C: Pointers, Arrays, and strings

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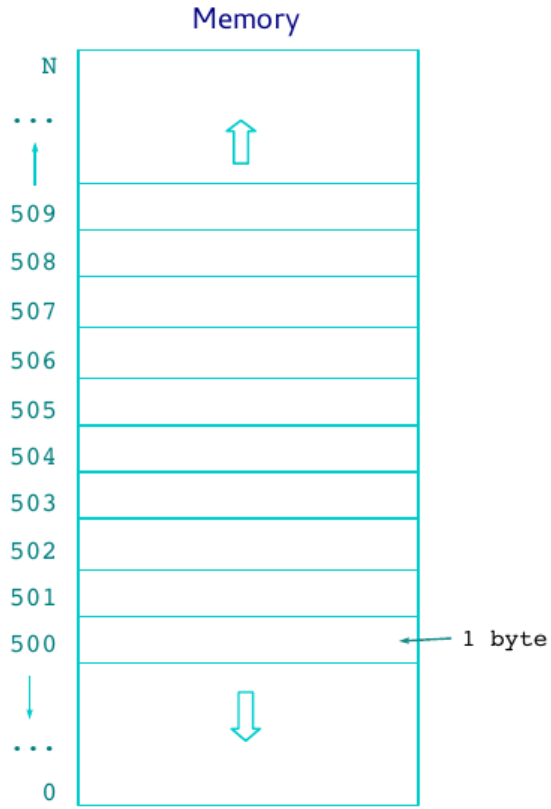
Pointers and Arrays

- A *pointer* is a variable that stores the address of another variable.
- Pointers are similar to *reference* variables in Java.
- May be used to produce more compact and efficient code (but can be tricky to understand and debug if not used carefully!)
- Pointers allow for complex "linked" data structures (e.g. linked lists, binary trees)
- Pointers allow for passing function parameters by reference instead of by value.
- Pointers and arrays are closely related.

Memory Organization

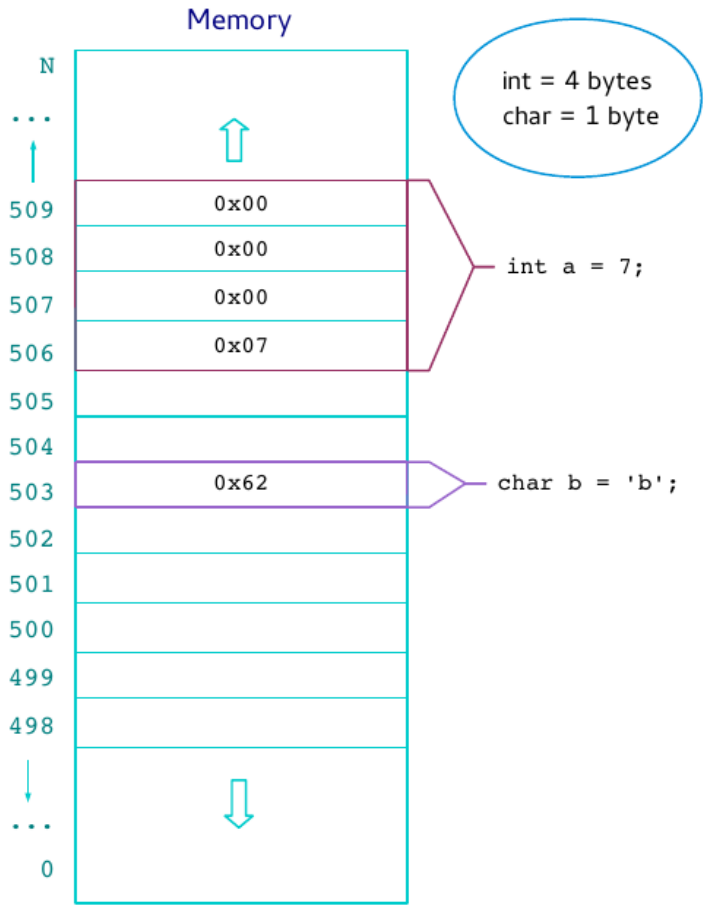
- Memory is an array of consecutively addressed cells.
- Typical size of each cell is 1 byte.
- A `char` takes one byte whereas other types use multiple cells depending on their size



Memory Organization

Example:

```
int a = 7;
char b = `b';
```



Pointer Syntax

- **Address operator (&):** gives the address in memory of an object.

