Introduction to Scientific Programming in C++/Fortran2003

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Contents

PART I

INTRODUCTION

Chapter 1

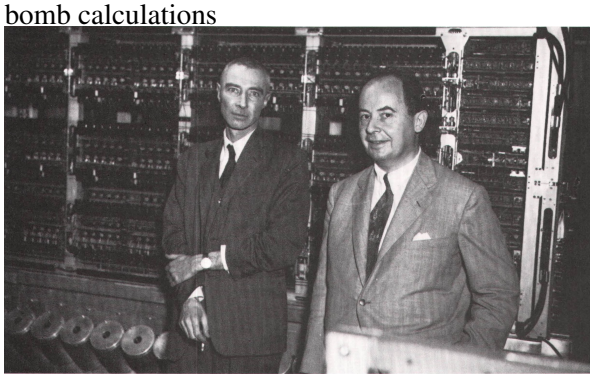
Introduction

1.1 Programming and computational thinking

1.1.1 History

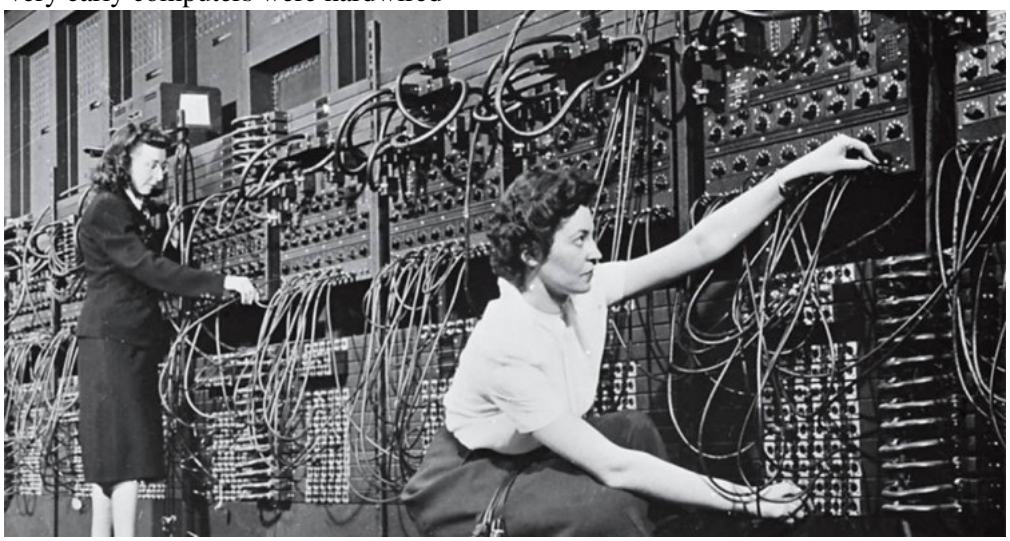
1.1. Earliest computers

Historically, computers were used for big physics calculations, for instance, atom bomb calculations



1.2. Hands-on programming

Very early computers were hardwired



1.3. Program entry

Later programs were written on punchcards

1.4. The first programming language

Initial programming was about translating the math formulas; after a while they made a language for that: FORmula TRANslation

1.5. Programming is everywhere

Programming is used in many different ways these days.

- You can make your own commands in *Microsoft Word*.
- You can make apps for your *smartphone*.
- You can solve the riddles of the universe using big computers.

This course is aimed at people in the last category.

1.1.2 Computational thinking

1.6. Programming is not simple

Programs can get pretty big

It's not just translating formulas anymore.

Translating ideas to computer code: computational thinking.

1.7. Examples of computational thinking

- Looking up a name in the phone book
  - start on page 1, then try page 2, et cetera
  - or start in the middle, continue with one of the halves.
- Elevator scheduling: someone at ground level presses the button, there are cars on floors 5 and 10; which one do you send down?

1.8. Abstraction

- The elevator programmer probably thinks: 'if the button is pressed', not 'if the voltage on that wire is 5 Volt'.
- The Google car programmer probably writes: 'if the car before me slows down', not 'if I see the image of the car growing'.
- ... but probably another programmer had to write that translation.

1.9. Data abstraction

What is the structure of the data in your program?

