Refreshing C

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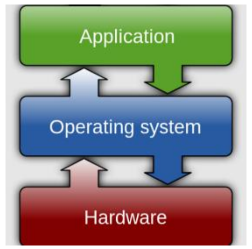
https://teaching.hkaiser.org/fall2025/csc7103

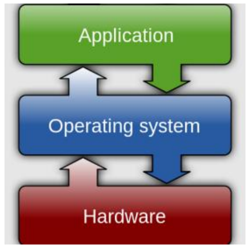
C History

- Developed in the 1970s – in conjunction with development of UNIX operating system
  - When writing an OS kernel, efficiency is crucial
  - This requires low-level access to the underlying hardware:
    - e.g. programmer can leverage knowledge of how data is laid out in memory, to enable faster data access
  - UNIX originally written in low-level assembly language – but there were problems:
    - No structured programming (e.g. encapsulating routines as “functions”, “methods”, etc.) – code hard to maintain
    - Code worked only for particular hardware – not portable



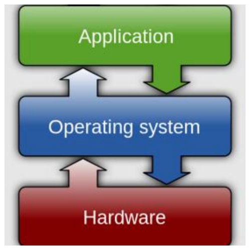
C Characteristics

- C takes a middle path between low-level assembly language…
  - Direct access to memory layout through pointer manipulation
  - Concise syntax, small set of keywords
- … and a high-level programming language like Java:
  - Block structure
  - Some encapsulation of code, via functions
  - Type checking (pretty weak)



C Dangers

- C is not object oriented!
  - Can't "hide" data as "private" or "protected" fields
  - You can follow standards to write C code that looks object-oriented, but you have to be disciplined – will the other people working on your code also be disciplined?
- C has portability issues
  - Low-level "tricks" may make your C code run well on one platform – but the tricks might not work elsewhere
- The compiler and runtime system will rarely stop your C program from doing stupid/bad things
  - Compile-time type checking is weak
  - No run-time checks for array bounds errors, etc. like in Java

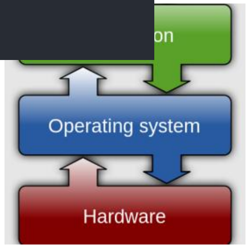


Compiling your C program

- `gcc intro.c -o intro`
  - and run the program using
  - `./intro arg1!`
- If we just run `./intro`
  - We may get a segfault!

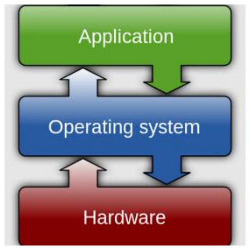
```c
#include <stdio.h>

int main(int argc, char *argv[]) {
    // printf prints out a formatted string
    printf("%s\n", "Hello world!")

    // Print out the first command line argument
    printf("%s\n", argv[1])

    // A return value of 0 means there were no errors
    return 0;
}
```

```
Output:
Hello world!
arg1! // Assuming we ran ./intro arg1!
```



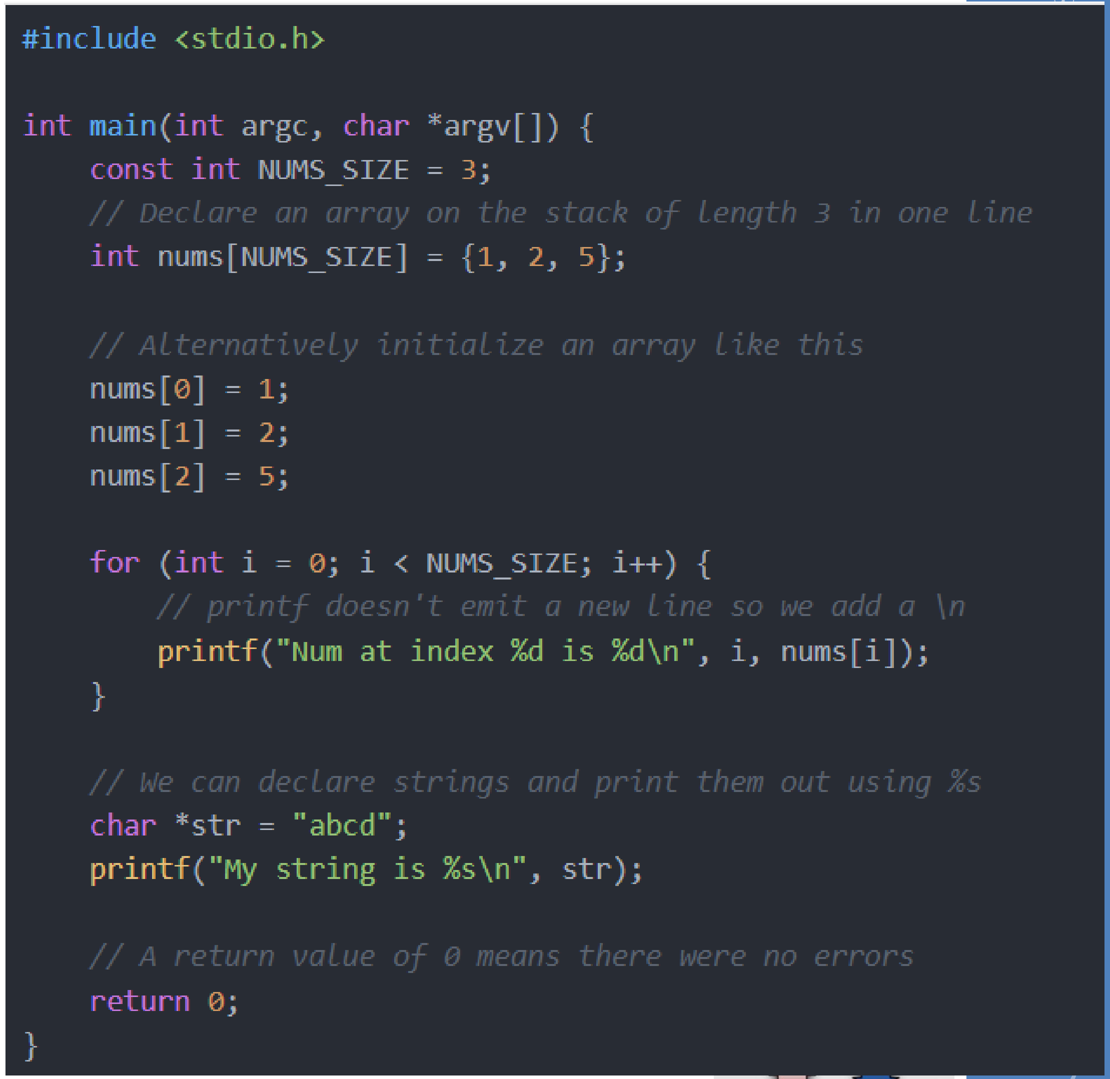
Compiling your C program

- All C programs begin with a `main` function
  - The first argument `argc` denotes the number of elements in `argv`
  - The second argument `argv` is a list of string arguments passed from the command line to the program
  - The return value of a function indicates the exit code where 0 means successful
- At the top of the file we have an `#include` statement to include `stdio.h`, a library that makes available functions such as `printf`.
- We can use `printf` to print formatted strings. In this case `%s` treats the input as a string.
  - `printf` is your friend for debugging!
  - `printf` doesn't emit a newline, so you'll have to add a `\n` if you want a newline



C Syntax

- At the top of the file we have an `include` statement to include `stdio.h`, a library that contains functions such as `printf`.
- Next is an array declaration using the `int {name}[{size}]` syntax.
- This array is declared on the stack. The distinction between declaration on the stack and heap is important to keep in mind!
- We can initialize the values by using the `{elem1, elem2, ...}` initializer syntax.



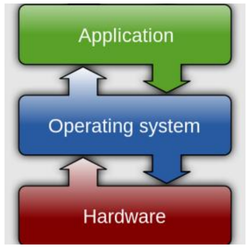
```c
#include <stdio.h>

int main(int argc, char *argv[]) {
    const int NUMS_SIZE = 3;
    // Declare an array on the stack of length 3 in one line
    int nums[NUMS_SIZE] = {1, 2, 5};

    // Alternatively initialize an array like this
    nums[0] = 1;
    nums[1] = 2;
    nums[2] = 5;

    for (int i = 0; i < NUMS_SIZE; i++) {
        // printf doesn't emit a new line so we add a \n
        printf("Num at index %d is %d\n", i, nums[i]);
    }

    // We can declare strings and print them out using %s
    char *str = "abcd";
    printf("My string is %s\n", str);

    // A return value of 0 means there were no errors
    return 0;
}
```

The printf() function

- `printf("Original input: %s\n", input);`
- `printf()` is a library function declared in `<stdio.h>`
- Syntax: `printf(FormatString, Expr...)`
  - `FormatString`: String of text to print
  - `Expr...`: Values to print
  - `FormatString` has placeholders to show where to put the values (note: #placeholders should match #Exprs)
  - Placeholders: %s (print as string), %c (print as char), %d (print as integer), %f (print as floating-point)

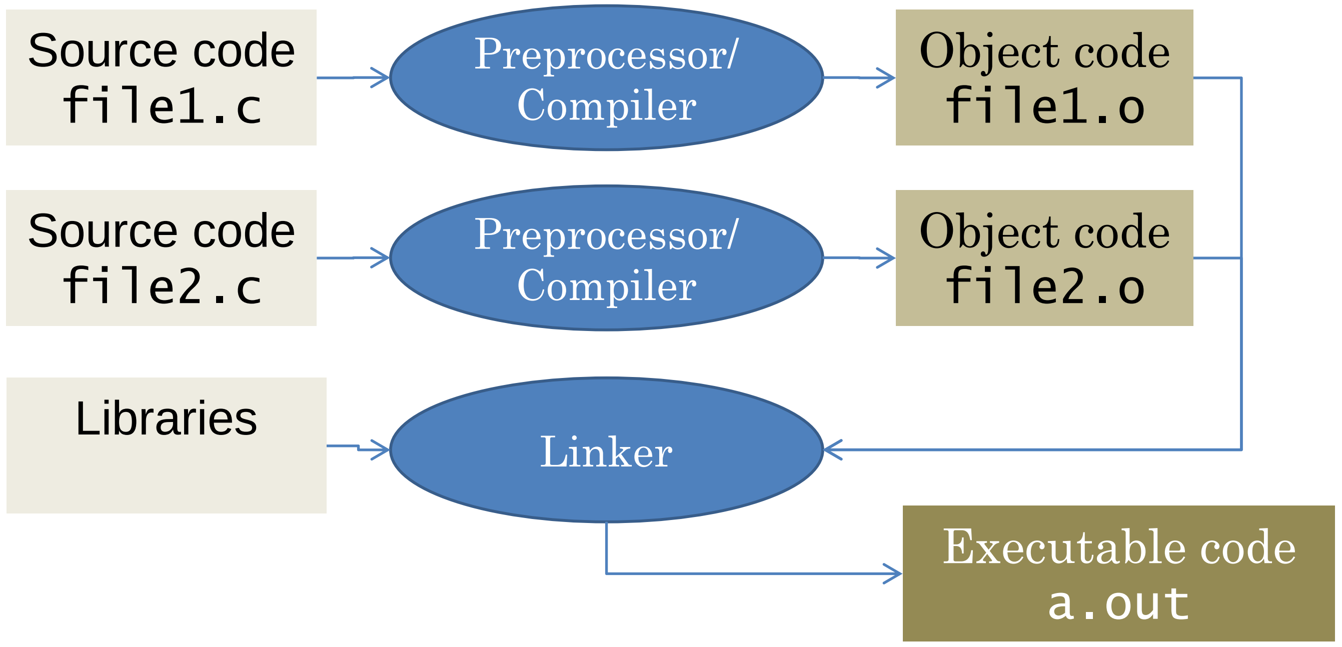
Make sure you pick the right one!

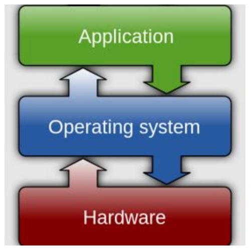
  - \n indicates a newline character



Separate compilation

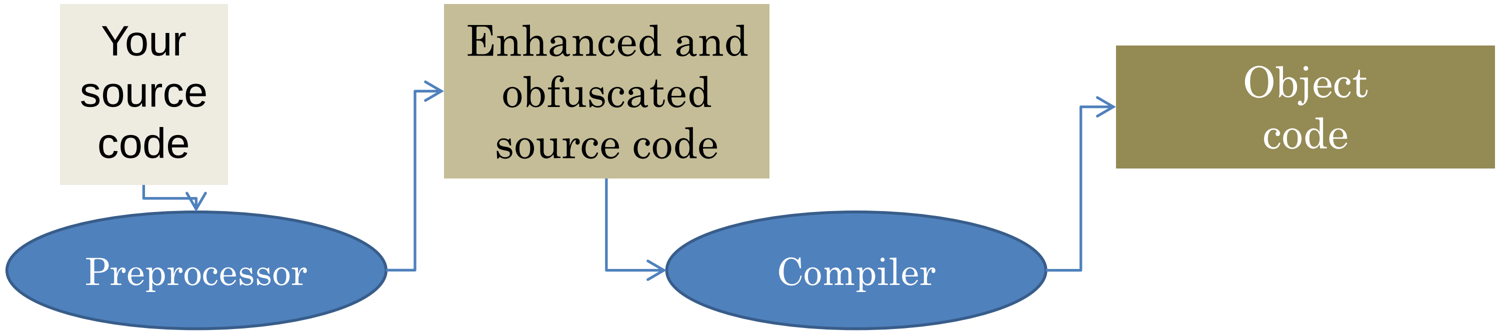
- A C program consists of source code in one or more files
- Each source file is run through the preprocessor and compiler, resulting in a file containing object code
- Object files are tied together by the linker to form a single executable program

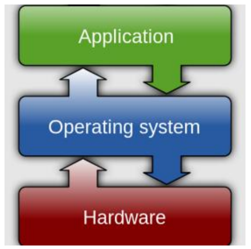




The Preprocessor

- The preprocessor takes your source code and – following certain directives that you give it – tweaks it in various ways before compilation.
- A directive is given as a line of source code starting with the # symbol
- The preprocessor works in a very crude, "word-processor" way, simply cutting and pasting –
  - it doesn't really know anything about C!