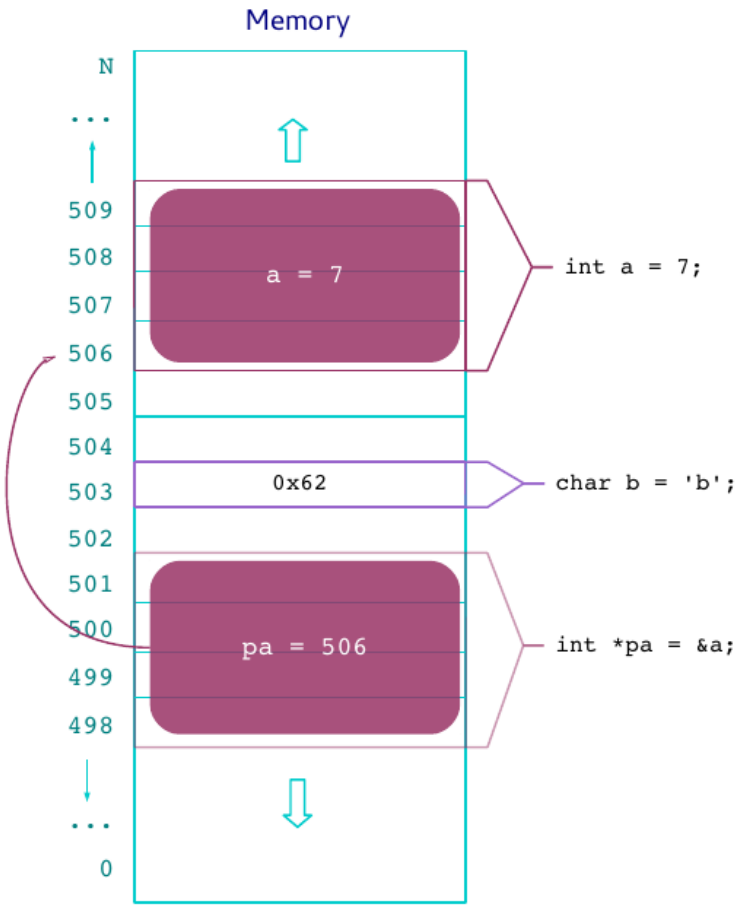
```
p = &c;     // p points to c
             // (address of c is assigned to p)
```

- **Indirection or dereferencing operator (*):** Gives access to the object a pointer points to.
- How to declare a pointer variable? Declare using the type of object the pointer will point to and the * operator.

```
int *pa; //a pointer that points to an int
double *pb; //a pointer that points to a double
```

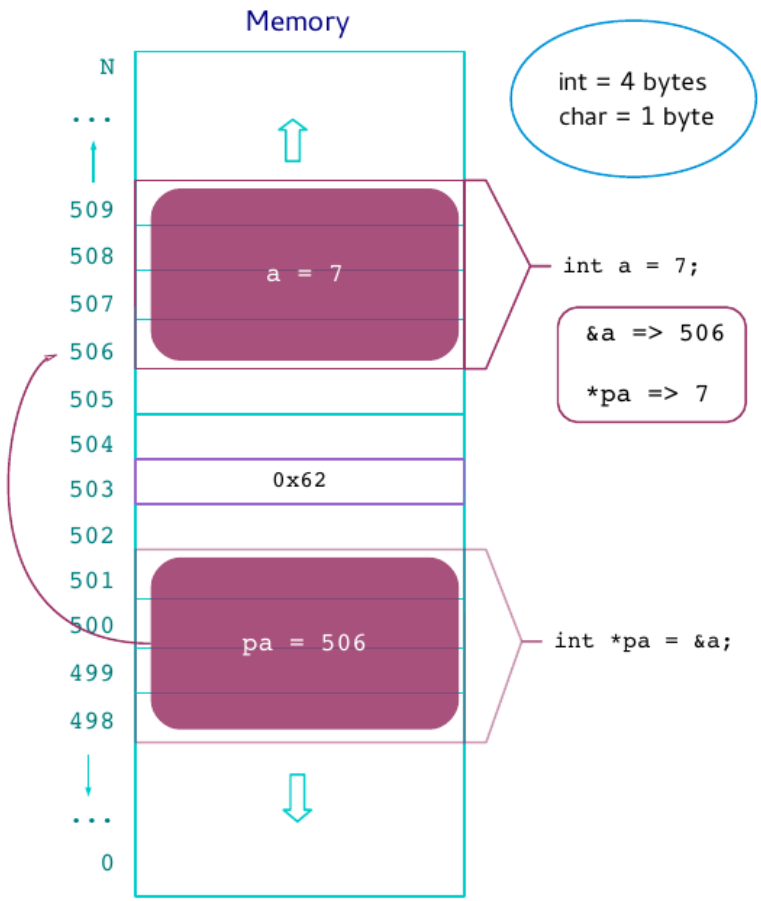
Pointers Illustrated (1)


```
int a = 7;
char b = `b';

int *pa = &a;    // pa points to a
```



