Computer Hardware Engineering (IS1200)
Computer Organization and Components (IS1500)

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Lecture 4: The C Programming Language Continued

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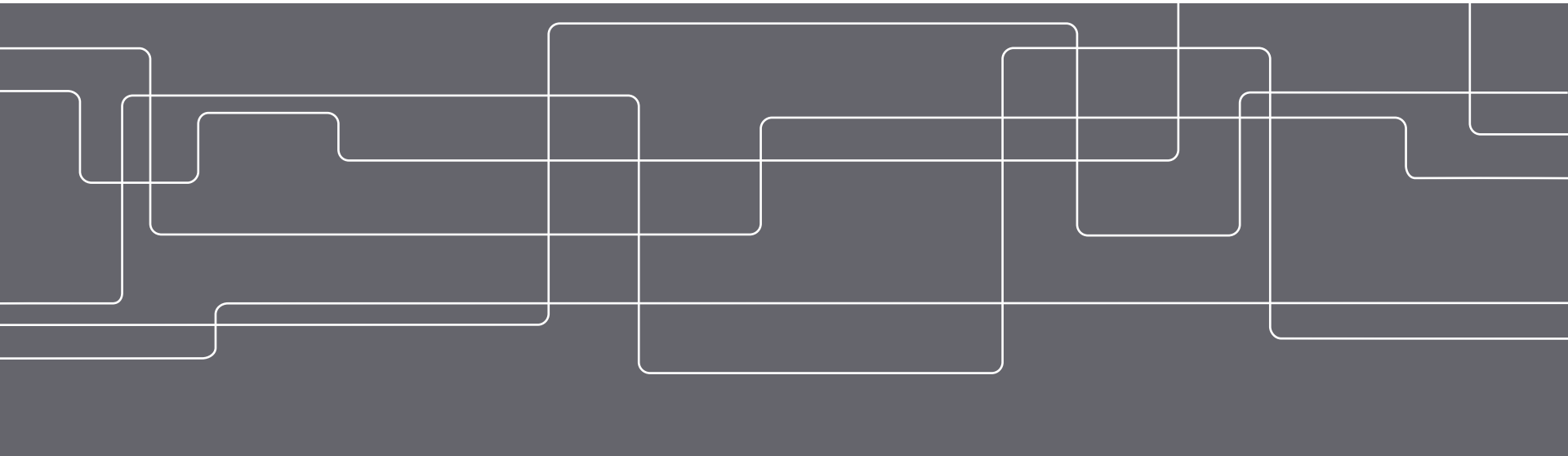
Slides by David Broman, KTH (Extensions by Artur Podobas, KTH)



