COMP1917: Computing 1

9. Pointers

Reading: Moffat, Chapter 6.

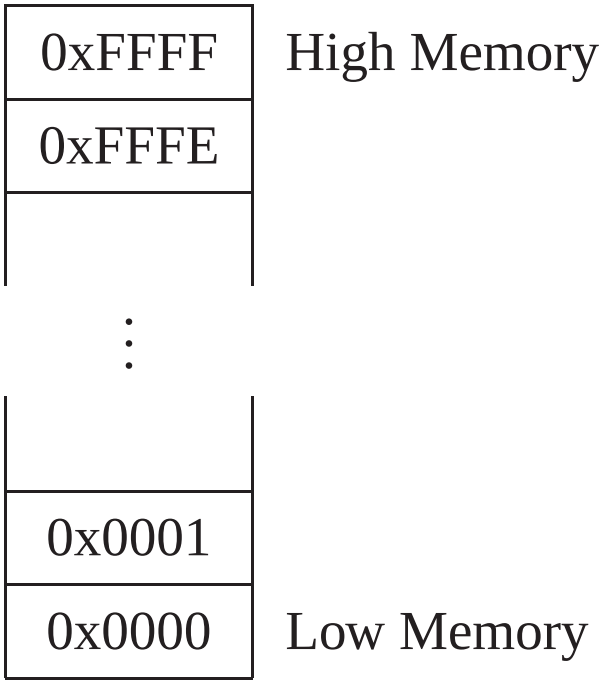
Pointers

Pointers:

- a pointer is a special type of variable for storing the memory location or “address” of another variable
- pointers shouldn’t be scary or confusing – provided they are used correctly
- pointers can make your code more compact and efficient.

Memory Structure

In order to fully understand how pointers are used to reference data in memory, here's a few basics on memory organisation.



Memory

- computer memory is a large array of consecutive data cells or bytes
- a `char` normally occupies one byte, a `short` 2 bytes, an `int` or `float` 4 bytes, a `double` 8 bytes, etc.
- when a variable is declared, the operating system finds a place in memory to store the appropriate number of bytes.
- if we declare a variable called `k`, the place where `k` is stored (also called the "address" of `k`) is denoted by `&k`
- it is convenient to print memory addresses in Hexadecimal notation

Variables in Memory

```
int k;
int m;

printf( "address of k is %X\n", &k );
printf( "address of m is %X\n", &m );
```

```
  address of k is BFFFFB80
  address of m is BFFFFB84
```

This means that `k` occupies the four bytes from `BFFFFB80 to BFFFFB83`, and `m` occupies the four bytes from `BFFFFB84 to BFFFFB87`.

Arrays in Memory

When an array is declared, the elements of the array are guaranteed to be stored in consecutive memory locations:

```
int array[5];


for( i=0; i < 5; i++ ) {
  printf("address of array[%d] is %X\n", i, &array[i]);
}
```

```
address of array[0] is BFFFFB60
address of array[1] is BFFFFB64
address of array[2] is BFFFFB68
address of array[3] is BFFFFB6C
address of array[4] is BFFFFB70
```

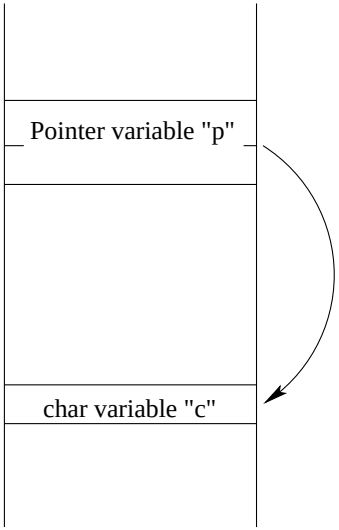
Size of a Memory Address

Just like any other variable of a certain type, a variable that is a pointer also occupies space in memory. The number of memory cells needed depends on the computer's architecture. For example:

- for an old computer, or a hand-held device with only 64KB of addressable memory, a pointer only requires 2 memory cells (i.e. 2 bytes) to hold any address from 0000 to $\text{FFFF}_{16} = 65535_{10}$
- for desktop machine with 4GB of addressable memory, a pointer requires 4 memory cells (i.e. 4 bytes) to hold any address from 00000000 to $\text{FFFFFFFF}_{16} = 4294967295_{10}$

Pointers

Suppose we have a pointer `p` that "points to" a `char` variable `c`. Assuming that the pointer `p` requires 2 bytes to store the address of `c`, here is what the memory map might look like:



The * Notation

Now that we have assigned to `p` the address of variable `c`, we need to be able to reference the data in that memory location.

operator `*` is used to access the object the pointer points to. Hence to change the value of `c` using the pointer `p`:

```
*p = 'T';    // sets the value of c to 'T'
```

The `*` operator is sometimes described as "dereferencing" the pointer, to access the underlying variable.

The * Notation *cont.*

Things to note:

- All pointers are constrained to point to a particular type of object.

```
// a potential pointer to any object of type char
char *s;

// a potential pointer to any object of type int
int *p;
```

- If pointer `p` is pointing to an integer variable `x`, then `*p` can occur in any context that `x` could.

Examples of Pointers

```
 int *p; int *q; // this is how pointers are declared
 int a[5];
 int x = 10, y;

 p = &x;    // p now points to x
*p = 20;    // whatever p points to is now equal to 20
 y = *p;    // y is now equal to whatever p points to
 p = &a[2]; // p points to an element of array a[]
 q = p;     // q and p now point to the same thing
 q++;       // q now points to the next element of a[]
```

Example - Swapping Variables

Question:

Can we write a function to “swap” two variables?

We will first show how to do it the wrong way, and then the right way (using pointers).

`swap()` - the wrong way

```
void swap( int a, int b )
{
  int temp;
  // only the local "copies" of a and b will swap
  temp = a;  a = b;  b = temp;
}
int main( void )
{
   int a = 5, b = 7;
   swap( a, b );
   // a and b will still have their original values
   printf( "a = %d, b = %d\n", a, b );
}
```

Function Parameters and Pointers

- in C, parameters are “call-by-value”
  - changes made to the value of a parameter do not affect the original variable
  - function `swap()` tries to swap the values of *a* and *b*, but fails because it only swaps the copies, not the “real” variables in `main()`
- we can achieve “simulated call-by-reference” by passing pointers as parameters
  - this allows the function to change the “actual” value of the variables.

`swap()` - the right way

```
void swap( int * p, int * q )
{
  int temp;
  // this will change the actual values of a and b
  temp = *p;  *p = *q;  *q = temp;
}
int main( void )
{
   int a = 5, b = 7;
   swap( &a, &b );
   // a and b will now be successfully swapped
   printf( "a = %d, b = %d\n", a, b );
}
```

Pointers and Arrays

Pointers and arrays are very similar. In general, any operation that can be achieved using an array can also be achieved using a pointer.

Hence if we have:

```
int a[10], x;
int *p;

p = &a[0]; // or equivalently   p = a;
```

then `p` now points to the start of the array `a`. Consequently:

`x = a[4]` is the same as `x = *(p+4)`

Pointers and Arrays *cont.*

- In general, if `p` points to `a[0]`, then

  `a[i]` is the same as `*(p+i)`

- This is true regardless of the *type* or *size* of the variables in the array `a[]`. Hence:
  - `(p+1)` always points to the next object;
  - `(p+i)` points to the i-th object beyond `p`

Pointers and Arrays *cont.*

The similarity between arrays and pointers does not end there. It is possible to write:

`*(p+i)` as `p[i]`

and

`a[i]` as `*(a+i)`

Given that it is possible to write `a[i]` as `*(a+i)`, then `a` must be a synonym for the location of the array's initial element. Hence the following are equivalent:

`p = &a[0]` is the same as `p = a`

Pointer Arithmetic

A subtle point to note:

- when you add (or subtract) an integer `n` from a pointer `p`, *e.g.*:

```
p += n;
```

  the result is that `p` now points to the n-th object beyond the one `p` previously pointed to.