Pointers Illustrated (2)


```
int a = 7;
char b = `b';

int *pa = &a;    // pa points to a
int c = *pa;     // c = 7
```



Pointers Example 1

- Consider the following declaration

```
int x = 1, y = 2 ;
int *ip;  // ip is a pointer to an int
```

- Now we use the address & and dereferencing * operators:

```
ip = &x;  /* ip now points to x */
y = *ip;  /* y is now 1 */
*ip = 10; /* x is now 10 */
```

- Note that `*ip` can be used any place `x` can be used. Continuing the example:

```
*ip = *ip + 1; /* x is now 11 */
*ip += 1;      /* x is now 12 */
++*ip;         /* x is now 13 */
(*ip)++;       /* x is now 14, parentheses required */
```

- See full example at C-examples/pointers-and-arrays/pointers1.c.

Pointers as Function Arguments


```c
/* WRONG! */
void swap(int x, int y)
{
    int tmp;
    tmp = x;
    x = y;
    y = tmp;
}
```

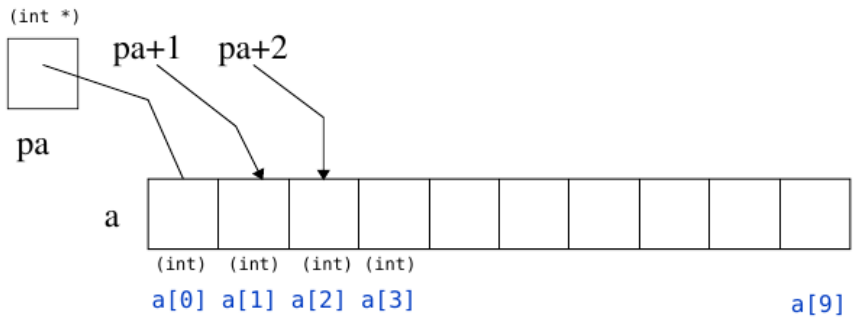
```c
/* swap *px and *py */
void swap(int *px, int *
    py)
{
    int tmp;
    tmp = *px;
    *px = *py;
    *py = tmp;
}
```

- The function on the left is called as `swap(a, b)` but doesn't work since C passes arguments to functions by value (same as Java).
- The one on the right will be called as `swap(&a, &b)` and works.
- See full example at C-examples/pointers-and-arrays/swap.c.
- Demo using the GDB debugger

Pointers and Arrays

- The name of an array is a pointer to the element zero of the array. So we can write

```
int a[10];
int *pa = &a[0]; // or int *pa = a;
```



- Accessing the ith element of an array, `a[i]`, can be written as `*(a + i)`. Similarly `*(pa + i)` can be written as `pa[i]`.
- Note that `pa + i` points to the ith object beyond `pa` (advancing by appropriate number of bytes for the underlying type)
- Note that the name of an array isn't a variable, so we can't change it's value. So `a = pa` or `a++` aren't legal.

In Class Exercise


```
int a[10];
int *pa = &a[0]; // or int *pa = a;
```

- What happens when we run the following code?

```
pa += 1;
for (i = 0; i < 10; i++)
    printf("%d ", pa[i]);
```

- What happens when we run the following code (after the above statements)?

