

Version 1.01

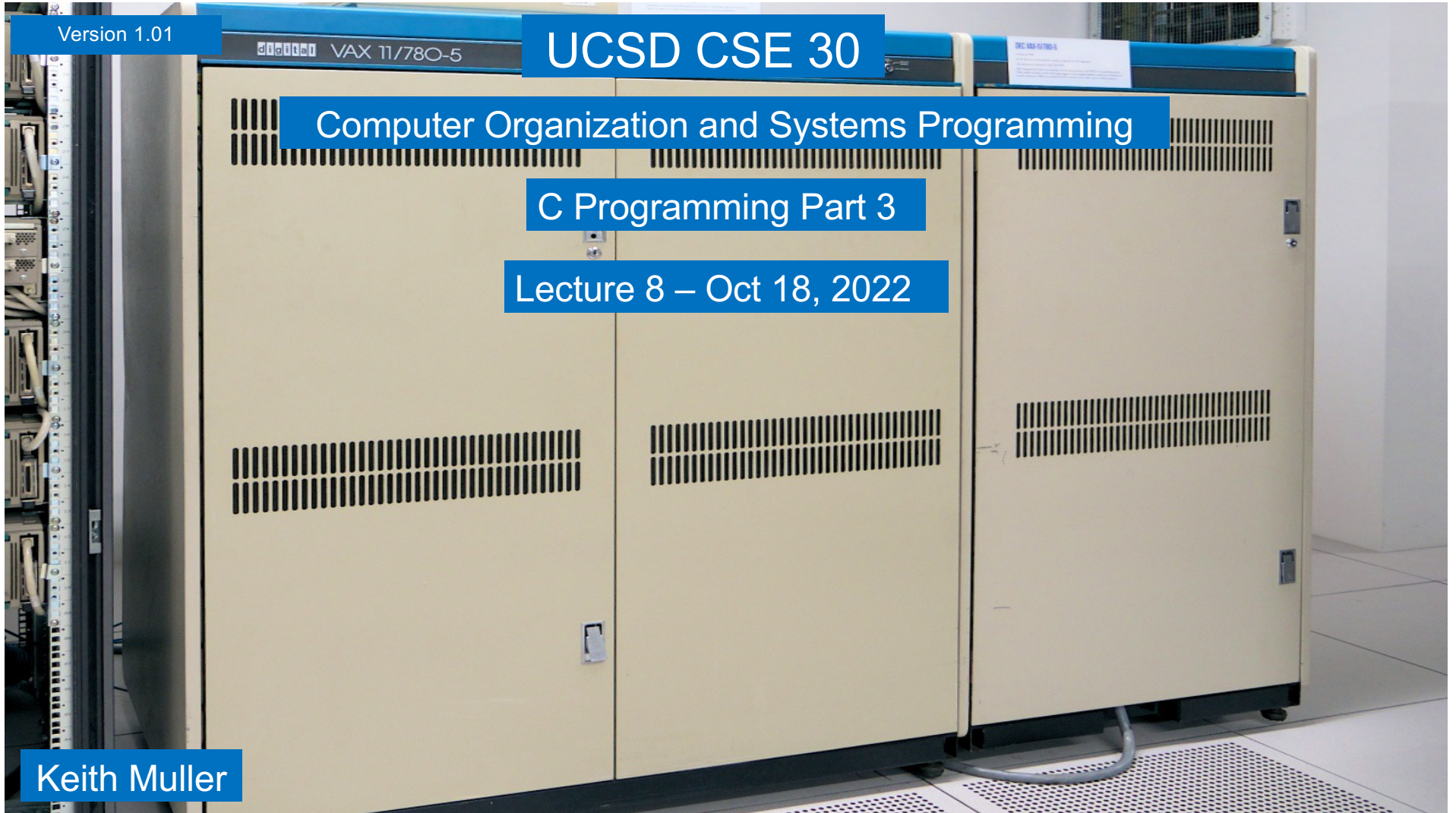
UCSD CSE 30

Computer Organization and Systems Programming

C Programming Part 3

Lecture 8 – Oct 18, 2022

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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

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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 ;
    