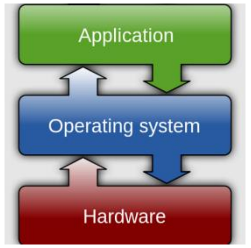


Preprocessor Directives

```
#define MAX_COLS    20
#define MAX_INPUT   1000
```

- The #define directives perform
  - “global replacements”:
  - every instance of `MAX_COLS` is replaced with `20`, and every instance of `MAX_INPUT` is replaced with `1000`.
- Other directives:

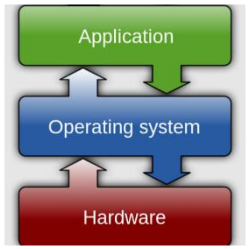
```
#include <> / #include ""
#ifdef / #else / #endif
```



Preprocessor directives

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
```

- The `#include` directives “paste” the contents of the files `stdio.h`, `stdlib.h` and `string.h` into your source code, at the very place where the directives appear.
- These files contain information about some library functions used in the program:
  - stdio stands for “standard I/O”, stdlib stands for “standard library”, and string.h includes useful string manipulation functions.
- Want to see the files? Look in `/usr/include` (or similar)



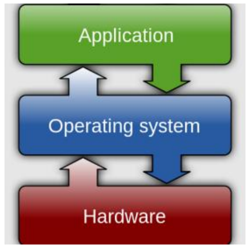
Pointers, Arrays, Strings

- The notions of string, array, and pointer are somewhat interchangeable:
  - An array of characters could be declared, for purposes of holding the input string:

```
char input[MAX_INPUT];
```

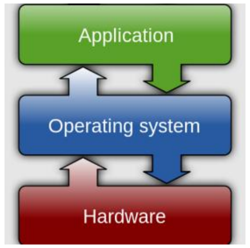
  - Yet when it's passed in as an argument to a function, `input` has morphed into a pointer to a character (`char *`):

```
void some_function(char const *input, ...)
```

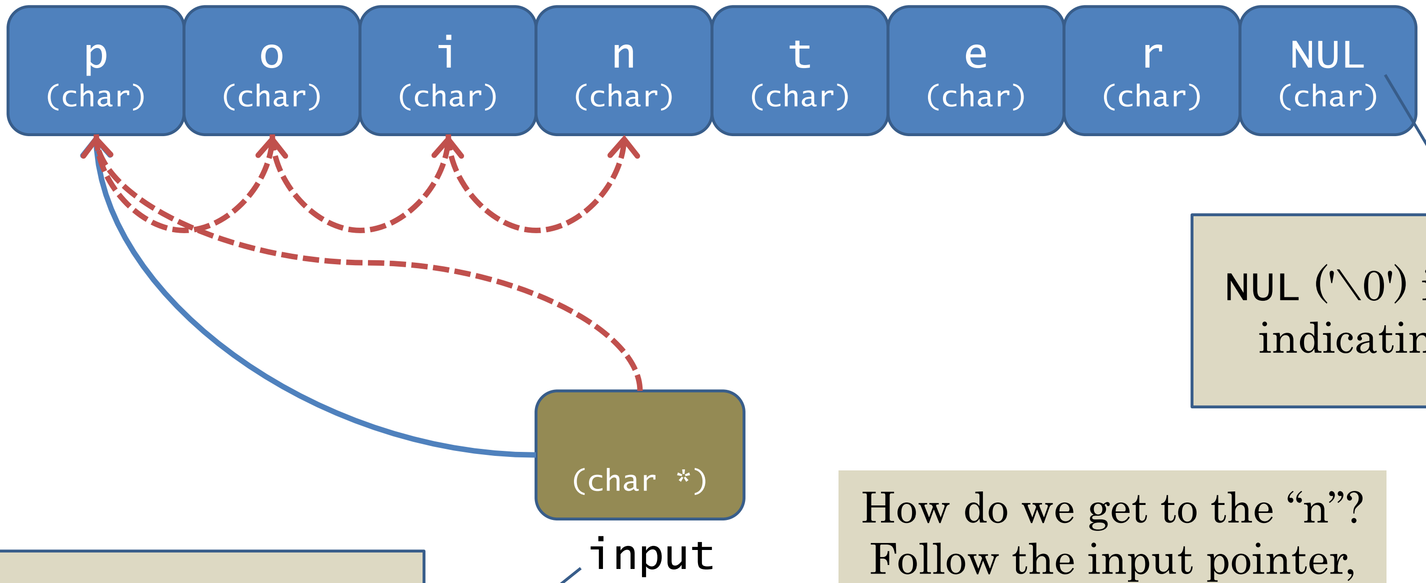


Pointers, Arrays, Strings

- In C, the three concepts are indeed closely related:
  - A pointer is simply a memory address. The type `char*` (i.e. “pointer to character”) signifies that the data at the address the pointer is holding is to be interpreted as a character.
  - An array is simply a pointer – of a special kind:
    - The array ‘name’ refers to the first of a sequence of data items stored sequentially in memory
    - How do you get to the other array elements? By incrementing the pointer value
  - A string is simply an array of characters – unlike Java, which has a predefined String class.



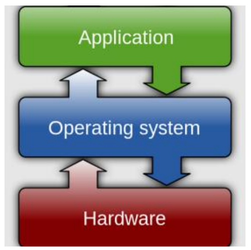
String Layout and Access



NUL ('\0') is a special value indicating end-of-string

What is `input`?
It's a string!
It's a pointer to `char`!
It's an array of `char`!

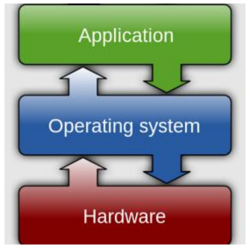
How do we get to the "n"?
Follow the input pointer, then hop 3 to the right
`*(input + 3)`
- or -
`input[3]`



Data Types in C

Four basic data types

- Integers: `char`, `short int`, `int`, `long int`, `enum`
- Floating-point types: `float`, `double`, `long double`
- Pointers
- Aggregates: `struct`, `union`
- Integer and floating-point types stand for themselves, but pointers and aggregate types combine with other types, to form a virtually limitless variety of types



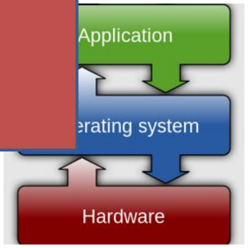
Characters are of integer Type

- From a C perspective, a character is indistinguishable from its numeric ASCII value –
  - the only difference is in how it's displayed

- Ex: converting a character digit to its numeric value
  - The value of `'2'` is not `2` – it's `50` (hexadecimal `0x32`)
  - To convert, subtract the ASCII value of `'0'` (which is `48`, or `0x30`)

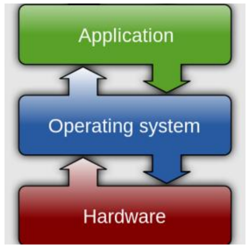
```
char digit, digit_num_value;
...
digit_num_value = digit - '0';
```

Behaviorally, this is identical to `digit - 48`
Why is `digit - '0'` preferable?



Integer Values play the Role of "Booleans"

- There is no "Boolean" type
  - Relational operators (`==`, `<`, etc.) return either `0` or `1`
  - Boolean operators (`&&`, `||`, etc.) return either `0` or `1`,
    - and take any `int` values as operands
- How to interpret an arbitrary `int` as a Boolean value:
  - `0` → `false`
  - Any other value → `true`



The infamous = Blunder

- Easy to confuse equality with assignment
  - In C, the test expression of an if statement can be any `int` expression — including an assignment expression

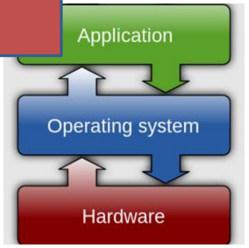
```
if (y = 0)
    printf("Sorry, can't divide by zero.\n");
else
    result = x / y;
```

Assignment performed; `y` set to `0` (oops)

Expression returns result of assignment: `0`, or "false"

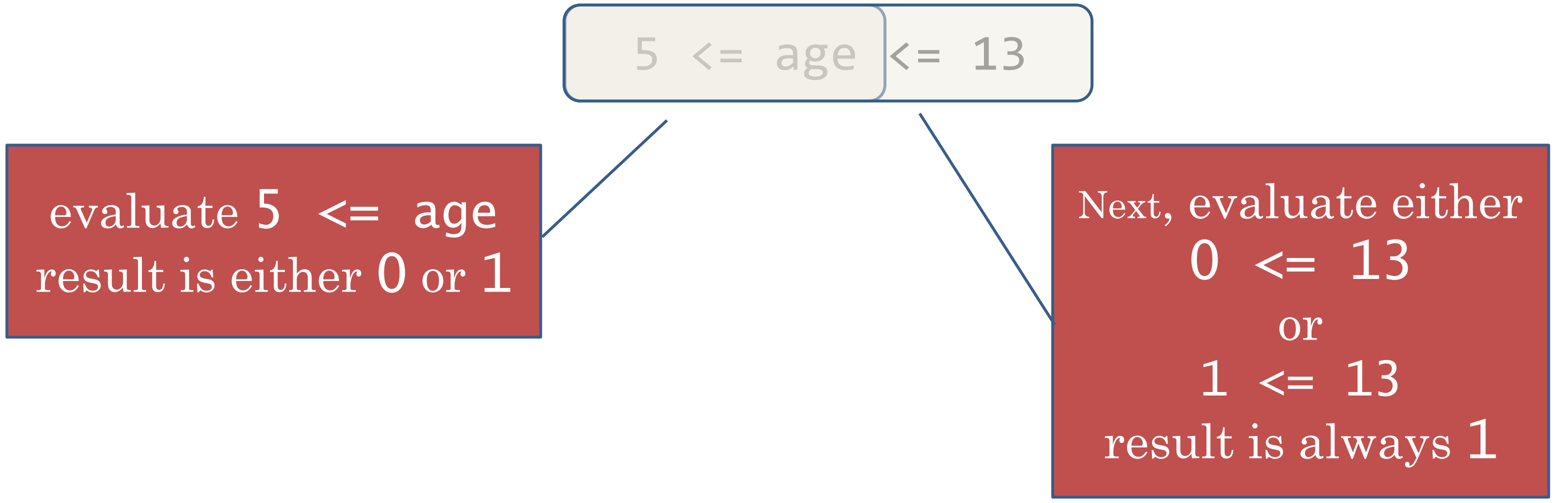
`else` clause executed: divide by `0`!

- The compiler will not catch this bug!
  - Some compilers will issue a warning



The less infamous “relational chain” Blunder

- Using relational operators in a “chain” doesn't work
- Ex: “age is between 5 and 13”

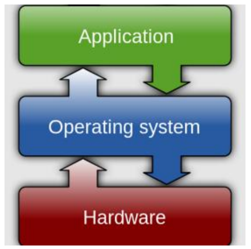


`5 <= age <= 13`

evaluate `5 <= age`
result is either `0` or `1`

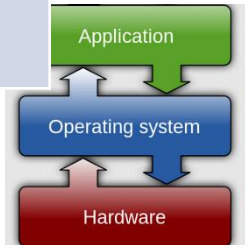
Next, evaluate either
`0 <= 13`
or
`1 <= 13`
result is always `1`

- A correct solution: `5 <= age && age <= 13`



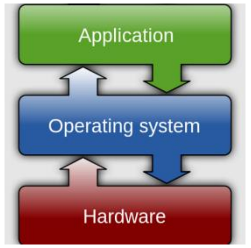
Ranges of Integer Types

Type	Min value	Max value
`char`	0	UCHAR_MAX (≥ 127)
`signed char`	SCHAR_MIN (≤ -127)	SCHAR_MAX (≥ 127)
`unsigned char`	0	UCHAR_MAX (≥ 255)
`short int`	SHRT_MIN (≤ -32767)	SHRT_MAX (≥ 32767)
`unsigned short int`	0	USHRT_MAX (≥ 65535)
`int`	INT_MIN (≤ -32767)	INT_MAX (≥ 32767)
`unsigned int`	0	INT_MAX (≥ 65535)
`long int`	LONG_MIN (≤ -2147483647)	LONG_MAX (≥ 2147483647)
`unsigned long int`	0	ULONG_MAX (≥ 4294967295)



Ranges of Integer Types

- Ranges for a given platform can be found at `/usr/include/limits.h`
- `char` can be used for very small integer values
- Plain `char` may be implemented as `signed` or `unsigned` on a given platform – safest to “assume nothing” and just use the range 0…127
- `short int` “supposed” to be smaller than `int` —
  - but it depends on the underlying platform

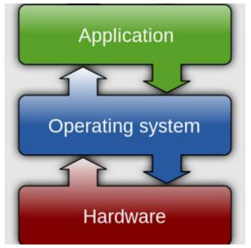


Ranges of Floating-Point Types

Type	Min value	Max value
`float`	`FLT_MIN` (≤ -10^{37})	`FLT_MAX` (≤ -10^{37})
`double`	`DBL_MIN` (≤ `-FLT_MIN`)	`DBL_MAX`(≥ `FLT_MAX`)
`long double`	`LDBL_MIN` (≤ `-DBL_MIN`)	`LDBL_MAX` (≥ `DBL_MAX`)

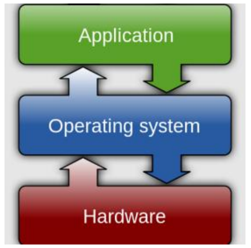
Floating-point literals must contain a decimal point, an exponent, or both.

```
3.14159                 25.             6.023e23
```



Danger: Precision of Floating-Point Values

- Testing for equality between two floating-point values: almost always a bad idea
  - One idea: instead of simply using ==, call an “equality routine” to check whether the two values are within some margin of error.

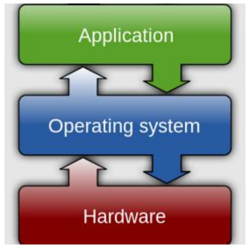


Casting: Converting one Type to Another

- The compiler will do a certain amount of type conversion for you (silently):

```
int a = 'A';    /* char literal converted to int */
```

- In some circumstances, you need to explicitly cast an expression as a different type – by putting the desired type name in parentheses before the expression
  - e.g. `(int)3.14159` will return the `int` value `3`



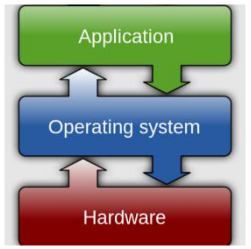
Pointers

Review of Pointers

- A pointer is just a memory location (an address).
- A memory location is simply an integer value, that we interpret as an address in memory.
- The contents at a particular memory location is just a collection of bits - there's nothing special about them that makes them `int`s, `char`s, etc.
  - How you want to interpret the bits is up to you (that's what types are for).

  - Is this… an `int` value?
  - … a pointer to a memory address?
  - … a series of char values?

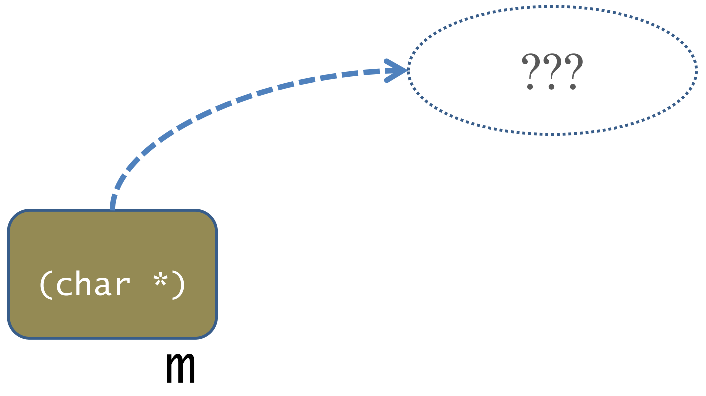
`0xfe4a10c5`

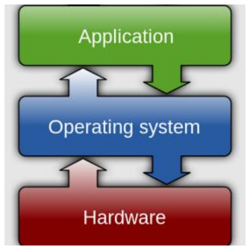


Review of pointer variables

- A pointer variable is just a variable, that contains a value that we interpret as a memory address.
- Just like an uninitialized `int` variable holds some arbitrary "garbage" value,
  - an uninitialized pointer variable points to some arbitrary "garbage address"

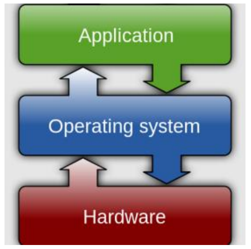
```
char* m;
```





Following a “garbage” pointer

- What will happen? Depends on what the arbitrary memory address is:
  - If it’s an address to memory that the OS has not allocated to our program, we get a segmentation fault
  - If it’s a nonexistent address, we get a bus error
  - Some systems require multibyte data items, like `int`s, to be aligned: for instance, an `int` may have to start at an even-numbered address, or an address that’s a multiple of 4. If our access violates a restriction like this, we get a bus error
  - If we’re really unlucky, we’ll access memory that is allocated for our program –
    - We can then proceed to destroy our own data!

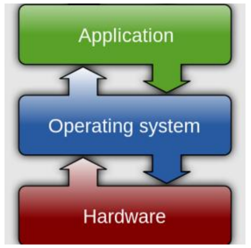


How can you Test whether a Pointer points to Something Meaningful?

- There is a special pointer value `NULL`, that signifies "pointing to nothing". You can also use the value `0`.