Course Structure

Module 1: C and Assembly Programming

LE1 → LE2 → LE3 → LE4 → EX1 LAB1 S1 LAB2

Module 2: I/O Systems

LE5 → LE6 → EX2 LAB3

Module 3: Logic Design **(IS1500 only)**

LE7 → LE8 → PROJ START EX3 LD-LAB

Module 4: Processor Design

LE9 → LE10 → EX4 S2 LAB4

Module 5: Memory Hierarchy

LE11 → EX5 S3

Module 6: Parallel Processors and Programs

LE12 → LE13 → EX6 S4

Proj. Expo LE14

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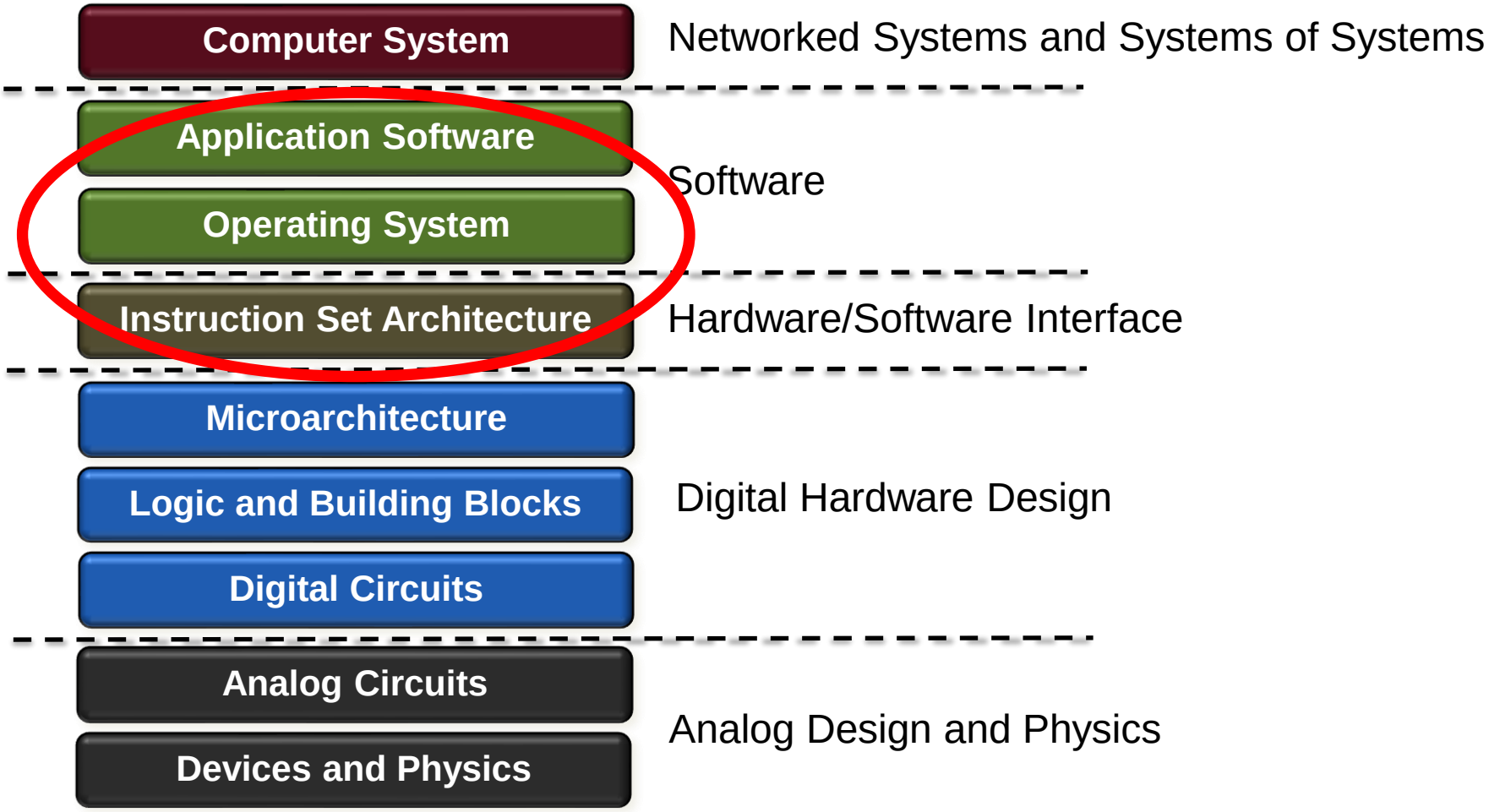
Part I
More on Control Structures and Functions

Part II
Arrays, Pointers, and Dynamic Memory

Part III
Floating-Point Numbers

Abstractions in Computer Systems



Agenda

Part I

More on Control Structures and Functions

Part II

Arrays, Pointers, and Dynamic Memory

Part III

Floating-Point Numbers

Part I

More on Control Structures and Function Calls

Primitive Data Types
Integers and Floating Points

```
int foo;
```

Defines an uninitialized integer. What does it mean?
We can use expression **`sizeof(foo)`** to find out the size.

Type	Size(bits)	Min	Max
char	8	$-2^7 = -128$	$2^7-1 = 127$
unsigned char	8	0	$2^8-1 = 255$
short	16	$-2^{15} = -32768$	$2^{15}-1 = 32767$
unsigned short	16	0	$2^{16}-1 = 65535$
long	32 or 64		
int	machine dependent (signed)		
unsigned int	machine dependent (unsigned)		
float	32		
double	64		

Floating-point numbers approximate the result.

Loops
do/while

```
int x = 0;
while(x < 10){
  x++;
  printf("%d\n",x);
}
```

```
int x = 0;
do{
  x++;
  printf("%d\n",x);
}while(x < 10);
```

What is the difference in result?

Do/while makes the check at then end.