```

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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 = x;
int j = 0;

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));

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

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

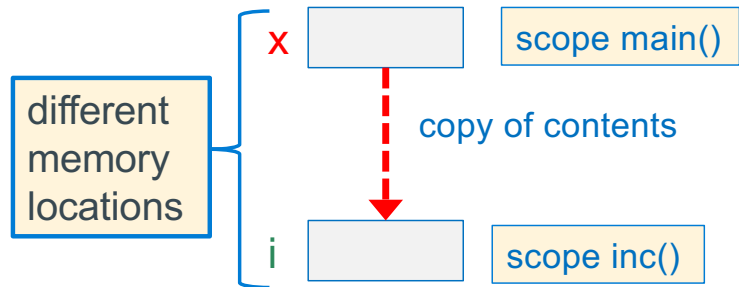
More common way to use pointers

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;
}

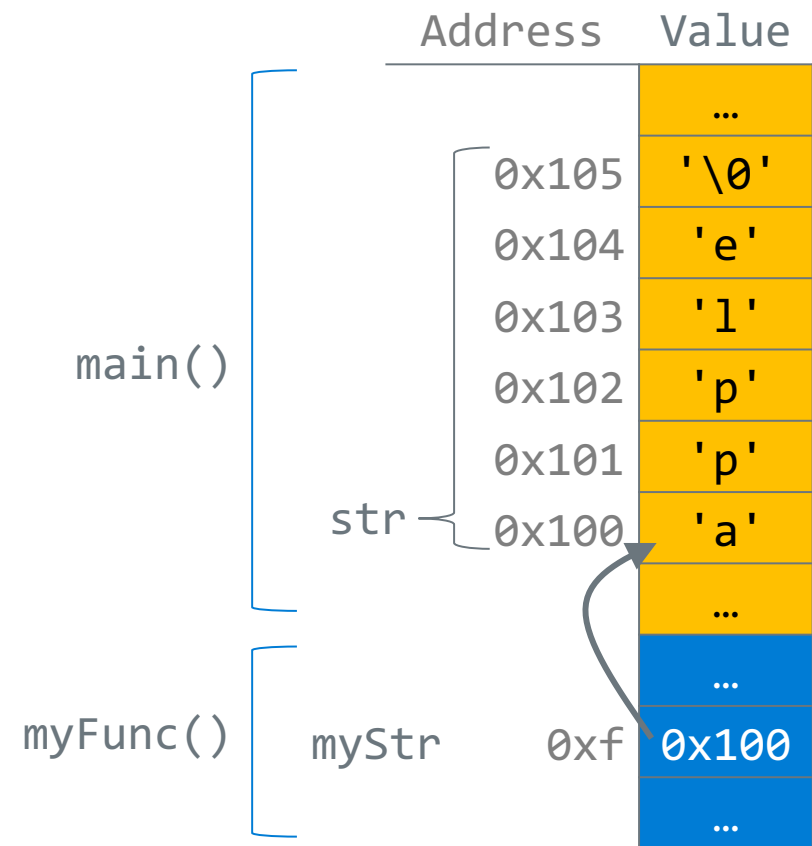
void
inc(int *p, char *cp, char **pcp)
{
    *p += 1; // or (*p)++
    printf("%s\n",cp);
    *pcp = cp + 1;
}
```

prints:
string
6 tring

Passing Arrays (Strings)

