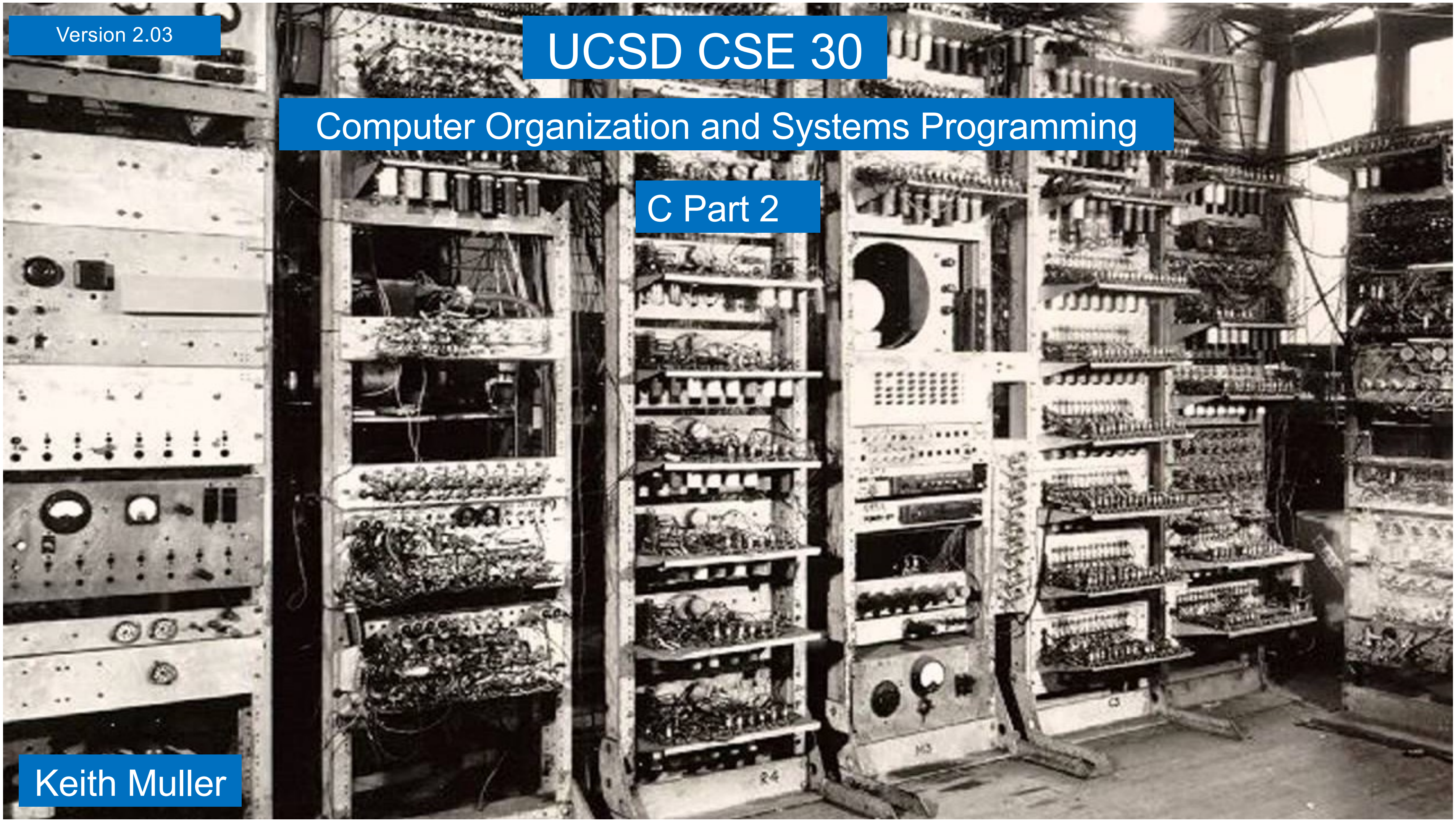


Version 2.03

UCSD CSE 30

Computer Organization and Systems Programming

C Part 2

Keith Muller

Review: Binary Numbering

- Binary is base 2
  - *adjective:* being in a state of one of two **mutually exclusive** conditions such as **on** or off, true or false, molten or frozen, presence or absence of a signal
  - From Late Latin *bīnārius* ("consisting of two")
- Two symbols:

  0 1

- Numbers in C that start with 0b are binary
- Example: What is 0b110 in base 10?
  - 0b110 = $110_2 = (1 \times 2^2) + (1 \times 2^1) + (0 \times 2^0) = 6_{10}$

powers of two

- A **bit** is a single binary digit
- A **byte** is an 8-bit value

$$Unsigned\ binary\ Number = \sum_{i=0}^{i=n-1} b_i\ x\ 2^i = b_{n-1}2^{N-1} + b_{n-2}2^{N-2} + \ldots + b_1 2^1 + b_0 2^0$$

x

Review: Hexadecimal Numbering

- hexadecimal is base 16
  - From "hexa" (Ancient Greek ἑξα-) ⇒ six
  - and from "decem" (Latin) ⇒ ten
- Sixteen symbols

  0 1 2 3 4 5 6 7 8 9 a b c d e f

- Numbers in C that start with 0x are hexadecimal numbers
  - **16_{10}** = $0x10_{16}$
- Example: What is 0xa5 in base 10?
  - 0xa5 = $a5_{16}$ = (10×16^1) + (5×16^0) = 165_{10}
- Hexadecimal numbers are very commonly used in programming to express binary values
  - Imagine the difficulty in correctly expressing a 64-bit binary value in your code

$$Unsigned\ Hex\ Number = \sum_{i=0}^{i=n-1} b_i\ x\ 16^i \ = \ b_{n-1}16^{N-1} + \ b_{n-2}16^{N-2} + \ \ldots + \ b_1 16^1 + \ b_0 16^0$$

x

Binary <---> Hexadecimal Equivalences

- Hex → Binary: $16^1 = 2^4$ 1 digit hex = 4 digits binary
  1. Replace hex digits with binary digits
  2. Drop leading zeros
  - Example: 0x2d to binary
    - 0x2 is 0b00**10,** 0xd is 0b1101
    - Drop two leading zeros, answer is 0b**10**1101
- Binary → Hex: $2^4 = 16^1$
  1. **Pad** with enough leading zeros until number of digits is a multiple of 4
  2. **Replace** each **group of 4** with the **HEX equivalent**
  - Example: 0b101101
    - **Pad on the left** to: 0b 0010 1101
    - Replace to get: 0x2d

x

Number Base Overview (as written in C)

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

Hex digit	0x0	0x1	0x2	0x3	0x4	0x5	0x6	0x7
Decimal value	0	1	2	3	4	5	6	7
Binary value	0b0000	0b0001	0b0010	0b0011	0b0100	0b0101	0b0110	0b0111

Hex digit	0x8	0x9	0xa	0xb	0xc	0xd	0xe	0xf
Decimal value	8	9	10	11	12	13	14	15
Binary value	0b1000	0b1001	0b1010	0b1011	0b1100	0b1101	0b1110	0b1111

x

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

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

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

$$\boxed{0b1111101001010011}$$

binary start with a 0b in C

x

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

- 4 binary bits is one Hex digit $2^4 = 16^1$

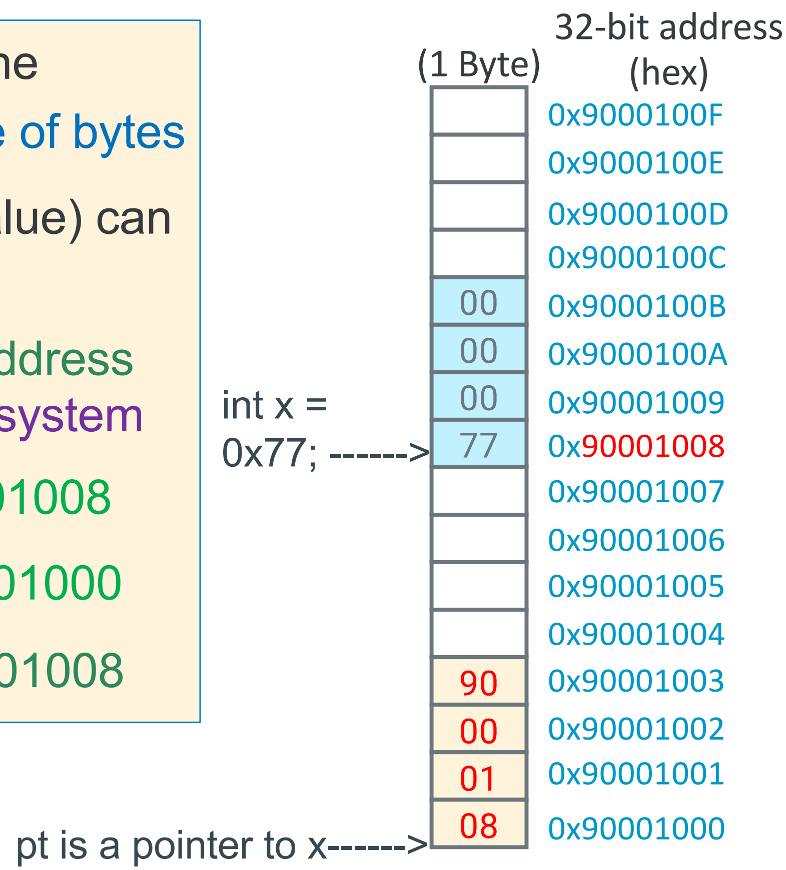
$$0b\ \underbrace{0110}_{6}\ \underbrace{1010}_{a}\ \underbrace{0011}_{3}\ \underbrace{1111}_{f}$$

$$\boxed{0x6a3f}$$

hex start with 0x in C

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



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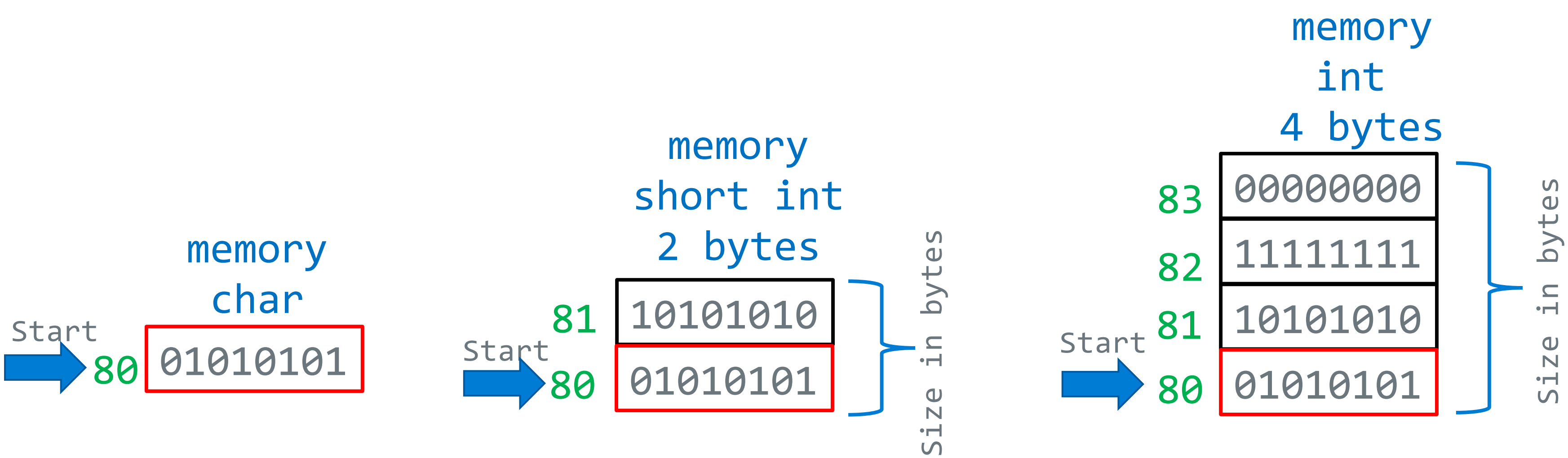
Variables in Memory: Size and Address

