CSCI-UA.0201

Computer Systems Organization

C Programming

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Many slides of this lecture are adapted from Lewis Girod, CENS Systems Lab
http://lecs.cs.ucla.edu/~girod/talks/c-tutorial.ppt
and Clark Barrett
In 1972 Dennis Ritchie at Bell Labs writes C and in 1978 the publication of The C Programming Language by Kernighan & Ritchie caused a revolution in the computing world.
Why C?

- Mainly because it produces code that runs nearly as fast as code written in assembly language. Some examples of the use of C might be:
  - Operating Systems
  - Language Compilers
  - Assemblers
  - Text Editors
  - Print Spoolers
  - Network Drivers
  - Language Interpreters
  - Utilities
Your first goal: Learn C!

• Resources
  – These lectures
  – Additional online resources (some links on the website)

• Learning a Programming Language
  – The best way to learn is to write programs
# Writing and Running Programs

1. Write text of program (source code) using an editor such as `gedit`, save as file e.g. `my_program.c`

```c
#include <stdio.h>
/* The simplest C Program */
int main(int argc, char **argv)
{
    printf("Hello World\n");
    return 0;
}
```

2. Run the compiler to convert program from source to an “executable” or “binary”:
   ```bash
   $ gcc -Wall -g -o my_program my_program.c
   ```

3. Compiler gives errors and warnings; edit source file, fix it, and re-compile

   Run it and see if it works 😊
   ```bash
   $ ./my_program
   Hello World
   $ ▶
   ```
$ gcc -Wall -g -o my_program my_program.c

- generate all warnings
- keep debugging information
- name the generated executable (default: a.out)
- one or more C files
About C

• **Procedural language**
  - Functions calling each other, starting with `main()`.

• **Case-sensitive**
C Syntax and Hello World

#include <stdio.h>
/* The simplest C Program */
int main(int argc, char **argv)
{
    printf("Hello World\n");
    return 0;
}

#include inserts another file. "h" files are called "header" files. They contain stuff needed to interface to libraries and code in other "c" files.

This is a comment. The compiler ignores this.

The main() function is always where your program starts running.

Blocks of code are marked by { ... }

Return '0' from this function

Print out a message. '\n' means "new line".
```c
#include <stdio.h>

/* The simplest C Program */
int main(int argc, char **argv)
{
    printf("Hello World\n");
    return 0;
}
```
In Preprocessing, source code is “expanded” into a larger form that is simpler for the compiler to understand. Any line that starts with ‘#’ is a line that is interpreted by the Preprocessor.

- Include files are “pasted in” (#include)
- Macros are “expanded” (#define)
- Comments are stripped out ( /* */ , // )
- Continued lines (i.e. very long lines) are joined ( \ )
#include <stdio.h>
/* The simplest C Program */
int main(int argc, char **argv)
{
    printf("Hello World\n");
    return 0;
}

• The compiler then converts the resulting text into binary code the CPU can run directly.
• The compilation process involves really several steps:
  • **Compiler**: high level language \(\rightarrow\) assembly
  • **Assembler**: assembly \(\rightarrow\) machine code
  • **Linker**: links all machine code files and needed libraries into one executable file.
• When you type `gcc` you really invoke the compiler, assembler, and linker.
What is “Memory”?

- Is like a big table of numbered slots.
- Each slot stores a byte.

- The number of a slot is its **Address**.
- One byte **Value** can be stored in each slot.

<table>
<thead>
<tr>
<th>Addr</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
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<tr>
<td>1</td>
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<td>3</td>
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<tr>
<td>4</td>
<td>‘H’ (72)</td>
</tr>
<tr>
<td>5</td>
<td>‘e’ (101)</td>
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<tr>
<td>6</td>
<td>‘l’ (108)</td>
</tr>
<tr>
<td>7</td>
<td>‘l’ (108)</td>
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<tr>
<td>8</td>
<td>‘o’ (111)</td>
</tr>
<tr>
<td>9</td>
<td>‘\n’ (10)</td>
</tr>
<tr>
<td>10</td>
<td>‘\0’ (0)</td>
</tr>
<tr>
<td>11</td>
<td></td>
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<tr>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

Some “logical” data values span more than one slot, like the character string “Hello\n”

A **Type** names a logical meaning to a span of memory. Some simple types are:

- **char** a single character (1 slot)
- **char [10]** an array of 10 characters
- **int** signed 4 byte integer
- **float** 4 byte floating point
What is a Variable?

A **Variable** names a place in memory where you store a **Value** of a certain **Type**.

You first **Define** a variable by giving it a name and specifying the type, and optionally an initial value.

```
char x;
char y='e';
```

Initial value of `x` is undefined

Initial value

Name

Type is single character (char)

The compiler puts them somewhere in memory.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Addr</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
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<tr>
<td>x</td>
<td>4</td>
<td>?</td>
</tr>
<tr>
<td>y</td>
<td>5</td>
<td>'e' (101)</td>
</tr>
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<td>6</td>
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<td>12</td>
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</tr>
</tbody>
</table>
Multi-byte Variables

Different types consume different amounts of memory. Most architectures store data on "word boundaries", or even multiples of the size of a primitive data type (int, char).

```
char x;
char y='e';
int z = 0x01020304;
```

0x means the constant is written in hex

An int consumes 4 bytes

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Addr</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>4</td>
<td>?</td>
</tr>
<tr>
<td>y</td>
<td>5</td>
<td>'e' (101)</td>
</tr>
<tr>
<td>z</td>
<td>8</td>
<td>4</td>
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<td>9</td>
<td>3</td>
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<td>1</td>
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<tr>
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<td>12</td>
<td></td>
</tr>
</tbody>
</table>
Every Variable is Defined within some scope. A Variable cannot be referenced from outside of that scope.