What is the difference if
int x = 10;

Conditional Statements
`switch`-statement

```
int op = 3;
int z = 0;
switch(op){
  case 1:
    z = 4;
    printf("case 1");
    break;
  case 2:
    printf("case 2");
    break;
  default:
    printf("default");
}
```

A **switch** is semantically equivalent to several if-then-else statements, but a switch is cleaner and can be implemented more efficiently.

After each case, we need to **break** out of the switch.

If no case matches, the **default** case is executed. In this case, the output will be “default” because the value 3 in not part of any case.

Exercise: What is written out in the code to left?

Example: Word Count - Incorrect Implementation

```
#include <stdio.h>
int main(){
  char c;
  int lines, words = 0;
  int chars, in_space = 1;
  while((c = getchar()) != EOF){
    chars++;
    if(c = '\n')
      lines++;
    if(c == ' ' || c == '\n')
      in_space = 1;
    else
      words += in_space;
      in_space = 0;
  }

  printf("%8d%8d%8d\n", lines, words, chars);
  return 0;
}
```

This example code should give the same result as the UNIX command **`wc`** (word count).

```
This is a text. We have
right now ten words.
```

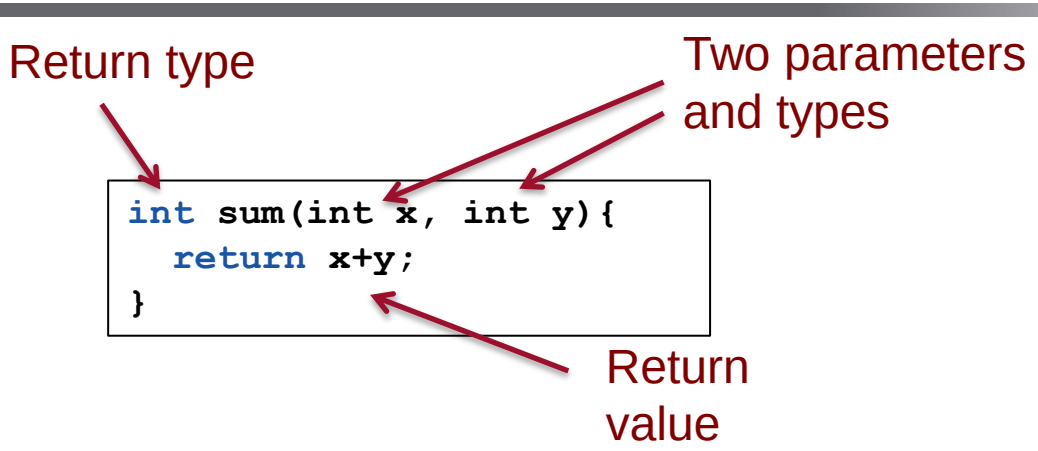
For a text file **`wctest.txt`** (above), we should get:

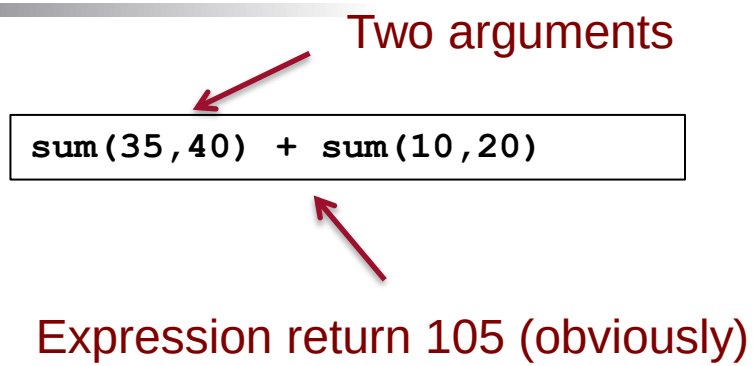
```
$ cat wctext.txt | wc
       2      10      45
```

lines words chars

Exercise:
Find 4 errors in the code!

Functions (1/3)
Parameters and Arguments





Exercise:
Write a function called **expo** that computes the exponential value x^n.
For instance `expo(4,3) = 64`

Functions (2/3)
Local and Global Variables

Global variable. Should in general be avoided. Violates the principle of **modularity**.

Local variable. Can only be used inside a function.

```
int ng = 2;
int r;

void expo_glob(int x){
  int i;
  r = 1;
  for(i=0; i<ng; i++)
    r *= x;
  ng += 2;
}
```

void type means that it is a procedure, it does not return a value.