Stack: you can only get at the top item

Queue:

items get added in the back, processed at the front

1.1.3 Hardware

1.10. Do you have to know much about hardware?

Yes, it's there, but we don't think too much about it in this course.
https://youtu.be/JEpsKnWZrJ8

1.1.4 Algorithms

1.11. What is an algorithm?

> An algorithm is a sequence of unambiguous instructions for solving a problem, i.e., for obtaining a required output for any legitimate input in a finite amount of time
>
> [A. Levitin, Introduction to The Design and Analysis of Algorithms, Addison-Wesley, 2003]

The instructions are in some language:

- We will teach you C++ and Fortran;
- the compiler translates those languages to machine language
- Abstraction: a program often defines its own language that implements concepts of your application.

1.12. Program steps

- Simple instructions: arithmetic.
- Compicated instructions: control structures
  - conditionals
  - loops

1.13. Program data

- Input and output data: to/from file, user input, screen output, graphics.
- Data during the program run:
  - Simple variables: character, integer, floating point
  - Arrays: indexed set of characters and such
  - Data structures: trees, queues
    - Defined by the user, specific for the application
    - Found in a library (big difference between C/C++!)

1.2 About the choice of language

1.14. Comparing two languages

Python vs C++ on bubblesort:

```
for i in range(n-1):
  for j in range(n-i-1):
    if numbers[j+1]<numbers[j]:
      swap = numbers[j+1]
      numbers[j+1] = numbers[j]
      numbers[j] = swap
```

```
for (int i=0; i<n-1; i++)
  for (int j=0; j<n-1-i; j++)
    if (numbers[j+1]<numbers[j]) {
      int swap = numbers[j+1];
      numbers[j+1] = numbers[j];
      numbers[j] = swap;
    }
```

```
[] python bubblesort.py 5000
Elapsed time: 12.1030311584
[] ./bubblesort 5000
Elapsed time: 0.24121
```

1.15. The right language is not all

Python with quicksort algorithm:

```
numpy.sort(numbers,kind='quicksort')
```

```
[] python arraysort.py 5000
Elapsed time: 0.00210881233215
```

1.3 Further reading

Tutorial, assignments: http://www.cppforschool.com/

Problems to practice: http://www.spoj.com/problems/classical/

Chapter 2

Warming up

2.1 Programming environment

Programming can be done in any number of ways. It is possible to use an Integrated Development Environment (IDE) such as *Xcode* or *Visual Studio*, but for the purposes of this course you should really learn a *Unix* variant.

- If you have a *Linux* computer, you are all set.
- If you have an *Apple* computer, it is easy to get you going. Install `XQuartz` and a *package manager* such as *homebrew* or *macports*.
- *Microsoft Windows* users can use *putty* but it is probably a better solution to install a virtual environment such as *VMware* (`http://www.vmware.com/`) or *Virtualbox* (`https://www.virtualbox.org/`).

Next, you should know a text editor. The two most common ones are *vi* and *emacs*.

2.2 Compiling

The word 'program' is ambiguous. Part of the time it means the *source code*: the text that you type, using a text editor. And part of the time it means the *executable*, a totally unreadable version of your code, that can be understood and executed by the computer. The process of turning your source code into an executable is called *compiling*, and it requires something called a *compiler*. (So who wrote the source code for the compiler? Good question.)

Let's say that

- you have a source code file `myprogram.cxx`,
- and you want an executable file called `myprogram`,
- and your compiler is `g++`, the C++ compiler of the *GNU* project. (If you have the Intel compilers, you will use *icpc* instead.)

To compile your program, you then type

```
g++ -o myprogram myprogram.cxx
```

On TACC machines, use the Intel compiler:

```
icpc -o myprogram myprogram.cxx
```

which you can verbalize as 'invoke `g++`, with output `myprogram`, on `myprogram.cxx`'.

So let's do an example.

This is a minimal program:

```
#include <iostream>
using namespace std;

int main() {
  return 0;
}
```

1. The first two lines are magic, for now. Always include them.
2. The `main` line indicates where the program starts; between its opening and closing brace will be the *program statements*.
3. The `return` statement indicates successful completion of your program.

As you may have guessed, this program does absolutely nothing.

Here is a statement that at least produces some output:

```
cout << "Hello world!" << endl;
```

Exercise 2.1. Make a program source file that contains the 'hello world' statement, compile it and run it. Think about where the statement goes.