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

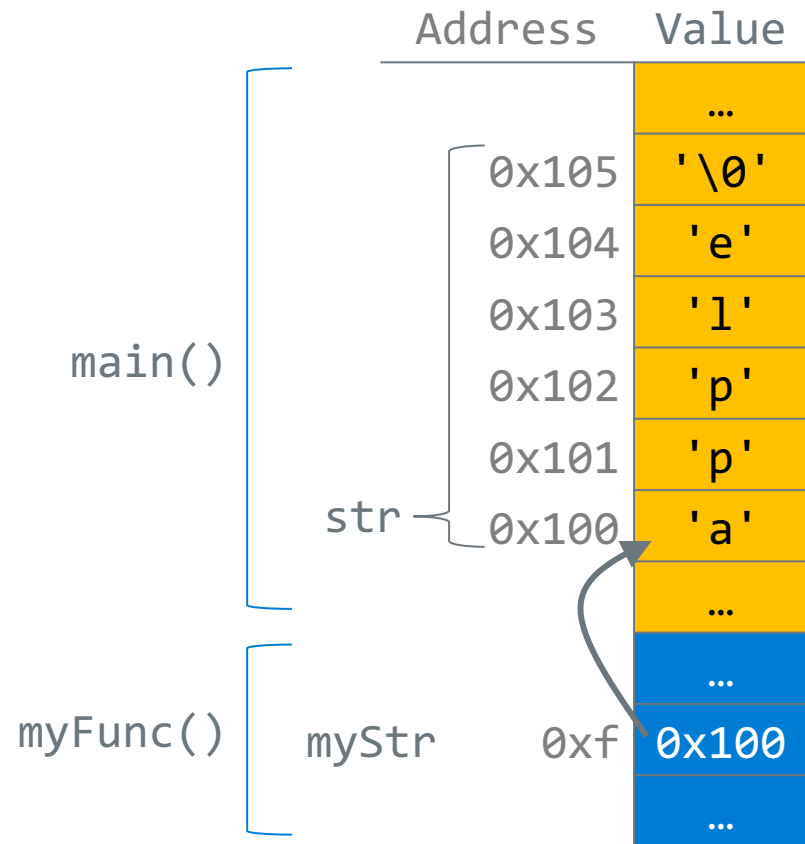
int
main(void) {
    char str[6];
    strcpy(str, "apple");
    myFunc(str);
    ...
}
```



Passing Arrays (Strings)

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

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

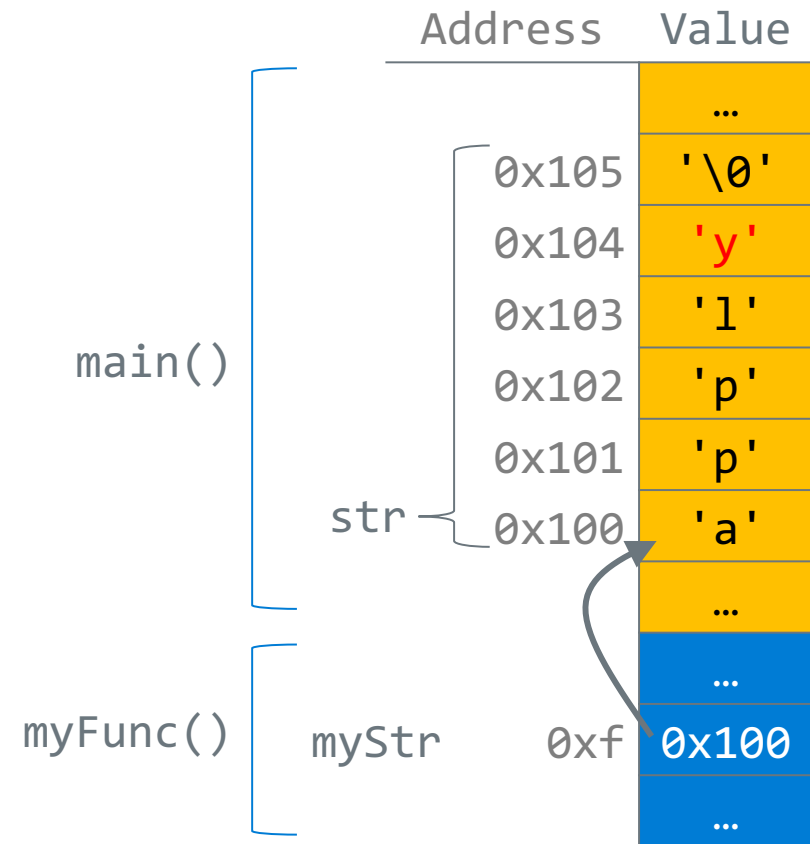


if we modify characters in **myFunc**, the changes will persist back in **main**!

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

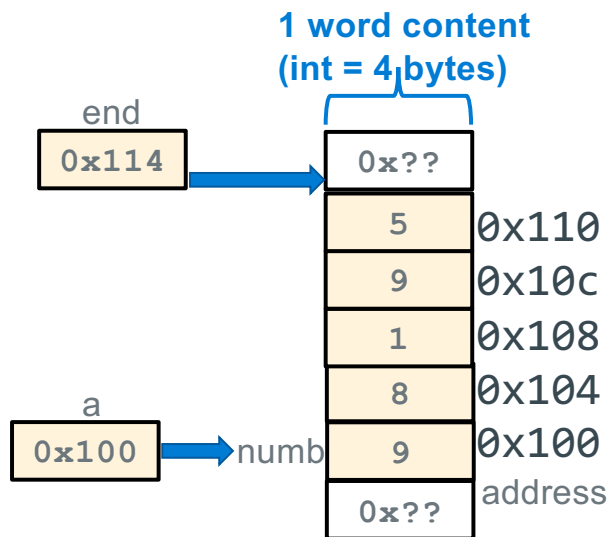
Arrays do not know their own size

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

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



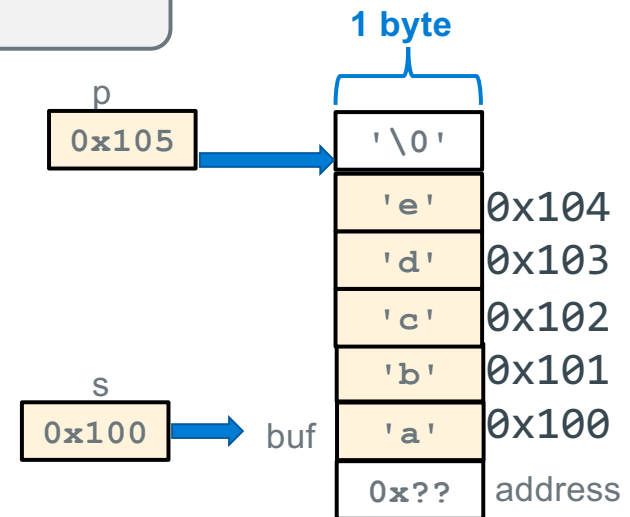
Arrays As Parameters, Approach 2: Use a sentinel element

- 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", my_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);
}
```