- 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



Variables: Size

- **Integer types**
  - `char`, `int`
- **Floating Point**
  - `float`, `double`
- Modifiers for each base type
  - `short` [int]
  - `long` [int, double]
  - `signed` [char, int]
  - `unsigned` [char, int]
  - `const`: variable read only
- **char type**
  - One byte in a byte addressable memory
  - **Signed** vs **Unsigned** Char implementations
  - **Be careful** char is unsigned on arm and signed on other HW like intel

C Data Type	AArch-32 contiguous Bytes	AArch-64 contiguous Bytes	printf specification
char (arm unsigned)	1	1	%c
short int	2	2	%hd
unsigned short int	2	2	%hu
int	4	4	%d / %i
unsigned int	4	4	%u
long int	4	8	%ld
long long int	8	8	%lld
float	4	4	%f
double	8	8	%lf
long double	8	16	%Lf
pointer *	4	8	%p

size of a pointer is the word size

x

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

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

sizeof() operator returns a value of type size_t:

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

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

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

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

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

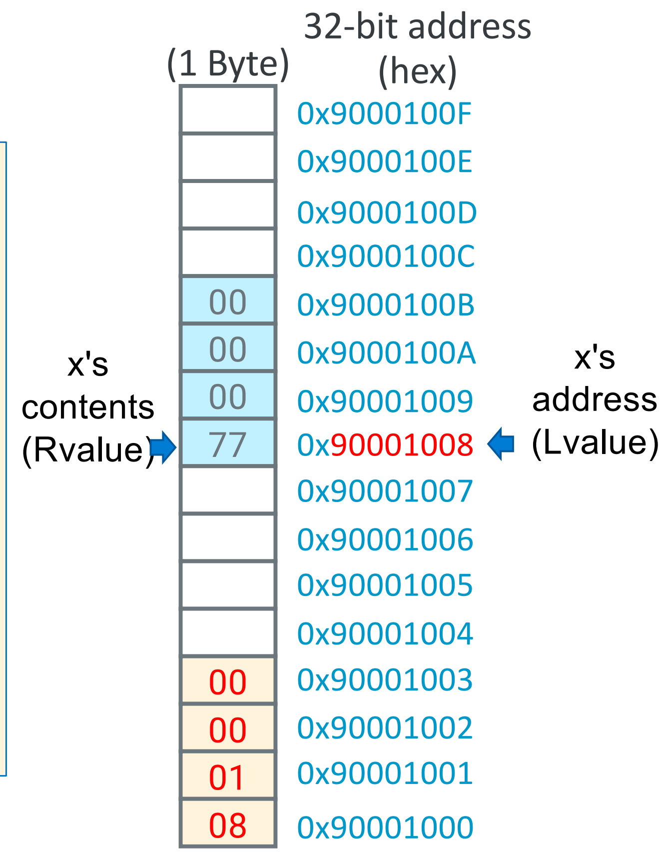
x

Memory Addresses & Memory Content

Variable names in a C statement evaluation

```
x = x + 1;     // Lvalue = Rvalue
```

- **Lvalue:** when on the left side (Lside or Left value) of the = sign
  - address where it is stored in memory – a constant
  - **Address assigned to a variable cannot be changed at runtime**
  - Does not require a memory read
  - **Lside Must evaluate to an address**
- **Rvalue:** when on the right side (Rside or Right value) of an = sign
  - **contents or value stored** in the variable (at its memory address)
  - requires a memory read to obtain contents



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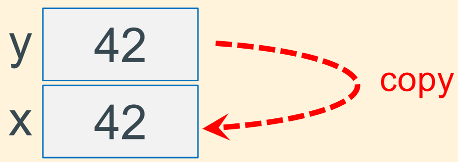
Memory Addresses & Memory Content

One memory write required

One memory read required

```
y = 42;
x = y;              // Lvalue = Rvalue
```



- **x** on left side (**Lside**) of the assignment operator = evaluates to:
  - **Address** of the memory assigned to the x – this is x's **Lvalue**
- **y** on right side (**Rside**) of the assignment operator = evaluates to:
  - **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**)

x

Introduction: Address Operator: &

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

```
int main(void)
{
    int g = 42;

    printf("value of g is: %d\n", g);
    printf("address of g is: %p\n", &g);
    return EXIT_SUCCESS;
}
```

- Example this might print:

  value *of g is: 42*

  address *of g is: 0x71a0a0*

  (the address will vary)

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

x

Introduction: Address Operator: &

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

x

Pointer Variables

- In C, there is a *variable* ***type*** for **storing an address**: a ***pointer***
  - **Contents** of a pointer is an **unsigned** (positive numbers) **memory address**

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

- A pointer is defined by placing a ***star (**or **asterisk) (*)*** ***before*** the identifier (name)
- You also must specify the type of variable to which the pointer points
- **Pointers are typed**! Why?
  - The compiler needs to know the size (sizeof()) of the data **you are pointing at** (number of consecutive bytes to access) to use (dereference) the pointer
- When the **Rside of a variable** contains a **memory address**, (it **evaluates** to an **address**) the variable is called a **pointer variable**

x

Pointer Variables - 2

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

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

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

```
% ./example
iptr(4) cptr(4)
```


x

Defining Pointer Variables

- Assigning a value to a pointer:

```
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 of 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

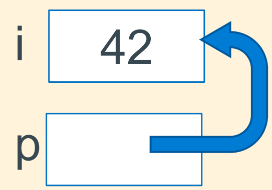
```
int  *p = &i;        /* Style A */
int * p = &i;        /* Style B */
int*  p = &i;        /* Style C */
```

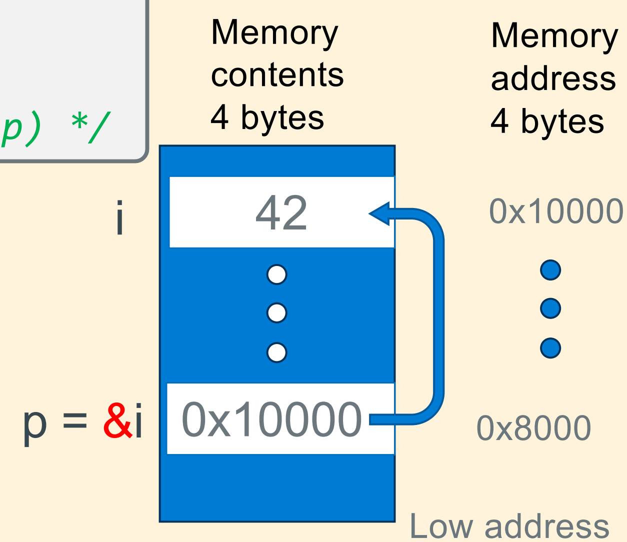

x

Using Pointer Variables and the Address Operator & - 1

```c
int i = 42;
int *p;  /* p contains the address of an integer */

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





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

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

Some find this clearer instead:

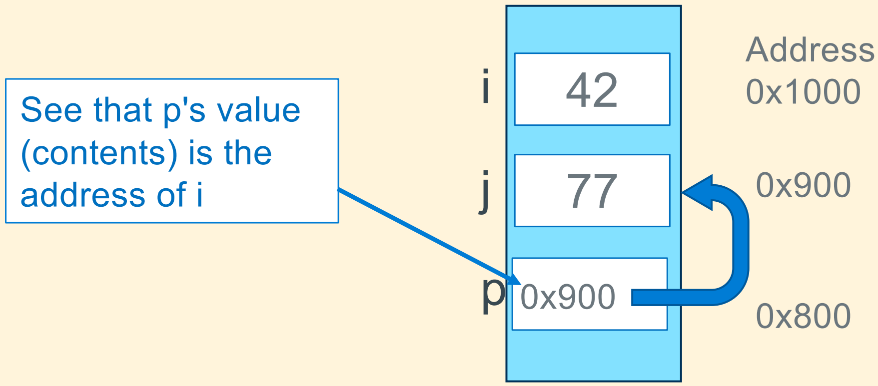
```c
int *p1;
int *p2;
```


x

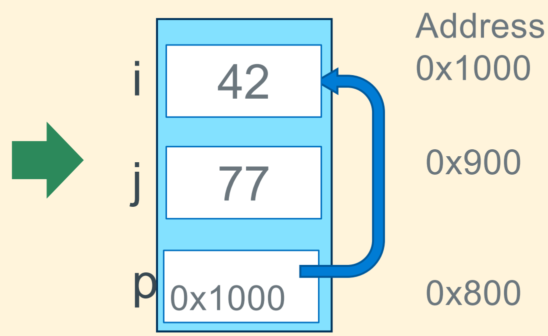
Using Pointer Variables and the Address Operator & - 2

- As with any variable, you can change a pointers value (contents)

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




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



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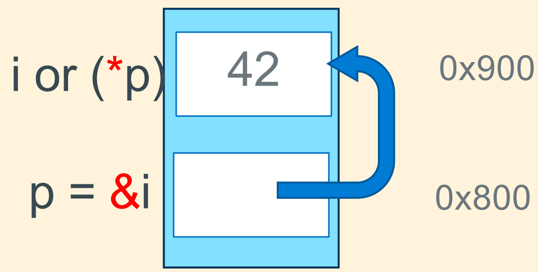
Indirection (or dereference) Operator: *

- 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”"



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

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

- **Indirection operator causes an additional read to occur**, when on either the Rside or Lside of a statement

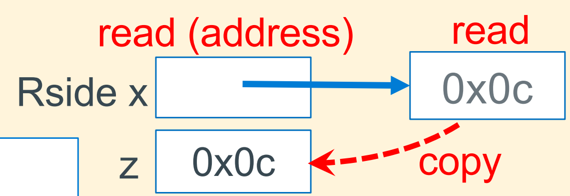
x

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

x

Rside Indirection (or dereference) Operator: *

*Contents of **p** is the address of **i***

(p points at i)