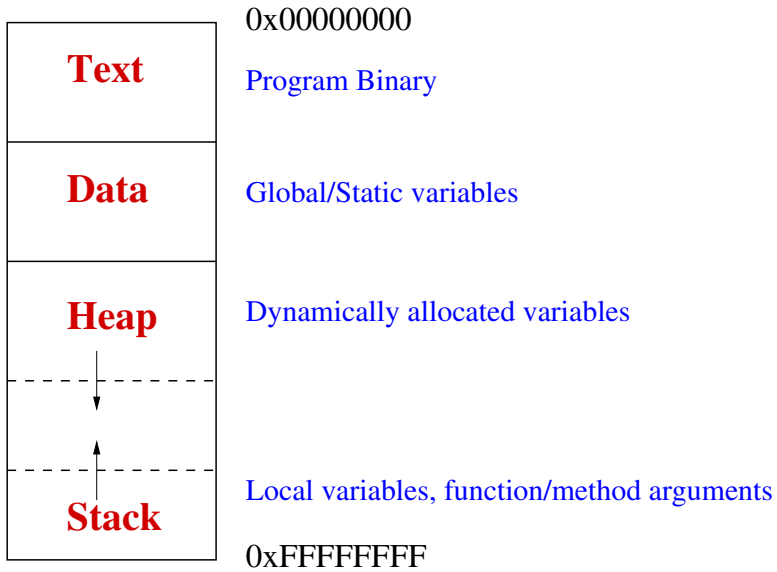
```
pa = a;
pa--;
printf("%d ", *pa);
```

1-dimensional Arrays

- Arrays can be statically declared in C, such as:

```
int A[100];
```

The space for this array is declared on the stack segment of the memory for the program (if A is a local variable) or in the data segment if A is a global variable.



Dynamically Allocating Memory (1)

- However, dynamically declared arrays are more flexible. These are similar to arrays declared using the *new* operator in Java.

```
/* Java array declaration */
int n = 100;
int[] A = new int[n];
for (i = 0; i < n; i++)
    A[i] = i; //example initialization
```

- The equivalent in C is the standard library call `malloc` and its variants.

```
int n = 100;
int *A = (int *) malloc (sizeof(int) * n);
for (i = 0; i < n; i++)
    A[i] = i; //example initialization
```

- The space allocated by malloc is in the heap segment of the memory for the program. To free the space, use the `free()` library call.

```
free(A);
```

Dynamically Allocating Memory (2)

- Use `malloc()` and `free()` to allocate and free memory dynamically.

```
#include <stdlib.h>
void *malloc(size_t size);
void free(void *ptr);
void *realloc(void *ptr, size_t size);
void *calloc(size_t nmemb, size_t size);
```

- `malloc()` takes as an argument the number of bytes of memory to allocate. Malloc does not initialize the allocated memory (why?)
- `calloc()` allocates and initializes the memory to zero. See man page for `realloc()`.
- These functions return a pointer to `void`. What does that mean?
- Example: C-examples/pointers-and-arrays/1d-arrays.c

The `void *` pointer (1)

- A `void *` pointer is a pointer that can contain the address of data without knowing its type. This allows pointers of any type to be assigned to it. This supports generic programming in C (similar to `Object` class in Java)
- Normally, we cannot assign a pointer of one type to a pointer to another type.
- A `void *` pointer cannot be dereferenced. It must be cast to the proper type of the data it points to before it can be used.
- Note that `malloc()` returns the `void *` pointer as it doesn't know what type of data we intend to store in the allocated memory. Hence, we need to cast the return value from `malloc()` to the appropriate type.

Swapping arrays using pointers

- How to swap two arrays? Here is the naive way.

```
int *A =  (int *) malloc(sizeof(int) * n);
int *B =  (int *) malloc(sizeof(int) * n);
// initialize A and B (code not shown here)
for (i = 0; i < n; i++) {
    int tmp = A[i]; A[i] = B[i]; B[i] = tmp;
}
```

- Using pointers we can merely swap the values of pointers.

```
int *B =  (int *) malloc(sizeof(int) * n);
// initialize A and B (code not shown here)
int *tmp = A; A = B; B = tmp;
```

  Simpler and far more efficient!
- Example: C-examples/pointers-and-arrays/array-swap.c

Address Arithmetic (1)

- Pointers of the same type can be assigned to each other. Pointers of any type can be assigned to a pointer of type `void *` as an exception.

```
int x = 101;
int *pa = &x;
int *pi = pa;
double *pd = pa; // ILLEGAL
void *pv = pa;
```

- The constant zero represents the null pointer, written as the constant `NULL` (defined in `<stdio.h>`). Assigning or comparing a pointer to zero is valid.

```
int *pa = NULL;
if(pa == NULL) {
   // don't try to dereference pa.
}
```

Address Arithmetic (2)

- Pointers can be compared or subtracted if they point to the members of the same array.
- Adding/subtracting a pointer and an integer is valid.
- All other pointer arithmetic is illegal.
- The C standard implies that we cannot do arithmetic with a `void *` pointer but most compilers implement it. For the purposes of arithmetic, they treat `void *` as a `char *`. For example, incrementing a `void *` pointer will increment it by one byte.
- Pointer and address arithmetic is one of the strengths of C.
- Example: C-examples/pointers-and-arrays/pointer-types.c

Pointer Exercise

Consider the following code:

```
int *A;
void *ptr;

A = (int *) malloc(sizeof(int) * n);
ptr = A;
```

Based on the above code, mark all of the following expressions that correctly access the value stored in `A[i]`.