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}  
};
```

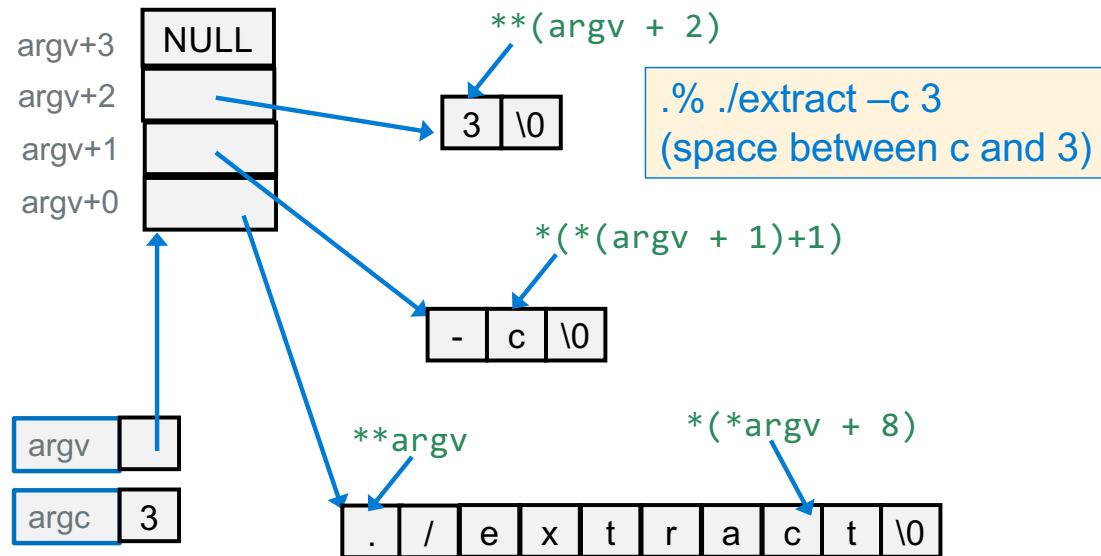
[1][0]	[1][1]	[1][2]	[1][3]	[1][4]
[0][0]	[0][1]	[0][2]	[0][3]	[0][4]

```
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

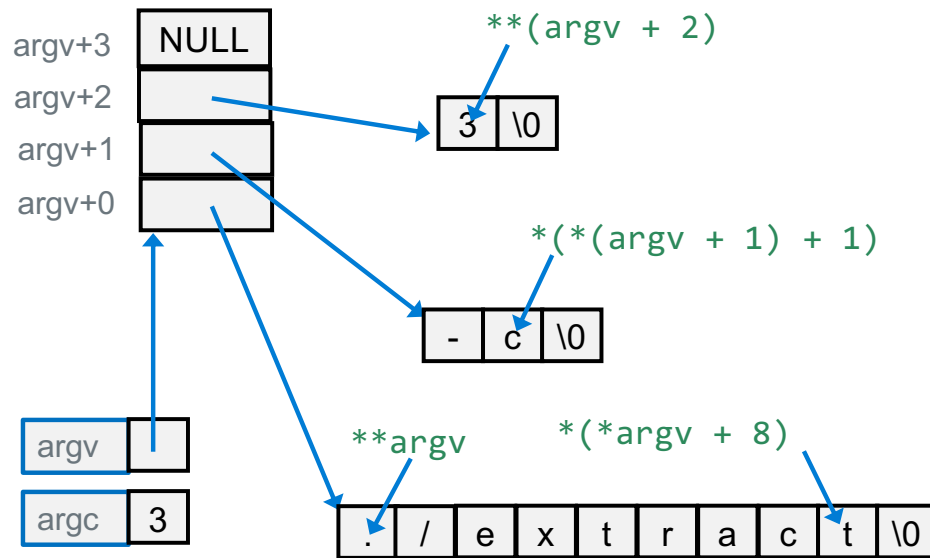
Array of Pointers: main() : argc, argv



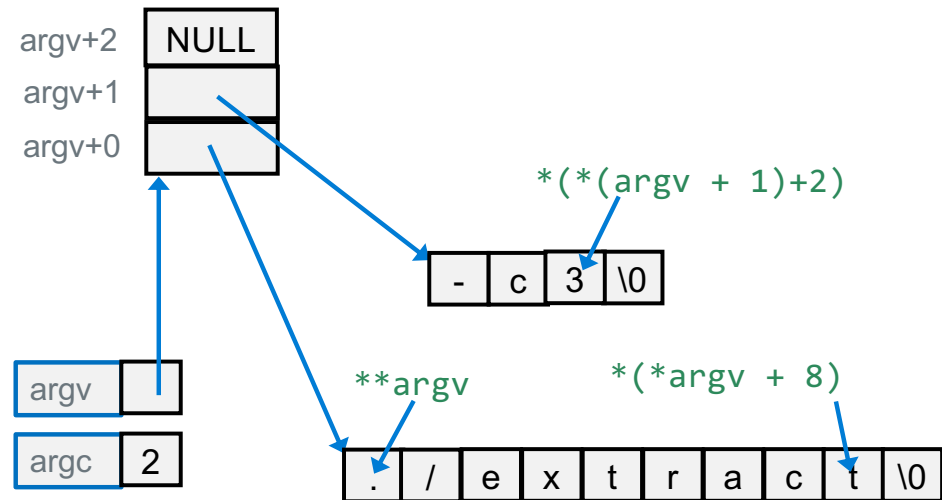
```
int main(int argc, char *argv[])
{
    for (int i = 0; argv[i] != NULL; i++) {
        for (int j = 0; argv[i][j] != '\0'; j++)
            putchar(argv[i][j]);
        putchar('\n');
    }
    return EXIT_SUCCESS;
}
```

