

Version 1.11

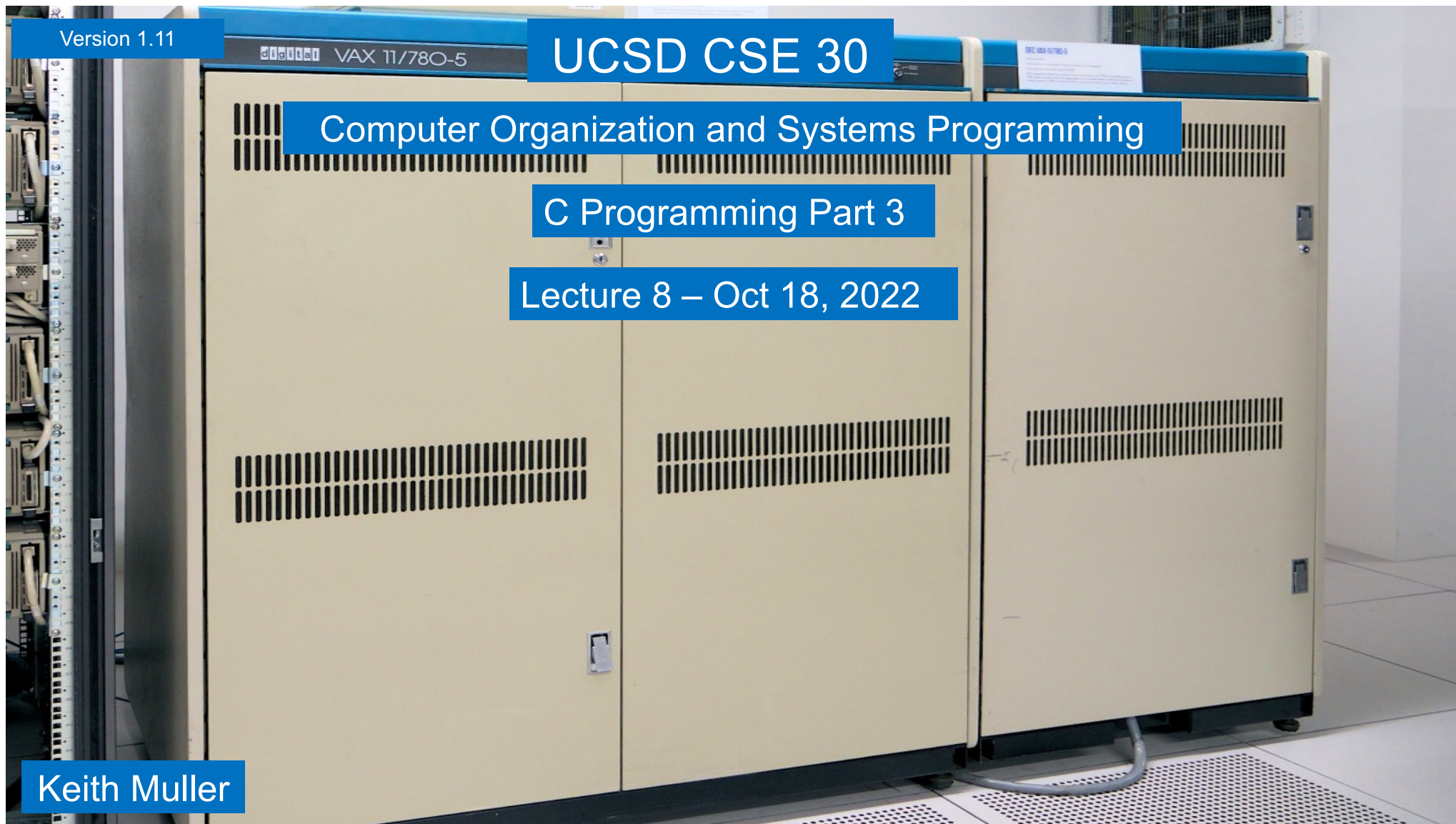
UCSD CSE 30

Computer Organization and Systems Programming

C Programming Part 3

Lecture 8 – Oct 18, 2022

Keith Muller



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 |

Pointer Practice

| Operator | Description | Associativity |
|---|---|---------------|
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| 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 |

Pointer Practice

```

int x;
int *p;
x = *(p+1); //contents of p[1]
x = *p + 1; //p[0] + 1
x = (*p)++;
    => x = *p ; *p = *p + 1;

x = *p++;
x = (*p++);
x = *(p)++;
x = *(p++);
    => x = *p ; p = p + 1;

x = *++p;
    => p = p + 1 ; x = *p ;
    
```

| Operator | Description | Associativity |
|---|---|---------------|
| () [] . -> ++ -- | Parentheses or function call Brackets or array subscript Dot or Member selection operator Arrow operator Postfix increment/decrement | left to right |
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| ++*p | ++(*p) | The 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
```

Using Pointers to Traverse an array

```
char x[] = "Word:One Two Three;
int cnt = (int)(sizeof(x) / sizeof(*x));
char *ptr;
int j = 0;
ptr = x;

while (j < cnt) {
    if (*(ptr + j++) == ':')
        break;
}
printf("%s\n", ptr + j); // One Two Three
```

Brute force translation to pointers

```
char x[] = "Word:One Two Three;
int cnt = (int)(sizeof(x) / sizeof(*x));

char *ptr;
char *xpt;
ptr = x; //or &x[0]
xpt = ptr + cnt;

while (ptr < xpt) {
    if (*ptr++ == ':')
        break;
}
printf("%s\n", ptr); // One Two Three
```

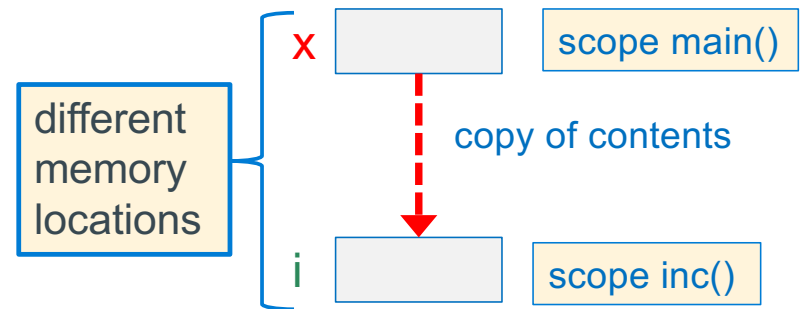
More common way to use pointers

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**
 - 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 *, char *, char **);
int main(void)
{
    int x = 5;
    char str[] = "string";
    char *ptr;
    inc(&x, str, &ptr);
    printf("%d %s\n", x, ptr );
    return EXIT_SUCCESS;
}
```

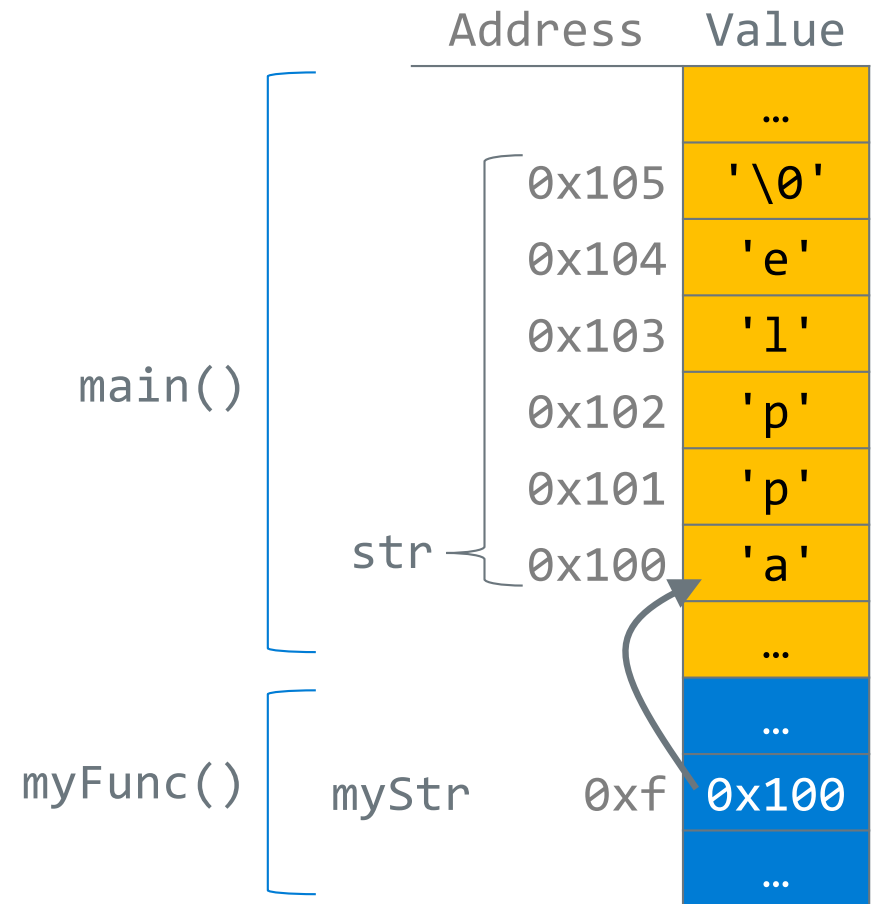
```
void
inc(int *p, char *cp, char **pcp)
{
    *p += 1; // or (*p)++
    printf("%s\n",cp);
    *pcp = cp + 1;
}
```