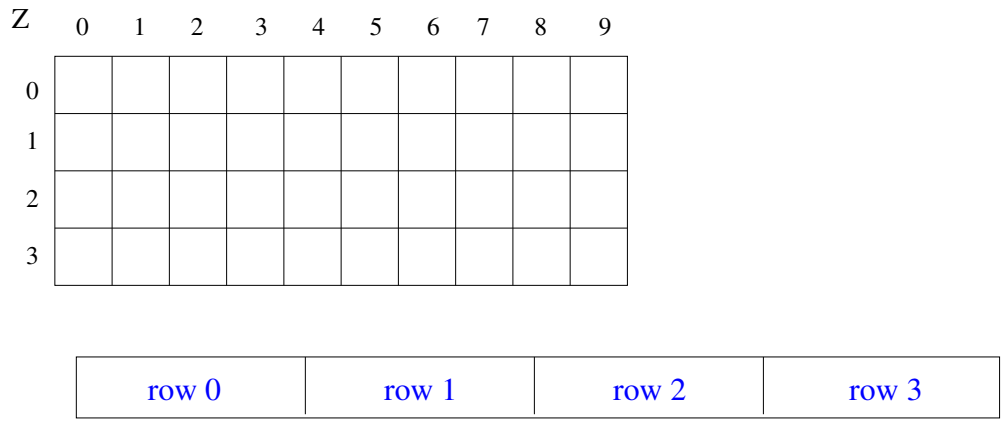
1. `*(A + i)`
2. `*(ptr + i)`
3. `*(int *)(ptr + i)`
4. `*((int *)ptr + i)`
5. `*(ptr + sizeof(int)*i)`

Two-dimensional Arrays

- A 2-dimensional array can be statically allocated in C as shown in the following example:

```
int Z[4][10];
```

- This array is laid out in memory in row major order, that is, it is laid out as a 1d array with row 0 first followed by row 1, row 2 and then row 3.



Row Major Layout

- Some languages use a column major layout for 2-d arrays, which is column 0, then column 1, . . . , and finally column 9 in the above example.

Two-dimensional Arrays

- A 2-dimensional array can be dynamically allocated in C as shown in the following example:

```
int **X;
X = (int **) malloc(n * sizeof(int *));
for (i=0; i<n; i++)
    X[i] = (int *) malloc(n * sizeof(int));
```