The **function** has side effects.

```
expo_glob(2);
expo_glob(2);
expo_glob(2);
```

First called. `ng = 4, r = 4`

Second called. `ng = 6, r = 16`

Third called. `ng = 8, r = 64`

Note that this is not an example of good code design...

Functions (3/3)
Recursive Functions

Exercise:
Create the factorial function **n!**, where **n** is an integer parameter. Create one imperative and one functional implementation. The latter one should use recursion.

Part II

Arrays, Pointers, and Dynamic Memory

Arrays (1/3) Declaration

```
int b[3];
b[0] = 10;
b[1] = 30;
b[2] = 20;
b[3] = 30;
```

An uninitialized array is declared by stating the element type, the array name, and its length (number of elements).

The array can then be given values using **assignment statements**.

The last assignment is an out-of-bound error. The compiler can sometimes issue a warning, but not always.

```
int a[5] = {12,23,15,100,9};
```

An array can be initialized directly.

```
int a[] = {12,23,15,100,9};
```

The length can be inferred.

```
printf("Total size in bytes: %d\n",
        (int)(sizeof(a)));
```

`sizeof()` can be used to get its size in bytes. Result: 20

Casting to integer (int) from unsigned long.

```
sizeof(a)/sizeof(int)
```

The number of elements can be computed like this. Result: 5

Arrays (2/3)
Accessing Elements

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

```
int k0 = a[0];
int k5 = a[5];
```

Out of bound for the **k5** case. An array of size **N** is **indexing** from **0** to **N-1**.

```
double mean1(int d[], int len){
  int i, sum = 0;
  for(i=0; i<len; i++)
    sum += d[i];
  return sum / len;
}
```

(returns 2.0)

```
double mean2(int d[], int len){
  int i;
  double sum = 0;
  for(i=0; i<len; i++)
    sum += d[i];
  return sum / len;
}
```

(returns 2.6)

Needs to be a double before dividing.

```
double mean3(int d[], int len){
  int i, sum = 0;
  for(i=0; i<len; i++)
    sum += d[i];
  return (double) (sum / len);
}
```

(returns 2.0)

```
double mean4(int d[], int len){
  int i,sum = 0;
  for(i=0; i<len; i++)
    sum += d[i];
  return (double) sum / len;
}
```

(returns 2.6)

Casting has higher precedence than div.

Exercise: Which function(s) return correct answers. Vote for mean1, mean2, mean3, or mean4.

Arrays (3/3)
Multi-Dimensional Arrays

```
void print_matrix(const int mtx[2][4]){
  int i,j;
  for(i=0; i<2; i++){
    for(j=0; j<4; j++)
      printf("%2d ", mtx[i][j]);
    printf("\n");
  }
}
```

```
int m[2][4] = {{42, 77, 92, 10},
               {31, 21, 33, 61}};
```

Rows Columns

Can declare two dimensional arrays.

Note that print function can have a const parameter (read only), but not the function with side effect.

```
#include <stdlib.h>
void random_matrix(int mtx[2][4]){
  int i,j;
  for(i=0; i<2; i++){
    for(j=0; j<4; j++)
      mtx[i][j] = rand() % 100;
  }
}
```

The random function rand() is part of the standard library.

```
int m2[2][4];
random_matrix(m2);
print_matrix(m2);
```

Pointers (1/3)

Swap values of two variables.

```
int x = 3, y = 7;
int t;
t = x;
x = y;
y = t;
```

Store one of the values in a temporary variable.

How can we write a function that performs the swap?

Problem 1: A function can only return one value.

```
void swap1(int x, int y){
  int t;
  t = x;
  x = y;
  y = t;
}
```

Arguments are passed as values. Variables **x** and **y** are only local variables.

```
int a = 3, b = 7;
swap1(a,b);
```

Problem 2: We cannot modify the content of variables outside a function, if they are passed as value arguments.

