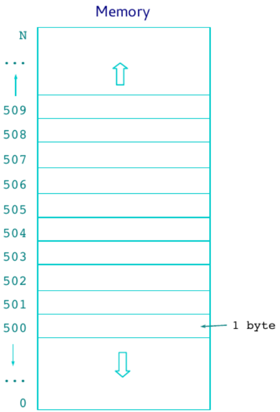
Pointers and Arrays

- 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

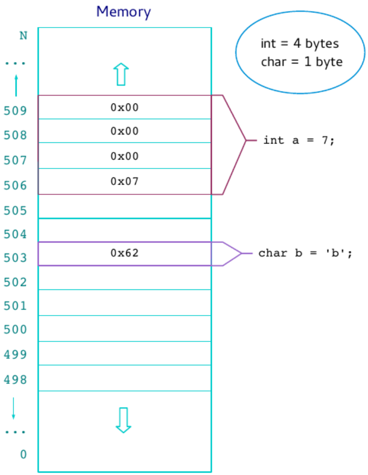
- Memory is an array of consecutively addressed memory cells.
- Typical size of each cell is 1 byte.
- A `char` takes one byte whereas other types use multiple cells depending on their size.



Memory Organization

Example:

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



Pointer Syntax

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

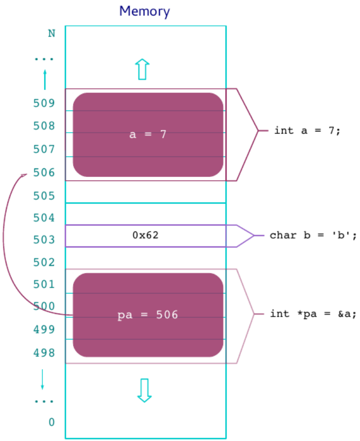
```
p = &c;     /* p points to c */
            /* (address of c is assigned to p) */
```

- 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 object */
double *pb; /* a pointer that points to a double object */
```

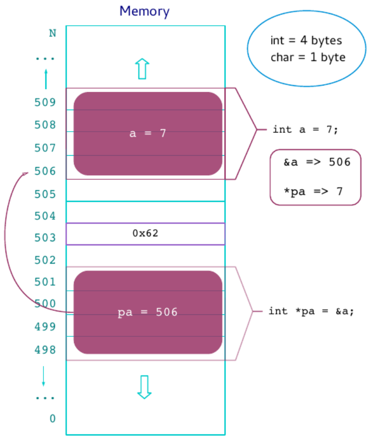
Pointers Illustrated (1)

```
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 are required */
```

- See full example at `C-examples/pointers-and-arrays/pointers1.c`
- Demo using the Eclipse debugger

Pointers as Function Arguments

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

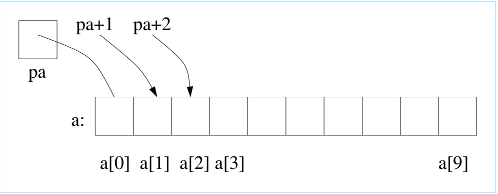
```
/* swap *px and *py */
void swap(int *px, int *py)
{
    int tmp;
    tmp = *px;
    *px = *py;
    *py = tmp;
}
```

- 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.

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]; /* same as pa = a */
```



- Accessing the *i*th 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 *i*th object beyond `pa` (advancing by appropriate number of bytes for the underlying type)
- Note that the name of an array isn't an variable unlike a pointer. So `a = pa` or `a++` aren't legal.

In Class Exercise

```
int a[10];
int *pa = &a[0]; /* same as 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?

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

- 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?

The `void *` pointer

- 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.
- 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.
- 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
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 *A =  (int *) malloc(sizeof(int) * n);
int *B =  (int *) malloc(sizeof(int) * n);
// initialize A and B

int *tmp = A; A = B; B = tmp;
```

  Simpler and far more efficient!
- Example `C-examples/pointers-and-arrays/1d-arrays.c`.

Address Arithmetic

- 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.
- 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.
- 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.
- Pointer and address arithmetic is one of the strengths of 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]`.

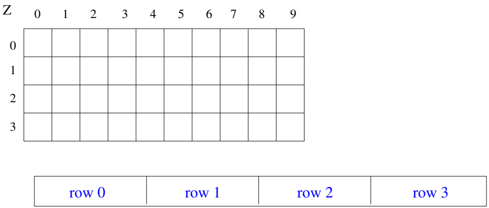
1. `*(A + i)`
2. `*(ptr + i)`
3. `*(int *)(ptr + i)`
4. `*((int *)ptr + i)`
5. `*(ptr + sizeof(int)*i)`