```
char* m = NULL;
...
if (m) { ... safe to follow the pointer ... }
```

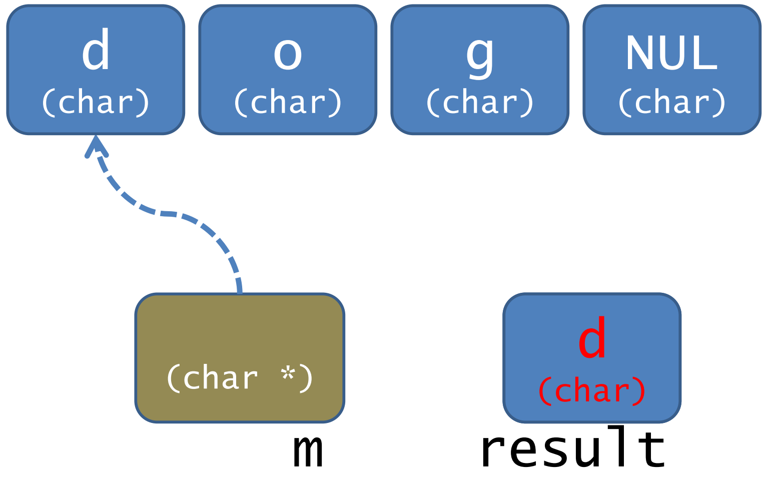
- Here, `m` is used as a boolean value
  - If `m` is "false", aka `0`, aka `NULL`, it is not pointing to anything
  - Otherwise, it is (presumably) pointing to something good
  - Note: It is up to the programmer to assign `NULL` values when necessary



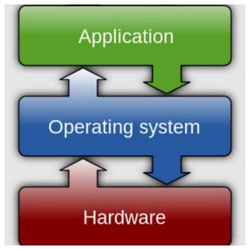
Indirection operator *

- Moves from address to contents

```
char* m = "dog";

char result = *m;
```



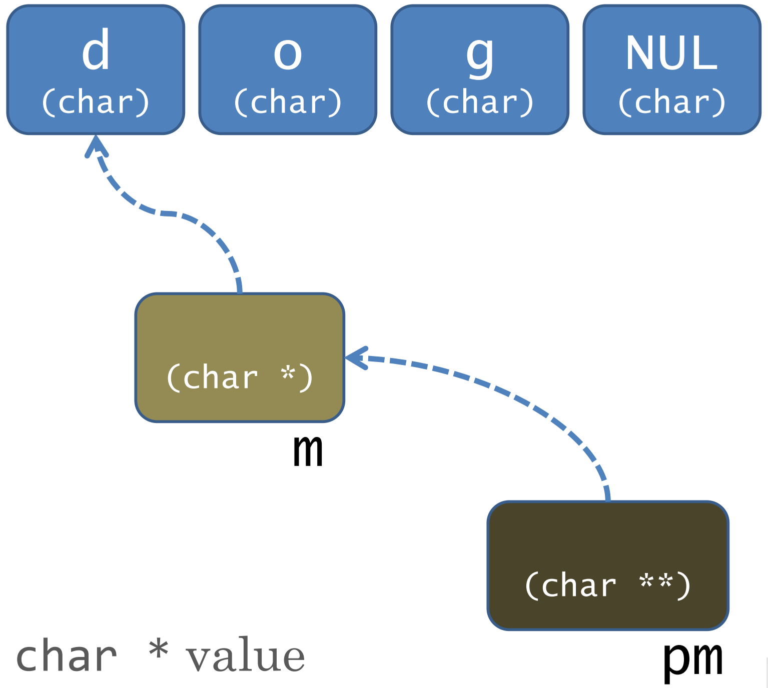
- m is an address of a char
  - *m instructs us to take the contents of that address
  - result gets the value ’d’



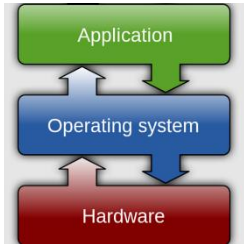
Address operator &

- Instead of contents, returns the address

```
char* m = "dog";
char** pm = &m;
```



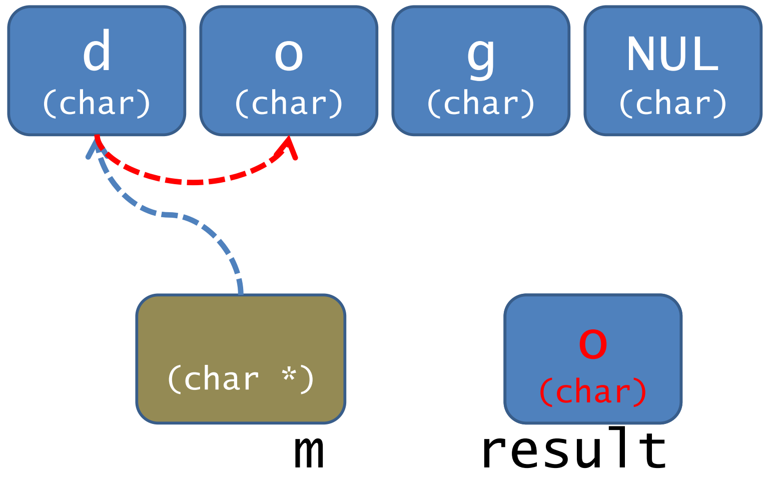
- pm needs a value of type `char **`
  - Can we assign to it `*m`? No – type is `char`
  - Can we assign to it `m`? No – type is `char *`
  - `&m` gives it the right value – the address of a `char *` value



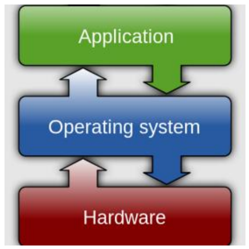
Pointer Arithmetic

- C allows pointer values to be incremented by integer values

```
char* m = "dog";

char result = *(m + 1);
```



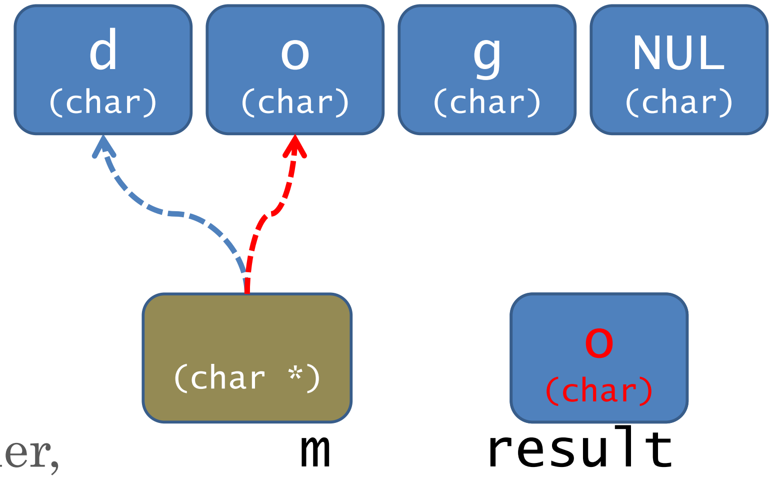
- `m` is an address of a `char`
  - `(m + 1)` is the address of the next `char`
  - `*(m + 1)` instructs us to take the contents of that address
  - result gets the value `'o'`



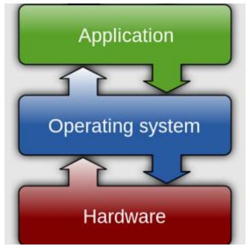
Pointer Arithmetic

- A slightly more complex example:

```
char* m = "dog";

char result = *++m;
```

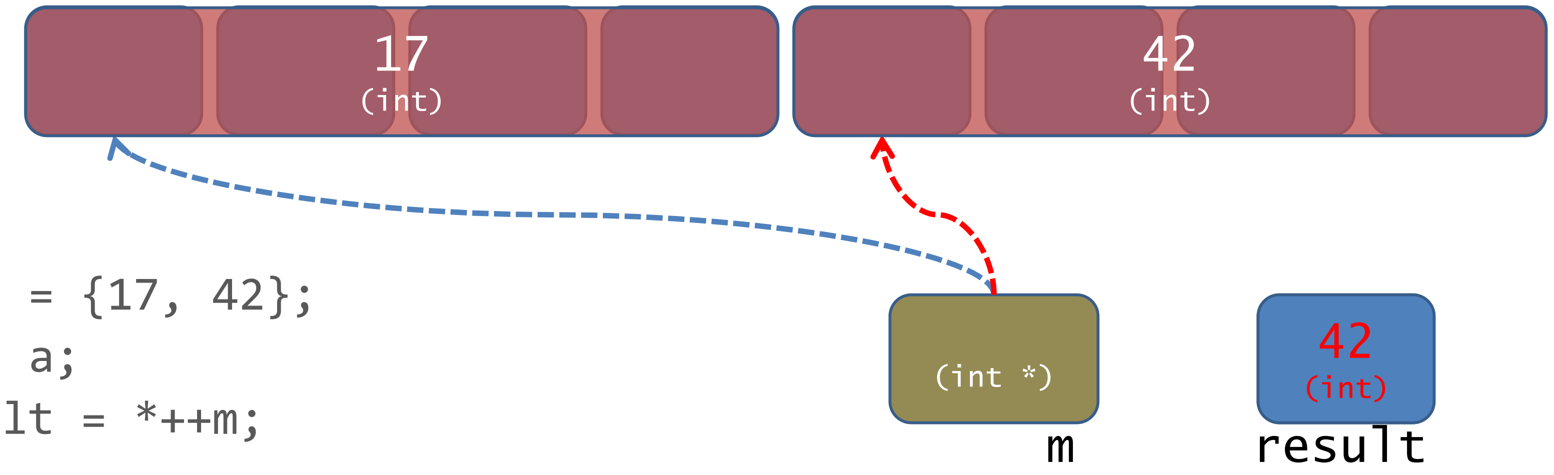


- m is an address of a char
- ++m changes m, to the address one byte higher,
  - and returns the new address
- *++m instructs us to take the contents of that location
- result gets the value 'o'

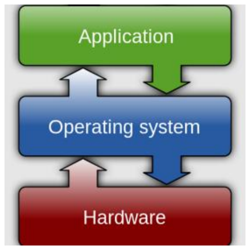


Pointer Arithmetic

- How about multibyte values?
  - Q: Each char value occupies exactly one byte, so obviously incrementing the pointer by one takes you to a new char value…
    - But what about types like `int` that span more than one byte?
  - A: C "does the right thing": increments the pointer by the size of one `int` value

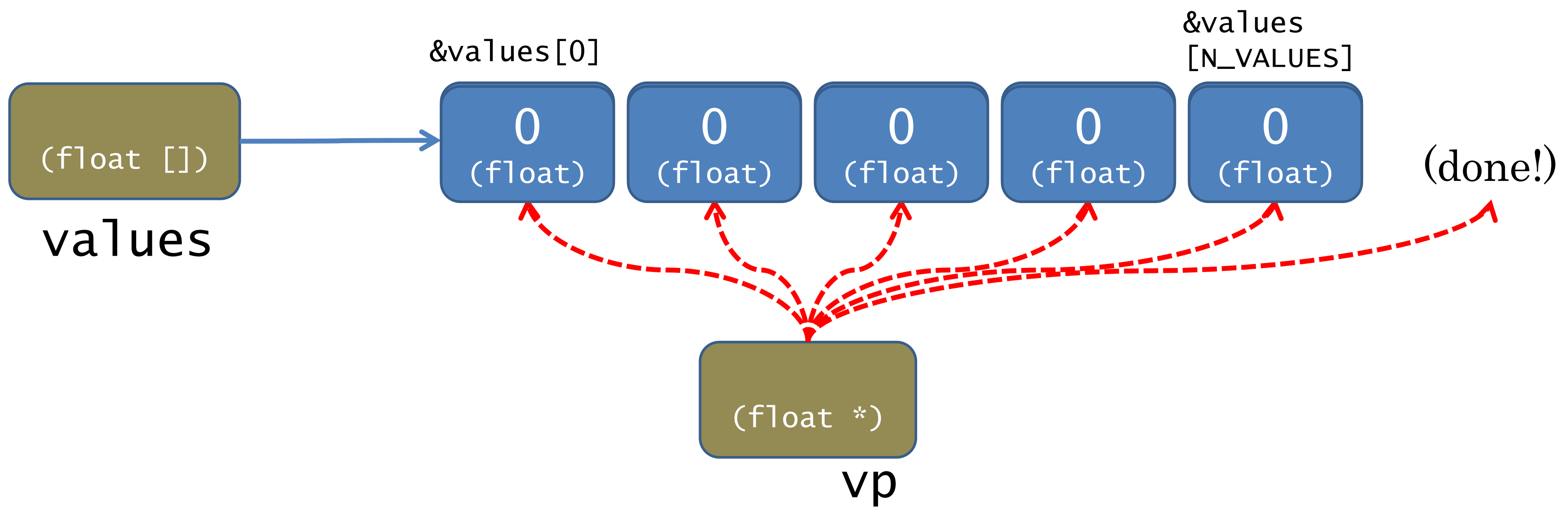


```
int a[2] = {17, 42};
int* m = a;
int result = *++m;
```

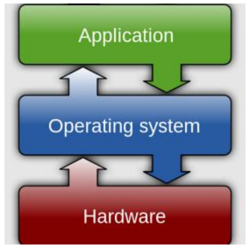


Example: Initializing an Array