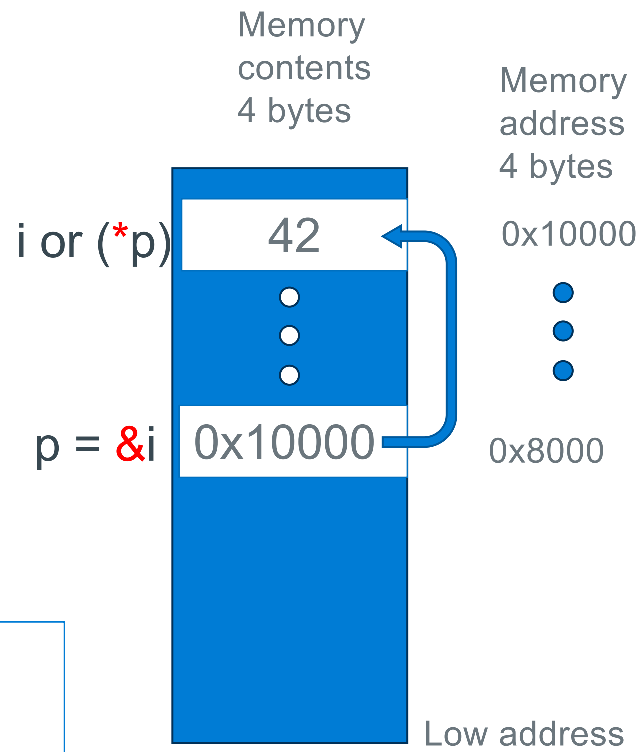
```
int i = 42;
int *p;

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



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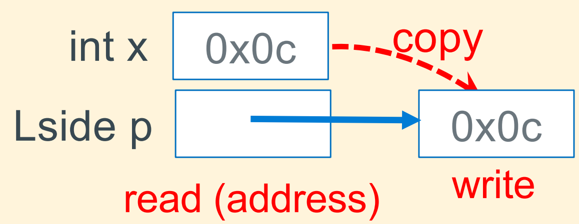
Lside Indirection Operator

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
```



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Lside Indirection (or dereference) Operator: *

*Contents of **p** is the address of **i***

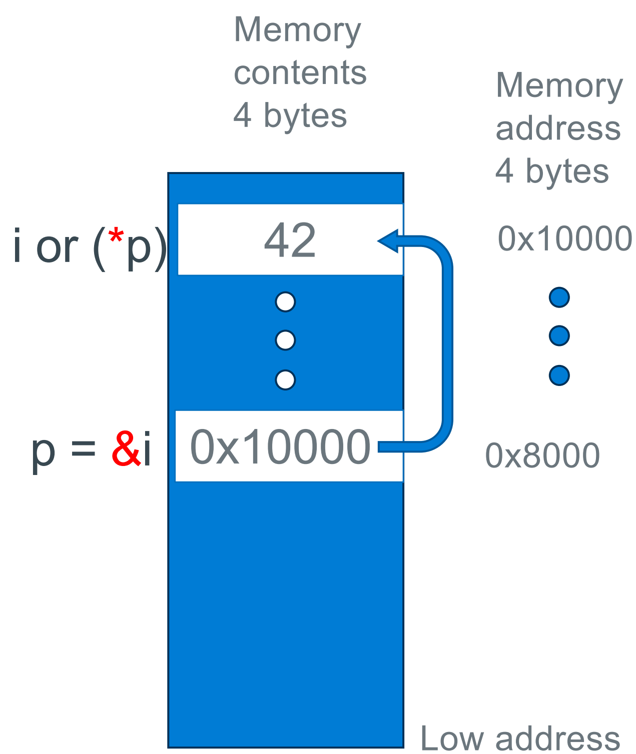
(p points at i)

```
int i;
int *p;

p = &i;
*p = 42;

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

No reads here
one write

One read here
(1) read to get
an address
(2) one write

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



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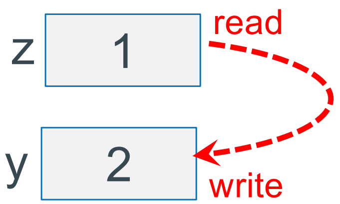
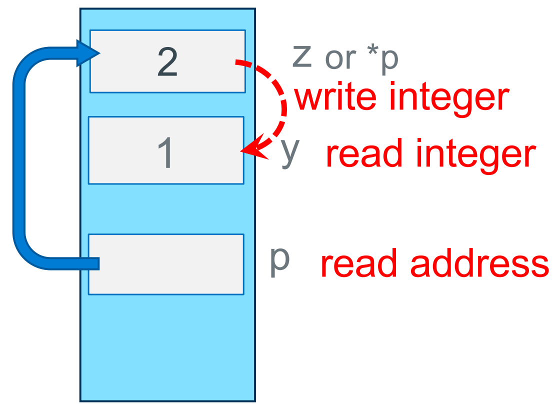
Each use of a * operator results in one additional read: Rside

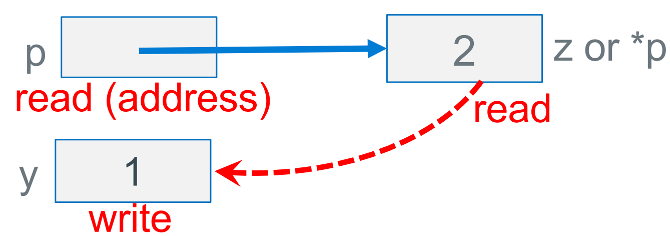
RULE: Each * when used as a dereference operator in a statement (either Lside or Rside) it causes an additional read to be performed

```
int z = 2;
int y = 1;

y = z; // one read
```






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

p = &z;
y = *p; // two reads on rside
```

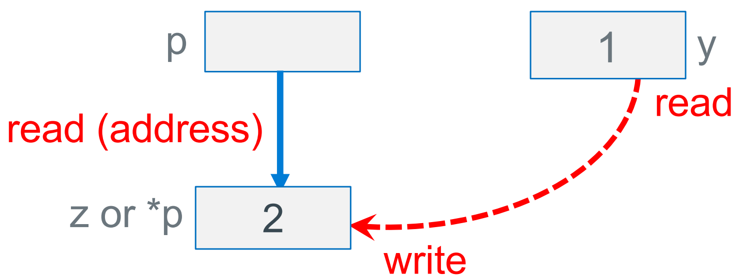


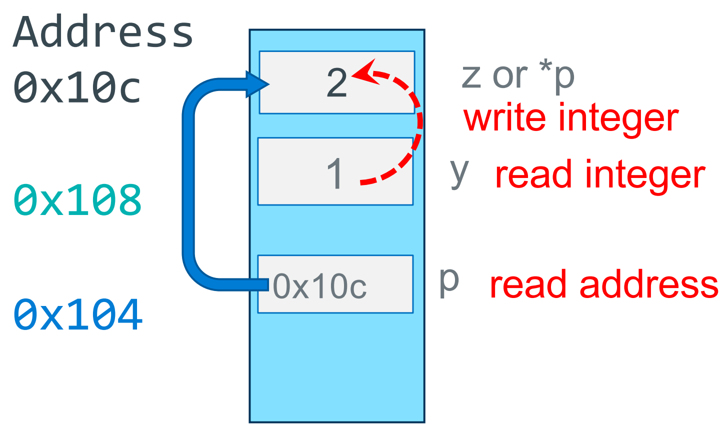
Aside: `y = *(&z); // same as y = z`

x

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
```





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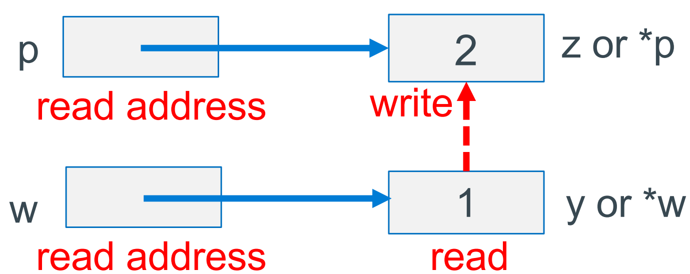
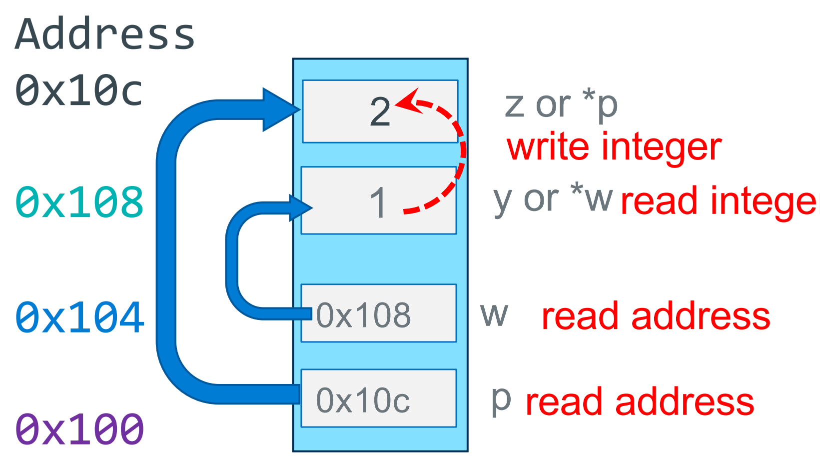
Each use of a * operator results in one additional read : both sides

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

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





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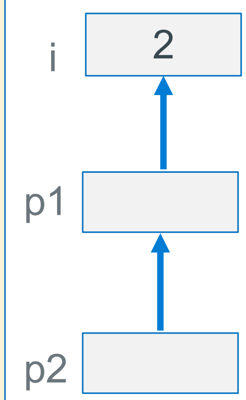
Pointer to Pointers (Double Indirection)

- Define a pointer to a pointer (p2 below)

```c
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 at 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**

  #reads to base type = number of * (in the definition) + 1

- Example:

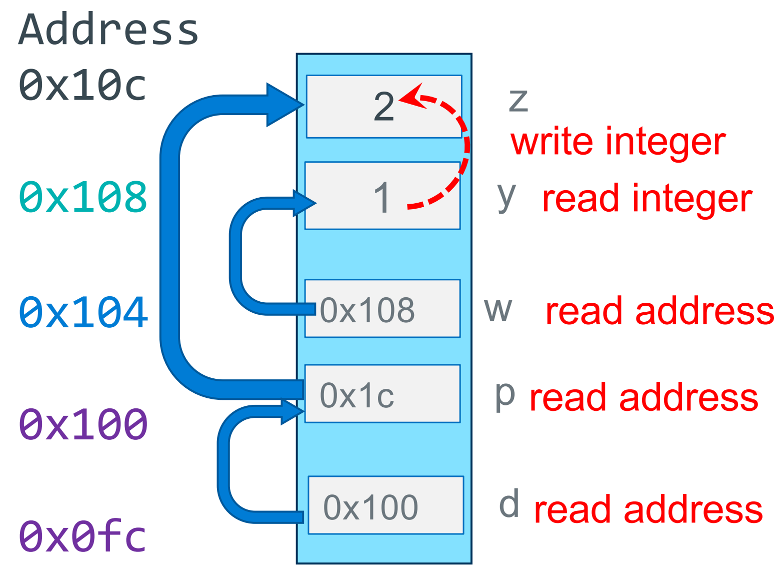
  `int **p2;      //` requires 3 reads to get to the int