- this is true regardless of the kind of object `p` points to.
- in other words, `n` is scaled according to the size of the type of object `p` points to, which is determined by the declaration of `p`.

Pointers and Arrays *cont.*

Beware: although there are lots of similarities between array names and pointers, the following caveats apply:

- a pointer is a variable, so `p++` is ok.
- an array name is **not** a variable, so `a++` is **not** ok
  (for this reason, an array is sometimes regarded as a “constant pointer”)
- an array definition causes an allocation of data storage space equal to the size specified.
- when a pointer is declared, no space is set aside to store anything other than the pointer itself.

Expression and Precedence

Both * and &, being unary operators, have a precedence higher than arithmetic operators. So assuming p is a pointer then:

```
*p  = *p + 3; // add 3 to whatever p points to
*p -=  2;     // subtract 2 from whatever p points to
*p != *q      // compare the values p and q point to
```

But note how * interacts with ++ and --

```
 x = *(p++);  // increment the pointer p itself
 x =  *p++;   // same as above, but considered bad style
 x = (*p)++;  // increment what p points to
```

Passing Arrays as Parameters

When an array is passed as a parameter to a function, what the function receives is actually a pointer to the first element of the array.
Hence, the function can change the actual values stored in the array (as in the “swap” example).

```
int main( void )
{
   int count[26] = { 0 };

   get_freq( count ); // count frequencies of input chars

   print_freq(count); // print the frequencies in a table
}
```

Pointer Hazards

If an uninitialized or otherwise invalid pointer is used, or an array is accessed with a negative or out-of-bounds index, one of a number of things might happen:

- program aborts immediately with a “segmentation fault”
- a mysterious failure much later in the execution of the program
- incorrect results, but no obvious failure
- correct results, but maybe not always, and maybe not when executed on another day, or another machine

The first is the most desirable, but cannot be relied on.

`malloc()` and `free()`

What happens if you do not know the size of an array at compile time?

You can dynamically create an array at run-time and assign it to a pointer, using the `malloc()` function.

The `malloc()` function is used to acquire a block of memory of a specified size from a central pool of memory called the "heap".
If successful, `malloc()` returns a pointer to the space requested,
else it returns a `NULL` pointer if the request cannot be satisfied.

The `free()` function is used to free up a previously `malloc`'ed block of memory, i.e. the parameter to `free()` must be a pointer to a space previously allocated by `malloc()`.

`malloc()` and `free()`

For example, let's assume we need a block of memory to hold an array of doubles, whose size is typed in by the user.

```
double *p;  int n;
printf("Enter size of array: ");
scanf("%d",&n);
p = (double *)malloc( n * sizeof(double));
if( p == NULL ) {
   printf( "Error: array could not be allocated.\n" );
   exit( 1 );
}

   //...we can now use p[] just like an array...

free(p);  // free up the memory that was used
```

`malloc()` and `free()`

- Because `malloc()` returns a `void *` pointer (i.e. a pointer that is not typed) we need to cast the pointer into an appropriately typed pointer, in this instance we cast the pointer into a `char` pointer.
- Once you've finished using the block of memory, the memory needs to be returned back to the "heap" (central pool) using the `free()` function.
- You are only allowed to `free()` a block of memory that was previously `malloc`'ed; if you attempt to free a `NULL` pointer, or an unallocated pointer, it might cause an error.
- A `malloc()` without a corresponding `free()` is called a memory leak. Memory leaks eventually lead the program to crash, and are very difficult to track down.

Two-Dimensional Arrays

When a two-dimensional array is declared, the elements of the first row are stored into consecutive memory locations, followed by those of the second row, and so on.

```
float table[2][3];
```

```
   table[0][0] is at BFFFFB80
   table[0][1] is at BFFFFB84
   table[0][2] is at BFFFFB88
   table[1][0] is at BFFFFB8C
   table[1][1] is at BFFFFB90
   table[1][2] is at BFFFFB94
```