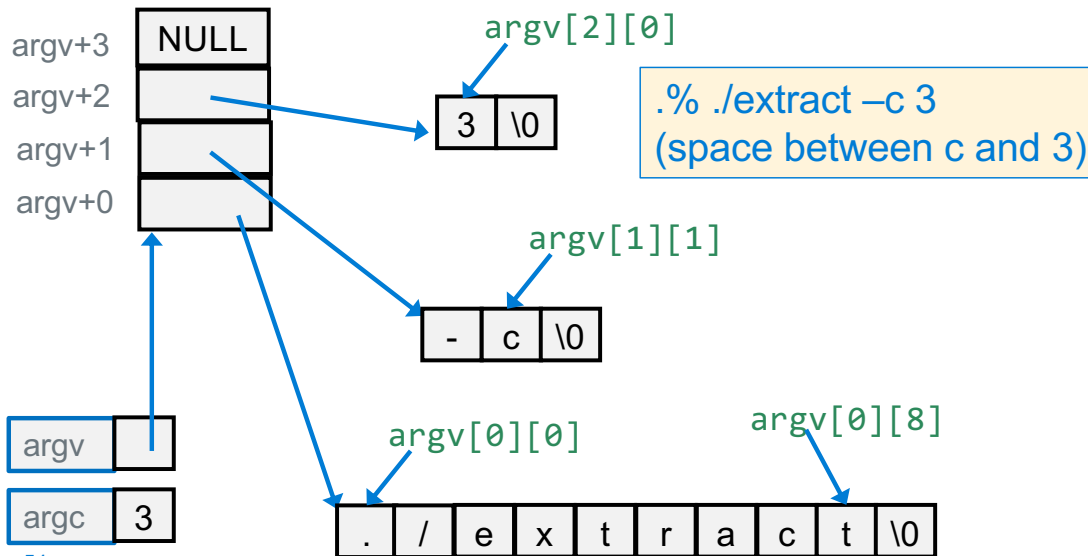


## main() Command line arguments: argc, argv

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

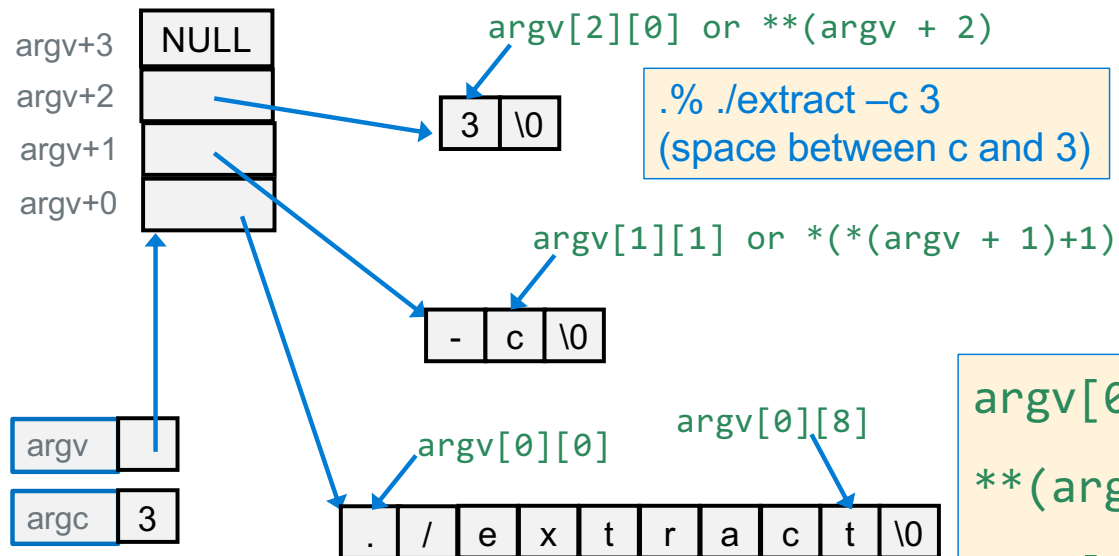
Conceptually: `% *argv[0] *argv[1] *argv[2] ...`