```
#define N_VALUES 5
float values[N_VALUES];
```



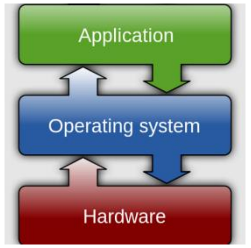
```
float* vp;
for (vp = &values[0]; vp < &values[N_VALUES]; /**/)
     *vp++ = 0;
```



Example: strcpy “string copy”

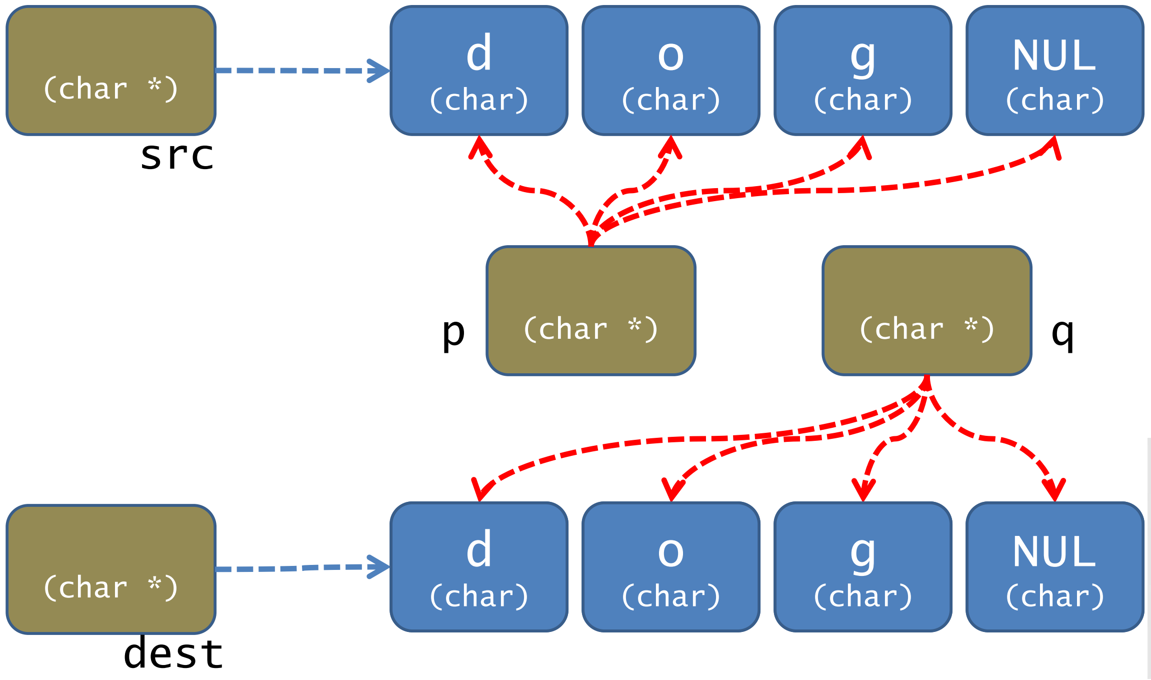
```
char* strcpy(char* dest, const char* src)
```

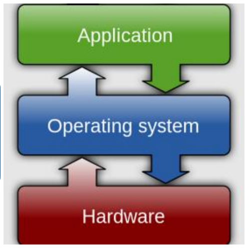
- (assume that) `src` points to a sequence of `char` values that we wish to copy, terminated by `'\0'`
- (assume that) `dest` points to an accessible portion of memory large enough to hold the copied `char`s
- `strcpy` copies the char values of `src` to the memory pointed to by `dest`
- `strcpy` also gives `dest` as a return value



Example: strcpy “string copy”

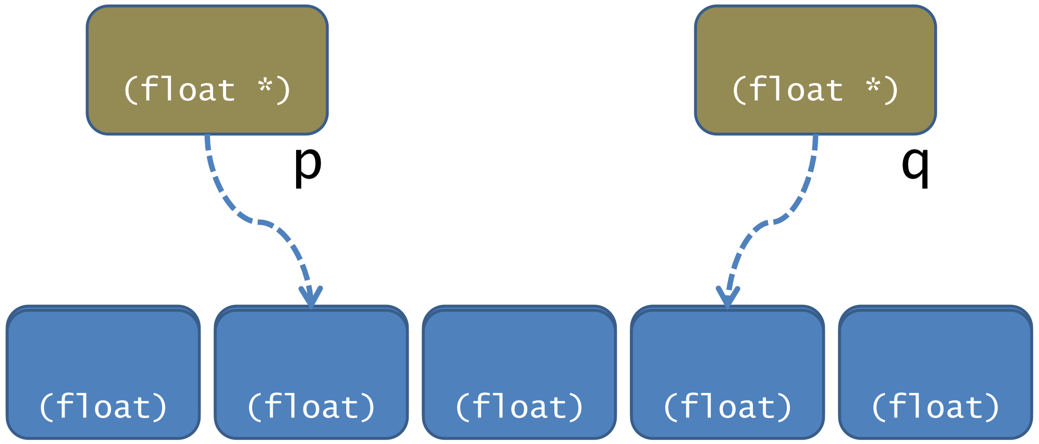
```
char* strcpy(char* dest, const char* src) {
    const char* p;
    char* q;
    for(p = src, q = dest; *p != '\0'; ++p, ++q)
        *q = *p;
    *q = '\0';
    return dest;
}
```

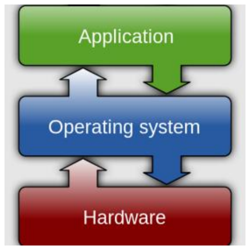




Pointer Subtraction and relational Operations

- Only meaningful in special context: where you have two pointers referencing different elements of the same array
  - `q - p` gives the difference (in number of array elements, not number of bytes between `p` and `q` (in this example, 2)
  - `p < q` returns `1` if `p` has a lower address than `q`; else `0`
    - (in this example, it returns `1`)

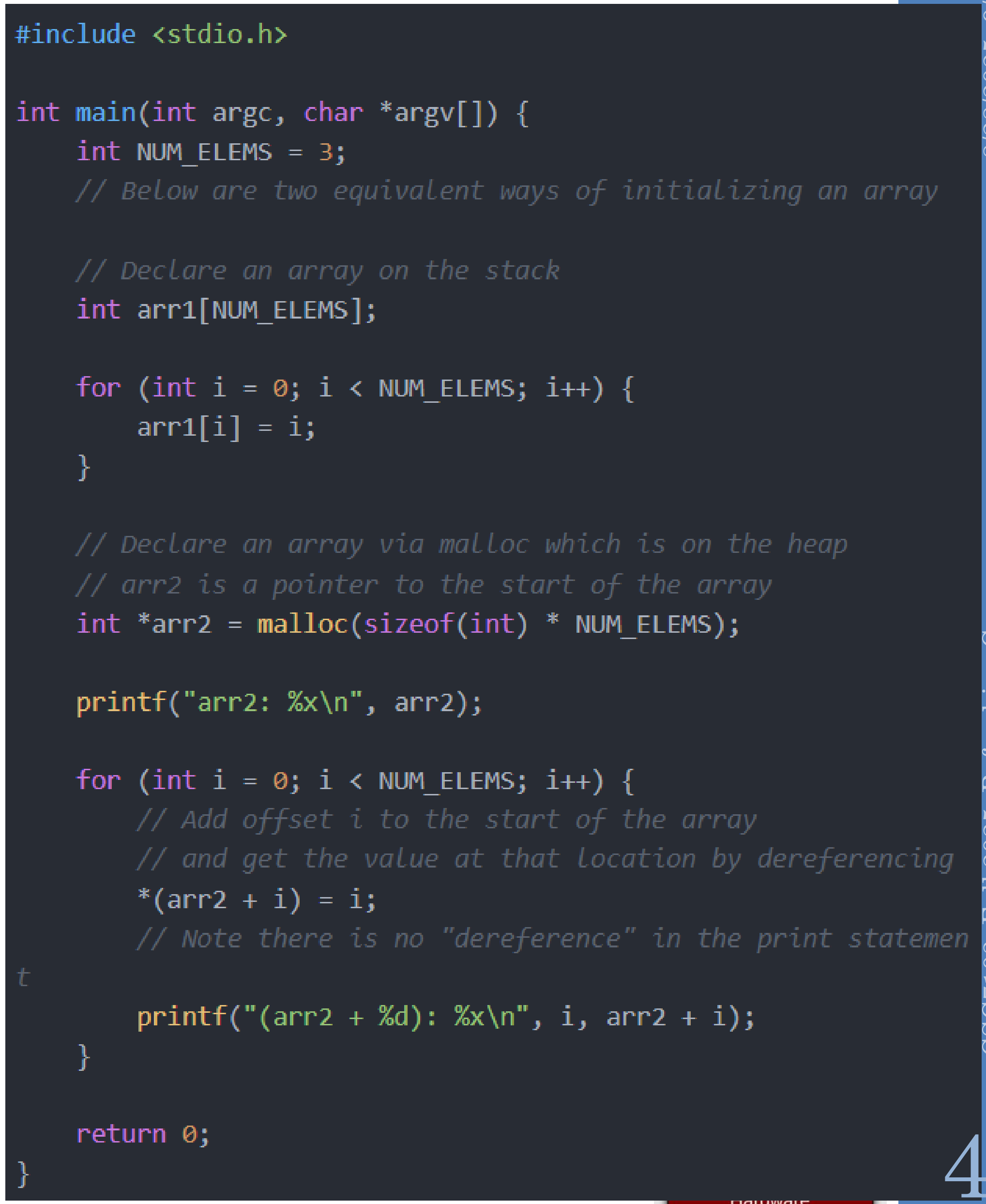




Arrays

Arrays

- C arrays can be tricky since we can represent them using the `[]` syntax or as pointers using the `*` syntax.
- In the case of the `[]` syntax
  - We can access elements by using the familiar `arr1[index]` syntax
- In the case of the pointer `*` syntax
  - `malloc` returns a pointer to the start of a buffer that is the same size as the argument that is passed in
  - The value of `int* arr2` in this case is a pointer to the start of a buffer of size `12`
    - Each `int` is `4` bytes and there are `3` of them

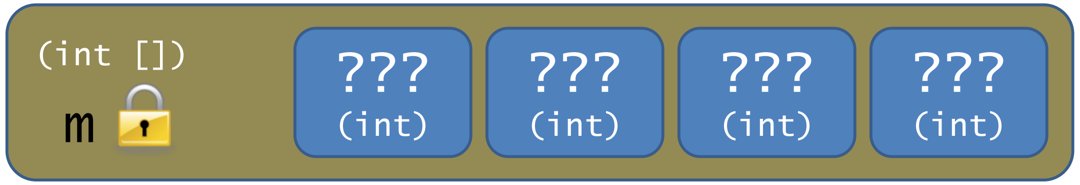


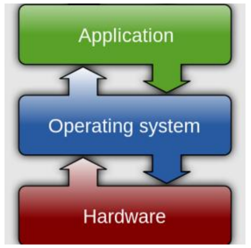
```
#include <stdio.h>

int main(int argc, char *argv[]) {
    int NUM_ELEMS = 3;
    // Below are two equivalent ways of initializing an array

    // Declare an array on the stack
    int arr1[NUM_ELEMS];

    for (int i = 0; i < NUM_ELEMS; i++) {
        arr1[i] = i;
    }

    // Declare an array via malloc which is on the heap
    // arr2 is a pointer to the start of the array
    int *arr2 = malloc(sizeof(int) * NUM_ELEMS);

    printf("arr2: %x\n", arr2);

    for (int i = 0; i < NUM_ELEMS; i++) {
        // Add offset i to the start of the array
        // and get the value at that location by dereferencing
        *(arr2 + i) = i;
        // Note there is no "dereference" in the print statemen
t
        printf("(arr2 + %d): %x\n", i, arr2 + i);
    }

    return 0;
}
```

Review of arrays

- There are no array variables in C – only array names
  - Each name refers to a constant pointer (address of first element of array)
  - Space for array elements is allocated at declaration time
- Can't change where the array name refers to…
  - but you can change the array elements,
    - via pointer arithmetic

```
int m[4];
```



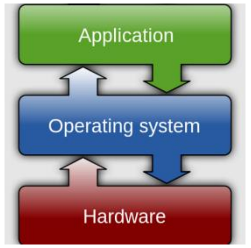


Subscripts and pointer arithmetic

- `array[subscript]` equivalent to `*(array + (subscript))`

- Strange but true: Given earlier declaration of `m`, the expression `2[m]` is legal!
  - Not only that: it's equivalent to:

```
2[m]
*(2+m)
*(m+2)
m[2]
```

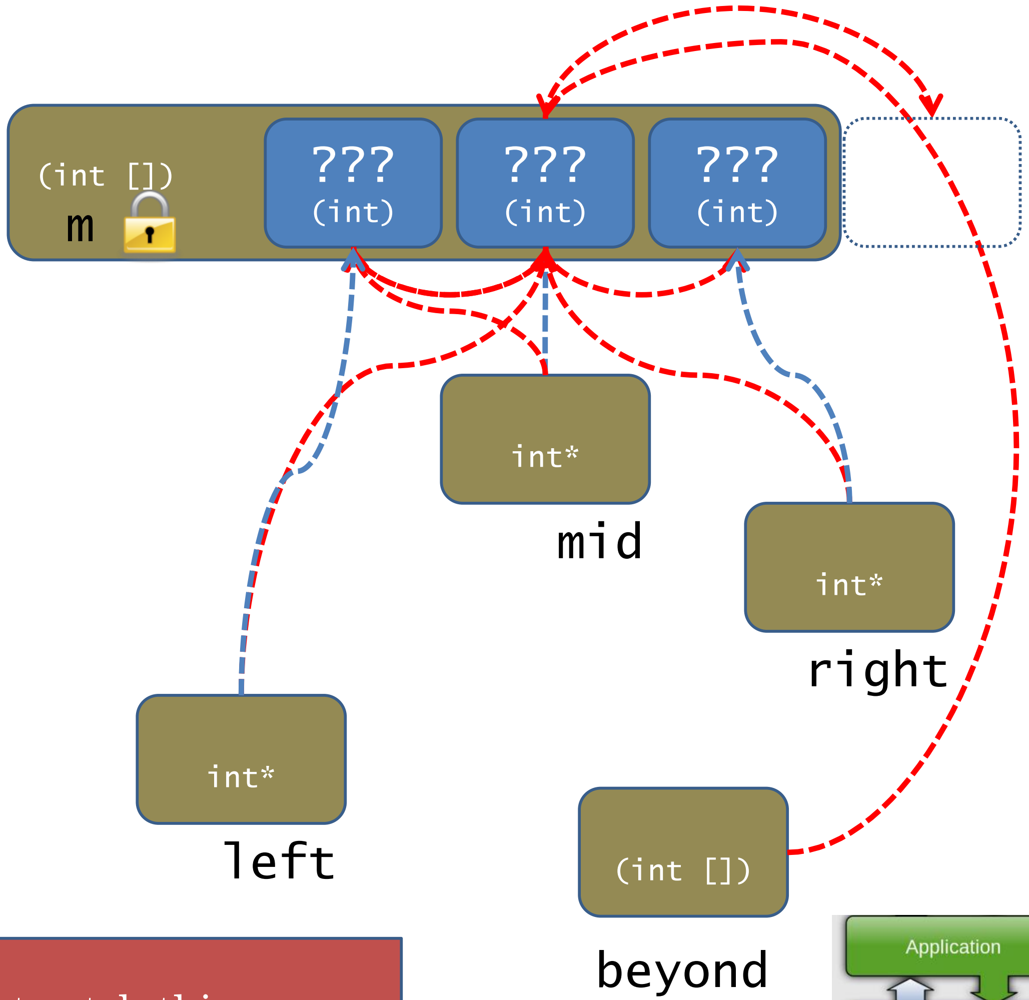


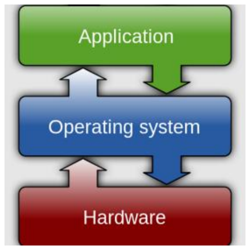
Array names and Pointer Variables, playing together