Scopes are defined with curly braces { }.

The scope of Function Arguments is the complete body of the function.

The scope of Variables defined inside a function starts at the definition and ends at the closing brace of the containing block.

The scope of Variables defined outside a function starts at the definition and ends at the end of the file. Called Global Vars.

```c
void p(char x) {
    char y;
    char z;
}
void q(char a) {
    char b;
    {
        char c;
    }
    char d;
}
```
Now that we know about variables, let’s combine them to form expressions!

Expression

\[ X = 2 \times Y + Z; \]

Statement
Expressions combine Values using Operators, according to precedence.

$$1 + 2 \times 2 \rightarrow 1 + 4 \rightarrow 5$$
$$\ (1 + 2) \times 2 \rightarrow 3 \times 2 \rightarrow 6$$

Comparison operators are used to compare values.
In C: 0 means “false”, and any other value means “true”.

```c
int x = 4;
(x < 5) \rightarrow (4 < 5) \rightarrow \langle true \rangle
(x < 4) \rightarrow (4 < 4) \rightarrow 0
((x < 5) || (x < 4)) \rightarrow (\langle true \rangle || (x < 4)) \rightarrow \langle true \rangle
```

Not evaluated because first clause was true
Precedence

- Highest to lowest
  - ()
  - *, /, %
  - +, -

When in doubt, use parenthesis.
Comparison and Mathematical Operators

== equal to
< less than
<= less than or equal
> greater than
>= greater than or equal
!= not equal
&& logical and
|| logical or
! logical not

Beware in division:
If second argument is integer, the result will be integer (rounded):
5 / 10 → 0 whereas 5 / 10.0 → 0.5

Don’t confuse & and &&
1 & 2 → 0 whereas 1 && 2 → <true>

More on these in later lectures when we discuss binary numbers.
Assignment Operators

- `x = y` assign `y` to `x`
- `x++` post-increment `x`
- `++x` pre-increment `x`
- `x--` post-decrement `x`
- `--x` pre-decrement `x`

Note the difference between `++x` and `x++`:

```c
int x=5;
int y;
y = ++x;
/* x == 6, y == 6 */
```
```
int x=5;
int y;
y = x++;  
/* x == 6, y == 5 */
```

Don’t confuse `=` and `==`

```c
int x=5;
if (x==6)    /* false */
{
    /* ... */
}
/* x is still 5 */
```
```
int x=5;
if (x=6)    /* always true */
{
    /* x is now 6 */
}
/* ... */
```
Functions
What is a Function?

A Function is a series of instructions to run. You pass Arguments to a function and it returns a Value.

“main()” is a Function. It’s only special because it always gets called first when you run your program.

Return type, or void

```
#include <stdio.h>
/* The simplest C Program */
int main(int argc, char **argv)
{
    printf("Hello World\n");
    return 0;
}
```

Function Arguments

“printf()” is just another function, like main(). It’s defined for you in a “library”, a collection of functions you can call from your program.

Returning a value
A More Complex Program: pow

```
#include <stdio.h>
float pow(float x, unsigned int exp)
{
    /* base case */
    if (exp == 0) {
        return 1.0;
    }
    /* "recursive" case */
    return x*pow(x, exp - 1);
}

int main(int argc, char **argv)
{
    float p;
    p = pow(10.0, 5);
    printf("p = %f\n", p);
    return 0;
}
```

“if” statement

```
/* if evaluated expression is not 0 */
if (expression) {
    /* then execute this block */
} else {
    /* otherwise execute this block */
}
```

Tracing “pow()”:
- What does pow(5,0) do?
- What about pow(5,1)?
- What does pow(5,0) do?
- What about pow(5,1)?
Recall scoping. If a variable is valid “within the scope of a function”, what happens when you call that function recursively? Is there more than one “exp”?

Yes. Each function call allocates a “stack frame” where Variables within that function’s scope will reside.

```
#include <stdio.h>
#include <inttypes.h>

float pow(float x, unsigned int exp) {
    /* base case */
    if (exp == 0) {
        return 1.0;
    }
    /* “recursive” case */
    return x*pow(x, exp - 1);
}

int main(int argc, char **argv) {
    float p;
    p = pow(5.0, 1);
    printf("p = %f\n", p);
    return 0;
}
```

Grows
The “for” loop

The “for” loop is just shorthand for this “while” loop structure.

```c
float pow(float x, unsigned int exp) {
    float result=1.0;
    int i;
    i=0;
    while (i < exp) {
        result = result * x;
        i++;
    }
    return result;
}

int main(int argc, char **argv) {
    float p;
    p = pow(10.0, 5);
    printf("p = %f\n", p);
    return 0;
}
```
When to Use?

Different Loop-constructs
• while
• do-while
• for

Conditions
• if-else
• switch-case
Pointers:
Very strong but dangerous concept!
Can a function modify its arguments?