Pointers (2/3)

Solution: Use pointers

A pointer is defined with the * symbol before the variable name in a variable definition. NOTE: we can also write

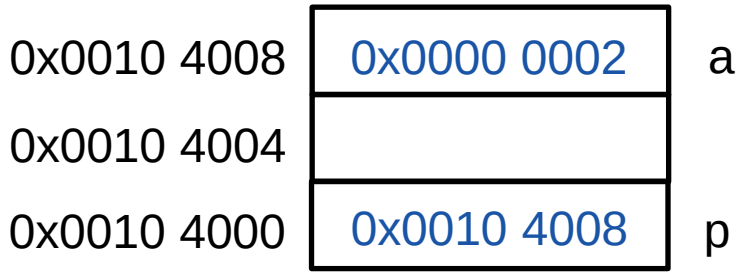
```
int* p;
```

& symbol is used in an expression for getting the memory address of a variable.

```
int a = 2;
int *p;
p = &a;
*p = 3 + *p;
printf("p=0x%x a=0x%x\n",
       (unsigned int)p, a);
```

* before a pointer variable **dereferences** a pointer, i.e., returns or assigns the value that the pointer points to.

What is the output when executing this code?



Memory content after executing the 3 first lines of code.

Pointers (3/3)

Back to the swap example…

```
void swap2(int *x, int *y){
   int t;
   t = *x;
   *x = *y;
   *y = t;
}
```

We define pointer parameters.

The pointer ***x** is dereferenced, that is, we get the value of a.

We dereference the pointer ***y** and get the value of b, followed by dereferencing ***x** and updating the value of **a**.

Finally, we dereference ***y**, and update **b** with the value of **t**.

```
int a = 3, b = 7;
swap2(&a,&b);
```

The memory addresses of **a** and **b** are passed as values, not the content of **a** and **b.**

A safer and simpler programming style with reference types is available in C++, but not in C.

Dynamic Memory Allocation

All examples have so far been using statically defined variables or allocation on the stack (local variables).

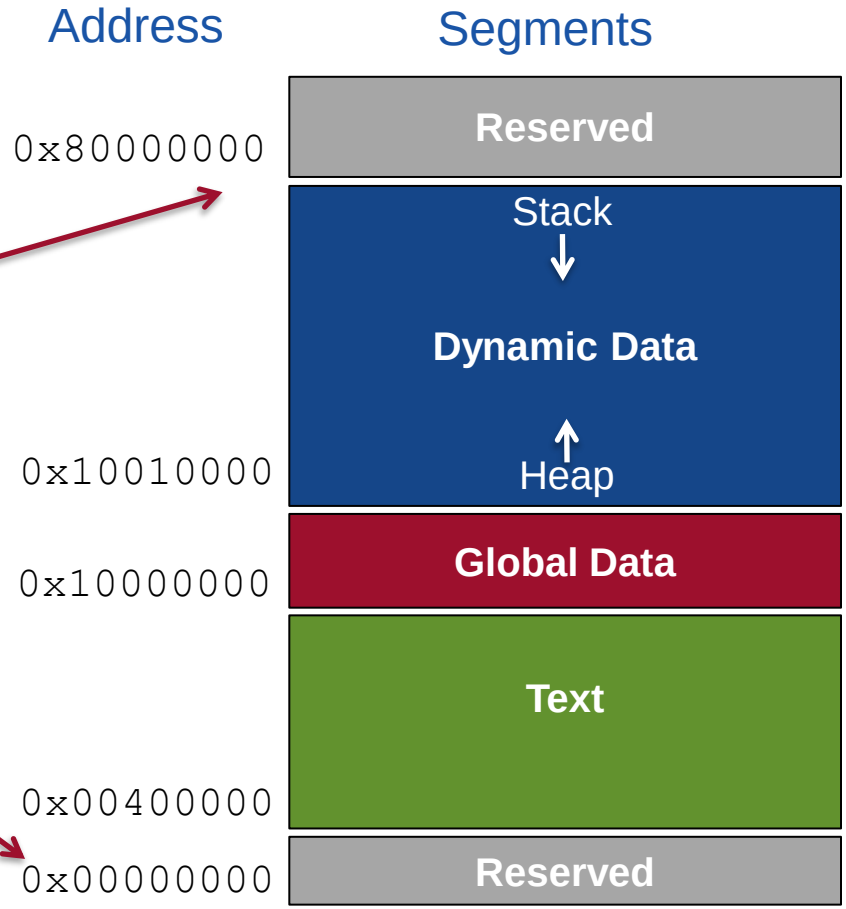
malloc dynamically allocates N number of bytes, where N is the argument. It returns a pointer to the new data.

```
int n = 100;
int *buf = (int *) malloc(sizeof(int)*n);
buf[4] = 10;
printf("%d\n", buf[4]);
free(buf);
```

We can access the array using array indexing.