prints:
string
6 tring

Passing Arrays (Strings)

```
void
myFunc(char *myStr) {
    ...
}

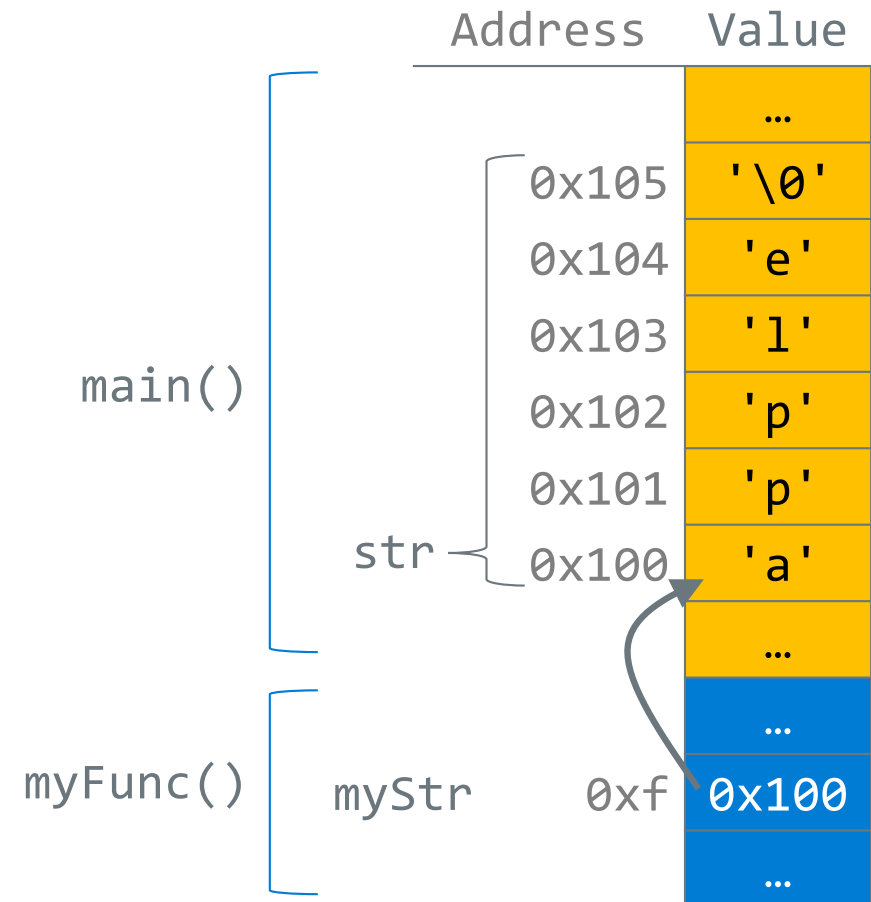
int
main(void) {
    char str[6];
    strcpy(str, "apple");
    myFunc(str);
    ...
}
```



Passing Arrays (Strings)

```
void
myFunc(char *myStr) {
    myStr[4] = 'y'; // not safe!
}

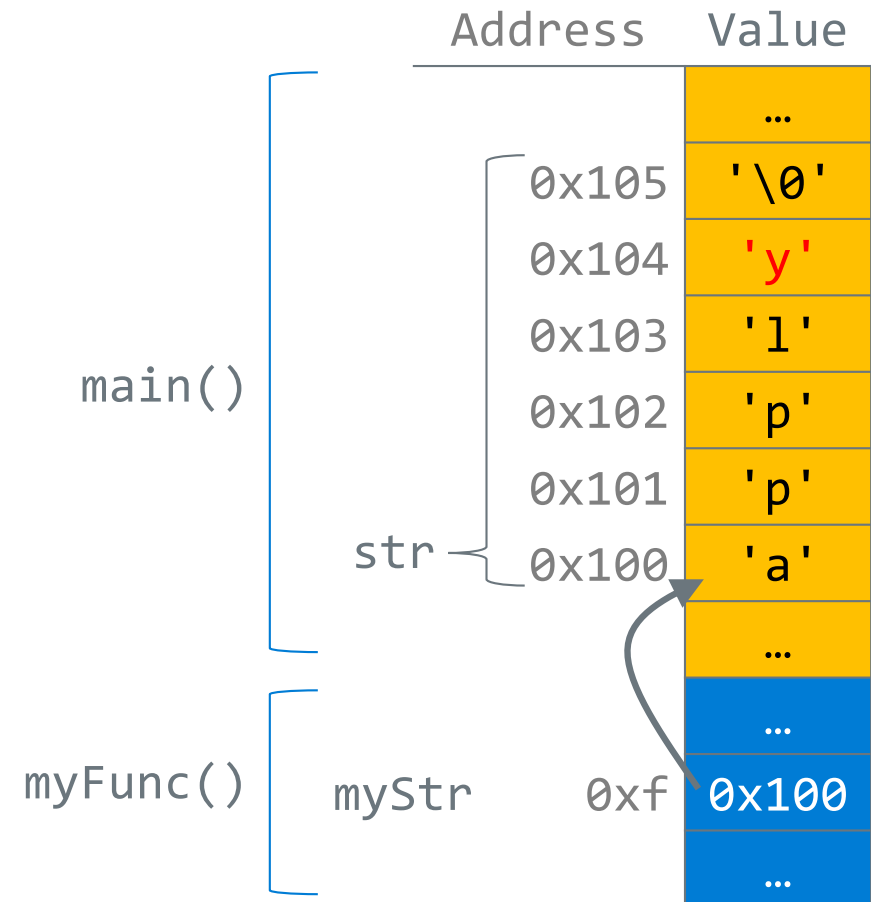
int
main(void) {
    char str[6];
    strcpy(str, "apple");
    myFunc(str);
    ...
}
```



if we modify characters in **myFunc**, the changes will persist back in **main**!

Passing Arrays (Strings)

```
void  
myFunc(char *myStr) {  
    myStr[4] = 'y'; // not safe!  
}  
  
int  
main(void) {  
    char str[6];  
    strcpy(str, "apple");  
    myFunc(str);  
    ...  
}
```



if we modify characters in **myFunc**, the changes will persist back in **main**!