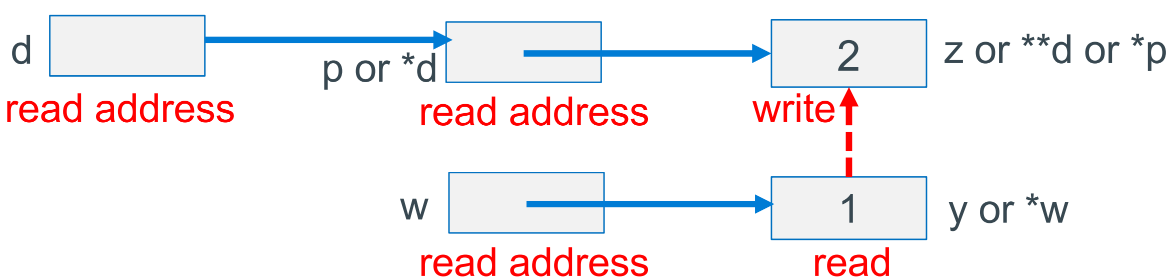
x

Double Indirection: Lside

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

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





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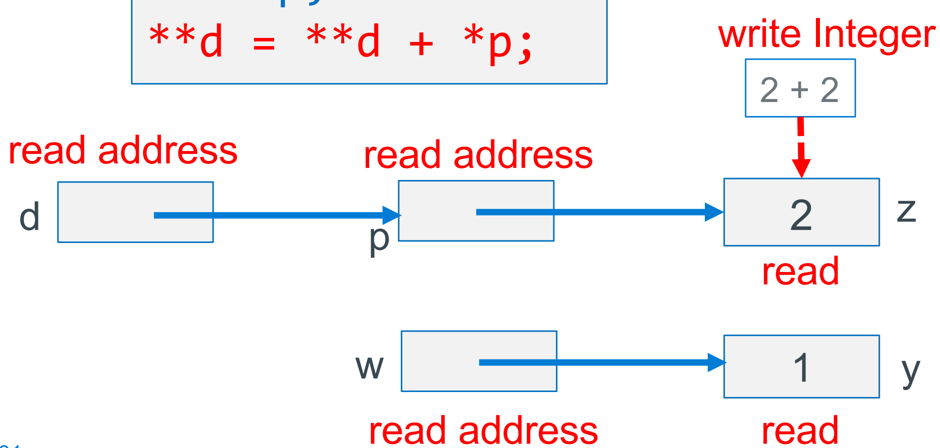
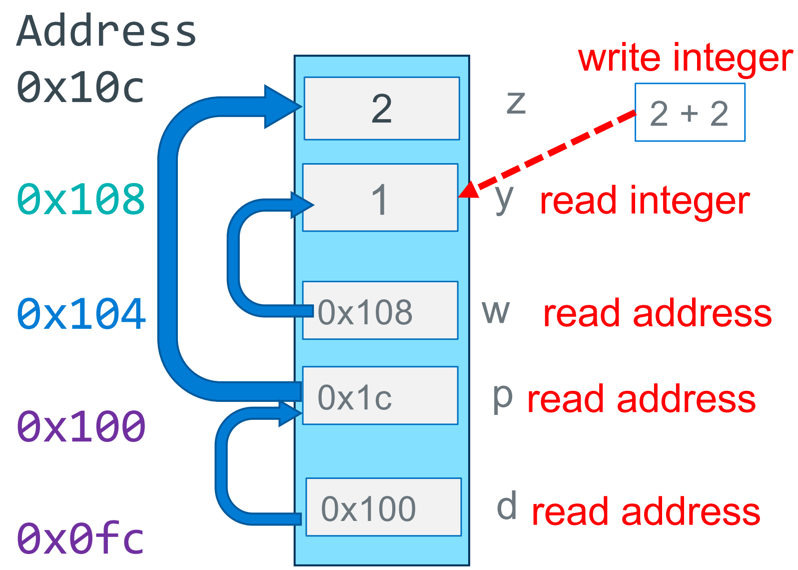
Double Indirection: Rside

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

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





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

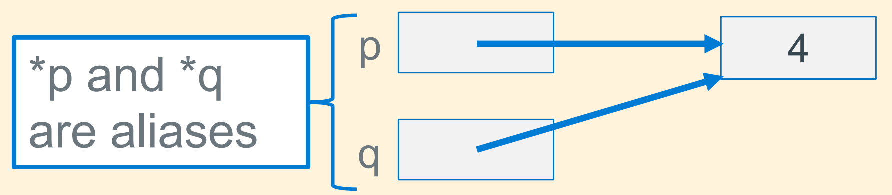
x

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

x

Defining Arrays

Definition: `type name[count]`

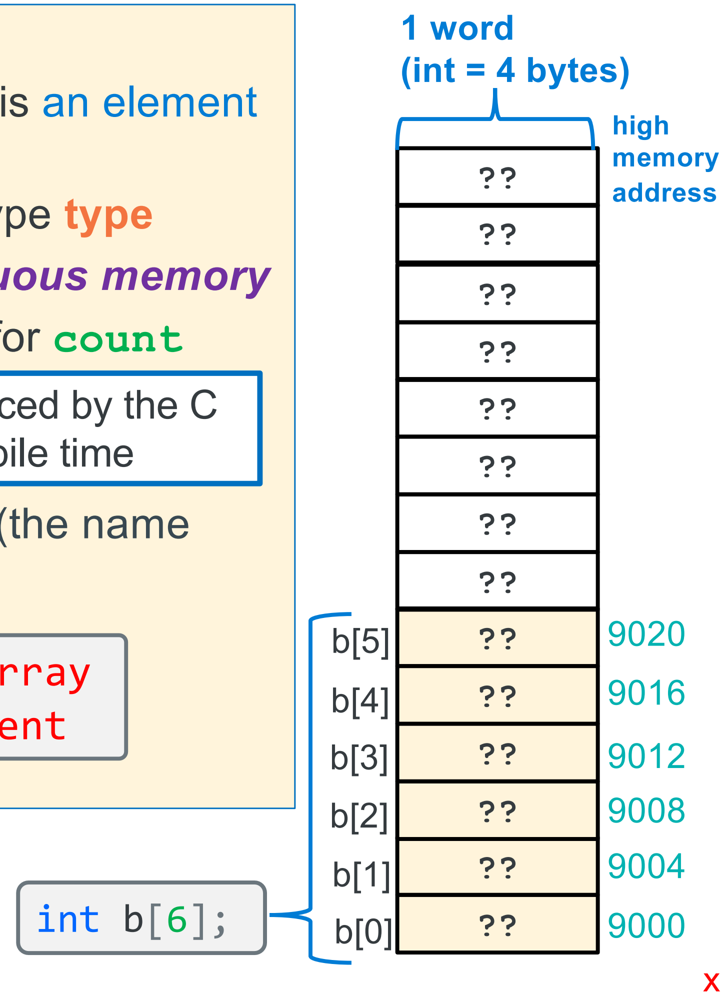
- *"Compound"* data type where each value in an array is an element of type
- Allocates **name** with a *fixed* count array elements of type **type**
- Allocates (`count * sizeof(type)`) bytes of ***contiguous memory***
- Common usage is to specify a compile-time constant for **`count`**

```c
#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)

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



Array Initialization

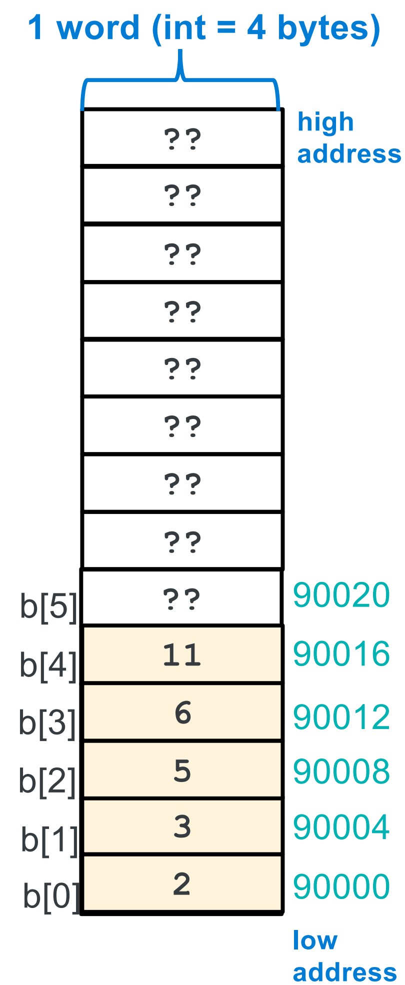
- Initialization: `type name[count] = {val0,…,valN};`
  - `{ }` *(optional)* initialization list can *only* be used at **time of definition**
  - If no `count` supplied, `count` is determined by compiler using the number of array initializers

    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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Accessing Arrays Using Indexing

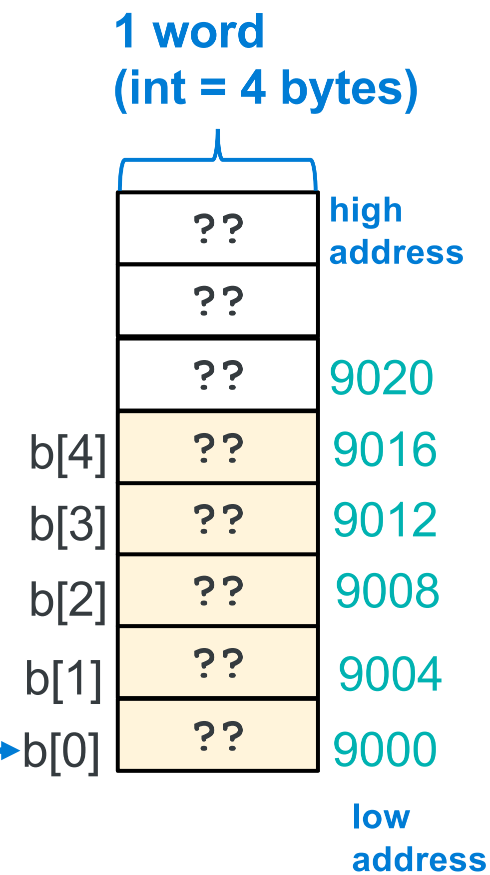
- **`name`**`[`**`index`**`]` selects the **`index`** element of the array
  - index **should be** unsigned
  - Elements range from: 0 to count – 1 (int x[count];)
- **`name[index]`** can be used as an assignment target or as a value in an expression