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


main() Command line arguments: argc, argv



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



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

PA4: Creating a 2D Array of Mutable String Pointers

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

char *buf

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

char **ptable

ptable	ptable+1	ptable+2

./extract -c3

```
// extract of a function body
// passed buf, ptable and cnt
```

```
char **endptr = ptable + cnt;
```

```
*ptable = buf; // base case
while ((ptable < endptr) && (*buf != '\0')) {
    *ptable++ = buf;
    while (*buf != '\0') {
        /* process the chars */
    }
}
```

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

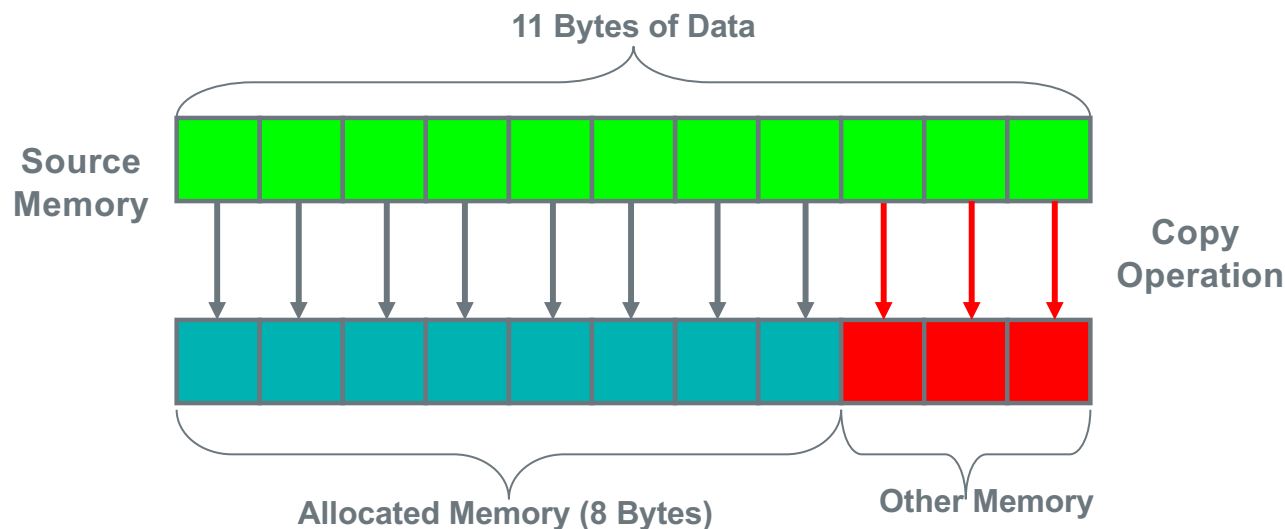
```
int *bad_idea2(int n)
{
    int a = n * n;
    return &a; // NEVER do this
}
```

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

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


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("s1: %s\ns2: %s\nr2:%s\n", s1, s2, r2);