PART II

C++

Chapter 3

Basic elements of C++

3.1 Statements

3.1. Program statements

- A program contains statements, each terminated by a semicolon.
- 'Curly braces' can enclose multiple statements.
- A statement corresponds to some action when the program is executed.
- Comments are 'Note to self', short:

```
cout << "Hello world" << endl; // say hi!
```

  and arbitrary:

```
cout << /* we are now going
            to say hello
          */ "Hello!" << /* with newline */ endl;
```

Exercise 3.1. Take the 'hello world' program you wrote earlier, and duplicate the hello-line. Compile and run.
Does it make a difference whether you have the two hellos on the same line or on different lines?
Experiment with other changes to the layout of your source. Find at least one change that leads to a compiler error.

3.2. Fixed elements

You see that certain parts of your program are inviolable:

- There are *keywords* such as `return` or `cout`.
- Curly braces and parentheses need to be matched.
- There has to be a `main` keyword.
- The `iostream` and `namespace` are usually needed.

Exercise 3.2. Experiment with the `cout` statement. Replace the string by a number or a mathematical expression. Can you guess how to print more than one thing, for instance the string `One third is` and the result of $1/3$, with the same `cout` statement?

3.2 Variables

3.3. Variable declarations

Programs usually contain data, which is stored in a *variable*. A variable has

- a *datatype*,
- a name, and
- a value.

These are defined in a *variable declaration* and/or *variable assignment*.

3.4. Variable names

- A variable name has to start with a letter,
- can contains letters and digits, but not most special characters (except for the underscore).
- For letters it matter whether you use upper or lowercase: the language is *case sensitive*.

3.5. Declaration

There are a couple of ways to make the connection between a name and a type. Here is a simple *variable declaration*, which establishes the name and the type:

```
int n;
float x;
int n1,n2;
double re_part,im_part;
```

Declarations can go pretty much anywhere in your program.

3.6. Datatypes

Variables come in different types;

- We call a variable of type `int`, `float`, `double` a *numerical variable*.
- For characters: `char`. Strings are complicated.
- You can make your own types. Later.

3.7. Floating point constants

- Default: `double`
- Float: `3.14f` or `3.14F`
- Long double: `1.41l` or `1.41L`.

This prevents numerical accidents:

```
double x = 3.;
```

converts float to double, maybe introducing random bits.

3.8. Assignment

Once you have declared a variable, you need to establish a value. This is done in an *assignment* statement. After the above declarations, the following are legitimate assignments:

```
n = 3;
x = 1.5;
n1 = 7; n2 = n1 * 3;
```

You see that you can assign both a simple value or an *expression*; see section 3.4 for more detail.

3.9. Assignments

A variable can be given a value more than once. You the following sequence of statements is a legitimate part of a program:

```
int n;
n = 3;
n = 2*n + 5;
n = 3*n + 7;
```

3.10. Special forms

Update:

```
x = x+2; y = y/3;
// can be written as
x += 2; y /= 3;
```

Integer add/subtract one:

```
i++; j--;  /* same as: */ i=i+1; j=j-1;
```

Pre/post increment:

```
x = a[i++]; /* is */ x = a[i]; i++;
y = b[++i]; /* is */ i++; y = b[i];
```

3.11. Initialization

You can also give a variable a value a in *variable initialization*. Confusingly, there are several ways of doing that. Here's two:

```
int n = 0;
double x = 5.3, y = 6.7;
double pi{3.14};
```

Exercise 3.3. Write a program that has several variables. Assign values either in an initialization or in an assignment. Print out the values.

3.12. Truth values

So far you have seen integer and real variables. There are also *boolean values* which represent truth values. There are only two values: `true` and `false`.

```
bool found{false};
```

Exercise 3.4. Print out `true` and `false`. What do you get?

3.3 Input/Output, or I/O as we say

3.13. Terminal output

You have already seen `cout`:

```
float x = 5;
cout << "Here is the root: " << sqrt(x) << endl;
```

3.14. Terminal input

There is also a *cin*, which serves to take user input and put it in a numerical variable.

```
int i;
cin >> i;
```

However, this function is somewhat tricky.
http://www.cplusplus.com/forum/articles/6046/.

3.15. Better terminal input

It is better to use `getline`. This returns a string, rather than a value, so you need to convert it with the following bit of magic:

```
#include <iostream>
#include <sstream>
using namespace std;
  /* ... */
  std::string saymany;
  int howmany;

  cout << "How many times? ";
  getline( cin,saymany );
  stringstream saidmany(saymany);
  saidmany >> howmany;
```

You can not use `cin` and `getline` in the same program.