- `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!**



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

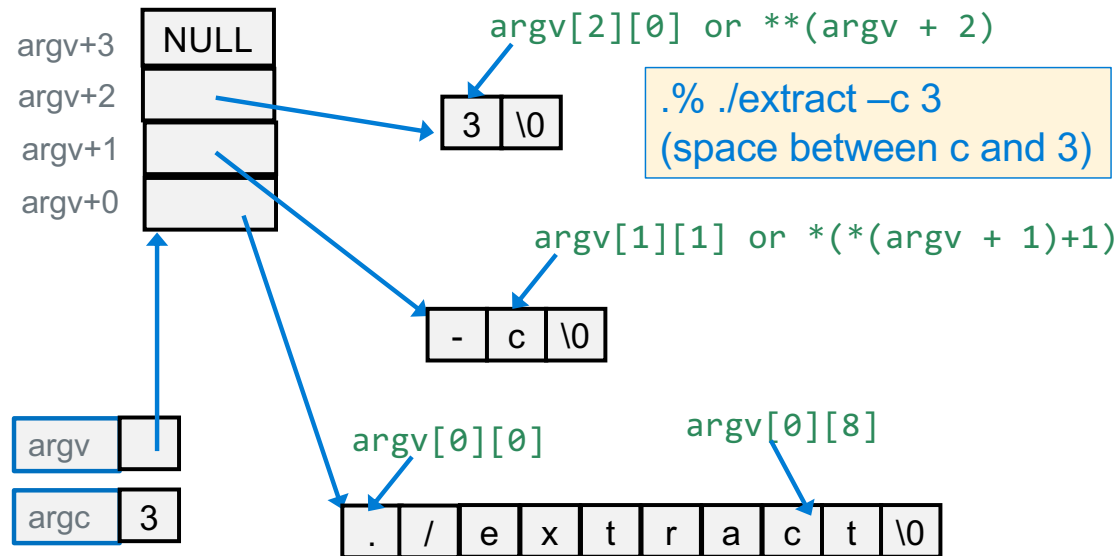
## main() Command line arguments: argc, argv



```
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)
```

## main() Command line arguments: argc, argv

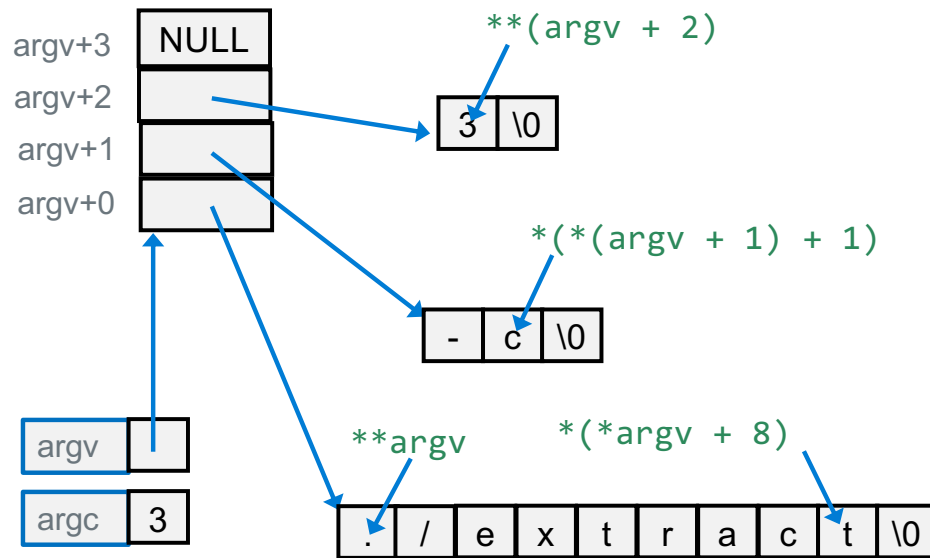


```
int main(int argc, char *argv[])
{
    for (int i = 0; argv[i] != NULL; i++) {
        for (int j = 0; argv[i][j] != '\0'; j++)
            putchar(argv[i][j]);
        putchar('\n');
    }
    return EXIT_SUCCESS;
}
```