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

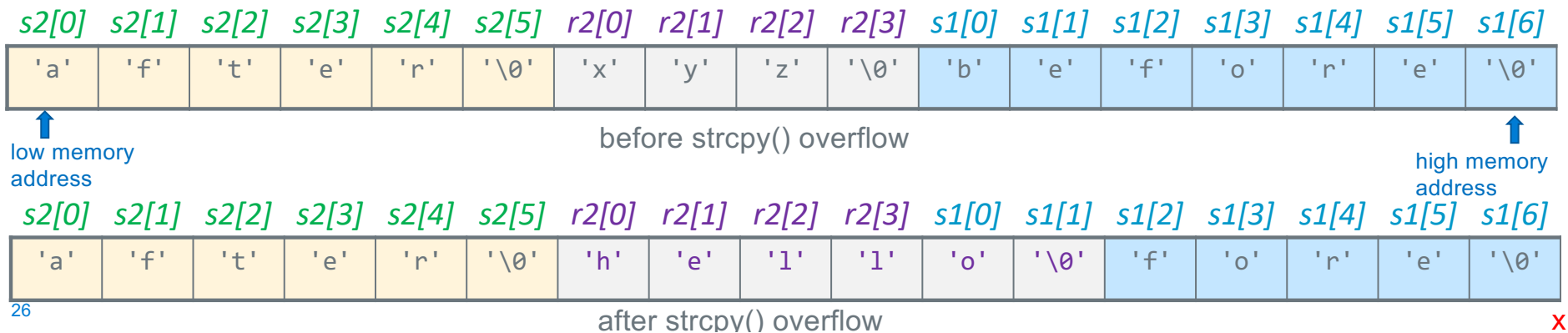
    printf("\ns1: %s\ns2: %s\nr2:%s\n", s1, s2, r2);
    return EXIT_SUCCESS;
}
```

these are mutable
arrays, not literals

compile on pi-cluster with
gcc test.c

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

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



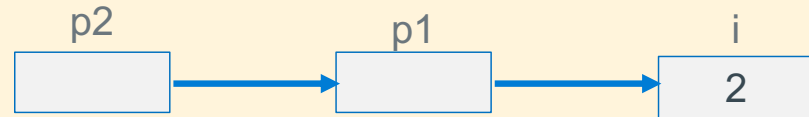
Pointer to Pointers (Double, Triple and ... Indirection)

- 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)

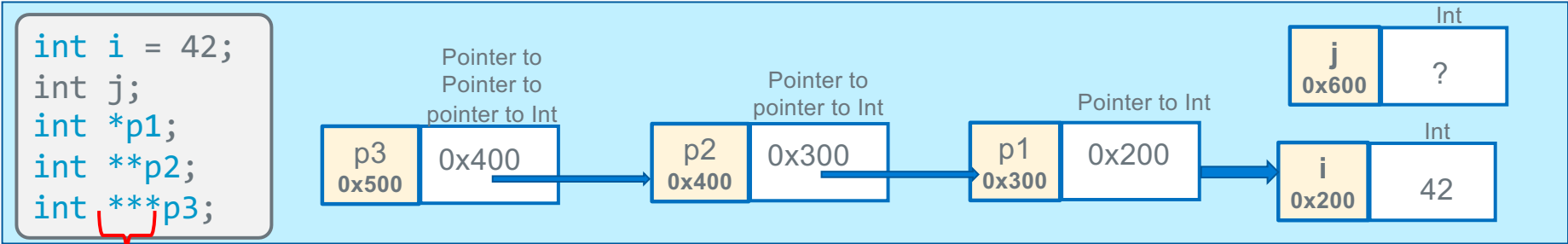
```
int i = 2;  
int *p1;  
int **p2;  
p1 = &i;  
p2 = &p1;  
printf("%d\n", **p2 * **p2);
```



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

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

Key:

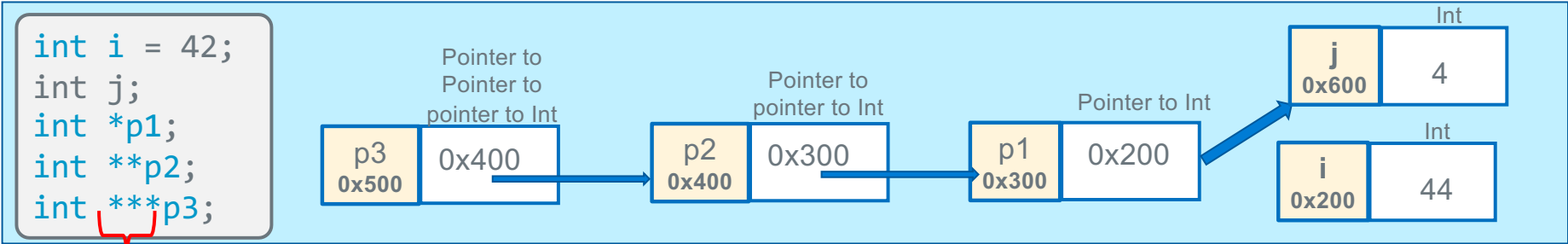
memory address or name	Memory contents
------------------------------	--------------------