What if we wanted to implement a function `pow_assign()` that modified its argument, so that these are equivalent:

```c
float p = 2.0;
/* p is 2.0 here */
p = pow(p, 5);
/* p is 32.0 here */
```

```c
float p = 2.0;
/* p is 2.0 here */
pow_assign(p, 5);
/* p is 32.0 here */
```

Would this work?

```c
void pow_assign(float x, uint exp)
{
    float result=1.0;
    int i;
    for (i=0; (i < exp); i++) {
        result = result * x;
    }
    x = result;
}
```
void pow_assign(float x, unsigned int exp) {
    float result=1.0;
    int i;
    for (i=0; (i < exp); i++) {
        result = result * x;
    }
    x = result;
}

main() {
    float p=2.0;
    pow_assign(p, 5);
}

In C, all arguments are passed as values.

But, what if the argument is the address of a variable?

Remember the stack!

<table>
<thead>
<tr>
<th>float x</th>
<th>32.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>uint32_t exp</td>
<td>5</td>
</tr>
<tr>
<td>float result</td>
<td>32.0</td>
</tr>
<tr>
<td>float p</td>
<td>2.0</td>
</tr>
</tbody>
</table>
## Passing Addresses

<table>
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<th>Value</th>
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</thead>
<tbody>
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<td>3</td>
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</tr>
<tr>
<td>char x</td>
<td>4</td>
<td>‘H’ (72)</td>
</tr>
<tr>
<td>char y</td>
<td>5</td>
<td>‘e’ (101)</td>
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</tbody>
</table>

address of \( x \) \( \rightarrow 4 \)
memory content at address 4 \( \rightarrow 72 \)
This is exactly how “pointers” work.

- address of x: &x
- if y is an address, the content of the memory at that address \( \rightarrow \) *y

A “pointer type”: pointer to char

```c
void f(char * p)
{
    *p = *p - 32;
}
```

```c
char y = 101; /* y is 101 */
f(&y); /* i.e. f(5) */
/* y is now 101-32 = 69 */
```

Pointers are used in C for many other purposes:
- Passing large objects without copying them
- Accessing dynamically allocated memory
- Referring to functions
A **Valid** pointer is one that points to memory that your program controls. Using invalid pointers will cause non-deterministic behavior, and will often cause Linux to kill your process (SEGV or Segmentation Fault).

There are two general causes for these errors:
- Program errors that set the pointer value to a strange number
- Use of a pointer that was at one time valid, but later became invalid

```
char * get_pointer()
{
    char x=0;
    return &x;
}

main()
{
    char * ptr = get_pointer();
    *ptr = 12; /* valid? */
}```

Will ptr be valid or invalid?
A pointer to a variable allocated on the stack becomes invalid when that variable goes out of scope and the stack frame is “popped”. The pointer will point to an area of the memory that may later get reused and rewritten.

```c
char * get_pointer()
{
    char x=0;
    return &x;
}
main()
{
    char * ptr = get_pointer();
    *ptr = 12; /* valid? */
    other_function();
}
```

But now, `ptr` points to a location that’s no longer in use, and will be reused the next time a function is called!
Now that we know pointers (I hope!), let’s go back to types.
More on Types

We’ve seen a few types at this point: char, int, float, char *

Types are important because:
• They allow your program to impose logical structure on memory
• They help the compiler tell when you’re making a mistake

In the next slides we will discuss:
• How to create logical layouts of different types (structs)
• How to use arrays
• How to parse C type names (there is a logic to it!)
• How to create new types using typedef
Structures

- a collection of related data items
- possibly of different types
- defined using the keyword \texttt{struct}
- The members of a struct type variable are accessed with the dot (.) operator:
  \texttt{<struct-variable>.<member_name>
struct basics

• Definition of a structure:

```
struct <struct-type>{
    <type> <identifier_list>;
    <type> <identifier_list>;
    ...
}
```

Each identifier defines a member of the structure.
• **Example:**

```c
struct Address {
    int zip;
    char street[50];
    char city[20];
};
```

```c
main() {
    struct Address adrs;
    ...
    adrs.zip = 10012;
}
```

Example of initializing a structure

```c
struct Address adrs = {10012, "Mercer", "New York"};
```
Arrays

Arrays in C are composed of a particular type, laid out in memory in a repeating pattern. Array elements are accessed by stepping forward in memory from the base of the array by a multiple of the element size.

/* define an array of 5 chars */
char x[5] = {'t','e','s','t','\0'};

/* accessing element 0 */
x[0] = 'T';

/* pointer arithmetic to get elt 3 */
char elt3 = *(x+3); /* x[3] */

/* x[0] evaluates to the first element;
 * x evaluates to the address of the
 * first element, or &(x[0]) */

/* 0-indexed for loop idiom */
#define COUNT 10
char y[COUNT];
int i;
for (i=0; i<COUNT; i++) {
    /* process y[i] */
    printf("%c\n", y[i]);
}

Brackets specify the count of elements. Initial values optionally set in braces.

Arrays in C are 0-indexed (here, 0..9)

x[3] == *(x+3) == ‘t’ (NOT ‘s’!)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Addr</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>char x [0]</td>
<td>100</td>
<td>‘t’</td>
</tr>
<tr>
<td>char x [1]</td>
<td>101</td>
<td>‘e’</td>
</tr>
<tr>
<td>char x [2]</td>
<td>102</td>
<td>‘s’</td>
</tr>
<tr>
<td>char x [3]</td>
<td>103</td>
<td>‘t’</td>
</tr>
<tr>
<td>char x [4]</td>
<td>104</td>
<td>‘\0’</td>
</tr>
</tbody>
</table>

For loop that iterates from 0 to COUNT-1.
Memorize it!
Pointers and Arrays in C

• An array name by itself is an address, or pointer in C.

• When an array is declared, the compiler allocates sufficient space beginning with some base address to accommodate every element in the array.

• The base address of the array is the address of the first element in the array (index position 0).

  – Example:  int num[10];

    &num[0] is the same as num
Pointers and Arrays in C

- Suppose we define the following array and pointer:

```c
int a[100]; int *ptr;
```

Assume that the system allocates memory bytes 400, 404, 408, ..., 796 to the array. Integers are allocated 32 bits = 4 bytes.

- The two statements: `ptr = a;` and `ptr = &a[0];` are equivalent and would assign the value of 400 to `ptr`.

- Pointer arithmetic provides an alternative to array indexing in C.

- The two statements: `ptr = a + 1;` and `ptr = &a[1];` are equivalent and would assign the value of 404 to `ptr`. 
Pointers and Arrays in C

• Assuming the elements of the array of integer have been assigned values, the following code would sum the elements of the array:

```c
sum = 0;
for (ptr = a; ptr < &a[100]; ++ptr)
    sum += *ptr;
```

• Here is another way to sum the array:

```c
sum = 0;
for (i = 0; i < 100; ++i)
    sum += *(a + i);
```

\[a[b] \text{ in C is just syntactic sugar for } *(a + b)\]
Strings

• Series of characters treated as a single unit
• Can include letters, digits, and certain special characters (*, /, $)
• String literal (string constant) - written in double quotes
  – "Hello"
• Strings are arrays of characters
• Each character is represented in numerical code called ASCII code.
• Example:
  – char name[] = “test”;
  – address of the above string can be expressed in two ways:
    • &name[0]
    • name
<table>
<thead>
<tr>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Char</th>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html; Chr</th>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html; Chr</th>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html; Chr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>000</td>
<td>NUL (null)</td>
<td>32</td>
<td>20</td>
<td>040</td>
<td><code>#32; Space</code></td>
<td>64</td>
<td>40</td>
<td>100</td>
<td><code>#64; @</code></td>
<td>96</td>
<td>60</td>
<td>140</td>
<td><code>#96; </code></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>001</td>
<td>SOH (start of heading)</td>
<td>33</td>
<td>21</td>
<td>041</td>
<td><code>#33; !</code></td>
<td>65</td>
<td>41</td>
<td>101</td>
<td><code>#65; A</code></td>
<td>97</td>
<td>61</td>
<td>141</td>
<td><code>#97; a</code></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>002</td>
<td>STX (start of text)</td>
<td>34</td>
<td>22</td>
<td>042</td>
<td><code>#34; &quot;</code></td>
<td>66</td>
<td>42</td>
<td>102</td>
<td><code>#66; B</code></td>
<td>98</td>
<td>62</td>
<td>142</td>
<td><code>#98; b</code></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>003</td>
<td>ETX (end of text)</td>
<td>35</td>
<td>23</td>
<td>043</td>
<td><code>#35; #</code></td>
<td>67</td>
<td>43</td>
<td>103</td>
<td><code>#67; C</code></td>
<td>99</td>
<td>63</td>
<td>143</td>
<td><code>#99; c</code></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>004</td>
<td>EOT (end of transmission)</td>
<td>36</td>
<td>24</td>
<td>044</td>
<td><code>#36; $</code></td>
<td>68</td>
<td>44</td>
<td>104</td>
<td><code>#68; D</code></td>
<td>100</td>
<td>64</td>
<td>144</td>
<td><code>#100; d</code></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>005</td>
<td>ENQ (enquiry)</td>
<td>37</td>
<td>25</td>
<td>045</td>
<td><code>#37; %</code></td>
<td>69</td>
<td>45</td>
<td>105</td>
<td><code>#69; E</code></td>
<td>101</td>
<td>65</td>
<td>145</td>
<td><code>#101; e</code></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>006</td>
<td>ACK (acknowledge)</td>
<td>38</td>
<td>26</td>
<td>046</td>
<td><code>#38; &amp;</code></td>
<td>70</td>
<td>46</td>
<td>106</td>
<td><code>#70; F</code></td>
<td>102</td>
<td>66</td>
<td>146</td>
<td><code>#102; f</code></td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>007</td>
<td>BEL (bell)</td>
<td>39</td>
<td>27</td>
<td>047</td>
<td><code>#39; '</code></td>
<td>71</td>
<td>47</td>
<td>107</td>
<td><code>#71; G</code></td>
<td>103</td>
<td>67</td>
<td>147</td>
<td><code>#103; g</code></td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>010</td>
<td>BS (backspace)</td>
<td>40</td>
<td>28</td>
<td>050</td>
<td><code>#40; (</code></td>
<td>72</td>
<td>48</td>
<td>110</td>
<td><code>#72; H</code></td>
<td>104</td>
<td>68</td>
<td>150</td>
<td><code>#104; h</code></td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>011</td>
<td>TAB (horizontal tab)</td>
<td>41</td>
<td>29</td>
<td>051</td>
<td><code>#41; )</code></td>
<td>73</td>
<td>49</td>
<td>111</td>
<td><code>#73; I</code></td>
<td>105</td>
<td>69</td>
<td>151</td>
<td><code>#105; i</code></td>
</tr>
<tr>
<td>10</td>
<td>A</td>
<td>012</td>
<td>LF (NL line feed, new line)</td>
<td>42</td>
<td>2A</td>
<td>052</td>
<td><code>#42; *</code></td>
<td>74</td>
<td>4A</td>
<td>112</td>
<td><code>#74; J</code></td>
<td>106</td>
<td>6A</td>
<td>152</td>
<td><code>#106; j</code></td>
</tr>
<tr>
<td>11</td>
<td>B</td>
<td>013</td>
<td>VT (vertical tab)</td>
<td>43</td>
<td>2B</td>
<td>053</td>
<td><code>#43; +</code></td>
<td>75</td>
<td>4B</td>
<td>113</td>
<td><code>#75; K</code></td>
<td>107</td>
<td>6B</td>
<td>153</td>
<td><code>#107; k</code></td>
</tr>
<tr>
<td>12</td>
<td>C</td>
<td>014</td>
<td>FF (NP form feed, new page)</td>
<td>44</td>
<td>2C</td>
<td>054</td>
<td><code>#44; ,</code></td>
<td>76</td>
<td>4C</td>
<td>114</td>
<td><code>#76; L</code></td>
<td>108</td>
<td>6C</td>
<td>154</td>
<td><code>#108; l</code></td>
</tr>
<tr>
<td>13</td>
<td>D</td>
<td>015</td>
<td>CR (carriage return)</td>
<td>45</td>