```
int m[3];

int* mid = m + 1;

int* right = &mid[1];

int* left = &mid[-1];

int* beyond = &mid[2];
```

subscript OK with pointer variable

compiler may not catch this – runtime environment certainly won't

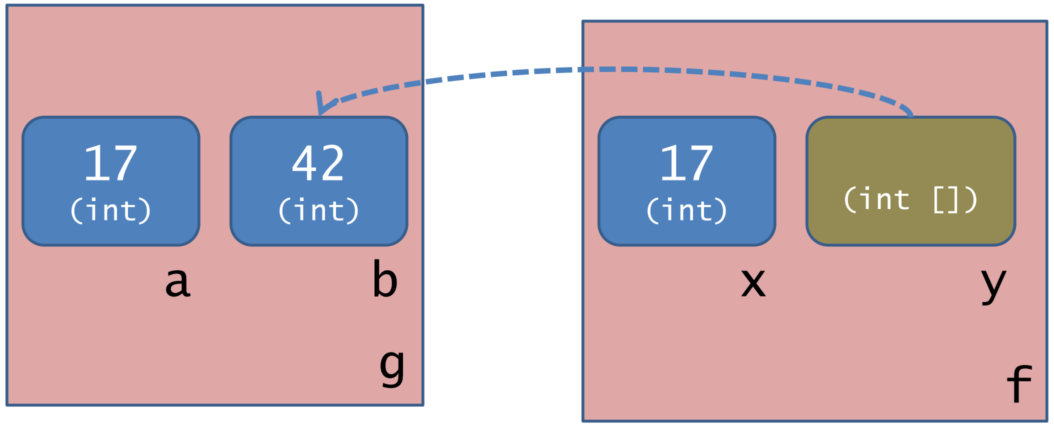




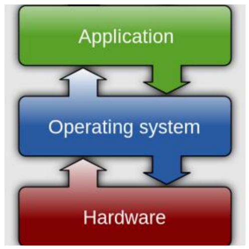
Array names as function arguments

- In C, arguments are passed "by value"
  - A temporary copy of each argument is created, solely for use within the function call:

```
void f(int x, int* y) { … }

void g(...) {
  int a = 17, b = 42;
  f(a, &b);
     …
}
```

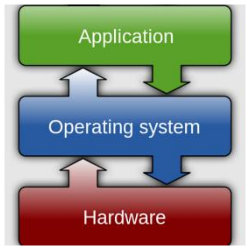


- Pass-by-value is "safe" in that the function plays only in its "sandbox" of temporary variables –
  - can't alter the values of variables in the callee (except via the return value)



Array Names as Function Arguments

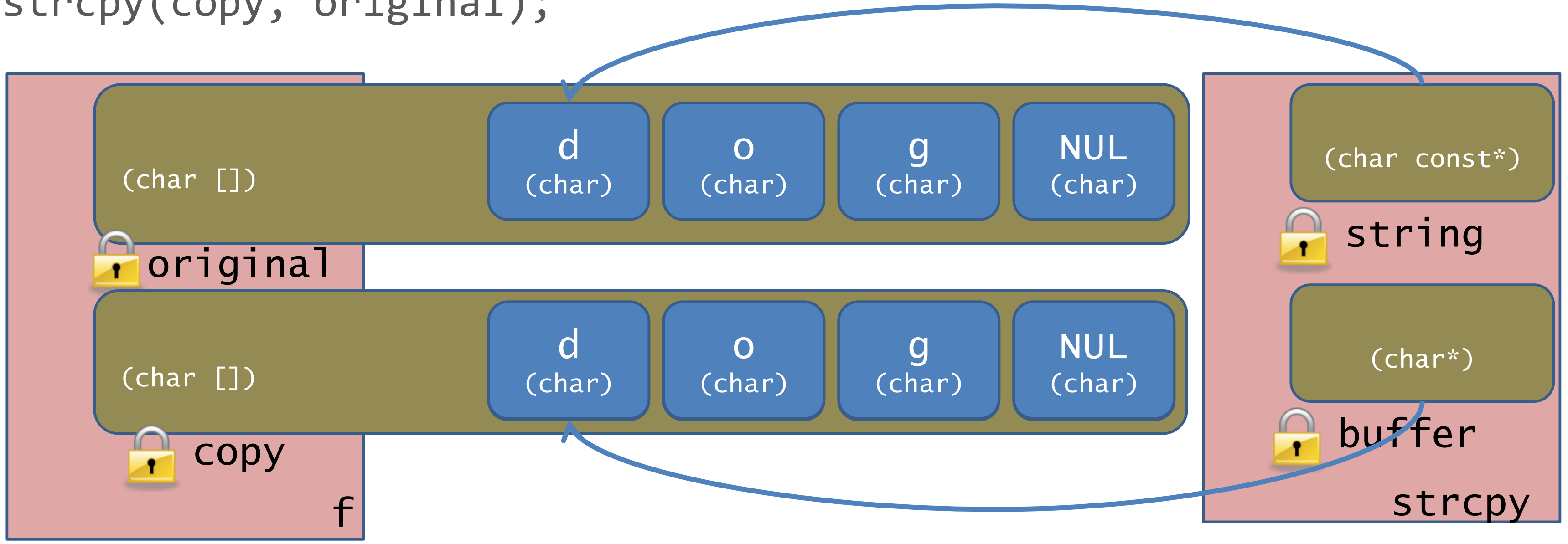
- But, functions that take arrays as arguments can exhibit what looks like “pass-by-reference” behavior, where the array passed in by the callee does get changed
  - Remember the special status of arrays in C
    - They are basically just pointers.
  - So arrays are indeed passed by value
    - but only the pointer is copied, not the array elements!
  - Note the advantage in efficiency (avoids a lot of copying)
    - But - the pointer copy points to the same elements as the callee’s array
    - These elements can easily be modified via pointer manipulation

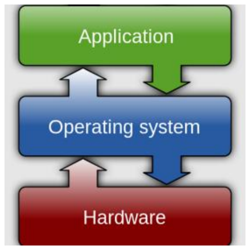


Array names as function arguments

- The `strcpy` "string copy" function puts this "pseudo" call-by-reference behavior to good use:

```
void strcpy(char* buffer, char const* string);
void f(...) {
  char original[4] = "dog";
  char copy[4];
  strcpy(copy, original);
}
```





When can array size be omitted?

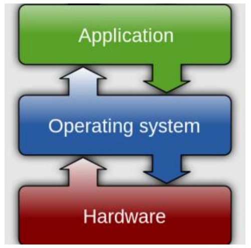
- There are a couple of contexts in which an array declaration need not have a size specified:
  - Parameter declaration:

```
int strlen(char string[]);  // same as: int strlen(char* string);
```

    - As we've seen, the elements of the array argument are not copied, so the function doesn't need to know how many elements there are.
  - Array initialization:

```
int vector[] = {1, 2, 3, 4, 5};
```

    - In this case, just enough space is allocated to fit all (five) elements of the initializer list

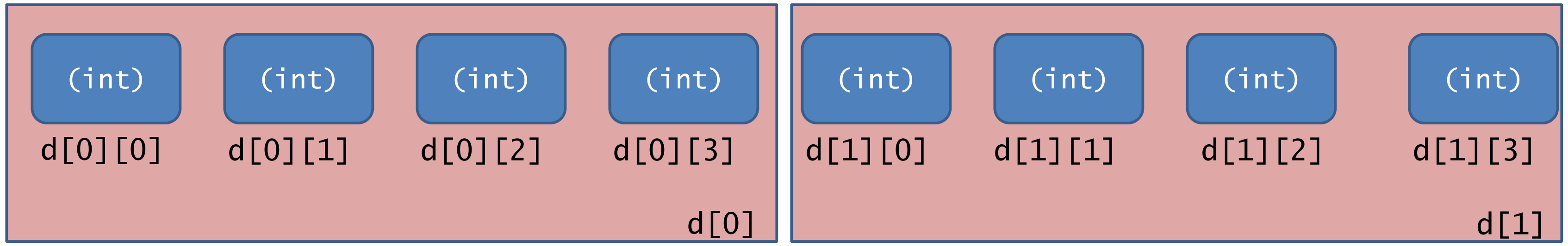


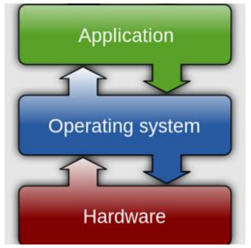
Multidimensional arrays

- How to interpret a declaration like:

```
int d[2][4];
```

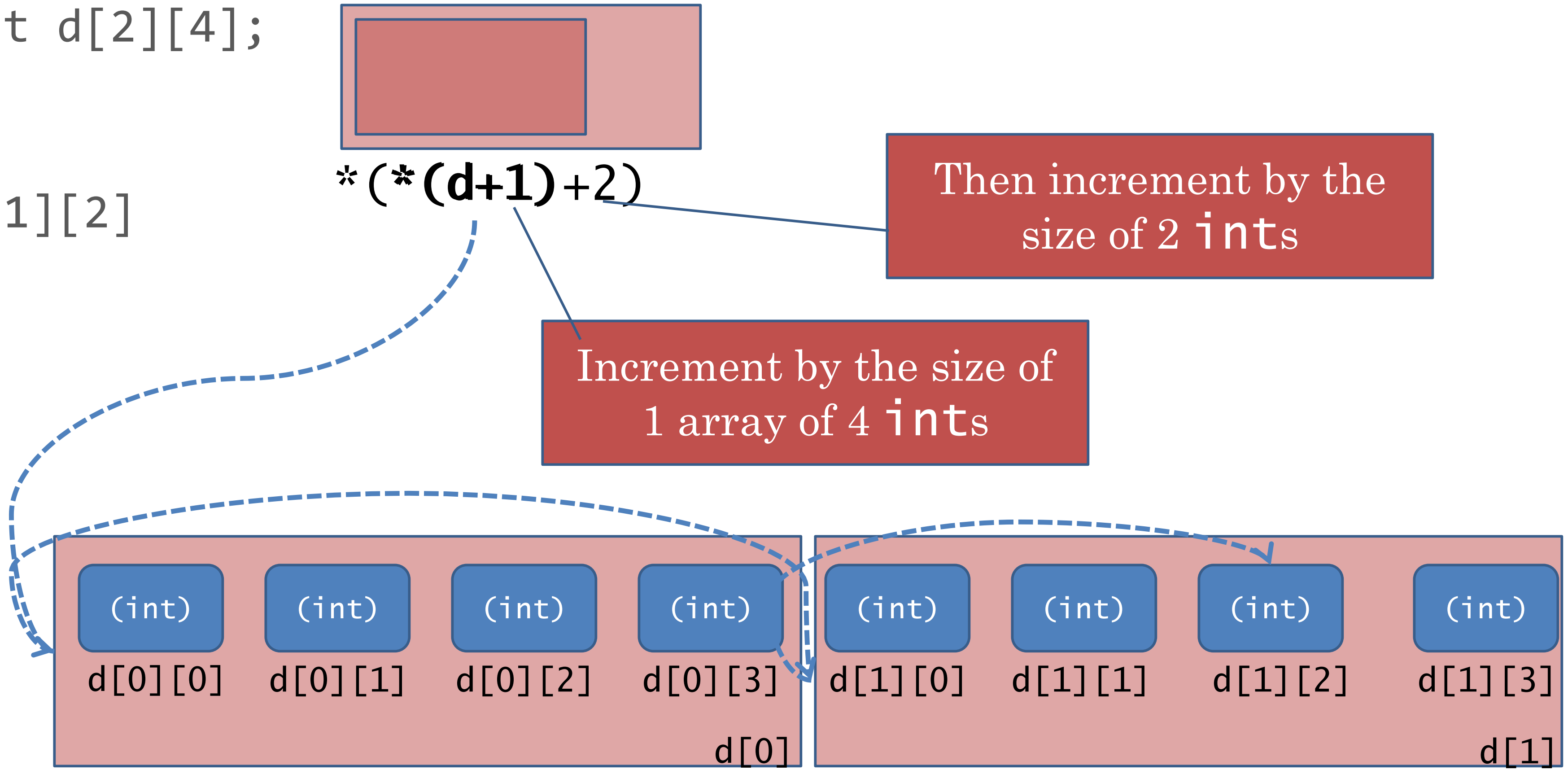
- This is an array with two elements:
  - Each element is an array of four `int` values
- The elements are laid out sequentially in memory, just like a one-dimensional array
  - Row-major order: the elements of the rightmost subscript are stored contiguously

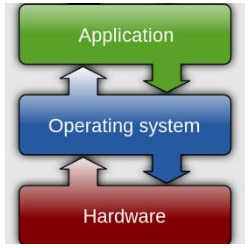




Subscripting in a multidimensional array

```
int d[2][4];

d[1][2]
```

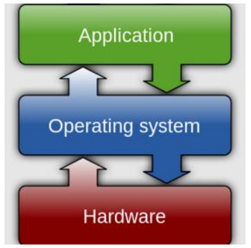




Why do we care about Storage Order?

- If you stay within the "paradigm" of the multidimensional array, the order doesn't matter…
- But if you use tricks with pointer arithmetic,
  - it matters a lot
- It also matters for initialization
  - To initialize `d` like this:
    - use this:
      ```
      int d[2][4] = {0, 1, 2, 3, 4, 5, 6, 7};
      ```
    - rather than this
      ```
      int d[2][4] = {0, 4, 1, 5, 2, 6, 3, 7};
      ```

0	1	2	3
4	5	6	7

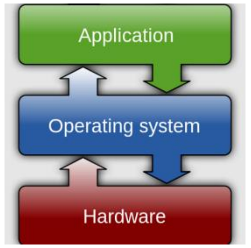


Multidimensional Arrays as Parameters

- Only the first subscript may be left unspecified:

```
void f(int matrix[][10]);    /* OK */
void g(int (*matrix)[10]);   /* OK */
void h(int matrix[][]);      /* not OK */
```

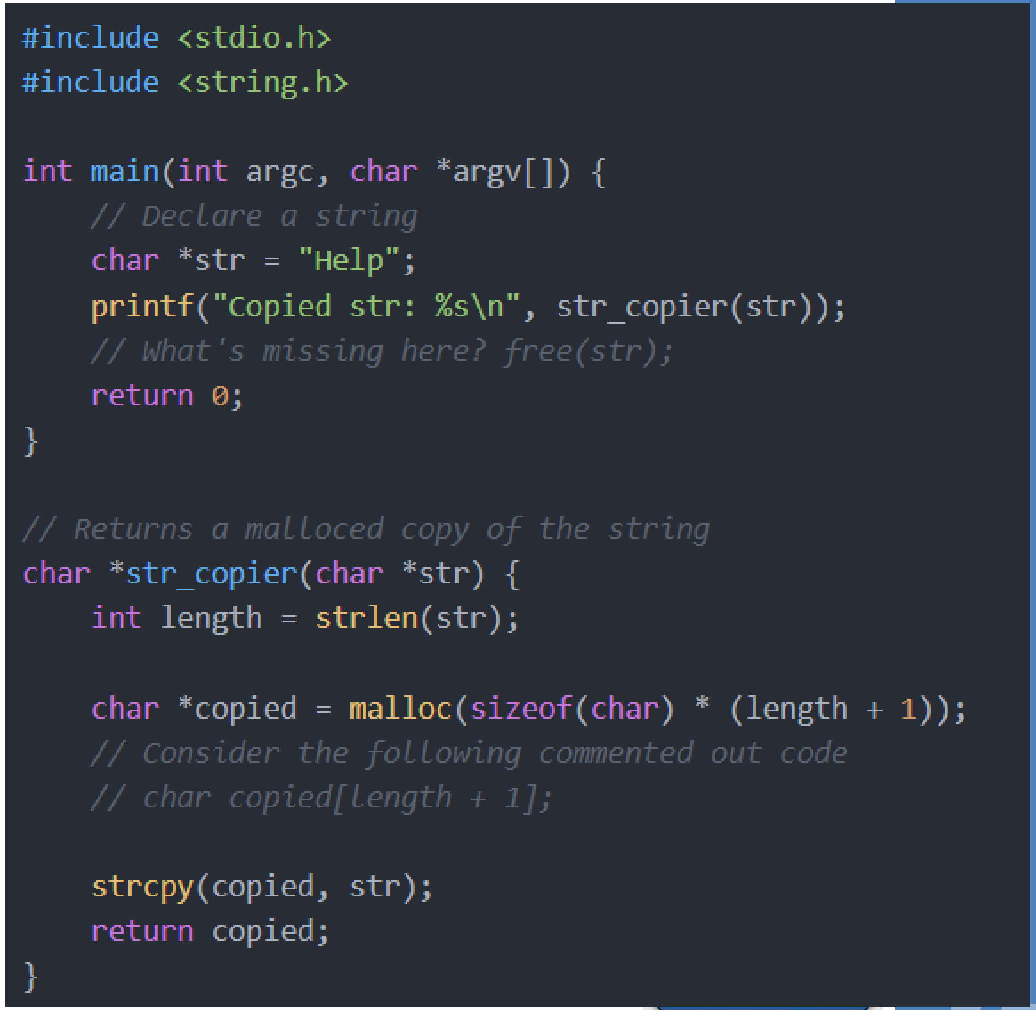
- Why?
  - Because the other sizes are needed for scaling when evaluating subscript expressions (see previous slides)
  - This points out an important drawback to C:
    - Arrays do not carry information about their own sizes!
    - If array size is needed, you must supply it somehow
    - (e.g., when passing an array argument, you often have to pass an additional "array size" argument) – bummer



Malloc

Using `malloc`

- `malloc` returns a pointer to the start of a region of memory on the heap. It takes in the number of bytes to allocate.
- Knowing the differences between `malloc`-ing data on the heap and declaring data on the stack is important for CSC4103.
- Consider the commented out code `char copied[length + 1]`
  - If we were to use this line of code instead of the line with `malloc`, what would happen?
  - It's possible we get a segfault or the returned string is garbage!
  - This happens because we declared our string on the stack inside the `str_copier` function frame and returned a pointer to the string located in the function frame
  - But when we return from `str_copier`, the stack frame is deallocated so now we have a dangling pointer to a location in the deallocated function frame!
  - So never declare things on the stack and then return them!



```c
#include <stdio.h>
#include <string.h>

int main(int argc, char *argv[]) {
    // Declare a string
    char *str = "Help";
    printf("Copied str: %s\n", str_copier(str));
    // What's missing here? free(str);
    return 0;
}

// Returns a malloced copy of the string
char *str_copier(char *str) {
    int length = strlen(str);

    char *copied = malloc(sizeof(char) * (length + 1));
    // Consider the following commented out code
    // char copied[length + 1];

    strcpy(copied, str);
    return copied;
}
```

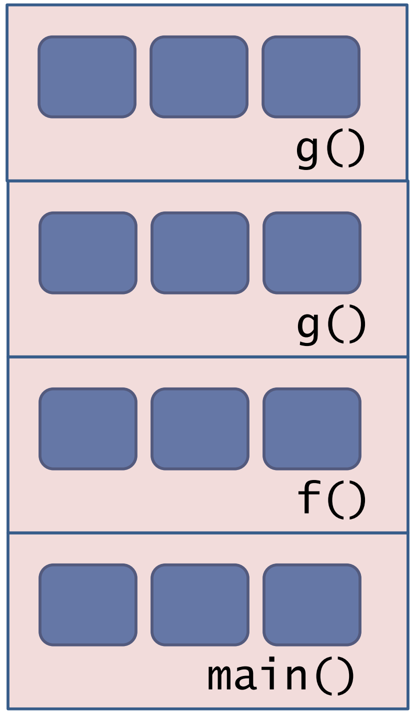
Overview of Memory Management

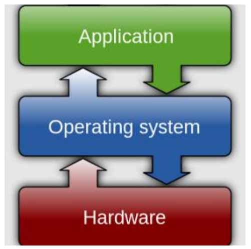
- Stack-allocated memory
  - When a function is called, memory is allocated for all of its parameters and local variables.
  - Each active function call has memory on the stack (with the current function call on top)
  - When a function call terminates,
    - the memory is deallocated ("freed up")

Ex: `main()` calls `f()`,

`f()` calls `g()`

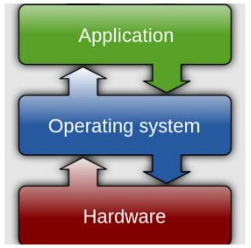
`g()` recursively calls `g()`





Overview of Memory Management

- Heap-allocated memory
  - This is used for persistent data, that must survive beyond the lifetime of a function call
    - global variables
    - dynamically allocated memory – C statements can create new heap data (similar to new in Java/C++)
  - Heap memory is allocated in a more complex way than stack memory
  - Like stack-allocated memory, the underlying system determines where to get more memory – the programmer doesn't have to search for free memory space!



Allocating new Heap Memory

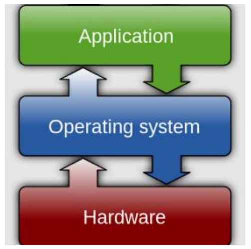
```
void* malloc(size_t size);
```

Note: `void *` denotes a generic pointer type

- Allocate a block of size bytes,
  - return a pointer to the block
  - (NULL if unable to allocate block)

```
void* calloc(size_t num_elements, size_t element_size);
```

- Allocate a block of num_elements * element_size bytes,
  - initialize every byte to zero,
  - return pointer to the block
  - (NULL if unable to allocate block)

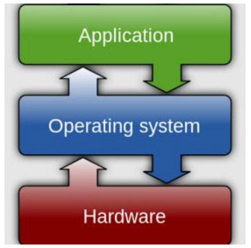


Allocating new Heap Memory

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

- Given a previously allocated block starting at ptr,
  - change the block size to new_size,
  - return pointer to resized block
    - If block size is increased, contents of old block may be copied to a completely different region
    - In this case, the pointer returned will be different from the ptr argument, and ptr will no longer point to a valid memory region
- If ptr is NULL, realloc is identical to malloc
- Note: may need to cast return value of malloc/calloc/realloc:

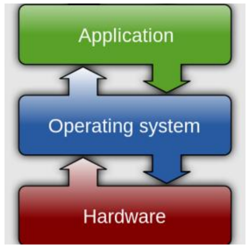
```
char* p = (char*) malloc(BUFFER_SIZE);
```



Deallocating Heap Memory

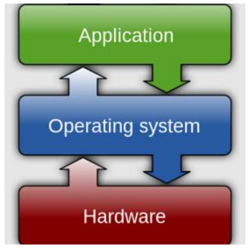
```
void free(void* pointer);
```

- Given a pointer to previously allocated memory,
  - put the region back in the heap of unallocated memory
- Note: easy to forget to free memory when no longer needed…
  - especially if you're used to a language with "garbage collection" like Java
  - This is the source of the notorious "memory leak" problem
  - Difficult to trace – the program will run fine for some time, until suddenly there is no more memory!



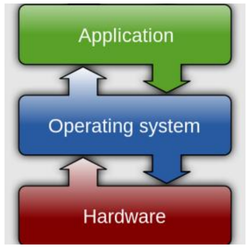
Checking for successful Allocation

- Call to `malloc` might fail to allocate memory, if there’s not enough available
- Easy to forget this check, annoying to have to do it every time `malloc` is called…



Memory errors

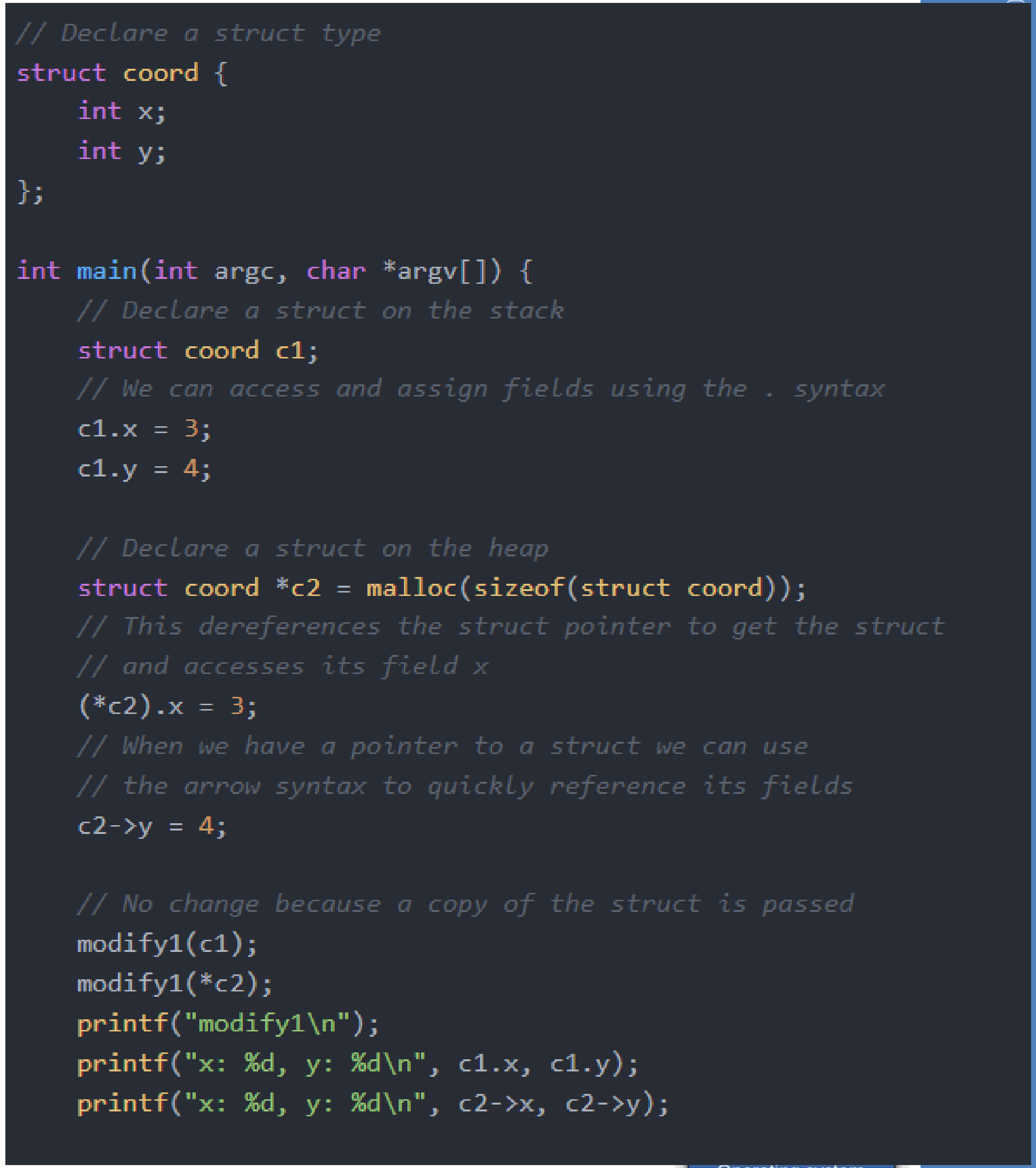
- Using memory that you have not initialized
- Using memory that you do not own
- Using more memory than you have allocated
- Using faulty heap memory management



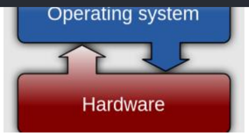
Structs

Structs

- Structs organize and group variables in a container so that they're easily accessible by a single pointer.
- As in other languages, creating objects is extremely helpful in keeping your abstractions clean!
- Let's analyze the code
  - We can declare a `struct` type by using the `struct name {fields};` syntax.
  - To access fields of a `struct` value, we can use the `.` (dot) syntax.
  - To access fields of a `struct` pointer, we have two choices
    - We can dereference the pointer to get a `struct` value and then use the `.` (dot) notation
    - Or we can use the arrow notation `->` to quickly do the first option
    - The arrow notation is probably the cleaner and quicker method

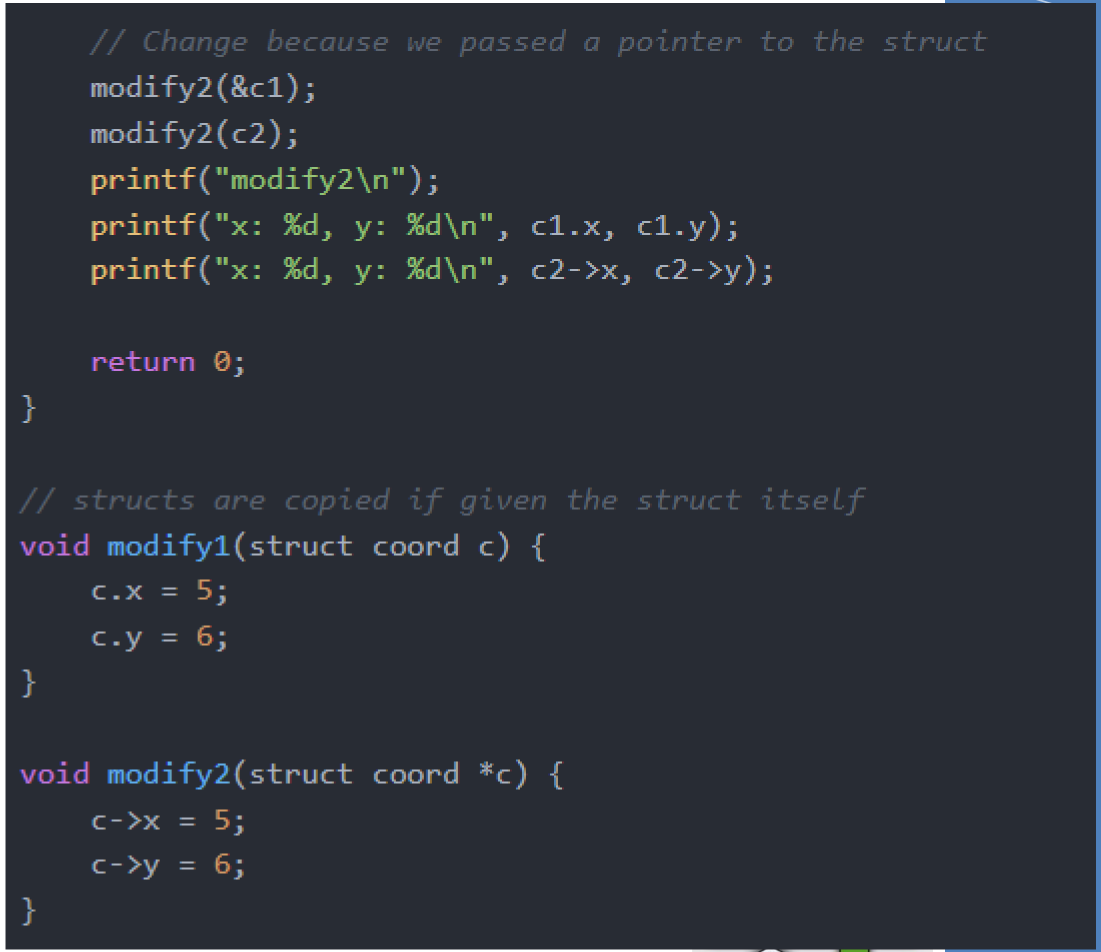