Arrays As Parameters, Approach 1: Pass the size

Two ways to pass array size

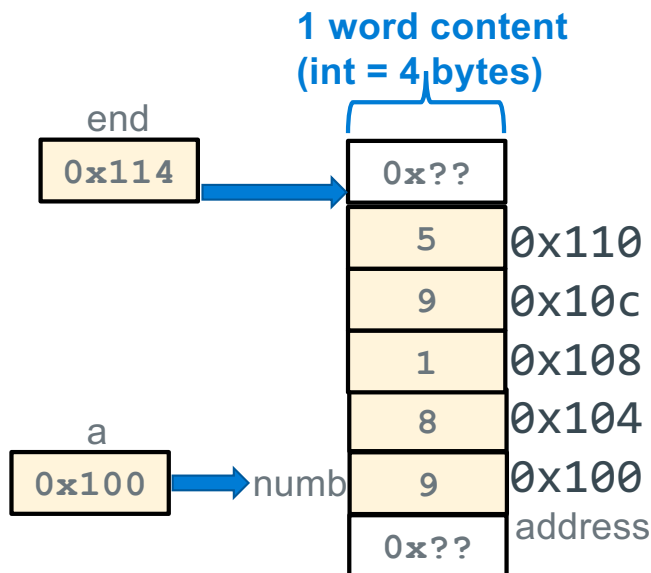
1. pass the **count** as an additional argument
2. add a **sentinel element** as the last element

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

Arrays do not know their own size

```
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;
}
```

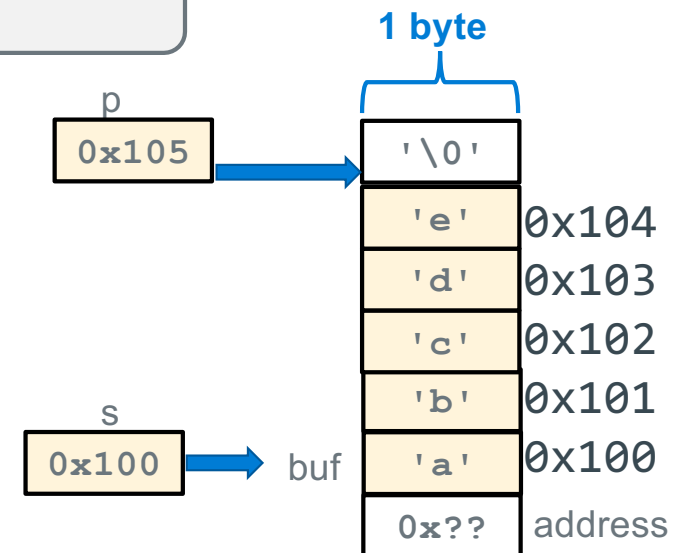
Arrays As Parameters, Approach 2: Use a sentinel element

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

    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);
}
```



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

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

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

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

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

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

```
char *strncpy(char *s0, char *s1, int len)  
{  
    char *str = s0;  
    if ((s0 == NULL) || (s1 == NULL))  
        return NULL;  
  
    while ((*s0++ = *s1++) && --len)  
        ;  
    return str;  
}
```

2D Arrays

- Generic (uniform) 2D array format:

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

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

```
// a 2-row, 3-column array of char
```

```
char matrix[2][3];
```

```
// a 2-row, 5-column (row length) array of ints
```

```
// Must specify row length, compiler counts rows
```

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

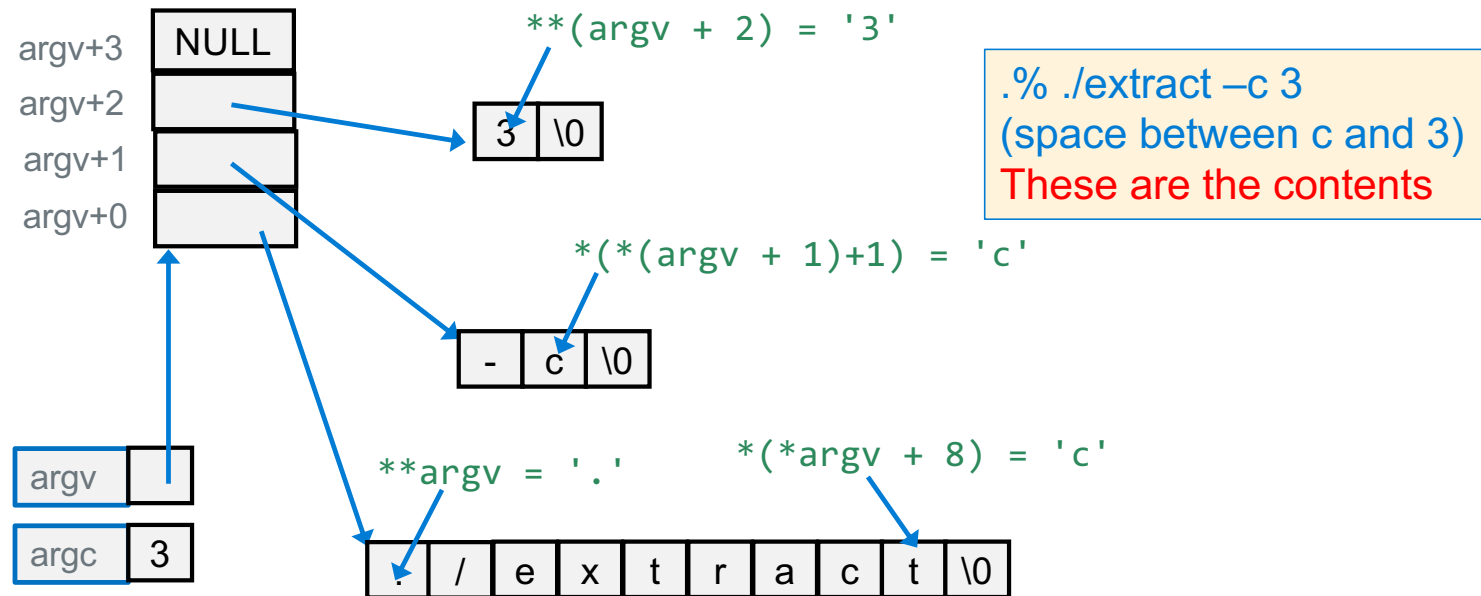
| | | | | |
|--------|--------|--------|--------|--------|
| [1][0] | [1][1] | [1][2] | [1][3] | [1][4] |
| [0][0] | [0][1] | [0][2] | [0][3] | [0][4] |

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

1 word (int = 4 bytes)

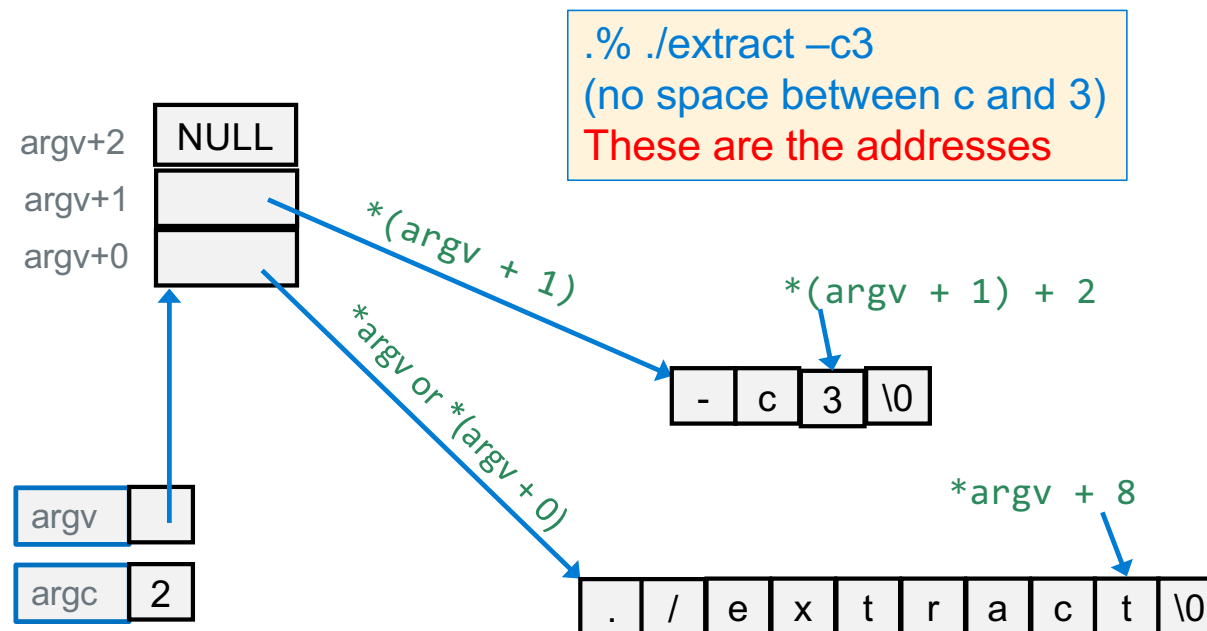
| | | |
|------------|---|-------------|
| | ? | high memory |
| grid[1][4] | 9 | 0x0024 |
| grid[1][3] | 8 | 0x0020 |
| grid[1][2] | 7 | 0x001c |
| grid[1][1] | 6 | 0x0018 |
| grid[1][0] | 5 | 0x0014 |
| grid[0][4] | 4 | 0x0010 |
| grid[0][3] | 3 | 0x000c |
| grid[0][2] | 2 | 0x0008 |
| grid[0][1] |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

Array of Pointers: main() : argc, argv Character Content

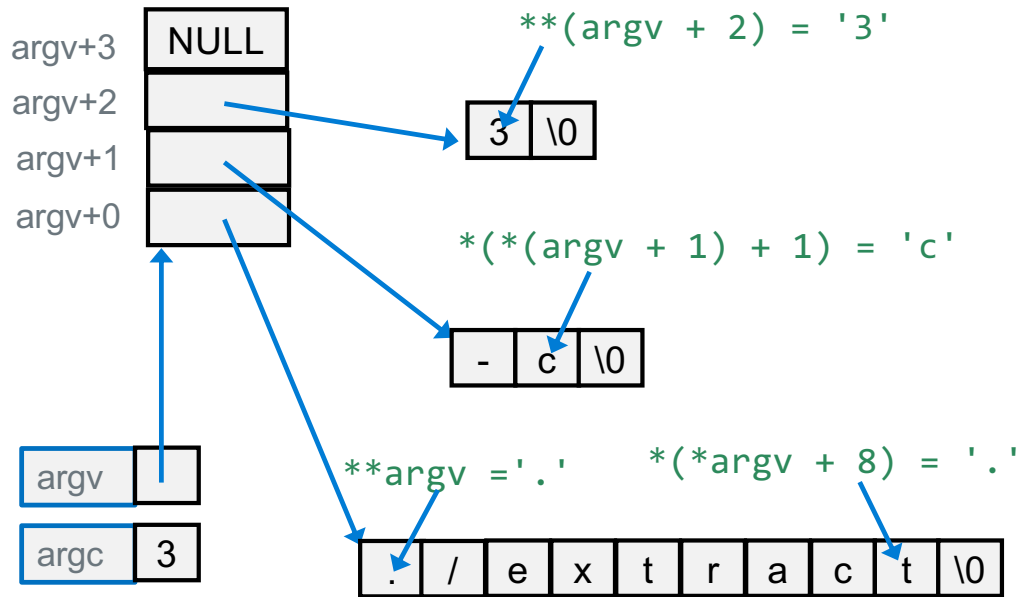