<td>2D</td>
<td>055</td>
<td><code>#45; -</code></td>
<td>77</td>
<td>4D</td>
<td>115</td>
<td><code>#77; M</code></td>
<td>109</td>
<td>6D</td>
<td>155</td>
<td><code>#109; m</code></td>
</tr>
<tr>
<td>14</td>
<td>E</td>
<td>016</td>
<td>SO (shift out)</td>
<td>46</td>
<td>2E</td>
<td>056</td>
<td><code>#46; .</code></td>
<td>78</td>
<td>4E</td>
<td>116</td>
<td><code>#78; N</code></td>
<td>110</td>
<td>6E</td>
<td>156</td>
<td><code>#110; n</code></td>
</tr>
<tr>
<td>15</td>
<td>F</td>
<td>017</td>
<td>SI (shift in)</td>
<td>47</td>
<td>2F</td>
<td>057</td>
<td><code>#47; /</code></td>
<td>79</td>
<td>4F</td>
<td>117</td>
<td><code>#79; O</code></td>
<td>111</td>
<td>6F</td>
<td>157</td>
<td><code>#111; o</code></td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>020</td>
<td>DLE (data link escape)</td>
<td>48</td>
<td>30</td>
<td>060</td>
<td><code>#48; 0</code></td>
<td>80</td>
<td>50</td>
<td>120</td>
<td><code>#80; P</code></td>
<td>112</td>
<td>70</td>
<td>160</td>
<td><code>#112; p</code></td>
</tr>
<tr>
<td>17</td>
<td>11</td>
<td>021</td>
<td>DC1 (device control 1)</td>
<td>49</td>
<td>31</td>
<td>061</td>
<td><code>#49; 1</code></td>
<td>81</td>
<td>51</td>
<td>121</td>
<td><code>#81; Q</code></td>
<td>113</td>
<td>71</td>
<td>161</td>
<td><code>#113; q</code></td>
</tr>
<tr>
<td>18</td>
<td>12</td>
<td>022</td>
<td>DC2 (device control 2)</td>
<td>50</td>
<td>32</td>
<td>062</td>
<td><code>#50; 2</code></td>
<td>82</td>
<td>52</td>
<td>122</td>
<td><code>#82; R</code></td>
<td>114</td>
<td>72</td>
<td>162</td>
<td><code>#114; r</code></td>
</tr>
<tr>
<td>19</td>
<td>13</td>
<td>023</td>
<td>DC3 (device control 3)</td>
<td>51</td>
<td>33</td>
<td>063</td>
<td><code>#51; 3</code></td>
<td>83</td>
<td>53</td>
<td>123</td>
<td><code>#83; S</code></td>
<td>115</td>
<td>73</td>
<td>163</td>
<td><code>#115; s</code></td>
</tr>
<tr>
<td>20</td>
<td>14</td>
<td>024</td>
<td>DC4 (device control 4)</td>
<td>52</td>
<td>34</td>
<td>064</td>
<td><code>#52; 4</code></td>
<td>84</td>
<td>54</td>
<td>124</td>
<td><code>#84; T</code></td>
<td>116</td>
<td>74</td>
<td>164</td>
<td><code>#116; t</code></td>
</tr>
<tr>
<td>21</td>
<td>15</td>
<td>025</td>
<td>NAK (negative acknowledge)</td>
<td>53</td>
<td>35</td>
<td>065</td>
<td><code>#53; 5</code></td>
<td>85</td>
<td>55</td>
<td>125</td>
<td><code>#85; U</code></td>
<td>117</td>
<td>75</td>
<td>165</td>
<td><code>#117; u</code></td>
</tr>
<tr>
<td>22</td>
<td>16</td>
<td>026</td>
<td>SYN (synchronous idle)</td>
<td>54</td>
<td>36</td>
<td>066</td>
<td><code>#54; 6</code></td>
<td>86</td>
<td>56</td>
<td>126</td>
<td><code>#86; V</code></td>
<td>118</td>
<td>76</td>
<td>166</td>
<td><code>#118; v</code></td>
</tr>
<tr>
<td>23</td>
<td>17</td>
<td>027</td>
<td>ETB (end of trans. block)</td>
<td>55</td>
<td>37</td>
<td>067</td>
<td><code>#55; 7</code></td>
<td>87</td>
<td>57</td>
<td>127</td>
<td><code>#87; W</code></td>
<td>119</td>
<td>77</td>
<td>167</td>
<td><code>#119; w</code></td>
</tr>
<tr>
<td>24</td>
<td>18</td>
<td>030</td>
<td>CAN (cancel)</td>
<td>56</td>
<td>38</td>
<td>070</td>
<td><code>#58; 8</code></td>
<td>88</td>
<td>58</td>
<td>130</td>
<td><code>#88; X</code></td>
<td>120</td>
<td>78</td>
<td>170</td>
<td><code>#120; x</code></td>
</tr>
<tr>
<td>25</td>
<td>19</td>
<td>031</td>
<td>EM (end of medium)</td>
<td>57</td>
<td>39</td>
<td>071</td>
<td><code>#59; 9</code></td>
<td>89</td>
<td>59</td>
<td>131</td>
<td><code>#89; Y</code></td>
<td>121</td>
<td>79</td>
<td>171</td>
<td><code>#121; y</code></td>
</tr>
<tr>
<td>26</td>
<td>1A</td>
<td>032</td>
<td>SUB (substitute)</td>
<td>58</td>
<td>3A</td>
<td>072</td>
<td><code>#5A; :</code></td>
<td>90</td>
<td>5A</td>
<td>132</td>
<td><code>#90; Z</code></td>
<td>122</td>
<td>7A</td>
<td>172</td>
<td><code>#122; z</code></td>
</tr>
<tr>
<td>27</td>
<td>1B</td>
<td>033</td>
<td>ESC (escape)</td>
<td>59</td>
<td>3B</td>
<td>073</td>
<td><code>#5B; ;</code></td>
<td>91</td>
<td>5B</td>
<td>133</td>
<td><code>#91; ]</code></td>
<td>123</td>
<td>7B</td>
<td>173</td>
<td><code>#123; {</code></td>
</tr>
<tr>
<td>28</td>
<td>1C</td>
<td>034</td>
<td>FS (file separator)</td>
<td>60</td>
<td>3C</td>
<td>074</td>
<td><code>#60; &lt;</code></td>
<td>92</td>
<td>5C</td>
<td>134</td>
<td><code>#92; \</code></td>
<td>124</td>
<td>7C</td>
<td>174</td>
<td>`#124;</td>
</tr>
<tr>
<td>29</td>
<td>1D</td>
<td>035</td>
<td>GS (group separator)</td>
<td>61</td>
<td>3D</td>
<td>075</td>
<td><code>#61; =</code></td>
<td>93</td>
<td>5D</td>
<td>135</td>
<td><code>#93; ]</code></td>
<td>125</td>
<td>7D</td>
<td>175</td>
<td><code>#125; }</code></td>
</tr>
<tr>
<td>30</td>
<td>1E</td>
<td>036</td>
<td>RS (record separator)</td>
<td>62</td>
<td>3E</td>
<td>076</td>
<td><code>#62; &gt;</code></td>
<td>94</td>
<td>5E</td>
<td>136</td>
<td><code>#94; ^</code></td>
<td>126</td>
<td>7E</td>
<td>176</td>
<td><code>#126; ~</code></td>
</tr>
<tr>
<td>31</td>
<td>1F</td>
<td>037</td>
<td>US (unit separator)</td>
<td>63</td>
<td>3F</td>
<td>077</td>
<td><code>#63; ?</code></td>
<td>95</td>
<td>5F</td>
<td>137</td>
<td><code>#95; _</code></td>
<td>127</td>
<td>7F</td>
<td>177</td>
<td><code>#127; DEL</code></td>
</tr>
</tbody>
</table>
Strings

- **String declarations**
  - Declare as a character array or a variable of type `char *`
    ```
    char color[] = "blue";
    char *colorPtr = "blue";