```
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;
```

p 9000



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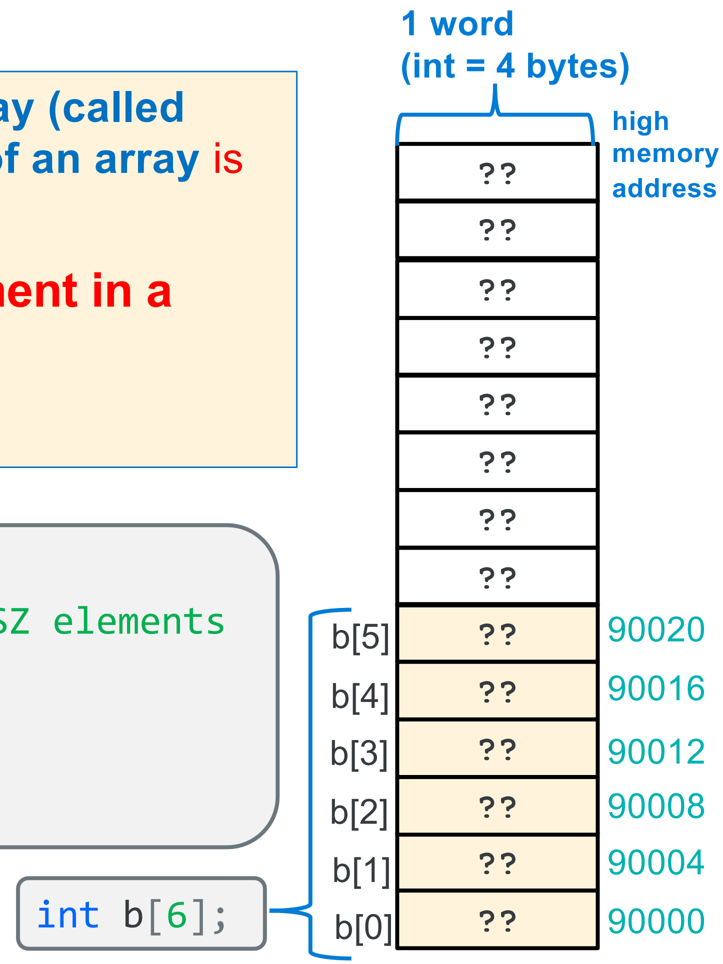
How many elements are in an array?

- **The number of elements of space allocated to an array (called element count) and indirectly the total size in bytes of an array** is <u>not stored anywhere</u>!!!!!!
- 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;
```



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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;
```


x

Pointers and Arrays - 1

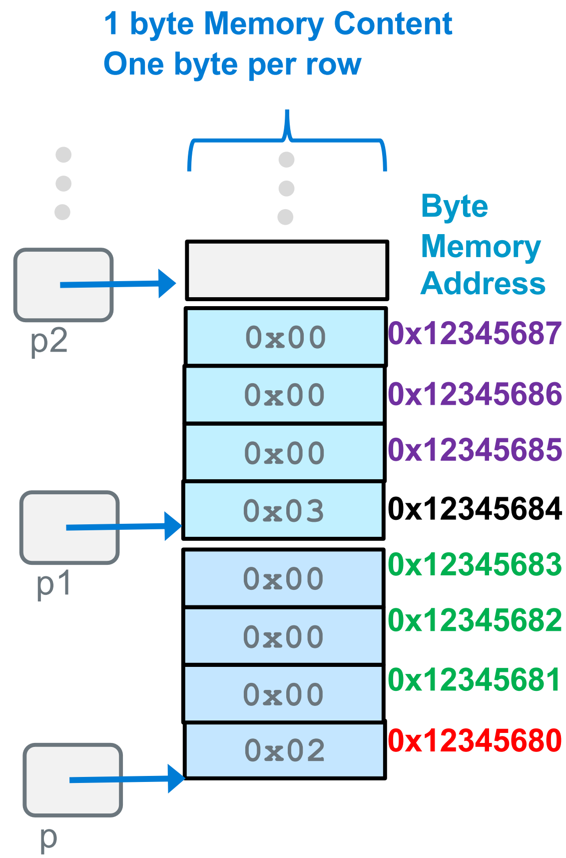
- A few slides back we stated: Array name (by itself) on the Rside evaluates to the address of the first element of the array

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

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

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

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



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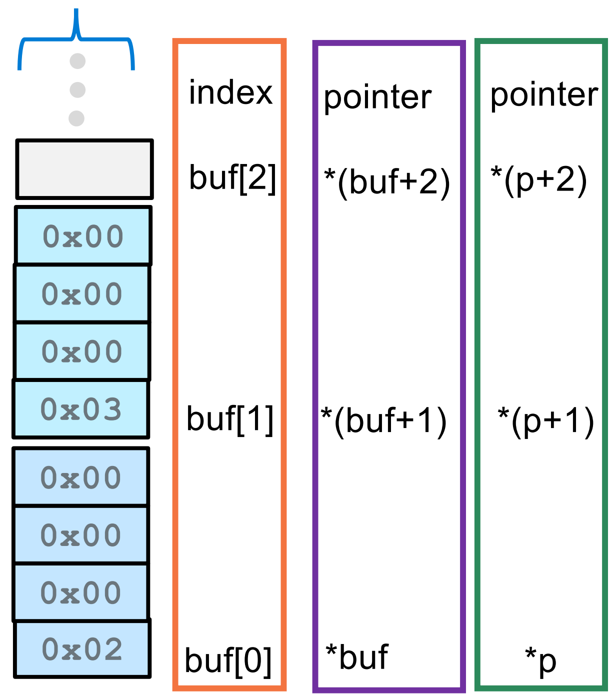
Pointers and Arrays - 2

- 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



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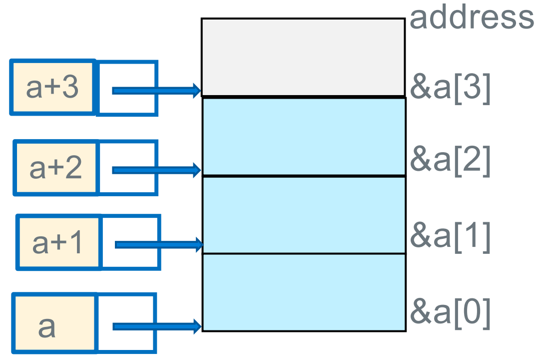
Pointer Arithmetic In Use – C's Performance Focus

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



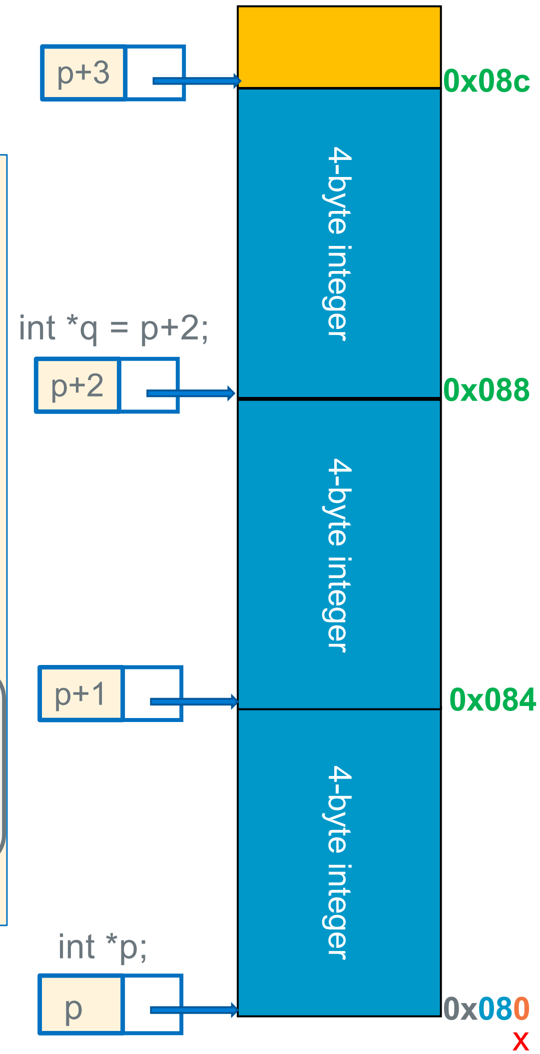
- **Alert!:** C performance focus **does not** perform any array “bounds checking”
- **Performance by Design**: *bound checking **slows down execution** of a properly written program*
- Example: array **a** of length i, C **does not verify** that **a[j] or *(a + j)** is valid (does not check: 0 ≤ j 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

x

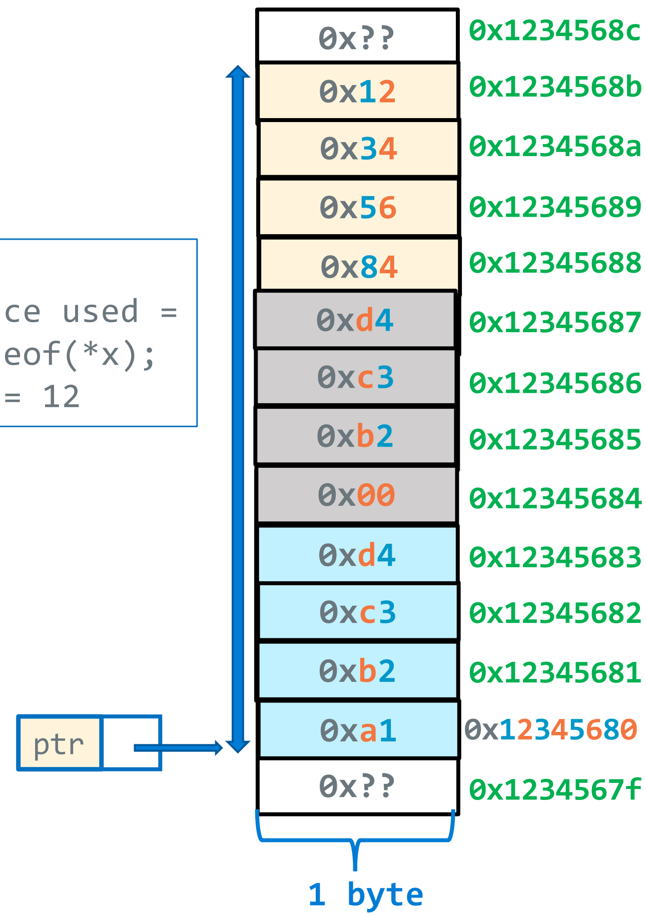
Using Pointers to Traverse an array