```
int main(int argc, char **argv)
{
    char *pt;
    while ((pt = *argv++) != NULL) {
        while (*pt != '\0')
            putchar(*pt++);
        putchar('\n');
    }
    return EXIT_SUCCESS;
}
```

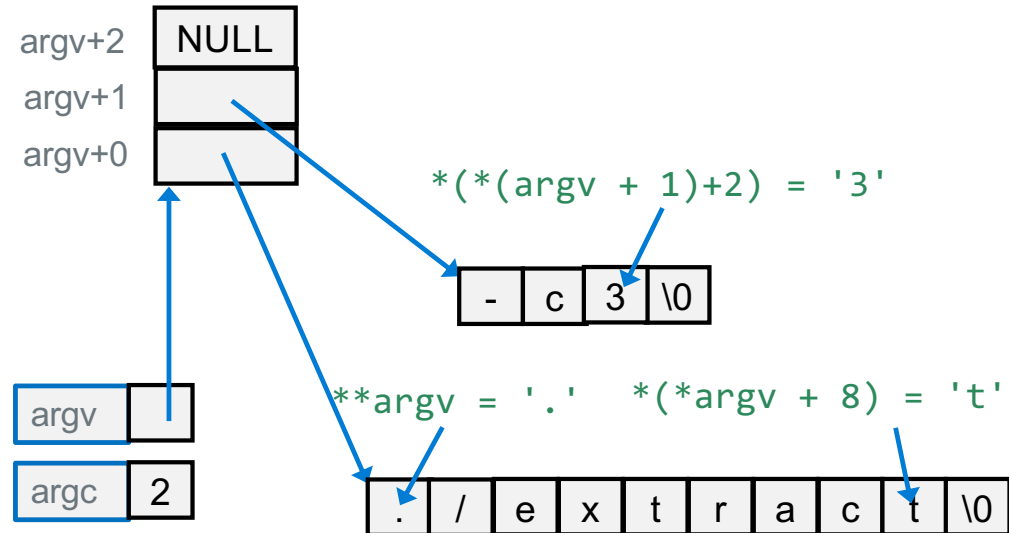
Array of Pointers: main() : argc, argv Character Address



main() Command line arguments: argc, argv



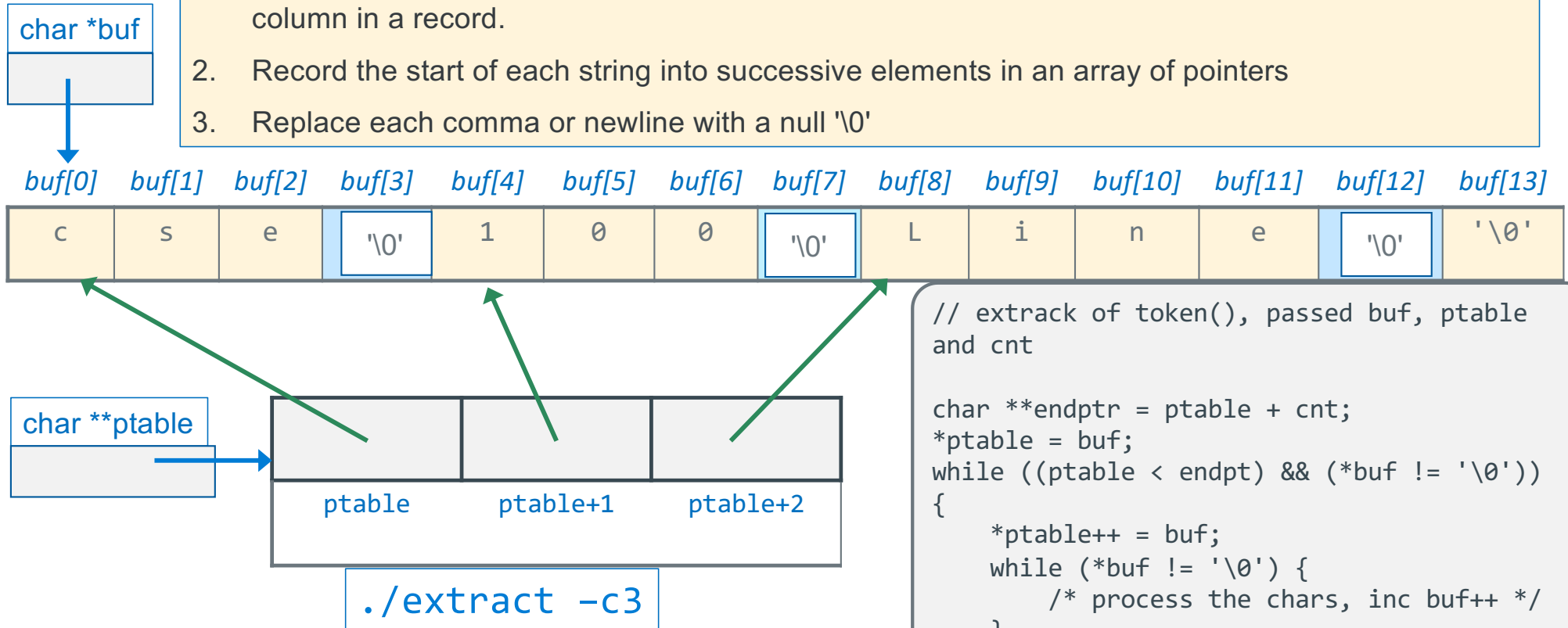
`./extract -c 3`
(space between c and 3)



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

PA4: Creating a 2D Array of Mutable String Pointers

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



```
// extract of token(), passed buf, ptable
// and cnt

char **endptr = ptable + cnt;
*ptable = buf;
while ((ptable < endptr) && (*buf != '\0'))
{
    *ptable++ = buf;
    while (*buf != '\0') {
        /* process the chars, inc buf++ */
    }
}
// check for too many or too few fields
```

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 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);
```