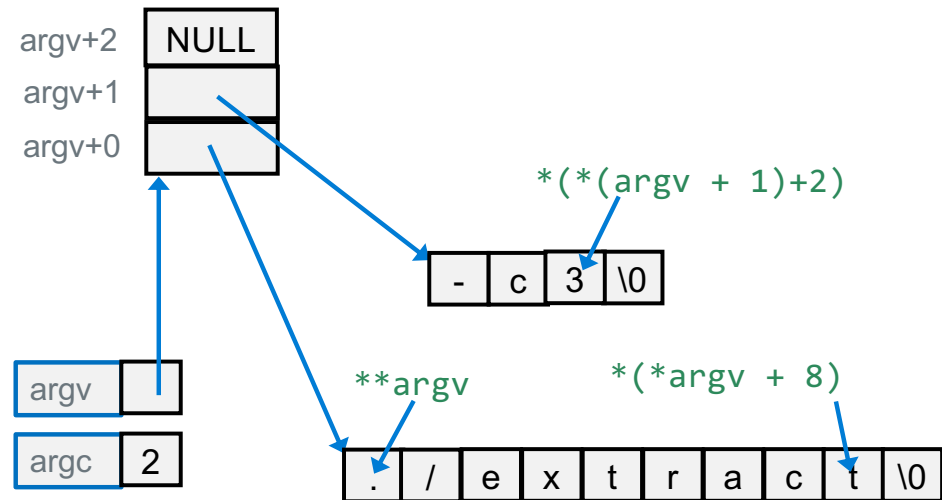
```
int main(int argc, char **argv)
{
    char *pt;
    while ((pt = *argv++) != NULL) {
        while (*pt != '\0')
            putchar(*pt++);
        putchar('\n');
    }
    return EXIT_SUCCESS;
}
```



## main() Command line arguments: argc, argv



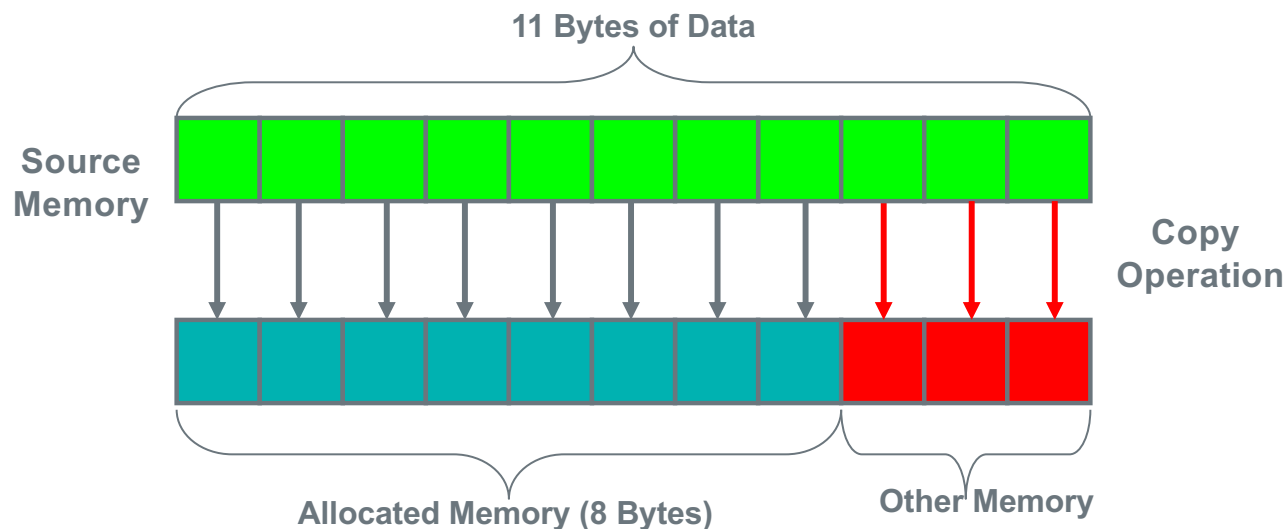
./extract -c 3  
(space between c and 3)



./extract -c3  
(No space between c and 3)

## 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**



# strcpy() buffer overflow: over-write of an adjacent variable

```
int main(void)          /* file test.c */
{
    char s1[] = "before";
    char r2[4] = "xyz";
    char s2[] = "after";

    printf("s2: %s\nr2: %s\nr2:%s\n", s2, r2, s1);

    strcpy(r2,"hello"); // length > buffer size

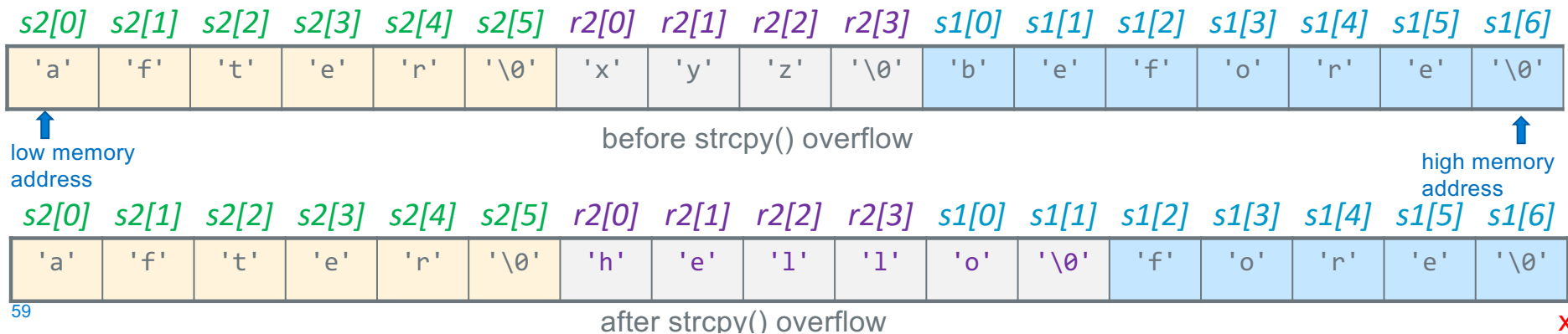
    printf("\ns2:%s\nr2: %s\nr2:%s\n",s2,r2,s1);
    return EXIT_SUCCESS;
}
```