```
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

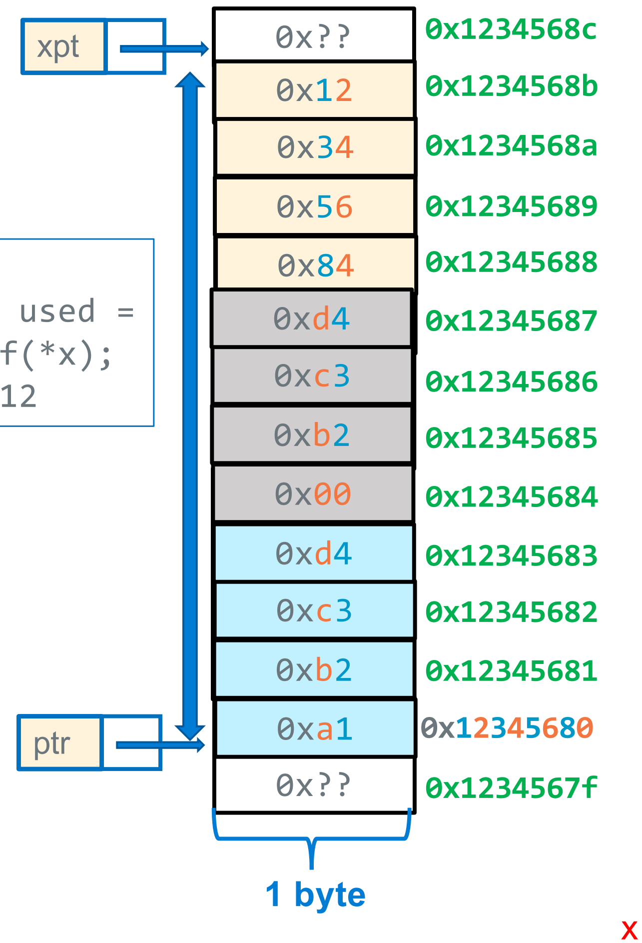
```
int x[] = {0xd4c3b2a1, 0xd4c3b200, 0x12345684};
int cnt = (int)(sizeof(x) / sizeof(*x));

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

xpt 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

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

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

X

Example of a hard-to-understand pointer statement

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

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

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

```
/* 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
```


x

C Strings - 1

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

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

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

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

x

C Strings - 2

- **First `'\0'` <u>encountered</u> from the start of the string** always indicates the end of a string
- The **'\0' does not have to be** in the **last element in the space allocated to the array**
  - 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'

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, first string length 3
char empty[] = "";                           // empty string – contains '\0'
                                             // string length = 0
```


x

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***

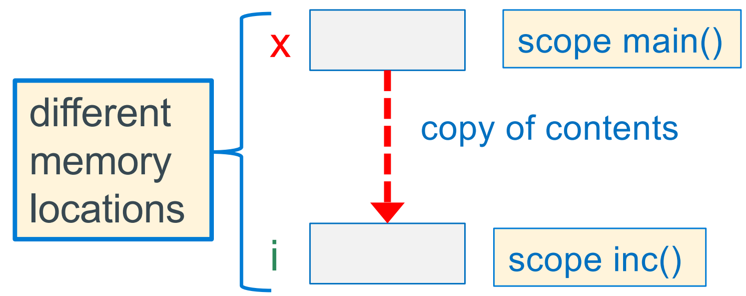
- The return value from a function in C is **by value**

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 <u>NOT</u> change the parameter in `main()`

x

Output Parameters (Mimics Call by Reference)

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

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


}

void
inc(int *p)
{



}
```


x

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)++
}
```

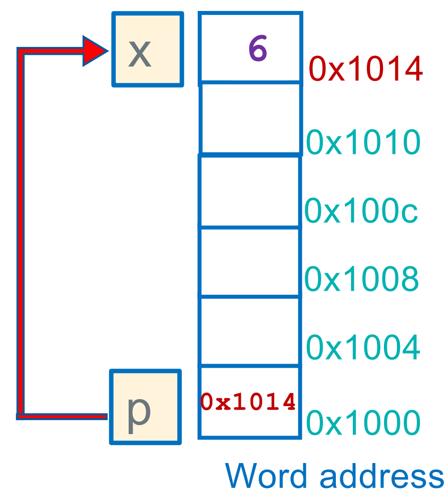
Pass the address of x (&x)

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



With a pointer to X,

inc() can change x in main()

this is called a side effect

p just like any other local variable

x

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

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

```
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

x

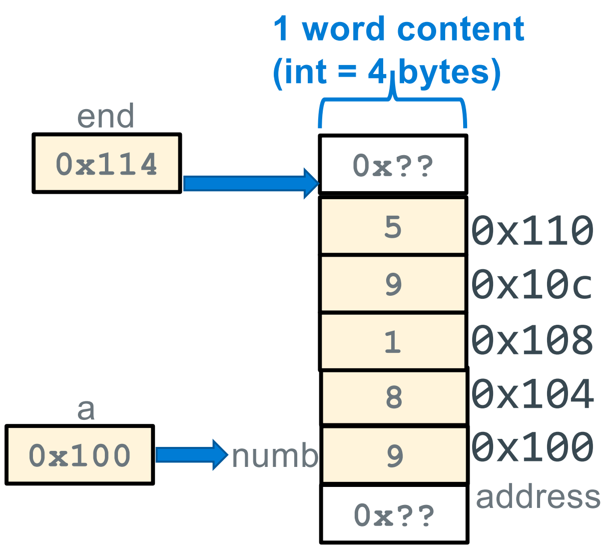
Arrays As Parameters, Approach 1: Pass the size

Two ways to pass array size

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

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

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

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




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

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

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

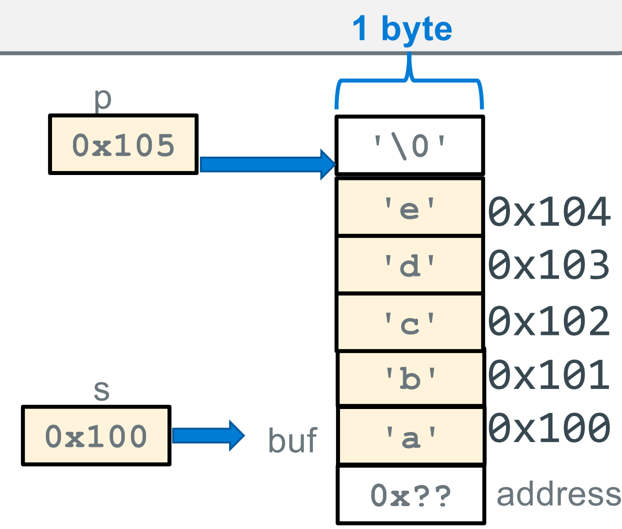
x

Arrays As Parameters, Approach 2: Use a sentinel element

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

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

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

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



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

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

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**

```c
int count_e(char *s)  // o(n²) !!!
{
   int count = 0;
   if (s == NULL)
       return 0;
   for (int j = 0; j < strlen(s); j++) {
       if (s[j] == 'e')
           count++
   }
   return count ;
}
```

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


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 */
```


x

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) ...
```


x

Simple String IO - Reading

Task	Example Function Calls

Read a string	`#include <stdio.h>`
	
	`char *strpt;`
	`char myStr[BFSZ];`
	
	`strptr = fgets(myStr, BFSZ, stdin);`

must pass the size of the array so fgets() knows how much space there is

```
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`**

X

Pointer returns from a function call

```
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:

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

- These errors are called a dangling pointer

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

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

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

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

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

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


X

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

index	0	1	2	3	4	5
char	'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;
}
```


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

x

String Literals, Mutable and Immutable arrays - 1

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

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

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

x

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*

```c
// 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

x

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

```
char aos2d[2][14] = {"my", "two dimension"};
```

aos2d[1][0] aos2d[1][1] aos2d[1][13]

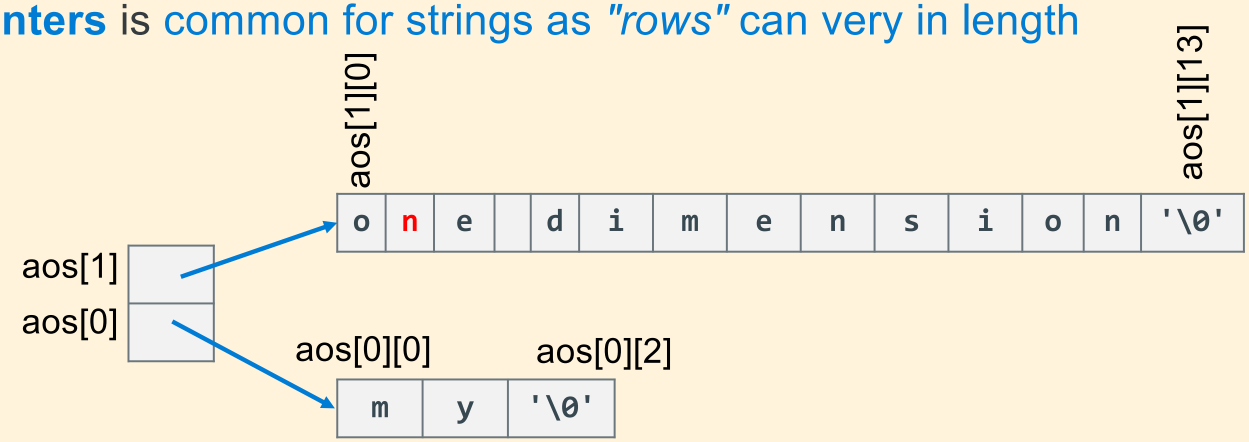
high memory	aos2d[1]	t	w	o		d	i	m	e	n	s	i	o	n	'\0'
	aos2d[0]	m	y	'\0'											
low memory															

aos2d[0][0]

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
- char *aos[2];



- `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

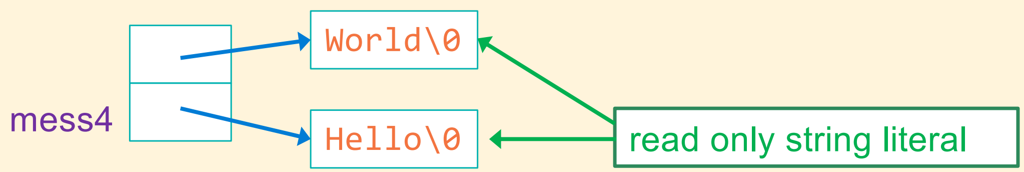
x

String Literals, Mutable and Immutable arrays - 2

- mess4 is an array of pointers to immutable arrays

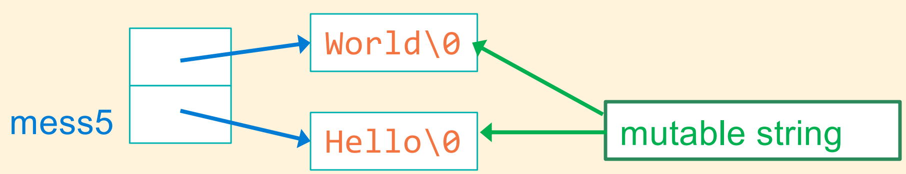
```
char *mess4[] = {"Hello","World"};  // immutable string
*(*mess4 + 1)  = '\0';              // bus error
```

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!
```