Exercise 3.5. Write a program that

- Displays the message `Type a number`,
- accepts an integer number from you (use `cin`),
- and then prints out three times that number plus one.

For more I/O, see chapter 11.

3.4 Expressions

3.16. Arithmetic expressions

- Expression looks pretty much like in math.
  With integers: `2+3`
  with reals: `3.2/7`
- Use parentheses to group `25.1*(37+42/3.)`
- Careful with types.
- There is no 'power' operator: library functions. Needs a line
  ```
  #include <cmath>
  ```
- Modulus: `%`

3.17. Boolean expressions

- Testing: `==` `!=` `<` `>` `<=` `>=`
- Not, and, or: `!` `&&` `||`
- Bitwise: `&` `|` `^`
- Shortcut operators:

```
if ( x>=0 && sqrt(x)<5 ) {}
```

3.18. Conversion and casting

Real to integer: round down:

```
double x,y; x = .... ; y = .... ;
int i; i =  x+y:
```

Dangerous:

```
int i,j; i = ... ; j = ... ;
double x ; x = 1+i/j;
```

The fraction is executed as integer division. Do:

```
(double)i/j /* or */ (1.*i)/j
```

Exercise 3.6. Write two programs, one that reads a temperature in Centigrade and converts to Fahrenheit, and one that does the opposite conversion.

$$C = (F - 32) \cdot 5/9, \qquad F = 9/5\, C + 32$$

Can you use Unix pipes to make one accept the output of the other?

Exercise 3.7. Write a program that ask for two integer numbers `n1,n2`.

- Assign the integer ratio n_1/n_2 to a variable.
- Can you use this variable to compute the modulus

  $$n_1 \mod n_2$$

  (without using the `%` modulus operator!)
  Print out the value you get.
- Also print out the result from using the modulus operator:`%`.

Complex numbers exist, see section 20.2.

3.5 Conditionals

3.19. If-then-else

A *conditional* is a test: 'if something is true, then do this, otherwise maybe do something else'. The C++ syntax is

```
if ( something ) {
  do something;
} else {
  do otherwise;
}
```

- The 'else' part is optional
- You can leave out braces in case of single statement.

3.20. Complicated conditionals

Chain:

```
if ( something ) {
  ...
} else if ( something else ) {
  ...
}
```

Nest:

```
if ( something ) {
  if ( something else ) {
    ...
  } else {
    ...
  }
}
```

3.21. Switch

```
switch (n) {
case 1 :
case 2 : cout << "very small" << endl;
  break;
case 3 : cout << "trinity" << endl;
  break;
default : cout << "large" << endl;
}
```

3.22. Local variables in conditionals

The curly brackets in a conditional allow you to define local variables:

```
if ( something ) {
  int i;
  .... do something with i
}
// the variable 'i' has gone away.
```

Exercise 3.8. Read in an integer. If it's a multiple of three print 'Fizz'; if it's a multiple of five print 'Buzz'. It it is a multiple of both three and five print 'FizzBuzz'. Otherwise print nothing.

3.5.1 Further practice

The website http://www.codeforwin.in/2015/05/if-else-programming-practice.html lists the following exercises for conditional:

1. Write a C program to find maximum between two numbers.
2. Write a C program to find maximum between three numbers.
3. Write a C program to check whether a number is even or odd.
4. Write a C program to check whether a year is leap year or not.

5. Write a C program to check whether a number is negative, positive or zero.
6. Write a C program to check whether a number is divisible by 5 and 11 or not.
7. Write a C program to count total number of notes in given amount.
8. Write a C program to check whether a character is alphabet or not.
9. Write a C program to input any alphabet and check whether it is vowel or consonant.
10. Write a C program to input any character and check whether it is alphabet, digit or special character.
11. Write a C program to check whether a character is uppercase or lowercase alphabet.
12. Write a C program to input week number and print week day.
13. Write a C program to input month number and print number of days in that month.
14. Write a C program to input angles of a triangle and check whether triangle is valid or not.
15. Write a C program to input all sides of a triangle and check whether triangle is valid or not.
16. Write a C program to check whether the triangle is equilateral, isosceles or scalene triangle.
17. Write a C program to find all roots of a quadratic equation.
18. Write a C program to calculate profit or loss.