```c
// Declare a struct type
struct coord {
    int x;
    int y;
};

int main(int argc, char *argv[]) {
    // Declare a struct on the stack
    struct coord c1;
    // We can access and assign fields using the . syntax
    c1.x = 3;
    c1.y = 4;

    // Declare a struct on the heap
    struct coord *c2 = malloc(sizeof(struct coord));
    // This dereferences the struct pointer to get the struct
    // and accesses its field x
    (*c2).x = 3;
    // When we have a pointer to a struct we can use
    // the arrow syntax to quickly reference its fields
    c2->y = 4;

    // No change because a copy of the struct is passed
    modify1(c1);
    modify1(*c2);
    printf("modify1\n");
    printf("x: %d, y: %d\n", c1.x, c1.y);
    printf("x: %d, y: %d\n", c2->x, c2->y);
```

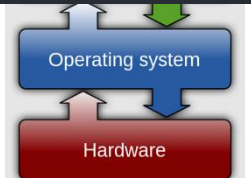


Structs

- When we pass struct values into functions (such as modify1), they are copied
  - This means any changes we make to that struct are not reflected in the original struct
- When we pass struct pointers into functions (such as modify2), the original struct may be modified
  - Since we have a pointer, we can go to the location of the struct and modify that struct

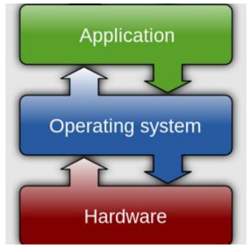


```
    // Change because we passed a pointer to the struct
    modify2(&c1);
    modify2(c2);
    printf("modify2\n");
    printf("x: %d, y: %d\n", c1.x, c1.y);
    printf("x: %d, y: %d\n", c2->x, c2->y);

    return 0;
}

// structs are copied if given the struct itself
void modify1(struct coord c) {
    c.x = 5;
    c.y = 6;
}

void modify2(struct coord *c) {
    c->x = 5;
    c->y = 6;
}
```



C structures: aggregate, yet scalar

- aggregate in that they hold multiple data items at one time
  - named members hold data items of various types
  - like the notion of class/field in C++
    - but without the data hiding features
- scalar in that C treats each structure as a unit
  - as opposed to the “array” approach: a pointer to a collection of members in memory
  - entire structures (not just pointers to structures) may be passed as function arguments, assigned to variables, etc.
  - Interestingly, they cannot be compared using ==
    - (rationale: too inefficient)

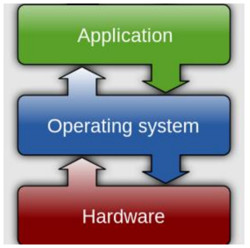


Structure Declarations

- Combined variable and type declaration
  `struct tag {member-list} variable-list;`
- Any one of the three portions can be omitted

```
struct { int a, b; char* p; } x, y;  /* omit tag (type name) */
```

- variables x, y declared with members as described:
  - int members a, b and char pointer p.
- x and y have same type, but differ from all others –
  - even if there is another declaration:
    - `struct { int a, b; char *p; } z;`
  - /* z has different type from x, y */



Structure Declarations

```
struct S { int a, b; char* p; };  /* omit variables */
```

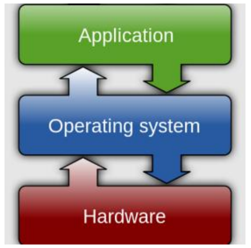
- No variables are declared, but there is now a type struct S that can be referred to later

```
struct S z;  /* omit members */
```

  - Given an earlier declaration of struct S, this declares a variable of that type

```
typedef struct { int a, b; char* p; } S;
/* omit both tag and variables */
```

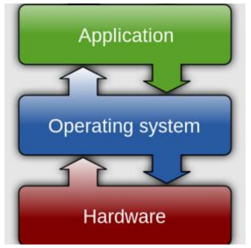
  - This creates a simple type name S
    - (more convenient than `struct S`)



Recursively defined Structures

- Obviously, you can't have a structure that contains an instance of itself as a member – such a data item would be infinitely large
- But within a structure you can refer to structures of the same type, via pointers

```
struct TREENODE {
  char *label;
  struct TREENODE *leftchild, *rightchild;
}
```

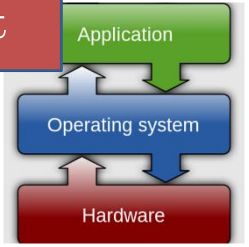


Recursively defined Structures

- When two structures refer to each other, one must be declared in incomplete (prototype) fashion

```
struct HUMAN;
struct PET {
  char name[NAME_LIMIT];
  char species[NAME_LIMIT];
  struct HUMAN* owner;
} fido = {"Fido", "Canis lupus familiaris", NULL};
struct HUMAN {
  char name[NAME_LIMIT];
  struct PET pets[PET_LIMIT];
} sam = {"Sam", {fido}};
```

We can't initialize the `owner` member at this point, since it hasn't been declared yet

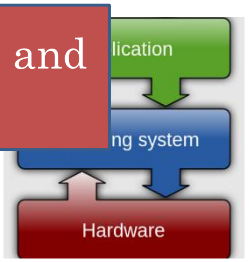


Member Access

- Direct access operator s.m
  - subscript and dot operators have same precedence and associate left-to-right, so we don't need parentheses for sam.pets[0].species
- Indirect access s->m: equivalent to (*s).m
  - Dereference a pointer to a structure, then return a member of that structure
  - Dot operator has higher precedence than indirection operator , so parentheses are needed in (*s).m
  - `(*fido.owner).name` or `fido.owner->name`

`.` evaluated first: access `owner` member
`*` evaluated next: dereference pointer to `HUMAN`

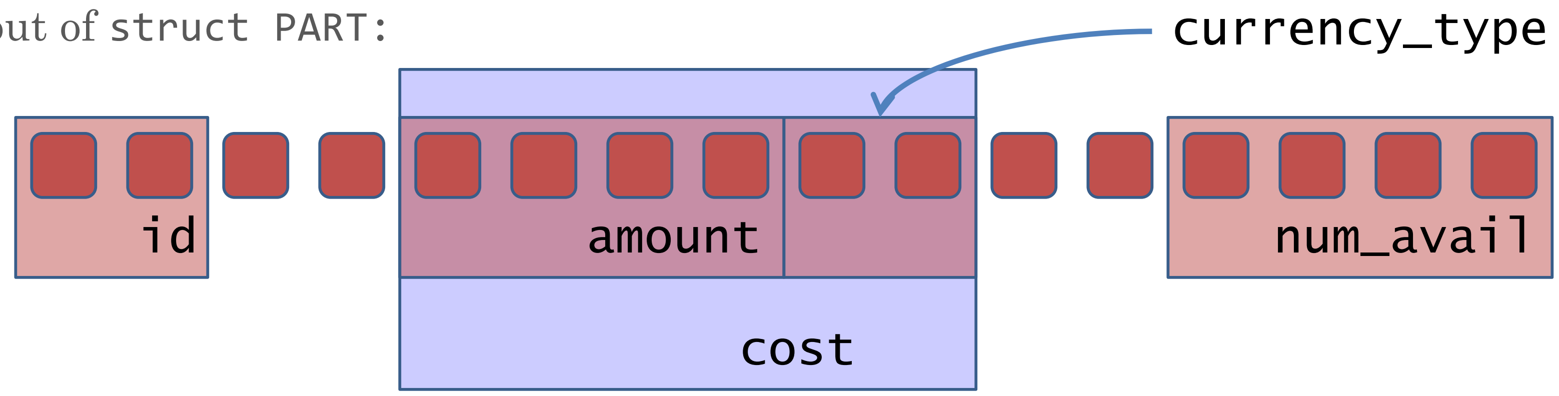
`.` and `->` have equal precedence and associate left-to-right



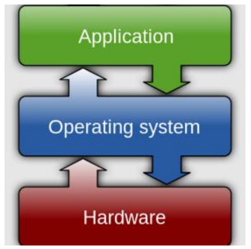
Memory Layout

```
struct COST { int amount;
              char currency_type[2]; };
struct PART { char id[2];
              struct COST cost;
              int num_avail; };
```

- layout of `struct PART:`



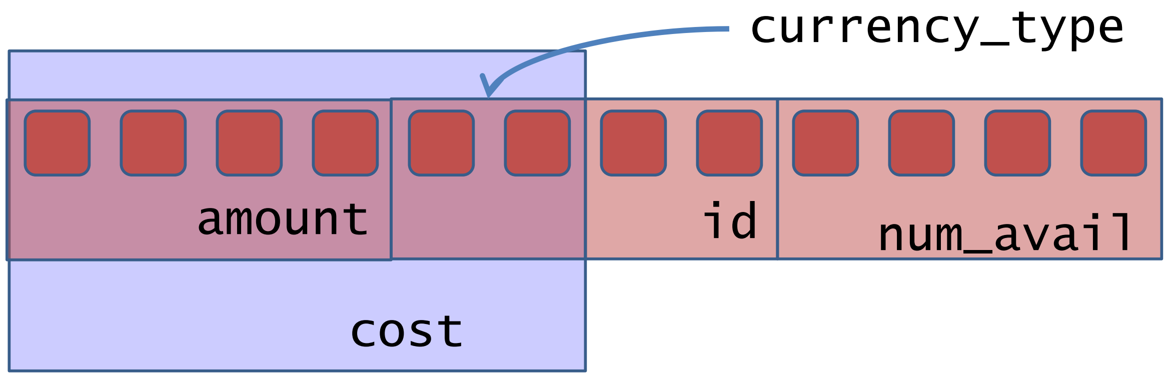
- Here, the system uses 4-byte alignment of integers,
  - so amount and num_avail must be aligned
- Four bytes wasted for each structure!

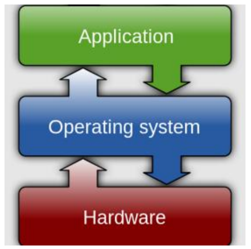


Memory layout

- A better alternative (from a space perspective):

```
struct COST { int amount;
              char currency_type[2]; };
struct PART { struct COST cost;
              char id[2];
              int num_avail; };
```





Structures as Function Arguments

- Structures are scalars, so they can be returned and passed as arguments – just like ints, chars

```
struct BIG changestruct(struct BIG s);
```

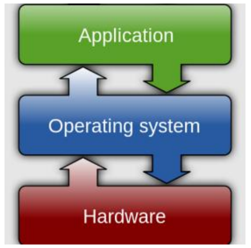
  - Call by value: temporary copy of structure is created
  - Caution: passing large structures is inefficient
    - – involves a lot of copying

- avoid by passing a pointer to the structure instead:

```
void changestruct(struct BIG* s);
```

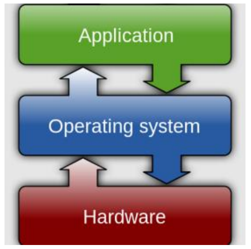
- What if the struct argument is read-only?
  - Safe approach: use const

```
void changestruct(struct BIG const* s);
```



OOP with C

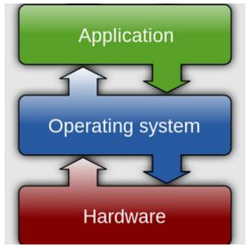
```
struct cost { int amount; char currency_type; };

struct cost* cost_init() { return malloc(sizeof(cost)); }

void cost_free(struct cost* c) { free(c); }

void cost_set(struct cost* c, int amount, char type)
    { c->amount = amount; c->currency_type = type; }

struct cost* c = cost_init();
if (c == NULL) { … error … }
cost_set(c, 42, '$');
cost_free(c);
```



Unions

- Like structures, but every member occupies the same region of memory!
  - Structures: members are placed consecutively in memory
  - Unions: members are place in the same spot in memory

```
union VALUE {
  float f;
  int i;
  char *s;
};
/* either a float or an int or a char* */
```

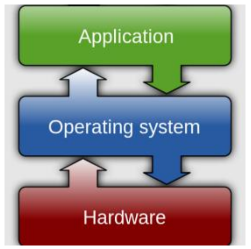


Unions

- Up to programmer to determine how to interpret a union (i.e. which member to access)
- Often used in conjunction with a “type” variable that indicates how to interpret the union value
  - Called ‘discriminated union’