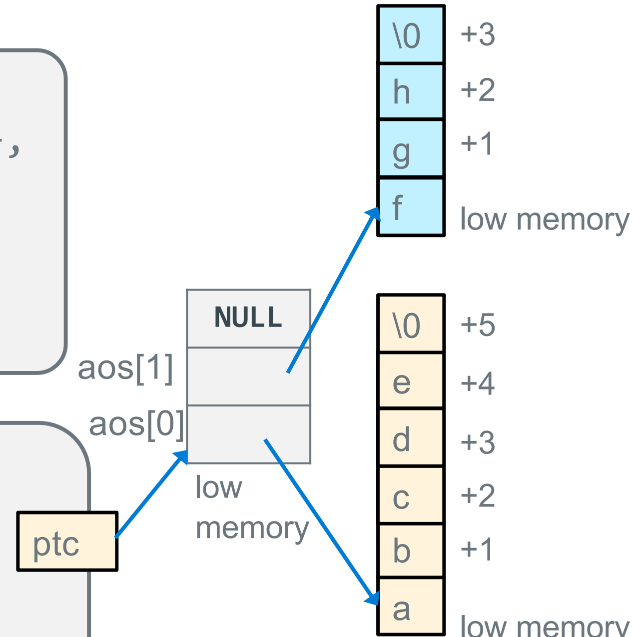
x

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
```

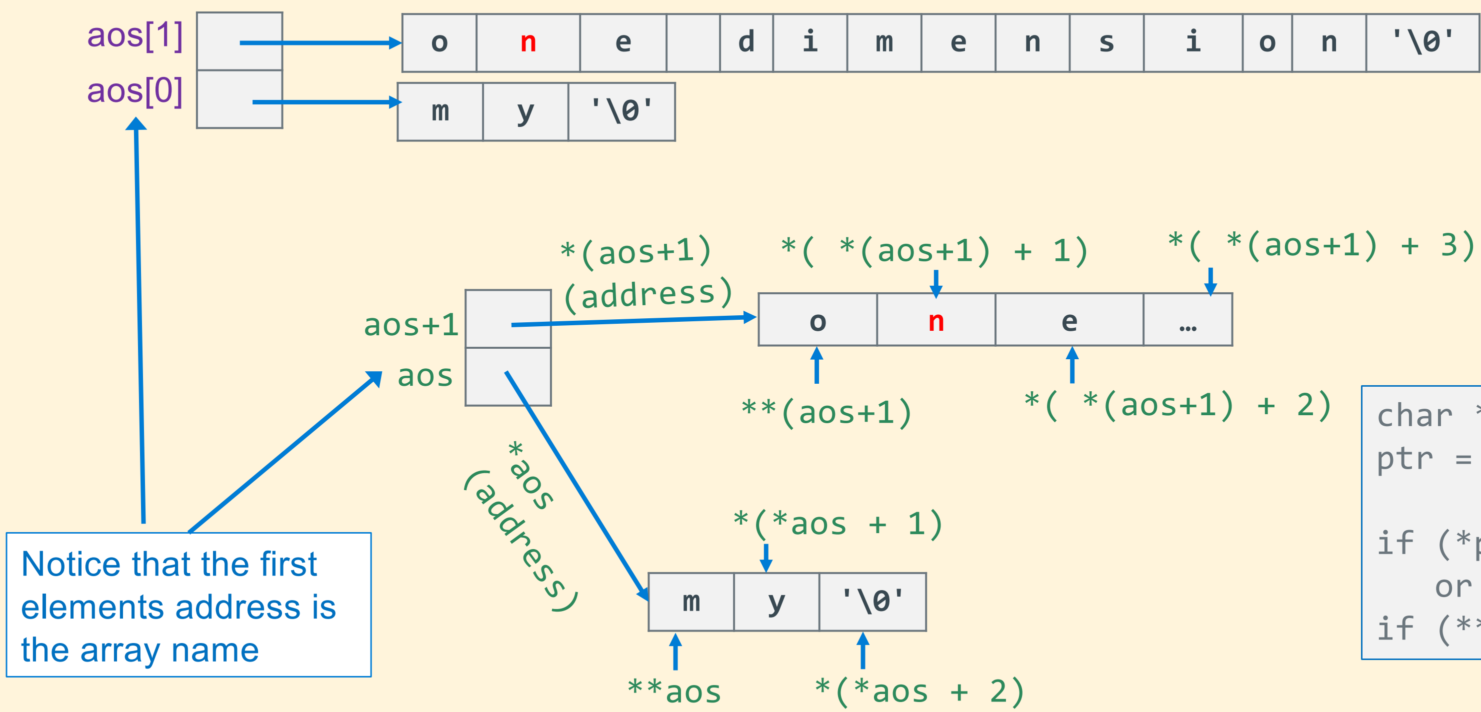

x

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)`



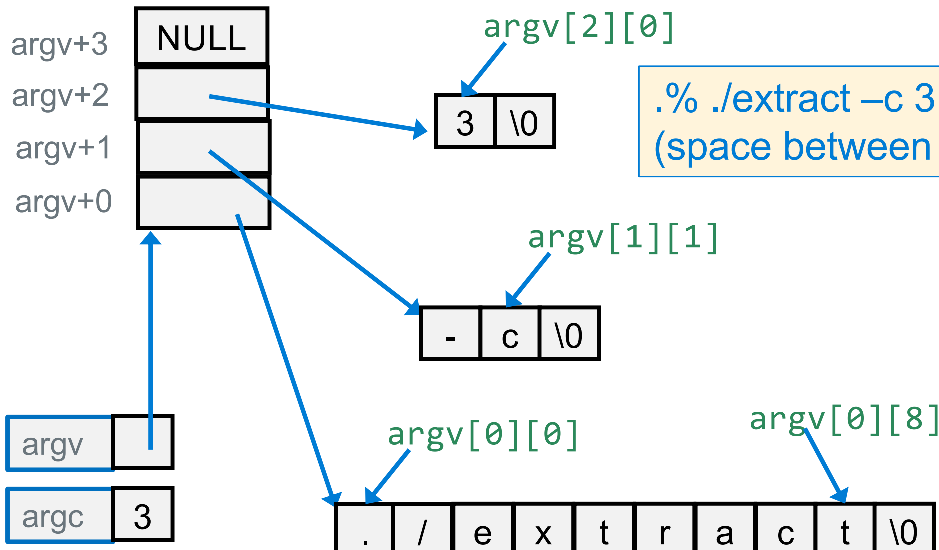

```
char *ptr;
ptr = *aos;

if (*ptr == ',')
   or
if (**aos) == ','
```


x

main() Command line arguments: argc, argv

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

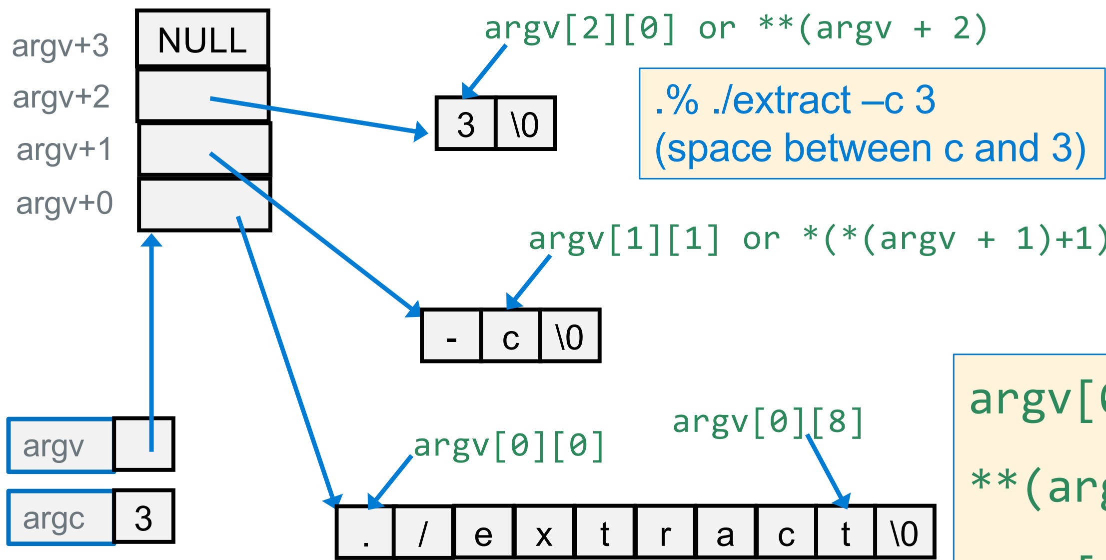
  `Conceptually: % *argv[0] *argv[1] *argv[2] ….`
- `argc` is the number of VALID elements (they point at something)
- `*argv (argv[0]) is` **usually** is the name of the executable file (% ./vim file.c)
- `*(argv + argc)` always contains a NULL (0) sentinel
- `*argv[] (or **argv)` elements point at **mutable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



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

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

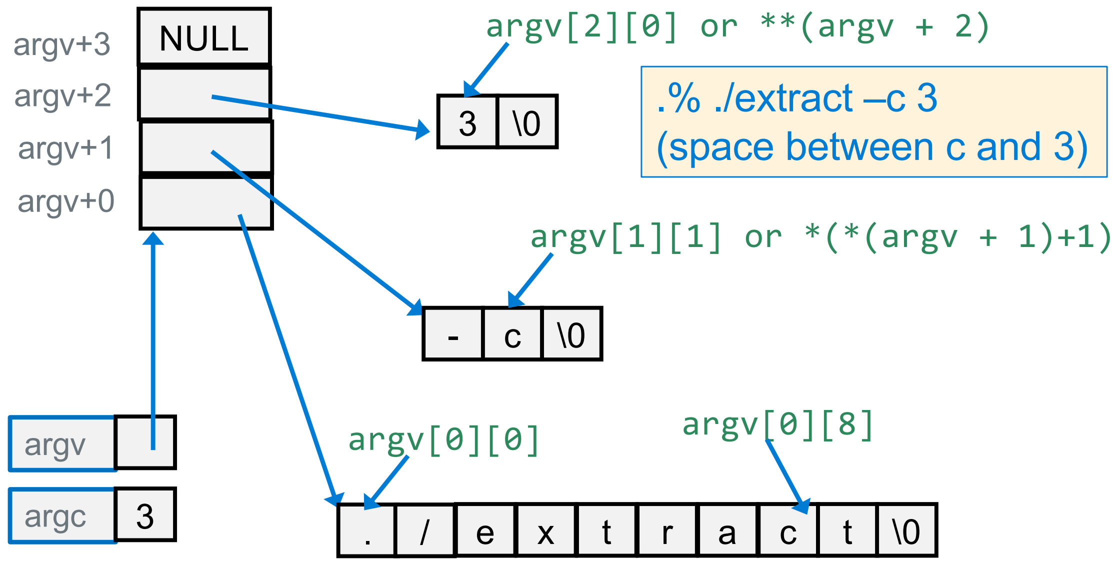
main() Command line arguments: argc, argv




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


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


x

Printing argv char at a time



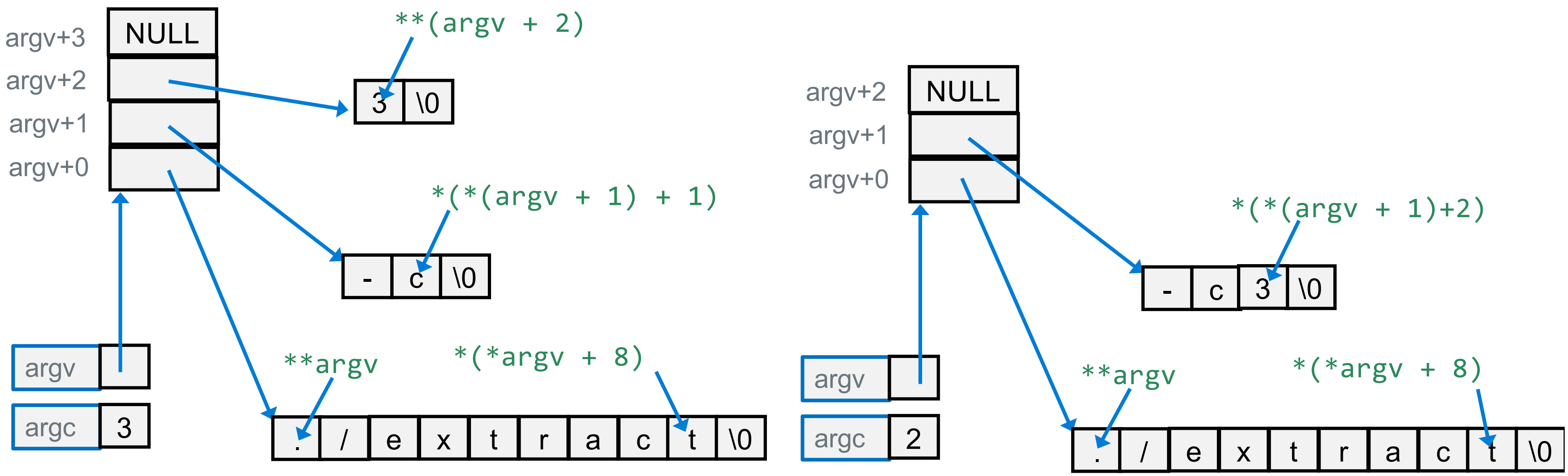
.% ./extract –c 3
(space between c and 3)