    ```
  - Remember that strings represented as character arrays end with '\0'
    - `color` has 5 elements

- **Inputting strings**
  - Use `scanf`
    ```
    scanf("%s", word);
    ```
    - Copies input into `word[]`, which does not need & (because a string is a pointer)
  - Remember to leave space for '\0'
### Character Handling Library

- In `<ctype.h>`

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>int isdigit( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is a digit and <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int isalpha( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is a letter and <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int isalnum( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is a digit or a letter and <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int isxdigit( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is a hexadecimal digit character and <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int islower( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is a lowercase letter and <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int isupper( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is an uppercase letter; <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int tolower( int c )</code></td>
<td>If <code>c</code> is an uppercase letter, <code>tolower</code> returns <code>c</code> as a lowercase letter.</td>
</tr>
<tr>
<td></td>
<td>Otherwise, <code>tolower</code> returns the argument unchanged.</td>
</tr>
<tr>
<td><code>int toupper( int c )</code></td>
<td>If <code>c</code> is a lowercase letter, <code>toupper</code> returns <code>c</code> as an uppercase letter.</td>
</tr>
<tr>
<td></td>
<td>Otherwise, <code>toupper</code> returns the argument unchanged.</td>
</tr>
<tr>
<td><code>int isspace( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is a white-space character—newline (<code>\n</code>), space (<code> </code>), form feed (<code>\f</code>), carriage return (<code>\r</code>), horizontal tab (<code>\t</code>), or vertical tab (<code>\v</code>)—and <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int iscntrl( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is a control character and <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int ispunct( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is a printing character other than a space, a digit, or a letter and <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int isprint( int c )</code></td>
<td>Returns <code>true</code> value if <code>c</code> is a printing character including space (<code> </code>) and <code>false</code> otherwise.</td>
</tr>
<tr>
<td><code>int isgraph( int c )</code></td>
<td>Returns <code>true</code> if <code>c</code> is a printing character other than space (<code> </code>) and <code>false</code> otherwise.</td>
</tr>
</tbody>
</table>

Each function receives a character (an `int`) or `EOF` as an argument.
String Conversion Functions

- **Conversion functions**
  - In `<stdlib.h>` (general utilities library)
  - Convert strings of digits to integer and floating-point values

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>double atof( const char *nPtr )</code></td>
<td>Converts the string <code>nPtr</code> to <code>double</code>.</td>
</tr>
<tr>
<td><code>int atoi( const char *nPtr )</code></td>
<td>Converts the string <code>nPtr</code> to <code>int</code>.</td>
</tr>
<tr>
<td><code>long atol( const char *nPtr )</code></td>
<td>Converts the string <code>nPtr</code> to <code>long</code>.</td>
</tr>
<tr>
<td><code>double strtod( const char *nPtr, char **endPtr )</code></td>
<td>Converts the string <code>nPtr</code> to <code>double</code>.</td>
</tr>
<tr>
<td><code>long strtol( const char *nPtr, char **endPtr, int base )</code></td>
<td>Converts the string <code>nPtr</code> to <code>long</code>.</td>
</tr>
<tr>
<td><code>unsigned long strtoul( const char *nPtr, char **endPtr, int base )</code></td>
<td>Converts the string <code>nPtr</code> to <code>unsigned long</code>.</td>
</tr>
</tbody>
</table>
# String Manipulation Functions

- In `<string.h>`
- String handling library has functions to
  - Manipulate string data
  - Search strings
  - Determine string length

<table>
<thead>
<tr>
<th>Function prototype</th>
<th>Function description</th>
</tr>
</thead>
<tbody>
<tr>
<td>char *strcpy( char *s1, const char *s2 )</td>
<td>Copies string <code>s2</code> into array <code>s1</code>. The value of <code>s1</code> is returned.</td>
</tr>
<tr>
<td>char *strncpy( char *s1, const char *s2, size_t n )</td>
<td>Copies at most <code>n</code> characters of string <code>s2</code> into array <code>s1</code>. The value of <code>s1</code> is returned.</td>
</tr>
<tr>
<td>char *strcat( char *s1, const char *s2 )</td>
<td>Appends string <code>s2</code> to array <code>s1</code>. The first character of <code>s2</code> overwrites the terminating null character of <code>s1</code>. The value of <code>s1</code> is returned.</td>
</tr>
<tr>
<td>char *strncat( char *s1, const char *s2, size_t n )</td>
<td>Appends at most <code>n</code> characters of string <code>s2</code> to array <code>s1</code>. The first character of <code>s2</code> overwrites the terminating null character of <code>s1</code>. The value of <code>s1</code> is returned.</td>
</tr>
</tbody>
</table>
**String Manipulation Functions**