```
enum TYPE { INT, FLOAT, STRING };
struct VARIABLE {
  enum TYPE type;
  union VALUE value;
};
```

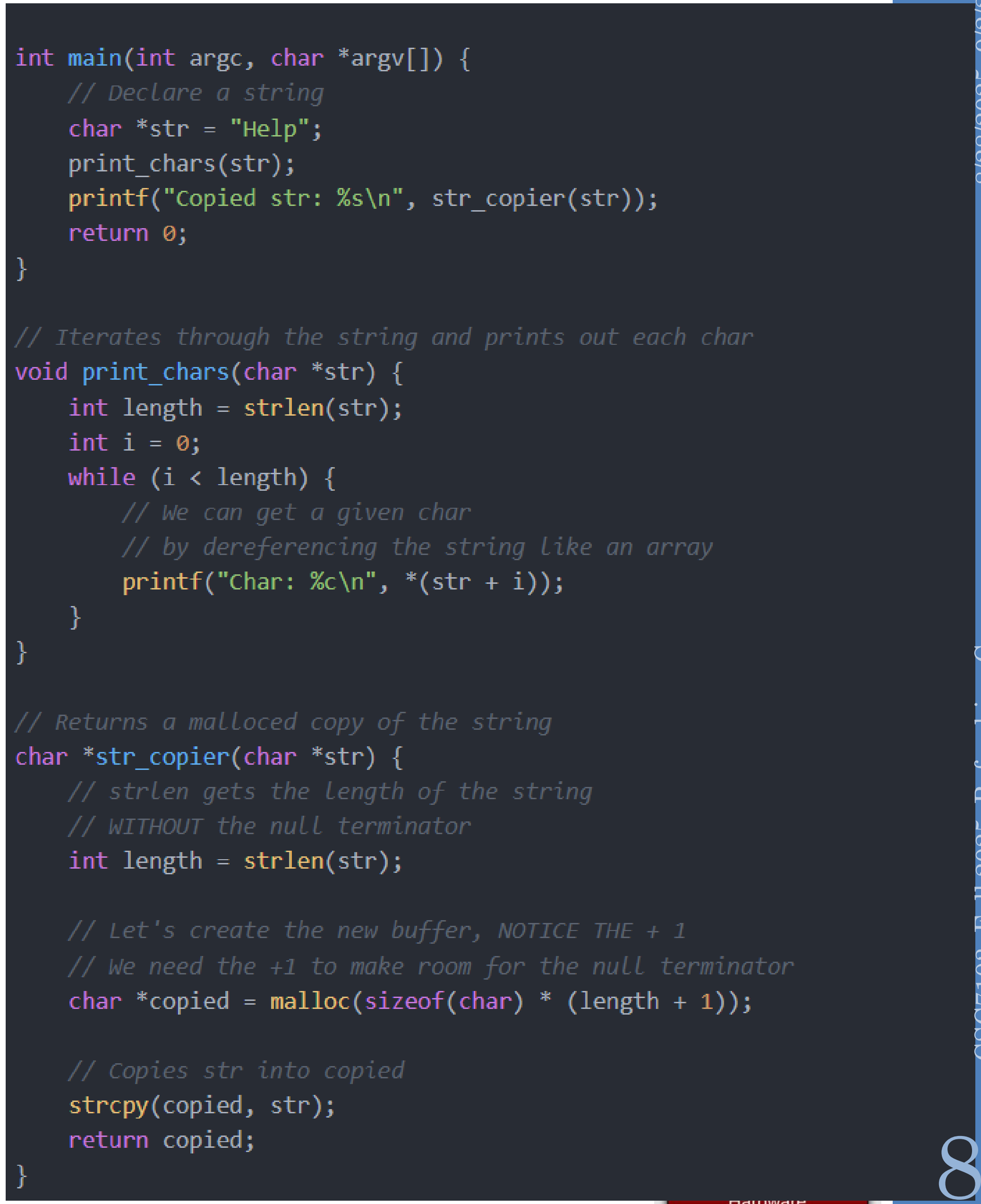
Access `type` to determine how to interpret `value`



Strings

Strings

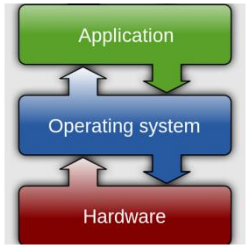
- A string is an array of characters ending with a null terminator `\0`.
- So, we can represent strings as a char * type (an array of chars).
- Let's analyze the code
  - We can declare a string as an array using either syntax, in this case we chose the pointer syntax.
  - In `print_chars`, we can iterate through the string by using the same array dereferencing and pointer arithmetic method.
  - In `str_copier`, notice that `strlen` returns the length of the string excluding the null terminator.
  - If we didn't have the `+ 1` in our `malloc` call, then we wouldn't have enough space to fit both help and the `\0`



```c
int main(int argc, char *argv[]) {
    // Declare a string
    char *str = "Help";
    print_chars(str);
    printf("Copied str: %s\n", str_copier(str));
    return 0;
}

// Iterates through the string and prints out each char
void print_chars(char *str) {
    int length = strlen(str);
    int i = 0;
    while (i < length) {
        // We can get a given char
        // by dereferencing the string like an array
        printf("Char: %c\n", *(str + i));
    }
}

// Returns a malloced copy of the string
char *str_copier(char *str) {
    // strlen gets the length of the string
    // WITHOUT the null terminator
    int length = strlen(str);

    // Let's create the new buffer, NOTICE THE + 1
    // We need the +1 to make room for the null terminator
    char *copied = malloc(sizeof(char) * (length + 1));

    // Copies str into copied
    strcpy(copied, str);
    return copied;
}
```

Review of strings

- Sequence of zero or more characters, terminated by `NUL` (literally, the integer value `'\0'`)
- `NUL` terminates a string, but isn't part of it
  - important for `strlen()` – length doesn't include the `NUL`
- Strings are accessed through pointers/array names
- `string.h` contains prototypes of many useful functions



String literals

- Evaluating "dog" results in memory allocated for three characters 'd ', ' o ', ' g ', plus terminating NUL

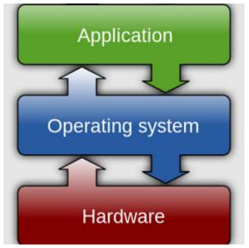
```
char* m = "dog";
```

- Note: If m is an array name, subtle difference:

```
char m[10] = "dog";
```

10 bytes are allocated for this array

This is not a string literal;
It's an array initializer in disguise!
Equivalent to
`{'d','o','g','\0'}`



String manipulation functions

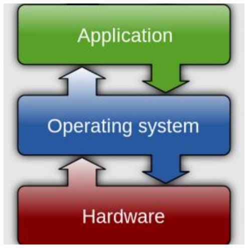
- Read some “source” string(s), possibly write to some “destination” location

```
char* strcpy(char* dst, char const* src);
char* strcat(char* dst, char const* src);
```

- Programmer’s responsibility to ensure that:
  - destination region large enough to hold result
  - source, destination regions don’t overlap
    - “undefined” behavior in this case
    - according to C spec, anything could happen!

```
char m[10] = "dog";
strcpy(m+1, m);
```

Assuming that the implementation of `strcpy` starts copying left-to-right without checking for the presence of a terminating `NUL` first, what will happen?



strlen() and size_t

```
size_t strlen(char const* string);
/* returns length of string */
```

- `size_t` is an unsigned integer type, used to define sizes of strings and (other) memory blocks
  - Reasonable to think of "size" as `unsigned`"...
  - But beware! Expressions involving strlen() may be unsigned (perhaps unexpectedly)

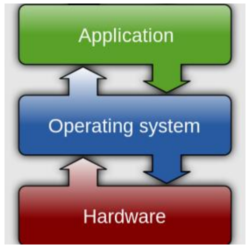
```
if (strlen(x) - strlen(y) >= 0) ...
```

always true!

- avoid by casting:

```
((int) (strlen(x) - strlen(y)) >= 0)
```

  - Problem: what if x or y is a very large string?
- a better alternative: `(strlen(x) >= strlen(y))`

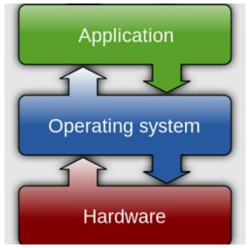


strcmp() “string comparison”

`int strcmp(char const* s1, char const* s2);`

- returns a value less than zero if `s1` precedes s2 in lexicographical order;
- returns zero if `s1` and `s2` are equal;
- returns a value greater than zero if s1 follows `s2`.

- Source of a common mistake:
  - seems reasonable to assume that `strcmp` returns “true” (nonzero) if `s1` and `s2` are equal; “false” (zero) otherwise
  - In fact, exactly the opposite is the case!



Restricted vs. unrestricted string functions

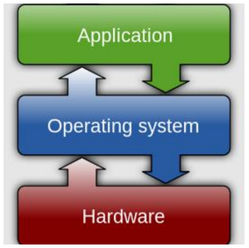
- Restricted versions: require an extra integer argument that bounds the operation

```
char* strncpy(char* dst, char const* src, size_t len);
char* strncat(char* dst, char const* src, size_t len);
```

```
int strncmp(char const* s1, char const* s2, size_t len);
```

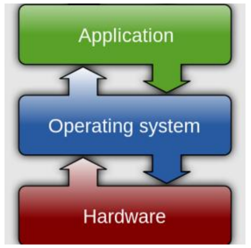
- "safer" in that they avoid problems with missing NUL terminators
- safety concern with `strncpy`:
- If bound isn't large enough, terminating NUL won't be written
- Safe alternative:

```
strncpy(buffer, name, BSIZE);
buffer[BSIZE-1] = '\0';
```



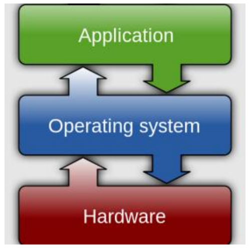
String searching

```
char* strpbrk(char const* str, char const* group);
/* return a pointer to the first character in str
   that matches *any* character in group;
   return NULL if there is no match */

size_t* strspn(char const* str, char const* group);
/* return number of characters at beginning of str
   that match *any* character in group */
```



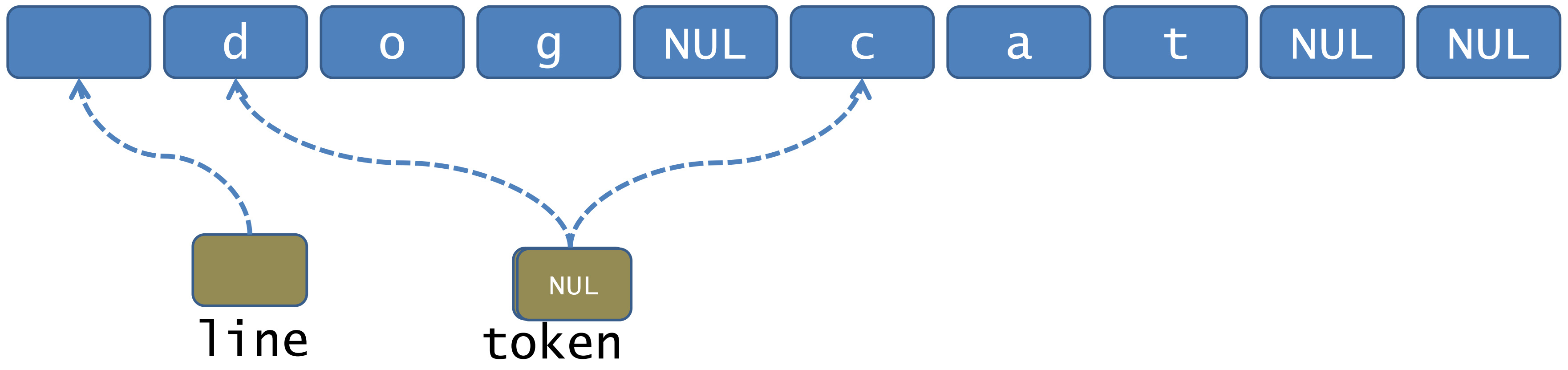
strtok “string tokenizer”

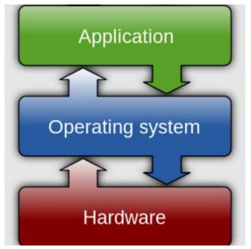
```
char* strtok(char* s, char const* delim);
/* delim contains all possible ”tokens”:
   characters that separate ”tokens”.
   if delim non-NULL:
      return ptr to beginning of first token in s,
      and terminate token with NUL.
   if delim is NULL:
      use remainder of untokenized string from the
      last call to strtok */
```



strtok in action

```
for (token = strtok(line, whitespace);
             token != NULL;
             token = strtok(NULL, whitespace))
      printf("Next token is %s\n", token);
```





An implementation of strtok

```
char* strtok(char* s, const char* delim) {
    static char *old = NULL;
    char *token;
    if (! s) { s = old; if (! s) return NULL; }
    if (s) {
      s += strspn(s, delim);
      if (*s == 0) { old = NULL; return NULL; }
    }
    token = s;
    s = strpbrk(s, delim);
    if (s == NULL) old = NULL;
    else { *s = 0; old = s + 1; }
    return token;
}
```

`old` contains the remains of an earlier `s` value (note use of `static`)

`NULL` has been passed in for `s`, so consult `old`

`strspn` returns number of delimiters at beginning of s – skip past these characters

strpbrk gives the position of the next delimiter. `s` is updated to this position, but `token` still points to the token to return.

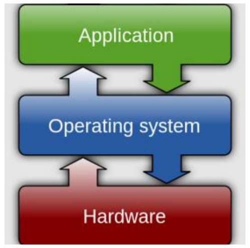
Memory operations

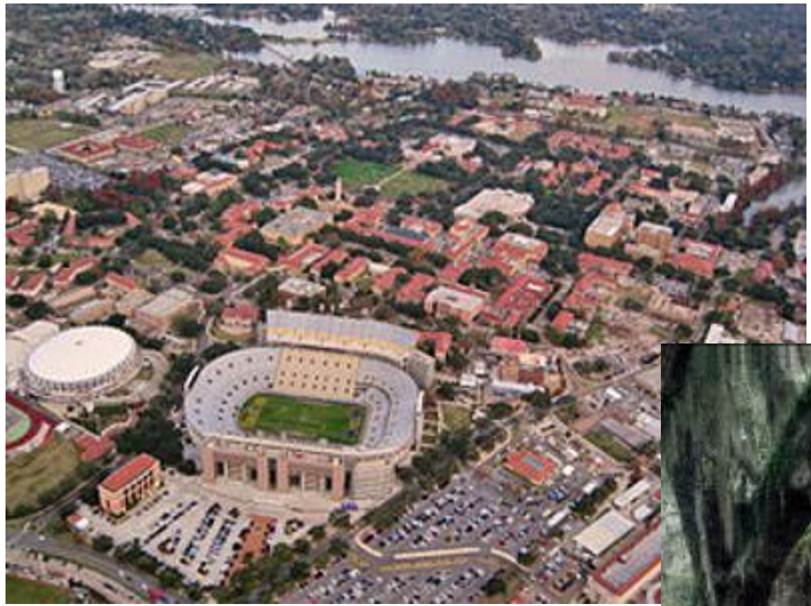
- Like string operations, work on sequences of bytes
  - but do not terminate when NUL encountered

```
void* memcpy(void* dst, void const* src, size_t length);
void* memcmp(void const* a, void const* b, size_t length);
```

- Note: `memmove` works like `memcpy`, but allows overlapping source, destination regions
- Remember, these operations work on bytes
  - If you want to copy N items of type T, get the length right:

```
    memcpy(to, from, N * sizeof(T))
```

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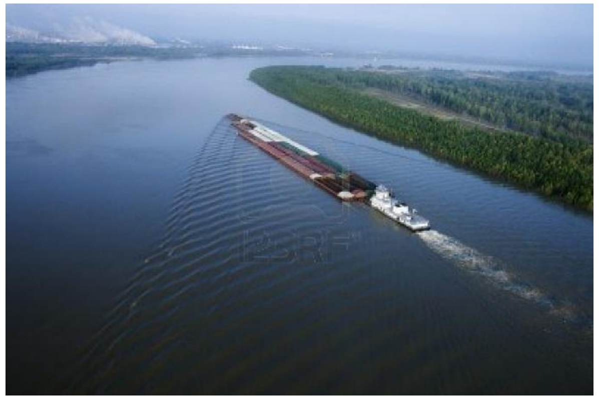

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