these are mutable  
arrays, not literals

compile on pi-cluster with  
gcc test.c

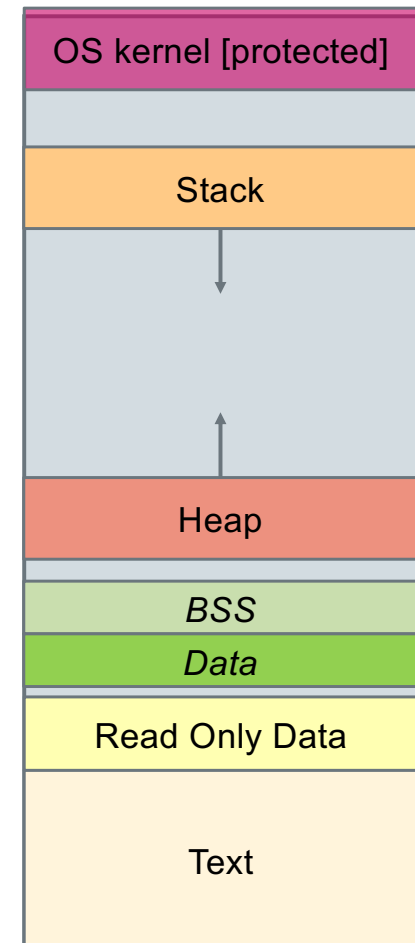
```
./a.out
s2: after
r2: xyz
s1: before

s2: after
r2: hello
s1: o
```



# 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



# Heap Dynamic Memory Allocation Library Functions

<code>#include &lt;stdlib.h&gt;</code>	args	Clears memory
<code>void *malloc(...)</code>	<code>size_t size</code>	no
<code>void *calloc(...)</code>	<code>size_t nmem, size_t memsize</code>	yes
<code>void *realloc(...)</code>	<code>void *ptr, size_size</code>	no
<code>void free(...)</code>	<code>void *ptr</code>	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**

## Use of Malloc

```
void *malloc(size_t size)
```

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

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

## Use of Malloc

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}
```

## 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()**

```
#define COLCNT 1024
char *ptr, *endptr, *bufptr;

bufptr = getbuf(COLCNT);      // do not lose bufptr!, NULL check not shown
ptr = bufptr;
endptr = ptr + COLCNT;
while (ptr < endptr)
    *ptr++ = 'a';             // fill each array element with 'a'
free(bufptr);                 // returns memory to the heap
bufptr = NULL;                // set bufptr to NULL
```



# 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(BKKSZ * sizeof(*bytes));  
    ...  
    /* code that never deallocates the memory */  
    return;  
}
```

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

## Valgrind – Finding Buffer Overflows and Memory leaks

```
1 #define SZ 50
2 #include <stdlib.h>
3 int main(void)
4 {
5     char *buf;
6     if ((buf = malloc(SZ * sizeof(*buf))) == NULL)
7         return EXIT_FAILURE;
8     *(buf + SZ) = 'A';
9     return EXIT_SUCCESS;
10 }
```

```
% valgrind -q --leak-check=full --leak-resolution=med -s ./valgexample
==651== Invalid write of size 1
==651==    at 0x10444: main (valg.c:8)
==651== Address 0x49d305a is 0 bytes after a block of size 50 alloc'd
==651==    at 0x484A760: malloc (vg_replace_malloc.c:381)
==651==    by 0x1041B: main (valg.c:6)
==651==
==651== 50 bytes in 1 blocks are definitely lost in loss record 1 of 1
==651==    at 0x484A760: malloc (vg_replace_malloc.c:381)
==651==    by 0x1041B: main (valg.c:6)
==651==
==651== ERROR SUMMARY: 2 errors from 2 contexts (suppressed: 0 from 0)
```