```c
int strcmp ( const char * str1, const char * str2 )
```

The `strcmp` function returns a value that indicates:

- `<0` if the first character that does not match has a lower value in `ptr1` than in `ptr2`.
- `0` if the contents of both strings are equal.
- `>0` if the first character that does not match has a greater value in `ptr1` than in `ptr2`. 

- The return value
  - `<0` indicates the first character that does not match has a lower value in `ptr1` than in `ptr2`.
  - `0` indicates the contents of both strings are equal.
  - `>0` indicates the first character that does not match has a greater value in `ptr1` than in `ptr2`.
C type names are parsed by **starting at the name** and working outwards according to the rules of precedence:

```
int (*x)[10];  x is an array of pointers to int
```

```
int (*x)[10];  x is a pointer to an array of int
```
At this point we have seen a few basic types, arrays, pointer types, and structures. So far we’ve glossed over how types are named.

```c
int x;        /* int; */ typedef int T;
int *y;       /* pointer to int; */ typedef int *U;
int z[10];    /* array of ints; */ typedef int V[10];
int *k[10];   /* array of pointers to int; */ typedef int *W[10];
int (*m)[10]; /* pointer to array of ints; */ typedef int (*N)[10];
```

typedef defines a new type

Now:

```c
T x; is the same as int x;
U y; is the same as int * y;
and so on ...
```
What if you want to allocate an array of $N$ elements, and you don’t know $N$ beforehand?
Dynamic Memory Allocation

So far all of our examples have allocated variables **statically** by defining them in our program. This allocates them in the stack.

But, what if we want to allocate variables based on user input or other dynamic inputs, at run-time? This requires **dynamic** allocation.