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

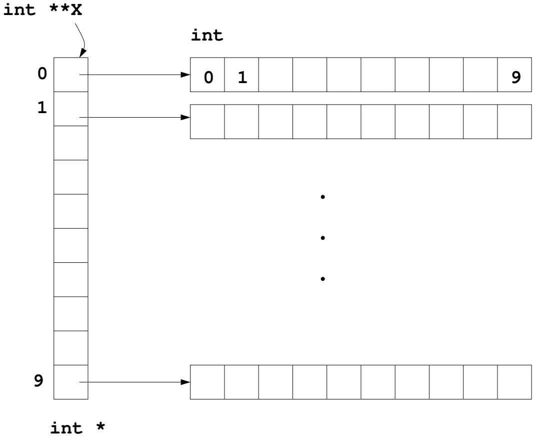
```
for (i=0; i<n; i++)
    for (j=0; j<n; j++)
        X[i][j] = i;
```

- 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`
- Watch demo movie showing how you can examine a 2-d array in the Eclipse debugger.
  http://cs.boisestate.edu/~amit/teaching/253/media/examine-2d-array-in-eclipse.mpg

Layout of a Dynamically Allocated 2d Array



3-dimensional Arrays

- **In-class team 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 team 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 (ASCII code = 0).

- The header file is `string.h`
- See man page for `string` for a list of all C string functions.
- Four ways of declaring a string.

```
char s0[] = "magma"; /* declares a fixed size array */
char *s1 = "volcano";
char s2[MAXLEN];
char *s3; /* uninitialized */
```

```
strcpy(s2, s1);
/* strncpy(s2, s1, MAXLEN); */ /* safer */
s3 = (char *) malloc(sizeof(char)*(strlen(s1)+1)); /* even safer */
strcpy(s3, s1);
```

- C doesn't provide strings as a basic type so we use functions to do operations with strings...
- Common string manipulation functions: `strlen()`, `strcat()`, `strncat()`, `strcpy()`, `strncpy()`, `strcmp()`, `strncmp()`, `strtok()`, `strsep()`, `strfry()` etc.

String Copy Example

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


/* 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.)

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

```
/* 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;
}
```

strings-ex1.c: A String Example

```
/* C-examples/strings/strings-ex1.c */
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
const int MAX_LENGTH = 256;
int main(int argc, char **argv) {
    char *r = "winnie";
    char *s;
    char q[MAXLEN];
    int stat;

    s = (char *) malloc(sizeof(char) * MAXLEN);
    strcpy(s,"tigger"); /* initialize string s */
    strcpy(q, "pooh");
    printf("String r = %s length of r = %d\n",r, strlen(r));
    strcpy(q, r); // r is copied to q
    strcat(s, r);
    printf("r = %s s = %s q = %s \n",r, s, q);

    stat = strcmp(r,s);
    if (stat < 0)
        printf("r < s (lexicographically)\n");
    else if (stat == 0)
        printf("r == s (lexicographically)\n");
    else
        printf("r > s (lexicographically)\n");

    free(s);
    exit(0);
}
```

strings-ex2.c: A String Tokenizing Example

```
/* C-examples/strings/strings-ex2.c */
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
const int MAX_LENGTH = 1024;
int main() {
    char *token;
    char *save;
    char *s;
    char *delimiter = " ;";

    s = (char *) malloc(sizeof(char)*MAX_LENGTH);
    strcpy(s, " tigger pooh abracadabra woo ;; woo & choo choo");
    /* save a copy because strtok will eat it up */
    save = (char *) malloc(sizeof(char)*(strlen(s)+1));
    strcpy(save, s);

    printf("starting to tokenize the string: %s\n", s);
    /* tokenize the string q */
    token = strtok(s, delimiter); /* use space as a delimiter */
    while (token != NULL)
    {
        printf("next token = %s\n", token);
        token = strtok(NULL,  delimiter);
    }
    s=save; /* restore s */
    return 0;
}
```

strings-ex3.c: A Better String Tokenizing Example

```
/* C-examples/strings/strings-ex3.c */
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
const int MAX_LENGTH = 1024;
const int MAX_TOKENS = 100;

int main(int argc, char **argv)
{
    char *s, *save, *nextToken, char *delimiter = " ;";
    char **token;
    int numTokens;
    s = (char *) malloc(sizeof(char) * MAX_LENGTH);
    strcpy(s, " tigger pooh abracadabra woo ;; woo & choo choo");
    save = (char *) malloc(sizeof(char)*(strlen(s)+1));
    strcpy(save, s);

    token = (char **) malloc (sizeof(char *) * MAX_TOKENS);
    /* tokenize the string s */
    nextToken = strtok(s, delimiter);
    numTokens=0;
    while (nextToken != NULL)
    {
        printf("next token = %s\n", nextToken);
        token[numTokens] = (char *) malloc(sizeof(char) * (strlen(nextToken)+1));
        strcpy(token[numTokens], nextToken);
        numTokens++;
        nextToken = strtok(NULL, delimiter);
    }
    // Now the tokens are copied into token[0..numTokens-1];
    strcpy(s, save); /* restore s */
    return 0;
}
```

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`.
- Draw the memory layout of the `argv` array.

Exercises

- Reading Assignment: Section 5.1, 5.2, 5.3, 5.5, 5.6, 5.7, 5.8, 5.9, and 5.10. Skip or skim Section 5.4. Skip Sections 5.11 and 5.12 for now.
- Exercises: 5-3, 5-5, 5-13.