Writing outside of allocated  
buffer space

Memory not freed

## More Dangling Pointers: Reusing "freed" memory

- 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

## strdup(): Allocate Space and Copy a String

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

- **strdup** is a function that returns a **null-terminated**, heap-allocated string copy of the provided text
- Alternative: **malloc** and copy the string

```
char *str = strdup("Hello, world!");  
*str = 'h';
```

```
free(str);  
str = NULL;
```

## 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
```

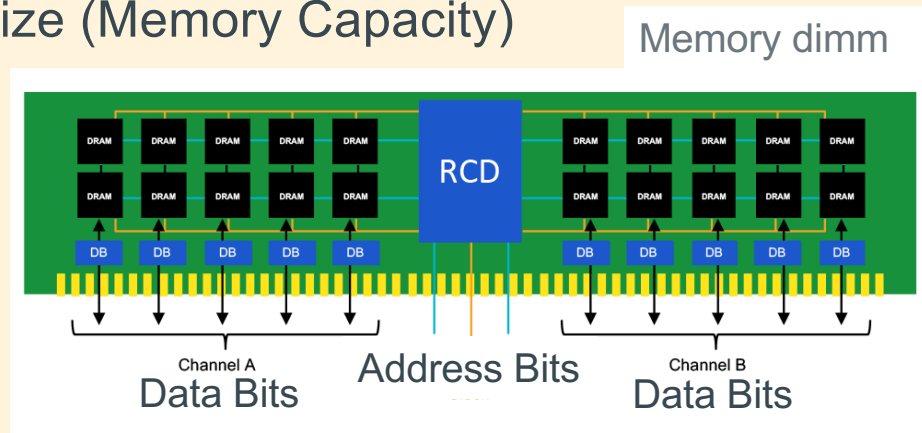
- Originally designed to allocate arrays but works for any memory allocation
  - calloc() multiplies the two parameters together for the total size
- calloc() is more expensive at runtime (uses both cpu and memory bandwidth) than malloc() because it must zero out memory it allocates at runtime
- Use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

## Extra Slides

-

# Memory Size

- Since memory addresses are implemented in hardware using binary
  - The **Size (number of byte sized cells)** of Memory is specified in **powers of 2**
- Memory size/capacity in **bytes** is specified by the “**Number of bits**” in an address
  - 32 bits of address =  $2^{32} = 4,294,967,296$
  - Address Range is 0 to  $2^{32} - 1$  (unsigned)
- Shorthand notation for address size (Memory Capacity)
  - KB =  $2^{10}$  (K=1024) kilobyte
  - MB =  $2^{20}$  megabyte
  - GB =  $2^{30}$  gigabyte
  - TB =  $2^{40}$  terabyte
  - PB =  $2^{50}$  petabyte



## Fixed size types in C (later addition to C)

- Sometimes programs need to be written for a particular range of integers or for a particular size of storage, regardless of what machine the program runs on
- In the file `<stdint.h>` the following fixed size types are defined for use in these situations:

Signed Data types	Unsigned Data types	Exact Size
<code>int8_t</code>	<code>uint8_t</code>	8 bits (1 byte)
<code>int16_t</code>	<code>uint16_t</code>	16 bits (2 bytes)
<code>int32_t</code>	<code>uint32_t</code>	32 bits (4 bytes)
<code>int64_t</code>	<code>uint64_t</code>	64 bits (8 bytes)



## 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
```

# 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;
```

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

```
int y = 2;
```

```
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

`ptr`

`x`  write

`y`  write

`ptr`  write → `x`   
`y`

`ptr`  read → `x`  read  
`y`  write

`ptr`  → `x`  write  
`y`  read

## 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 used by the string

- **Example**: string is to contain just positive numbers  $\geq 0$  (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);
```

## Copying Strings: Use the Sentinel; libc: strcpy()

- 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

<i>index</i>	0	1	2	3	4	5
<i>char</i>	'H'	'e'	'l'	'l'	'o'	'\0'

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

```
char *strcpy(char *s0, char *s1)  
{  
    char *str = s0;  
  
    if ((s0 == NULL) || (s1 == NULL))  
        return NULL;  
    while (*s0++ = *s1++)  
        ;  
    return str; // address of dest string  
}
```