```
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);
```

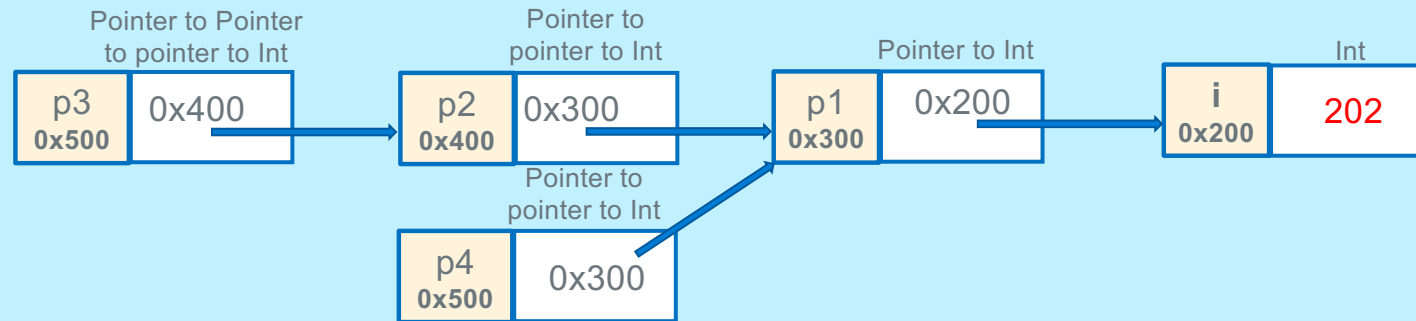
Key:

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 = &i;
int **p2 = &p1;
int ***p3 = &p2;
p3 = &p2;
int **p4;
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:

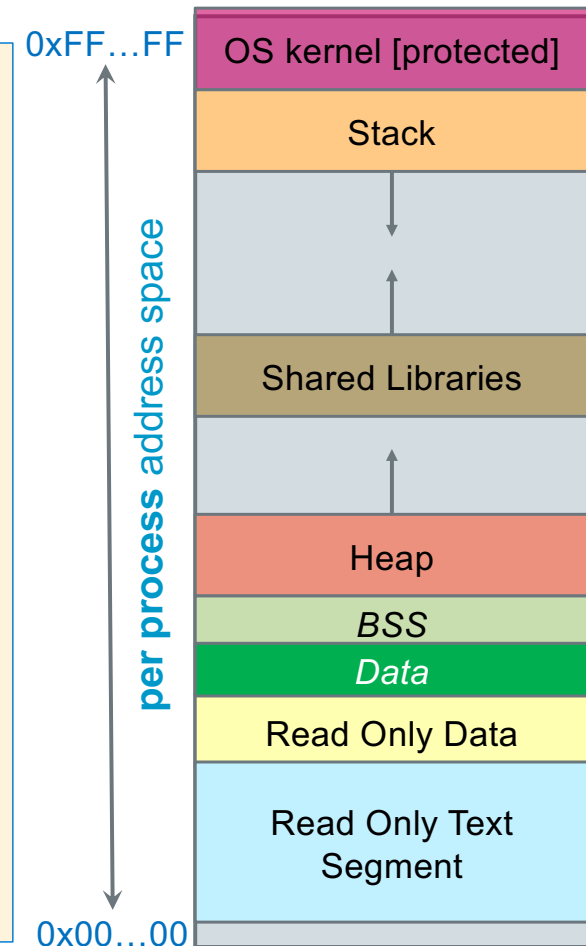
memory address or name	Memory contents
------------------------------	--------------------

(slide is best viewed in pptx presentation mode)

x

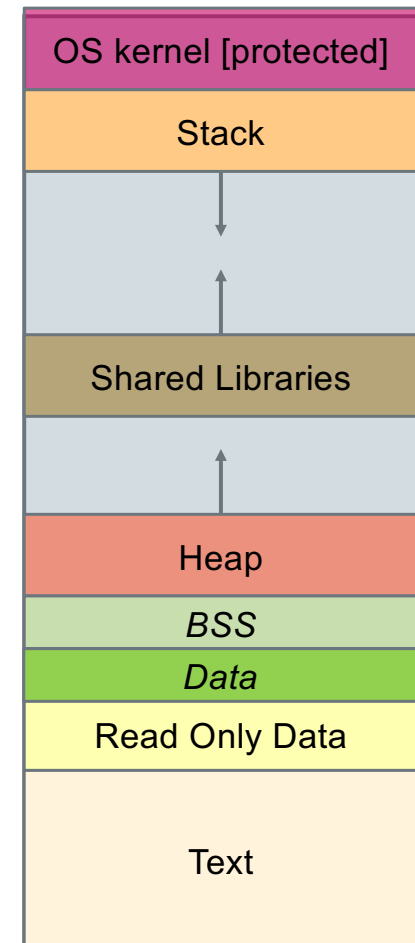
Process Memory Under Linux

- 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 nmem, size_t memsize</code>	yes
<code>void *realloc(...)</code>	<code>void *ptr, size_size</code>	no
<code>void free(...)</code>	<code>void *ptr</code>	no

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

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

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

Use of Malloc

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

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

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

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!)

Dangling Pointers

- When a pointer points to a memory location that is no longer “valid”
- Really hard to debug as the use of the return pointers may not generate a seg fault

```
char *dangling_freed_heap(void)
{
    char *buff = malloc(BLKSZ * sizeof(*buff));
    ...
    free(buff);
    return buff;
}
```

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

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));  
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: either a letter or a letter followed by
 - Colon (:), the flag requires an argument and then (char ***optarg**) points at the argument