When the buffer is not needed anymore, it must be deallocated using **free**()

Layout of Memory – the Memory Map for MIPS



Dynamic data contains the **stack** and the **heap**

Stack pointer
$sp = 0x7FFFFFFC

The global data contains global variables. ".data" in assembly code

Global pointer
$gp = 0x10008000

The text segment stores the code. ".text" in assembly code

PC (Program Counter)
. Program starts at
PC = 0x00400000

The reserved memory may be used for memory mapped I/O

C/ASM Pointer Example (2/2)

```
.data
.align 2
numbers: .space   40

.align 2
.text
         la       $t1,numbers
         addi     $s0, $0, 10
loop:
         sw       $s0, 0($t1)
         addi     $t1, $t1, 4
         addi     $s0, $s0, -1
         bne      $s0, $0, loop

         la       $t1,numbers
         lw       $s0,0($t1)
         lw       $s1,4($t1)
         add      $s2, $s0, $s1

stop:    j        stop
```

Home Exercise (fun todo after this lecture):
Write a C program (using pointers) that performs the same task.

Part III

Floating-Point Numbers

Floating-Point Numbers (1/2) Basics

Floating point numbers can represent an approximation of real numbers in a computer. Used heavily in high performance scientific computing.

$$3.7 \times 10^{-3} = 0.0037$$

mantissa, base, exponent

Standard IEEE 754 defines

- 32-bit floating point number (**float** in C)
- 64-bit floating point number (**double** in C)

Other (IEEE 754):

- 16-bit floating point number (half-precision)

Other (non-IEEE 754)

- B(rain)FLOAT-16, Posits

C-code. Type float represents a 32-bit floating-point number.

```
float x = 3.7e-3;
float y = 0.0037;
printf("%f,%f,%d\n",x,y,x==y);
```

Output: 0.003700,0.003700,1

Special numbers

- + infinity
- - inifinty
- NaN (Not a number)

Floating-Point Numbers (2/2) Rounding

Surprising fact about floating point numbers:
0.1 + 0.1 + 0.1 + 0.1 + 0.1 +
0.1+ 0.1+ 0.1+ 0.1+ 0.1 ≠ 1.0

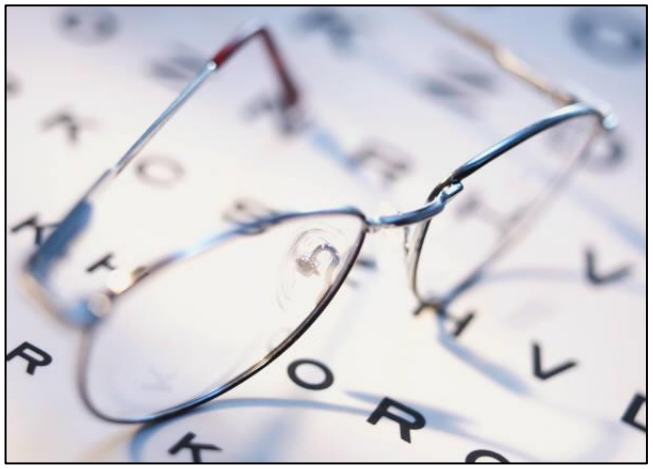
A+(B+C) /= (A+B)+C
(Not Associative)

```
double z = 0.1;
double r = 0.0;
double k = 1.0;
for(int i = 0; i < 10; i++)
   r += z;
printf("%f,%f,%d\n",r,k,r==k);
```

Exercise: What is the output of the program

Yes, there will be coffee in just second…

Reading Guidelines



Next Module 2 (I/O Systems)

H&H Chapters 8.5-8.7

For the labs, focus on 8.6.2-8.6.5 (GPIO, Timers, and Interrupts).

The rest is useful for the project.

Reading Guidelines
See the course webpage for more information.

Summary

Some key take away points:

- **Arrays** and **pointers** are expressive, low-level data structures in C.
- **Floating-point numbers** are very useful, but should be used carefully when comparing numbers.

Thanks for listening!