String Literals (Read-Only) in Expressions

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

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

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

String Literals, Mutable and Immutable arrays

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

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

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

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

Be Careful with C Strings and Arrays of Chars

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

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

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

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

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

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
}
```

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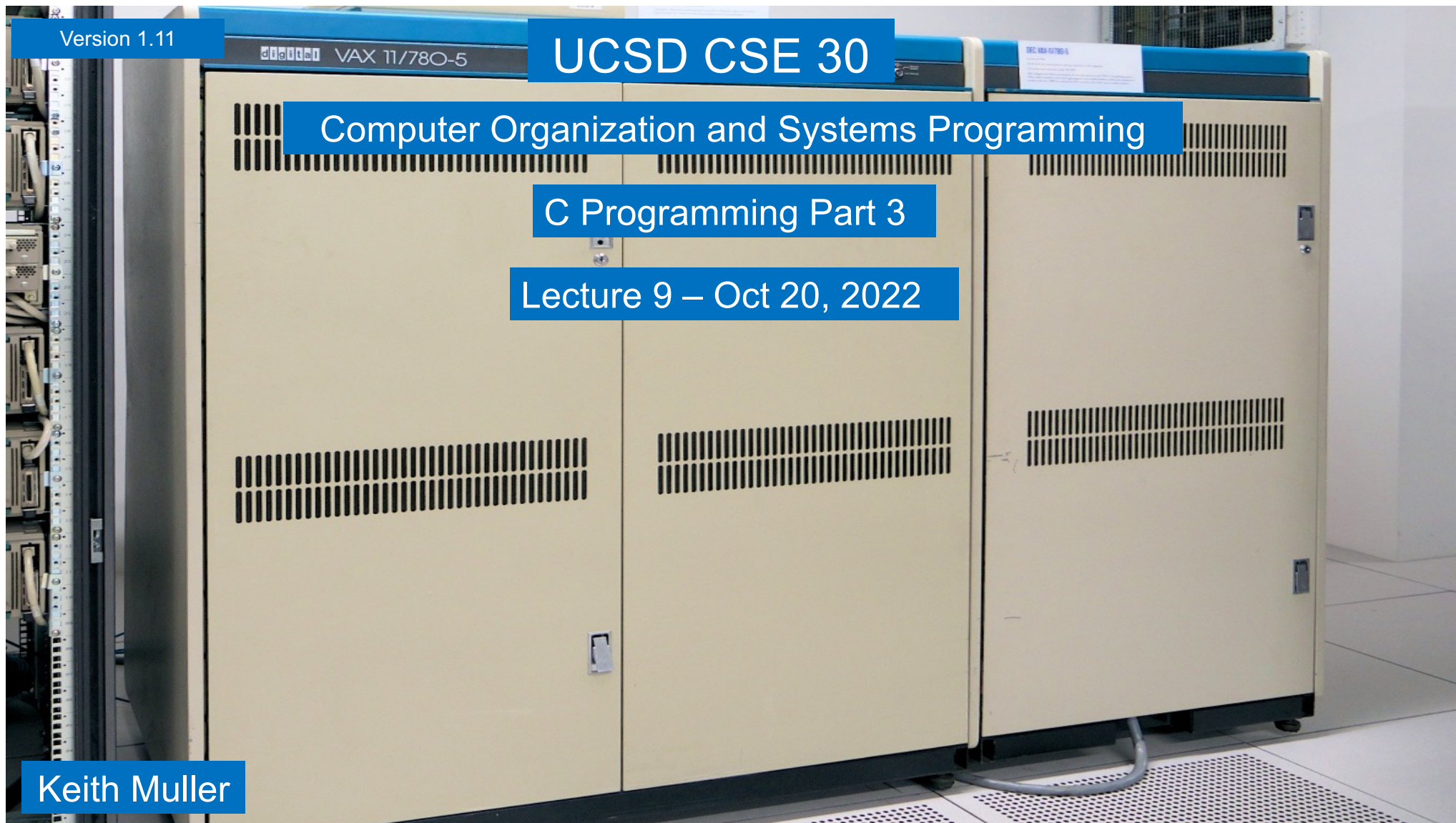
UCSD CSE 30

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C Programming Part 3

Lecture 9 – Oct 20, 2022

Keith Muller



String Literals (Read-Only) in Expressions

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printf("literal\n");  
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- **String literals** are a type of **anonymous variable**
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- 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

- **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" is a 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
```

cast to (char [])
makes mutable

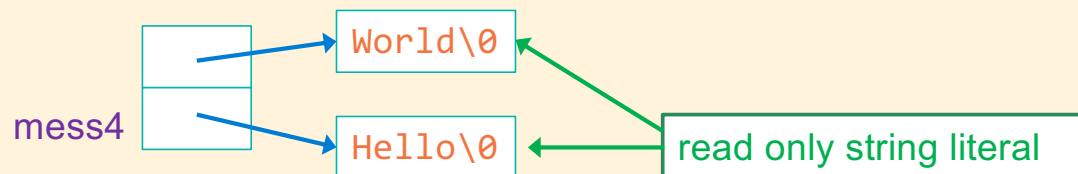
mess3 → Hello World\0 ← mutable string

String Literals, Mutable and Immutable arrays

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

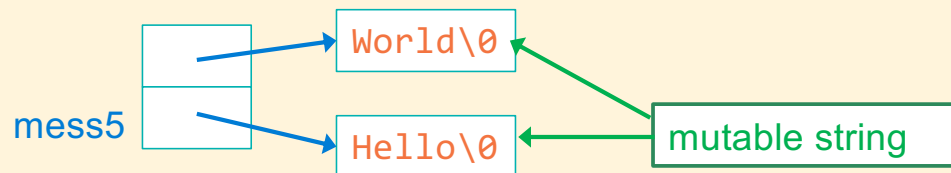
```
char *mess4[] = {"Hello", "World"}; // immutable string  
*(mess4 + 1) = '\0';                // bus error
```

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



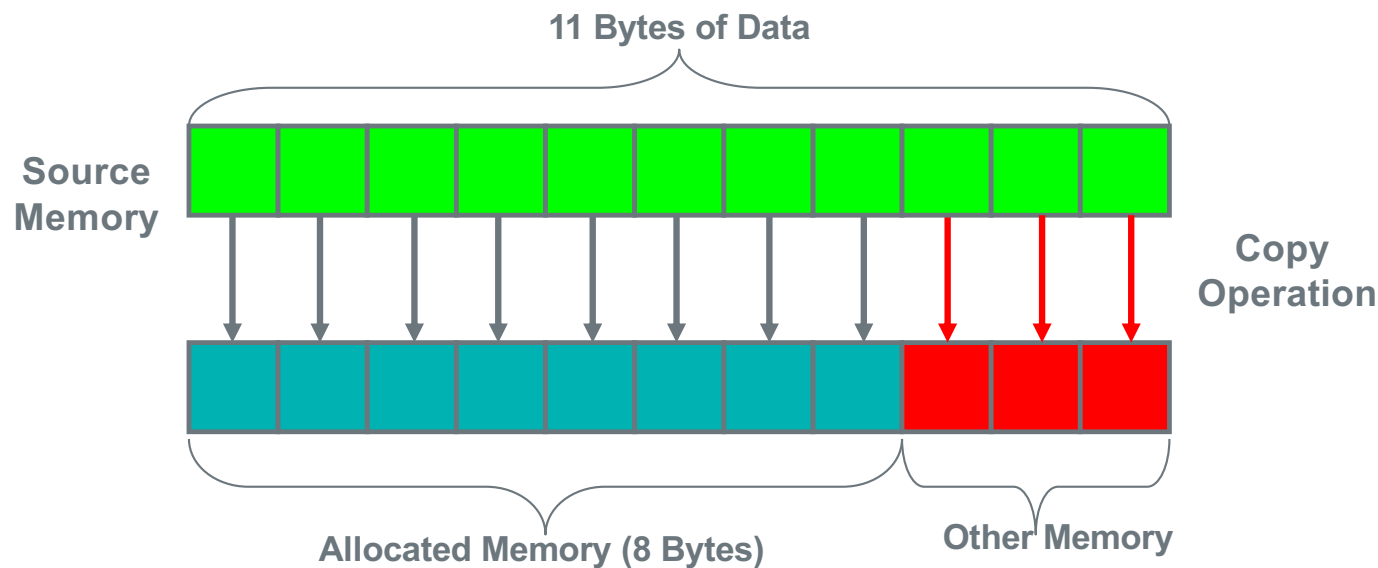
- `mess5` is an array of pointers to mutable arrays