```
% ./extract -c 3 1 2 3
```

when processing -c **optarg** (char *) points at the 3

- Call **getopt()** in a loop; it returns the next option flag (a char in an **int** like **getchar()**):
 - Next command line flag
 - -1 if there are none left
 - '?' indicates flag is not one specified (error) or the flag is specified but has a missing argument
 - **optopt** contains the flag that was detected, but is the cause for the error
- When **getopt** finishes, **optind** contains the index to the next non-flag argument to process

```
% ./extract -c 3 1 2
```

```
optind = 3; // int  
outcols = argc - optind (# of args after the 3)
```

getopt() sample

- For this example, the options are
 1. a single flag **x**
 2. a flag **f** with a required argument to the flag
- Additional arguments are not options flags, but filenames to process

% ./a.out -f file.txt a b c

optind = 3; // int

```
while ((opt = getopt(argc, argv, "xf:")) != -1) {
    switch (opt) {
        case 'x':
            xFlag = 1;
            printf("-x flag found\n");
            break;
        case 'f':
            datafile = optarg; // string (char *)
            printf("-f %s found\n", optarg);
            break;
        case '?':
            if (optopt == 'f')
                fprintf(stderr, "%s -f datafile is missing\n", argv[0]);
            /* fall through */
        default:
            error = 1; /* error = 0 above getopt(); have an error */
            break;
    }
}
if (error != 0) {
    fprintf(stderr, "Usage: %s [-x] -f datafile\n", argv[0]);
    return EXIT_FAILURE;
}
for (int i = optind; i < argc; i++)
    printf("argv[%d] is: %s\n", i, argv[i]); // additional args
```

Struct Variable Definitions

- Variable definitions like any other data type:

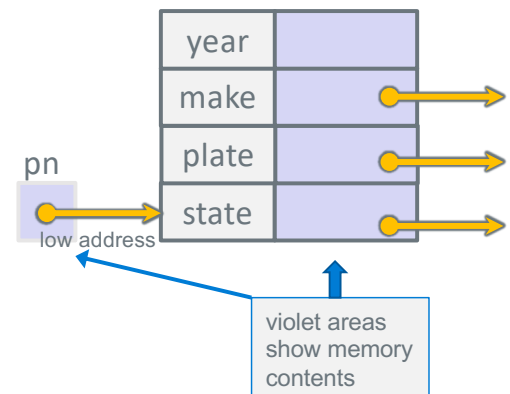
```
struct vehicle name1, *pn, ar[3];
```

↑ type: "struct vehicle"
↑ single variable instance
↑ pointer
↑ array

- Can combine struct and variable definition:
 - This syntax can be harder to read, though

```
struct vehicle {  
    char *state;  
    char *plate;  
    char *make;  
    int year;  
} name1, *pn = &name1, ar[3];
```

```
struct vehicle {  
    char *state;  
    char *plate;  
    char *make;  
    int year;  
};  
struct vehicle name1;  
struct vehicle *pn;  
struct vehicle ar[3];  
pn = &name1;
```



Accessing members of a struct

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

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

```
struct date bday; // struct instance
```

```
bday.month = 1;
```

```
bday.day = 24;
```

day	24
month	1

```
// shorter initializer syntax
```

```
struct date new_years_eve = {12, 31};
```

```
struct date final = {.day= 24, .month= 1};
```

- Now create a *pointer* to a struct

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

- Two options to reference a member via a struct pointer (`.` is higher precedence than `*`):

- Use `*` and `.` operators:

```
(*ptr).month = 11;
```

- Use `->` operator for shorthand:

```
ptr->month = 11;
```

More to come....

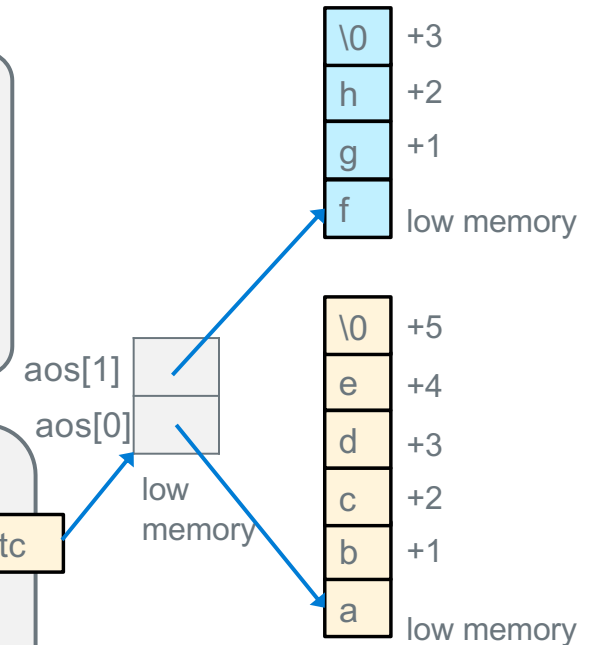
Extra Slides

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
```