- Now `X` can be used with the normal array syntax, as below

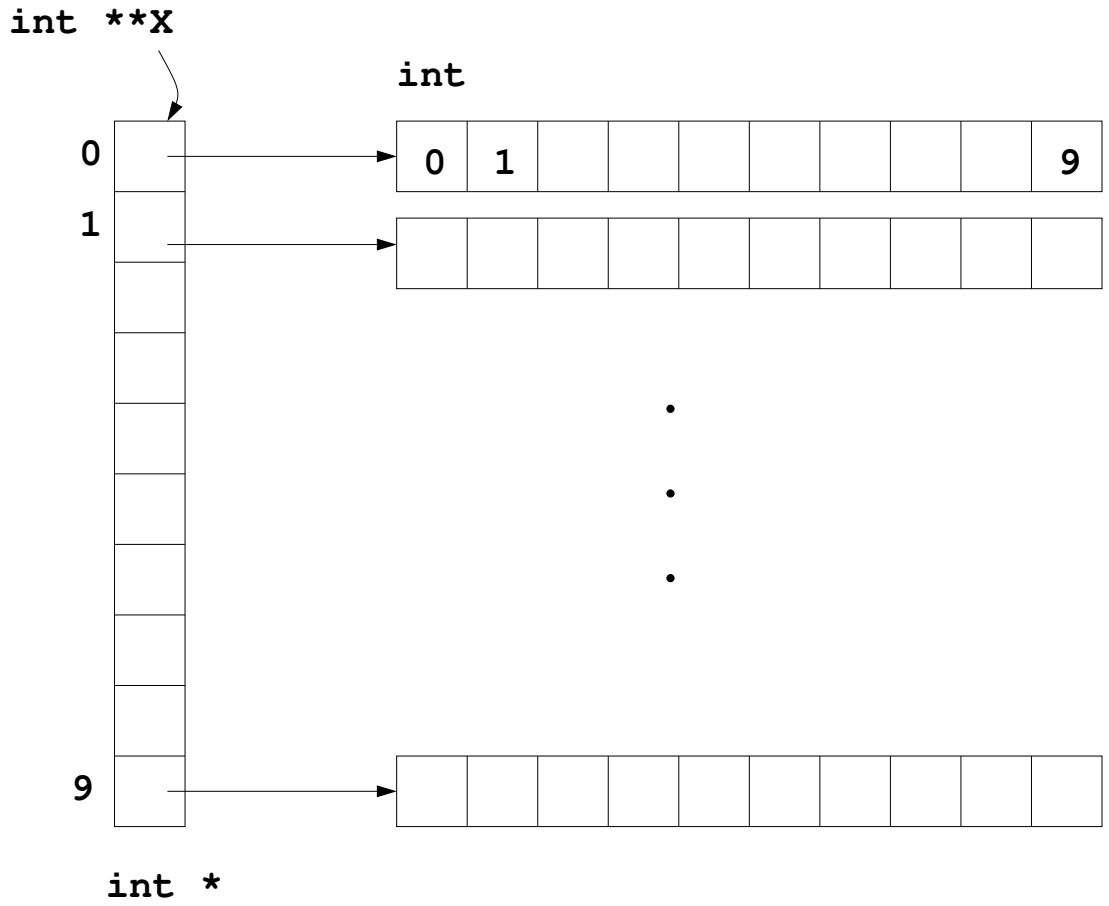
```
for (i=0; i<n; i++)
    for (j=0; j<n; j++)
        X[i][j] = i;
```

- To free the 2-dimensional array, we need to reverse all the calls to `malloc()`, as shown below:

```
for (i=0; i<n; i++)
        free(X[i]);
free(X);
```

- See full example at C-examples/pointers-and-arrays/2d-arrays.c

Layout of a Dynamically Allocated 2d Array



3-dimensional Arrays

- **In-class exercise**.Write code to dynamically allocate a 3-dimensional array of characters named `X` with size $p \times q \times r$ (*Hint: Mind your p's and q's* :-))
- **In-class exercise**. Come up with some application examples that could benefit from a 3-dimensional array
- Draw a picture of the memory layout for the 3-dimensional array allocated above.
- **Takeaway!** Write code to properly free the 3-dimensional array allocated above

C-style Strings

A C-style string is an array of characters terminated by the null character - '\0' (ASCII code = 0).

- There are four ways to declare a string.
  - Modifiable, fixed size array. Compiler determines size based on string literal (e.g. magma takes 6 chars). Use this if you know the length or value of the string at compile-time.

```
char s0[] = "magma";
s0[0] = 'd'; /* legal */
s0 = "magma"; /* illegal */
```

  - Pointer to un-named, static, read-only array.

```
char *s1 = "volcano";
s1[0] = 'm'; /* illegal - read only*/
s1 = "lava"; /* legal */
```

  - Empty, fixed size array.

```
char s2[MAXLEN];
```

  - Uninitialized pointer. Use this if you don't know the length of the potential string until run-time.

```
char *s3;
/* Some later point in your program...*/
s3 = (char *) malloc(sizeof(char) * (strlen(s0) +
1));
```

C-style Strings

- C doesn't provide strings as a basic type so we use functions to do operations with strings...
- The header file is `string.h`
- See man page for `string` for a list of all C string functions.
- Common string manipulation functions: `strlen()`, `strcat()`, `strncat()`, `strcpy()`, `strncpy()`, `strcmp()`, `strncmp()`, `strtok()`, `strsep()`, `strfry()` etc.
- Copying strings. What is wrong with the following? Read man 3 strcpy.

```
strcpy(dest, src); /* not safe */
```

We can solve this using `strncpy()`

```
strncpy(dest, src, MAXLEN); /* safer, but read man page */
```