```c
int * alloc_ints(size_t requested_count)
{
    int * big_array;
    big_array = (int *)calloc(requested_count, sizeof(int));
    if (big_array == NULL) {
        printf("can't allocate %d ints: %m\n", requested_count);
        return NULL;
    }
    /* now big_array[0] .. big_array[requested_count-1] are * valid and zeroed. */
    return big_array;
}
```

`calloc(N, K)` allocates memory for `N` elements of size `k`

Returns NULL if can’t alloc

`sizeof()` reports the size of a type in bytes

It’s OK to return this pointer. It will remain valid until it is freed with `free()`
Dynamic Memory Allocation

- `void *malloc (size_t size);`
- `void* calloc (size_t num, size_t size);`
- `void free (void* ptr);`
- Unary operator `sizeof` is used to determine the size in bytes of any data type. Examples:
  - `sizeof(double)`
  - `sizeof(int)`
Caveats with Dynamic Memory

Dynamic memory is useful. But it has several caveats:

Whereas the stack is automatically reclaimed, dynamic allocations must be tracked and free()’d when they are no longer needed. With every allocation, be sure to plan how that memory will get freed. Losing track of memory is called a “memory leak”.

Because dynamic memory always uses pointers, there is generally no way for the compiler to statically verify usage of dynamic memory. This means that errors that are detectable with static allocation are not with dynamic
I/O in C
I/O

• reading from:
  – standard input (usually the keyboard)
  – file

• writing to:
  – standard output (usually the screen)
  – file

• A library of functions is supplied to perform these operations.

• The I/O library functions are listed the header file `<stdio.h>`.
printf();

• This function provides for formatted output to the screen. The syntax is:
  printf ( "format", var1, var2, ... );
• The “format” includes a listing of the data types of the variables to be output and, optionally, some text and control character(s).
• Example:
  float a; int b;
  scanf ( "%f%d", &a, &b );
  printf ( "You entered %f and %d \n", a, b );
Formatted Output with printf

Format Conversion Specifiers (This list is not exhaustive):

\( \text{d} \) -- displays a decimal (base 10) integer

\( \text{l} \) -- used with other specifiers to indicate a long

\( \text{f} \) -- displays a floating point value

\( \text{x} \) -- displays a number hexadecimal format

\( \text{c} \) -- displays a single character

\( \text{s} \) -- displays a string of characters
**Reading from stdin**

```c
scanf();
```

- This function provides for formatted input from the keyboard. The syntax is:
  ```c
  scanf("format", &var1, &var2, ...);
  ```
- The "format" is a listing of the data types of the variables to be input and the & in front of each variable name tells the system WHERE to store the value that is input. It provides the address for the variable.
- Example:
  ```c
  float a; int b;
  scanf("%f%d", &a, &b);
  ```
Files

• In *C*, each file is simply a sequential stream of bytes.
• *C* imposes no structure on a file.
• Steps to deal with files
  – open a file
  – check that the open was successful
  – read/write to a file
  – close a file
First step

• Declaration:

```c
FILE *fptr1, *fptr2;
```
Opening Files

• The statement:
  
  fptr1 = fopen ( "filename", "r" );

  would open the file filename for input (reading).

  – r: read
  – w: write
  – a: append
  – … there are some more
Testing for Successful Open

• If the file was not able to be opened, then the value returned by the `fopen` routine is NULL.

• For example, let's assume that the file `mydata` does not exist. Then:

```c
FILE *fptr1;
fptr1 = fopen ("myfile", "r");
if (fptr1 == NULL)
{
    printf ("File 'mydata' did not open.\n");
}
```
Reading From Files

• In the following segment of C language code:

```c
int a, b;
FILE *fptr1, *fptr2;
fptr1 = fopen("mydata", "r");
fscanf( fptr1, "%d%d", &a, &b);
```
the `fscanf` function would read values from the file "pointed" to by `fptr1` and assign those values to `a` and `b`. 
End of File

- The end-of-file indicator informs the program when there are no more data (no more bytes) to be processed.
- There are a number of ways to test for the end-of-file condition. One is to use the `feof` function which returns a true or false condition:
  ```c
  fscanf (fptr1, "%d", &var) ;
  if (feof (fptr1))
  {
      printf ("End-of-file encountered.\n");
  }
  ```
- Another (better) way of testing EOF:
  ```c
  while(fscanf(fp,"%d ", &current) == 1)
  {
      
  }
  ```
int a = 5, b = 30;
FILE *fp1, *fp2;
fptr2 = fopen("filename", "w");
fprintf(fp2, "%d %d\n", a, b);

the **fprintf** functions would write the values stored in **a** and **b** to the file "pointed" to by **fp2**.
Closing Files

fclose (fptr1);

Once the files are open, they stay open until you close them or end the program (which will close all files.)
One last concept ...
Macros can be a useful way to customize your interface to C and make your code easier to read and less redundant. However, when possible, use a static inline function instead.

Format is very simple:

```
#define identifier replacement-text
```

Example:

```
#define NUM 10
```

Notes:
- Each occurrence of NUM in your code will be replaced by 10.
- This happens by the preprocessor before compilation.
- In the rest of the code you cannot change NUM.

We can take this idea further. Instead of defining a constant, we define operations.
Macros

• Sophisticated Example

```c
#define CIRCLE_AREA( x ) ( PI * ( x ) * ( x ) )
area = CIRCLE_AREA( 4 );
    becomes
area = ( 3.14159 * ( 4 ) * ( 4 ) );

– See how parentheses are used. Always enclose parameters in ()..
```

• More sophisticated example:

```c
#define RECTANGLE_AREA( x, y ) ( ( x ) * ( y ) )
rectArea = RECTANGLE_AREA( a + 4, b + 7 );
    becomes
rectArea = ( ( a + 4 ) * ( b + 7 ) );
```
Macros: More examples

- `#define foreover for(;;)`
- `#define max(i,j) ((i) > (j) ? (i) : (j))`
- `#define SWAP(a, b) {
    a ^= b;
    b ^= a;
    a ^= b;
}
`
Conclusions

• We took a quick look at the different features of C

• To get deeper look: check online tutorials. You will find some links at the course webpage

• To become an expert: write code … write code … write code