```
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

main() Command line arguments: argc, argv



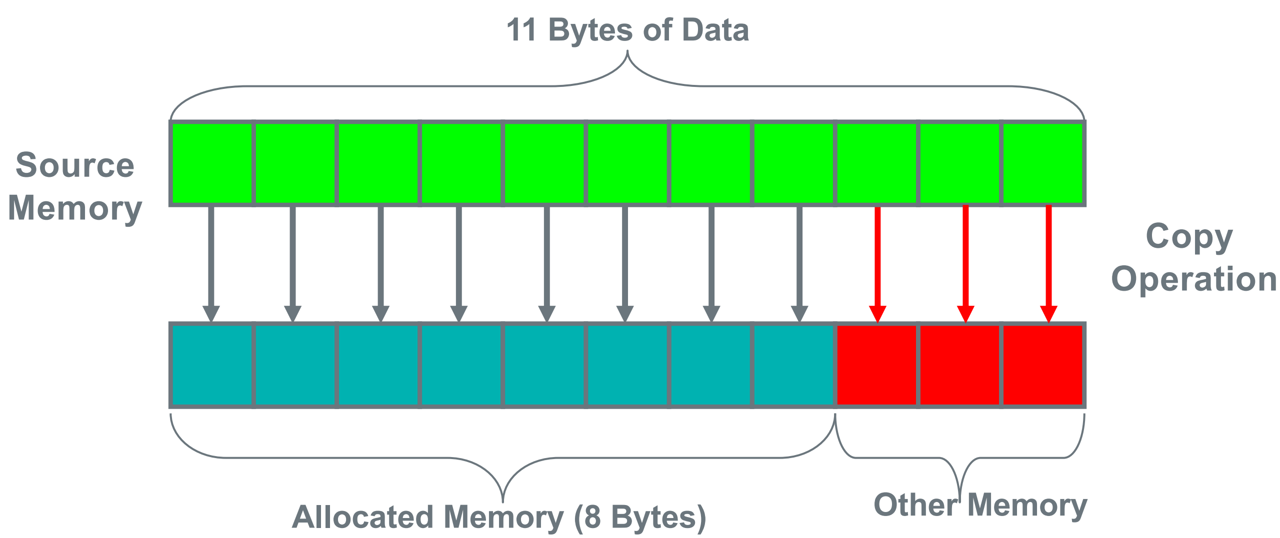
.% ./extract –c 3
(space between c and 3)

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

x

string buffer overflow: common security flaw

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



x

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

```c
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
```

s2[0]	s2[1]	s2[2]	s2[3]	s2[4]	s2[5]	r2[0]	r2[1]	r2[2]	r2[3]	s1[0]	s1[1]	s1[2]	s1[3]	s1[4]	s1[5]	s1[6]
'a'	'f'	't'	'e'	'r'	'\0'	'x'	'y'	'z'	'\0'	'b'	'e'	'f'	'o'	'r'	'e'	'\0'

low memory address

before strcpy() overflow

high memory address

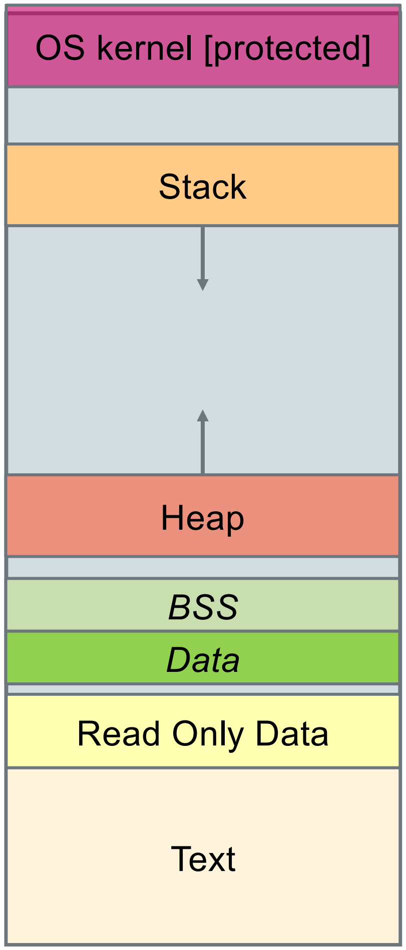
s2[0]	s2[1]	s2[2]	s2[3]	s2[4]	s2[5]	r2[0]	r2[1]	r2[2]	r2[3]	s1[0]	s1[1]	s1[2]	s1[3]	s1[4]	s1[5]	s1[6]
'a'	'f'	't'	'e'	'r'	'\0'	'h'	'e'	'l'	'l'	'o'	'\0'	'f'	'o'	'r'	'e'	'\0'

after strcpy() overflow

x

The Heap Memory Segment

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



x

Heap Dynamic Memory Allocation Library Functions

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

- **void *** means these library functions return a pointer to generic (untyped) memory
  - Be careful with void * pointers and pointer math as void * points at untyped memory (not allowed in C, but allowed in gcc). The assignment to a typed pointer *"converts"* it from a void *
- **size_t is** an unsigned integer data type, the result of a sizeof() operator

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

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

x

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
}
```


X

Use of Malloc

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{
    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
}
```


x

Using and Freeing Heap Memory

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

```
#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
```


x

Heap Memory "Leaks"

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

```
void
leaky_memory (void)
{
    char *bytes = malloc(BLKSZ * sizeof(*bytes));
…
    /* code that never 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!)

x

Valgrind – Finding Buffer Overflows and Memory leaks

```c
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

x

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

x

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

X

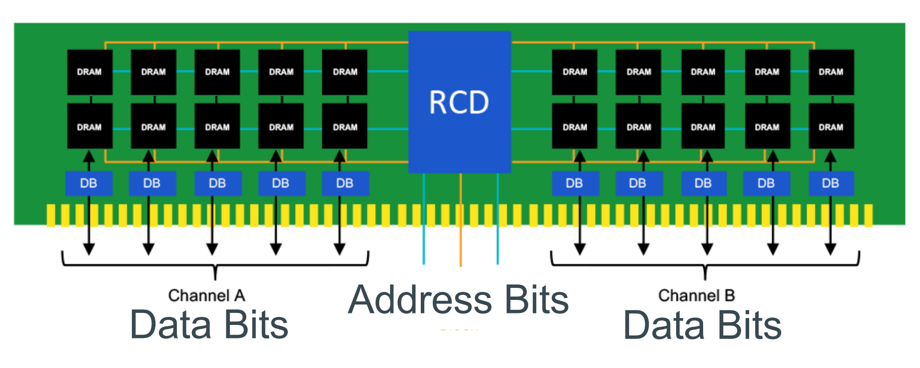
Extra Slides

-

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

Memory dimm



x

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
int8_t	uint8_t	8 bits (1 byte)
int16_t	uint16_t	16 bits (2 bytes)
int32_t	uint32_t	32 bits (4 bytes)
int64_t	uint64_t	64 bits (8 bytes)

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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
```


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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 `int`s, and *initializes* them to 5 and 2, respectively

```
ptr = &x;
```

Sets `ptr` to contain the address of `x` (“`ptr` points to `x`”)

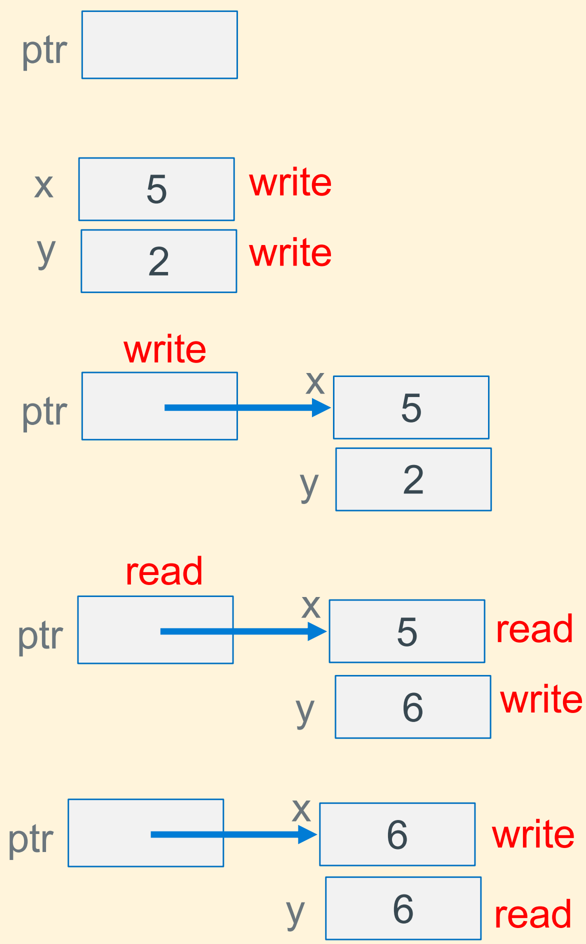
```
y = 1 + *ptr;
```

“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



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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 >= 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 <u>does</u> <u>not</u> 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)

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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);
```


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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

index	0	1	2	3	4	5
char	'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
}
```


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