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



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

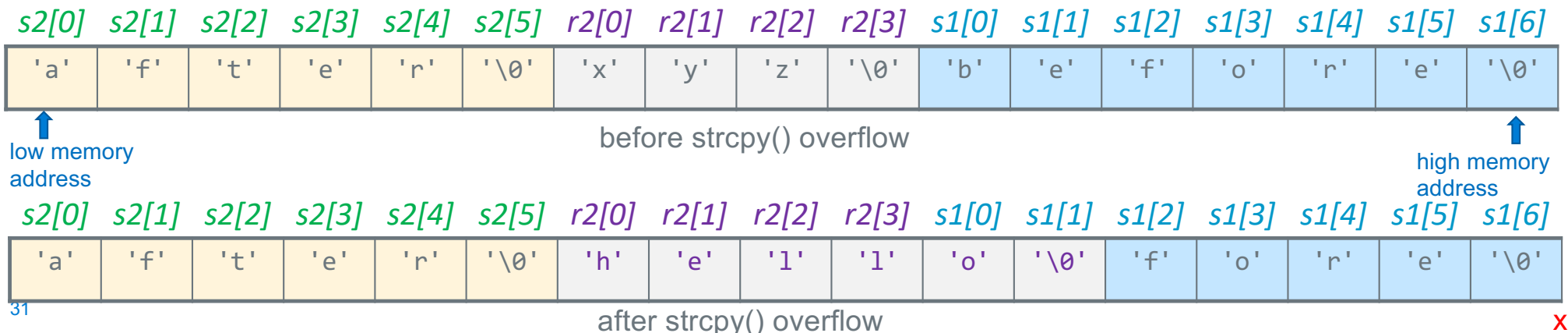
    printf("\ns2:%s\nr2: %s\nr2:%s\n", s2, r2, s1);
    return EXIT_SUCCESS;
}
```

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
```



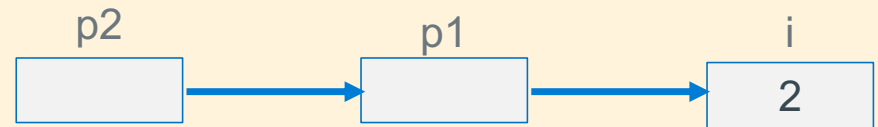
Pointer to Pointers (Double, Triple and ... Indirection)

- A pointer cannot point at itself, why?

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

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

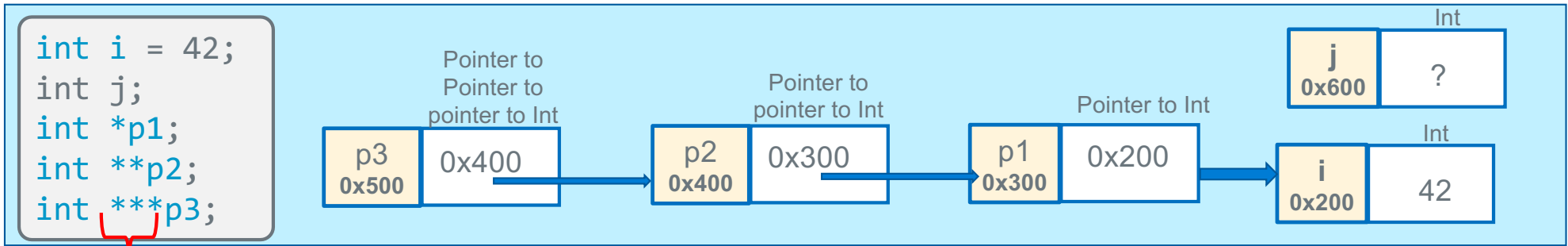
```
int i = 2;  
int *p1;  
int **p2;  
p1 = &i;  
p2 = &p1;  
printf("%d\n", (**p2) * (**p2));
```



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

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

Pointers to Pointers to Pointers.... Rside Practice



number of **"reads + 1"** to base type on Rside

Rside evaluations

| | Address | Contents | *contents | **contents | ***contents |
|----|---------|----------|-----------|------------|-------------|
| j | 0x600 | ? | | | |
| i | 0x200 | 42 | | | |
| p1 | 0x300 | 0x200 | 42 | | |
| p2 | 0x400 | 0x300 | 0x200 | 42 | |
| p3 | 0x500 | 0x400 | 0x300 | 0x200 | 42 |

Key:

| | |
|------------------------------|--------------------|
| memory address or name | Memory contents |
|------------------------------|--------------------|

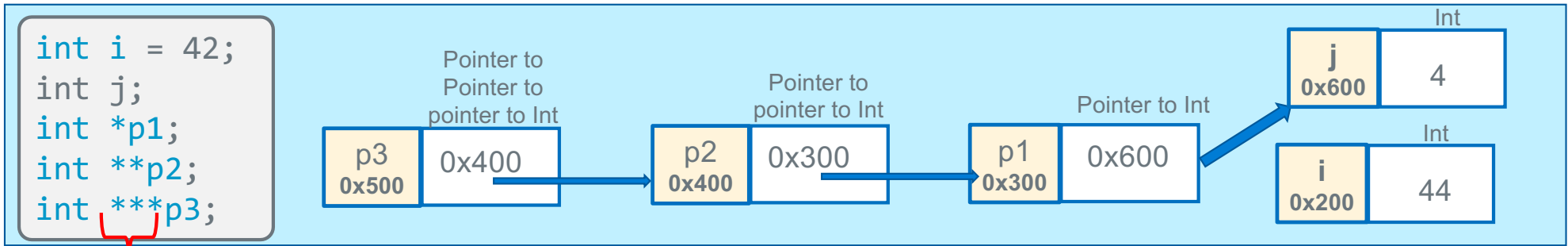
```
% ./a.out
j:43 i:44
j:132 i:44
```

```
p1 = &i;
p2 = &p1;
p3 = &p2;

j = *p1 + 1;
**p2 = *p1 + 2;
printf("j:%d i:%d\n",j, i);

j = ***p3 + **p2 + *p1;
printf("j:%d i:%d\n",j, i);
```

Pointers to Pointers to Pointers.... Rside Practice



number of **"reads + 1"** to base type on Rside

Rside evaluations

| | Address | Contents | *contents | **contents | ***contents |
|----|---------|----------|-----------|------------|-------------|
| j | 0x600 | 4 | | | |
| i | 0x200 | 44 | | | |
| p1 | 0x300 | 0x600 | 4 | | |
| p2 | 0x400 | 0x300 | 0x600 | 4 | |
| p3 | 0x500 | 0x400 | 0x300 | 0x600 | 4 |

```
//continued from previous slide
p1 = &j;
***p3 = 4;
printf("*p1:%d i:%d\n",*p1, i);
```

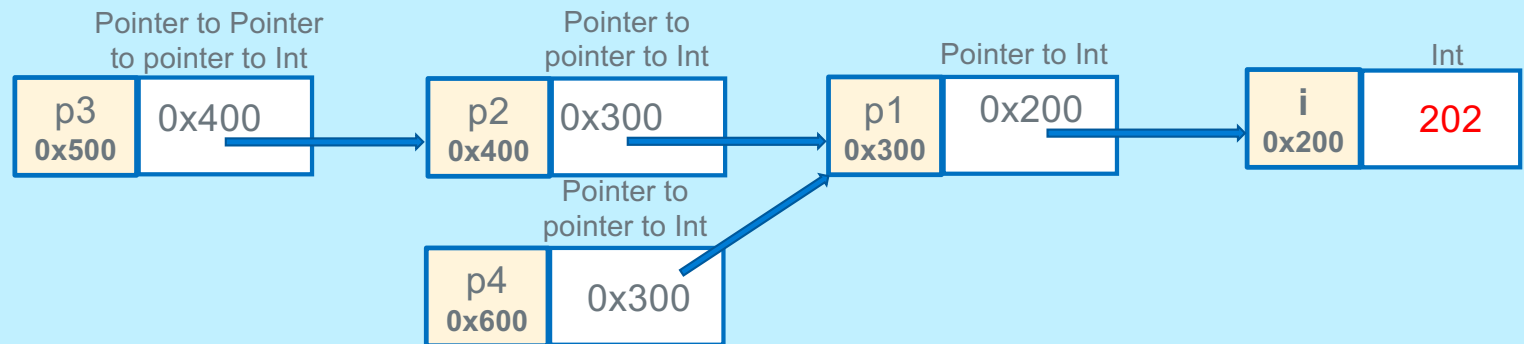
Key:

| | |
|------------------------------|--------------------|
| memory address or name | Memory contents |
|------------------------------|--------------------|

```
% ./a.out
j:43 i:44
j:132 i:44
*p1:4 i:44
```