Better solution is to allocate correct size, then copy.

```
char *dest = (char *) malloc(sizeof(char)*(strlen(src)+1));
strcpy(dest, src);
```

String Copy Example


```c
/* strcpy; copy t to s, array version */
void strcpy(char *s, char *t) {
    int i=0;
    while ((s[i] = t[i]) != '\0')
        i++;
}
```

```c
/* strcpy; copy t to s, pointer version 1 */
void strcpy(char *s, char *t) {
    int i=0;
    while ((*s = *t) != '\0'){
        s++;
        t++;
    }
}
```

String Copy Example (contd.)


```c
/* strcpy; copy t to s, pointer version 2 */
void strcpy(char *s, char *t) {
    while ((*s++ = *t++) != '\0')
        ;
}
```

```c
/* strcpy; copy t to s, pointer version 3 */
void strcpy(char *s, char *t) {
    while ((*s++ = *t++))
        ;
}
```

See page 51 of K&R for why you can use an assignment expression as a boolean.

Recommend the use of parentheses around assignment used as a boolean

String Comparison

- `strcmp(s, t)` returns negative, zero or positive if `s` is lexicographically less, equal or greater than `t`. The value is obtained by subtracting the characters at the first position where `s` and `t` differ.

```
/* strcmp: return <0 if s<t, 0 if s==t, >0 if s>t */
int strcmp(char *s, char *t) {
    int i;
    for (i = 0; s[i] == t[i]; i++)
        if (s[i] == '\0')
            return 0;
    return s[i] - t[i];
}
```

String Comparison (contd.)

The pointer version of `strcmp`:

```
/* strcmp: return <0 if s<t, 0 if s==t, >0 if s>t */
int strcmp(char *s, char *t) {
    for ( ; *s == *t; s++, t++)
        if (*s == '\0')
            return 0;
    return *s - *t;
}
```

String Examples

- A String Example: C-examples/strings/strings-ex1.c
- A String Tokenizing Example: C-examples/strings/strings-ex2.c
- A Better String Tokenizing Example: C-examples/strings/strings-ex3.c

Other String Tokenizing Functions

- Use `strsep()` in cases where there are empty fields between delimiters that `strtok()` cannot handle.

Command line arguments

- Recommended prototype for the main function:

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

or

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

- `argc` C-style strings are being passed to the main function from `argv[0]` through `argv[argc-1]`. The name of the executable is `argv[0]`, the first command line argument is `argv[1]` and so on. Thus `argv` is an array of pointers to `char`.
- **In-class Exercise**. Draw the memory layout of the `argv` array.

Variable Argument Lists in C (1)

- C allows a function call to have a variable number of arguments with the variable argument list mechanism.
- Use *ellipsis* `...` to denote a variable number of arguments to the compiler. the ellipsis can only occur at the end of an argument list.
- Here are some standard function calls that use variable argument lists.

```
int printf(const char *format, ...);
int scanf(const char *format, ...);
int execlp(const char *file, const char *arg,
    ...);
```

- See `man stdarg` for documentation on using variable argument lists. In particular, the header file contains a set of macros that define how to step through the argument list.
- See Section 7.3 in the K&R C book.

Variable Argument Lists in C (2)

Useful macros from `stdarg` header file.

- `va_list argptr;` is used to declare a variable that will refer to each argument in turn.
- `void va_start(va_list argptr, last);` must be called once before `argptr` can be used. `last` is the name of the last variable before the variable argument list.
- `type va_arg(va_list ap, type);` Each call of `va_arg` returns one argument and steps ap to the next; `va_arg` uses a type name to determine what type to return and how big a step to take.
- `void va_end(va_list ap);` Must be called before program returns. Does whatever cleanup is necessary.
- It is possible to walk through the variable arguments more than once by calling `va_start` after `va_end`.

Variable Argument Lists Example


```c
/* C-examples/varargs/test-varargs.c */
#include <stdio.h>
#include <stdarg.h>

void strlist(int n, ...)
{
  va_list ap;
  char *s;

  va_start(ap, n);
  while (1) {
    s = va_arg(ap, char *);
    printf("%s\n",s);
    n--;
    if (n==0) break;
  }
  va_end(ap);
}
int main()
{
  strlist(3, "string1", "string2", "string3");
  strlist(2, "string1", "string3");
}
```

Exercises

- Reading Assignment: Section 5.1-10. Skim through Sections 5.11 and 5.12 for now.
- Exercises: 5-3, 5-5, 5-13.