Pointers to Pointers to Pointers.... Lside Practice

```
int i = 42;
int *p1;
int **p2;
int ***p3;
int **p4;
p3 = &p2;
p1 = &i;
p2 = &p1;
p3 = &p2;
```



```
→ *p1 = 34; // +1 read lside
→ **p2 = 19; //+2 reads lside
→ ***p3 = 101; //+3 reads lside
→ **p2 = *p1 + i;
→ p4 = *p3;
→ (**p4)++;
→ --(*p1);
```

destination addresses for data write when on **Lside**

| | address | variable | *variable | **variable | ***variable |
|----|---------|----------|-----------|------------|-------------|
| i | 0x200 | 0x200 | | | |
| p1 | 0x300 | 0x300 | 0x200 | | |
| p2 | 0x400 | 0x400 | 0x300 | 0x200 | |
| p3 | 0x500 | 0x500 | 0x400 | 0x300 | 0x200 |

Key:

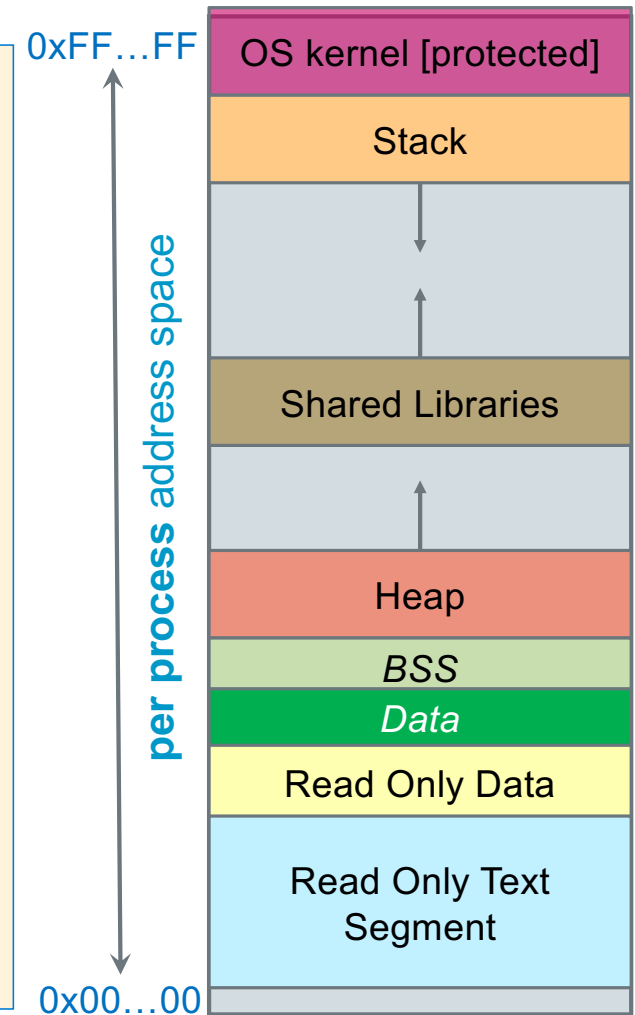
| | |
|------------------------------|--------------------|
| memory address or name | Memory contents |
|------------------------------|--------------------|

(slide is best viewed is in pptx presentation mode)

X

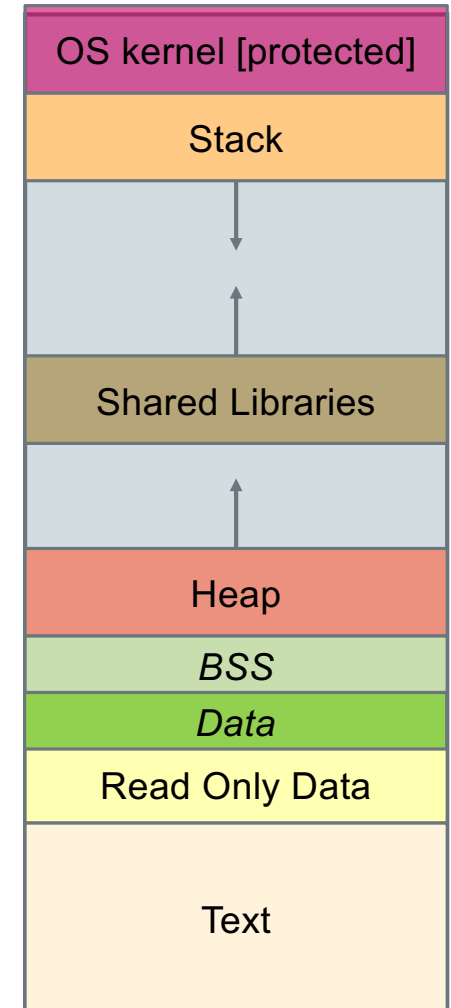
Process Memory Under Linux

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



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 <stdlib.h></code> | args | Clears memory |
|--|---|---------------|
| <code>void *malloc(...)</code> | <code>size_t size</code> | no |
| <code>void *calloc(...)</code> | <code>size_t nmemb, 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
}
```

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!, memory leak
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
```

Mis-Use of Free()

- Call `free()` only with only the same memory returned from the heap
 - It is NOT an error to pass `free()` a pointer to NULL
- Continuing to write to memory after you `free()` it is likely to corrupt the heap or return changed values
 - Later calls to heap routines (`malloc()`, `realloc()`, `calloc()`) may fail or seg fault

```
char *bytes = malloc(1024 * sizeof(*bytes));
char *ptr = "cse30";

...

/* some code */
free(bytes + 5);      // not ok
free(ptr);            /* not memory on the heap */
```

```
char *bytes = malloc(1024 * sizeof(*bytes));
...

/* some code */
free(bytes);
strcpy(bytes, "cse30"); // INVALID! used after free

.....
```

Heap Memory "Leaks"

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

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

- Your **program is responsible for cleaning up any memory it allocates** but no longer needs
 - If you keep allocating memory, you may run out of memory in the heap!
- **Memory leaks** may cause **long running programs to fault** when they **exhaust OS memory limits**
 - Make sure you **free memory when you no longer need it**
- **Valgrind** is a tool for finding memory leaks (not pre-installed in all linux distributions though!)

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[0] = '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)); // same size as malloc(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**

Realloc

```
void *realloc(void *ptr, size_t size);
```

- **realloc** function takes an existing allocation pointer and enlarges to a new requested size, It returns the new pointer (may be same or different address)
 - If a new buffer, ptr is no longer valid!
- realloc() only accepts pointers that were previously returned by malloc etc.
- Make sure to not lose original pointer if realloc() fails (newstr versus str)

```
char *str = strdup("Hello");
char *addition = " World!\n";
int len = strlen(str);
char *newstr;

if ((newstr = realloc(str, len + strlen(addition) + 1)) != NULL) {
    strcpy(newstr + len, addition);
    printf("%s", newstr);
    free(newstr);
} else // realloc() failed so free orig buffer
    free(str);
```

Heap Allocation Routine Summary

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

Heap **memory allocation** guarantee:

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

Undefined behavior occurs:

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

PA5: getopt() usage- parsing command line Arguments

```
int getopt(int argc, char *argv[], const char *optstring); // please see man 3 getopt
```

- Option string describes the option flags. Two ways
 - Single letter example: -x
 - flag x is in the **optstring** ("x")
 - Single letter followed by a Colon (:) example: -f 33
 - Flag f is in the **optstring** ("f:")
 - **getopt()** sets the **global variable optarg** (char ***optarg**) to point at the argument to the flag
 - "33" in this example
- **Call getopt()** in a loop; it returns the next option flag stored in an int

```
int opt;
while ((opt = getopt(argc, argv, "xf:")) != -1) {
    switch (opt) {
        case 'f':
            printf("-f %s found\n", optarg);
    }
}
```
- Returns -1 if there are no options left
- Returns a '?' indicates flag is not specified (error) or the flag is specified but has a missing argument
 - **Global variable optopt** contains the flag that was detected, but is the cause for the error
- When getopt finishes, **optind** (operands index) contains the index # into argv of the first non-flag argument (the one right after the last flag) to process

getopt() sample

optind starts here

```
% ./a.out -x -f 33 1 2 3 4 5 6
-x flag found
-f 33 found
argv[4] is: 1
argv[5] is: 2
argv[6] is: 3
argv[7] is: 4
argv[8] is: 5
argv[9] is: 6
% ./a.out -x 1 2 3
-x flag found
argv[2] is: 1
argv[3] is: 2
argv[4] is: 3
```

```
#include <unistd.h> // other #includes not shown
int main(int argc, char **argv)
{
    int opt;
    while ((opt = getopt(argc, argv, "xf:")) != -1) {
        switch (opt) {
            case 'x':
                printf("-x flag found\n");
                break;
            case 'f':
                printf("-f %s found\n", optarg);
                break;
            case '?':
                /* fall through */
            default:
                fprintf(stderr, "Usage: %s [-x] -f datafile\n", argv[0]);
                return EXIT_FAILURE;
        }
    }
    for (int i = optind; i < argc; i++) // Loop through operands
        printf("argv[%d] is: %s\n", i, argv[i]); //print each operand
    return EXIT_SUCCESS;
}
```

```
% ./a.out -f
./a.out: option requires an argument -- f
Usage: ./a.out [-x] -f datafile
```

number of operands = argc - optind

getopt() arg reordering

- Linux getopt() will reorder the elements in argv so the operands are at the end

```
./a.out 1 2 3 -f33
-f 33 found
argv[2] is: 1
argv[3] is: 2
argv[4] is: 3
```

- If you do not want the reorder, put a + at the front of the getopt conversion string: "+xf:" Then you get

```
./a.out 1 2 3 -f33
argv[1] is: 1
argv[2] is: 2
argv[3] is: 3
argv[4] is: -f33
```

```
#include <unistd.h> // other #includes not shown
int main(int argc, char **argv)
{
    int opt;
    while ((opt = getopt(argc, argv, "xf:")) != -1) {
        switch (opt) {
            case 'x':
                printf("-x flag found\n");
                break;
            case 'f':
                printf("-f %s found\n", optarg);
                break;
            case '?':
                /* fall through */
            default:
                fprintf(stderr, "Usage: %s [-x] -f datafile\n", argv[0]);
                return EXIT_FAILURE;
        }
    }
    for (int i = optind; i < argc; i++) // Loop through operands
        printf("argv[%d] is: %s\n", i, argv[i]); //print each operand
    return EXIT_SUCCESS;
}
```

PA5: Printing a Subset Of the Columns

char *buf

- Create an index table that specifies the order to print a (sub)set of the fields/columns
- out_table specifies the in order and which columns to print

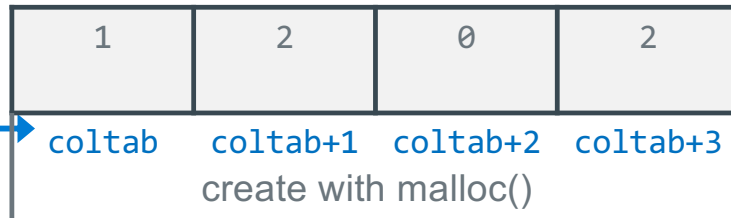
buf[0] buf[1] buf[2] buf[3] buf[4] buf[5] buf[6] buf[7] buf[8] buf[9] buf[10] buf[11] buf[12] buf[13]

| | | | | | | | | | | | | | |
|---|---|---|----|---|---|---|----|---|---|---|---|----|------|
| c | s | e | \0 | 1 | 0 | 0 | \0 | L | i | n | e | \0 | '\0' |
|---|---|---|----|---|---|---|----|---|---|---|---|----|------|

char **ptable



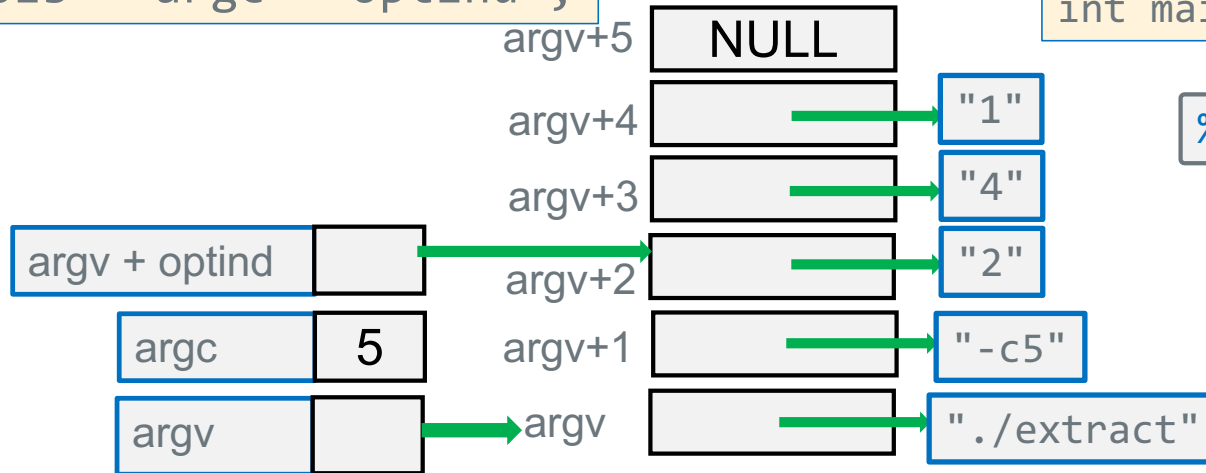
int *coltab



| Print Order | Input Column | Contents | Column String Printed |
|-------------|--------------|----------|-----------------------|
| coltab+0 | 2 | 1 | 100 |
| coltab+1 | 3 | 2 | Line |
| coltab+2 | 1 | 0 | cse |
| coltab+3 | 3 | 2 | Line |

PA5: Getting Columns numbers from argv

```
outcols = argc - optind ;
```



```
int main(int argc, char **argv)
```

```
% ./extract -c5 2 4 1
```

optind

- To create the coltab table of indexes, convert each string in argv from optind until argc-1 using strtol() and then subtract 1 to get the index offset and copy it into the coltab

| | | |
|--------|----------|----------|
| 1 | 3 | 0 |
| coltab | coltab+1 | coltab+2 |

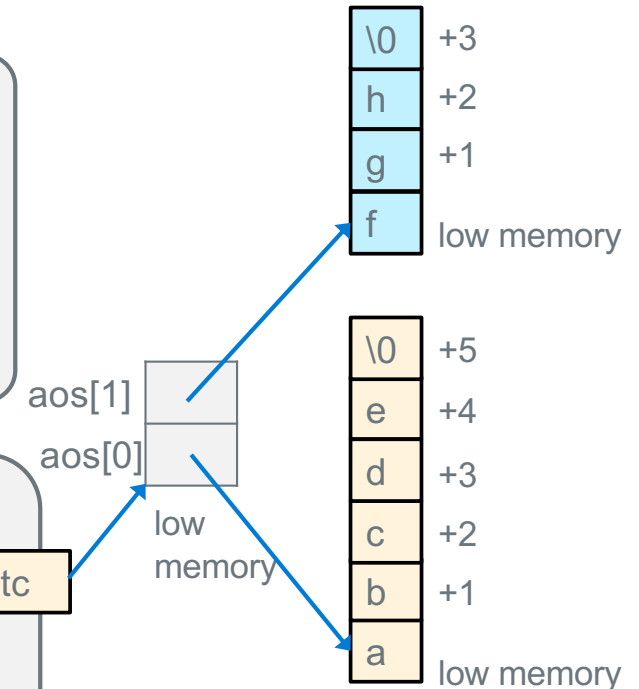
Extra Slides

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