Chapter 4

Looping

4.1 Basic 'for' statement

4.1. Repeat statement

Sometimes you need to repeat a statement a number of times. That's where the *loop* comes in. A loop has a counter, called a *loop variable*, which (usually) ranges from a lower bound to an upper bound.

Here is the syntax in the simplest case:

```
for (int var=low; var<upper; var++) {
  // statements involving var
  cout << "The square of " << var << " is " << var*var << endl;
}
```

C difference: Use compiler flag `-std=c99`.

Exercise 4.1. Read an integer value, and print 'Hello world' that many times.

4.2. Loop syntax

- The loop variable can be defined outside the loop:

```
int var;
for (var=low; var<upper; var++) {
```

- The stopping test be any test; can even be empty.
- The increment can be a decrement or something like `var*=10`
- Any and all of initialization, test, increment can be empty:
  `for(;;) ...`

4.3. Nested loops

Traversing a matrix:

```
for (int i=0; i<m; i++)
  for (int j=0; j<n; j++)
    ...
```

4.2 Looping until

4.4. Indefinite looping

Sometimes you want to iterate some statements not a predetermined number of times, but until a certain condition is met. There are two ways to do this.
First of all, you can use a 'for' loop and leave the upperbound unspecified:

```
for (int var=low; ; var=var+1) { ... }
```

4.5. Break out of a loop

This loop would run forever, so you need a different way to end it. For this, use the `break` statement:

```
for (int var=low; ; var=var+1) {
  statement;
  if (some_test) break;
  statement;
}
```

4.6. Skip iteration

```
for (int var=low; var<N; var++) {
  statement;
  if (some_test) {
    statement;
    statement;
  }
}
```

Alternative:

```
for (int var=low; var<N; var++) {
  statement;
  if (!some_test) continue;
  statement;
  statement;
}
```

4.7. While loop

The other possibility is a `while` loop, which repeats until a condition is met.
Syntax:

```
while ( condition ) {
  statements;
}
```

or

```
do {
  statements;
} while ( condition );
```

The while loop does not have a counter or an update statement; if you need those, you have to create them yourself.

4.8. While syntax 1

```
cout << "Enter a positive number: " ;
cin >> invar;
while (invar>0) {
  cout << "Enter a positive number: " ;
  cin >> invar;
}
cout << "Sorry, " << invar << " is negative" << endl;
```

Problem: code duplication.

4.9. While syntax 2

```
do {
  cout << "Enter a positive number: " ;
  cin >> invar;
} while (invar>0);
cout << "Sorry, " << invar << " is negative" << endl;
```

More elegant.

Exercise 4.2. One bank account has 100 dollars and earns a 5 percent per year interest rate. Another account has 200 dollars but earns only 2 percent per year. In both cases the interest is deposited into the account.
After how many years will the amount of money in both accounts be the same?

Chapter 5

Scope, functions, classes

5.1 Scope

Global variables, local variables.

When you defined a function for primality testing, you placed it outside the main program, and the main program was able to use it. There are other things than functions that can be defined outside the main program, such as *global variables*.

Here is a program that uses a global variable:

```
int i=5;
int main() {
  i = i+3;
  cout << i << endl;
  return 0;
}
```

5.2 Functions

A *function* (or *subprogram*) is a way to abbreviate a block of code and replace it by a single line.

Any program you can write with functions you can also write without. It will be just as fast, but maybe harder to read, it may be longer, and harder to debug.

5.1. Turn blocks of code into functions

- Code fragment with clear function:
- Turn into *subprogram*: function *definition*.
- Use by single line: function *call*.

5.2. Function definition and call

```
for (int i=0; i<N; i++) {
  cout << i;
  if (i%2==0)
    cout << " is even";
  else
    cout << " is odd";
  cout << endl;
}
```

```
void report_evenness(int n) {
  cout << i;
  if (i%2==0)
    cout << " is even";
  else
    cout << " is odd";
  cout << endl;
}
...
int main() {
  ...
  for (int i=0; i<N; i++)
    report_evenness(i);
}
```

5.3. Why functions?

- Easier to read
- Shorter code: reuse
- Maintainance and debugging

- Functions make your code easier to read: you replace a block of code by a descriptive name.
- Your code may become shorter: if you find yourself writing the same block of code twice, you replace it by one function definition, and twice a single line *function call*. This is known as *code reuse*.
- Easier to debug: if you use the same (or roughly the same) block of code twice, and you find an error, you need to fix it twice.
- Maintainance: if a block occurs twice, and you change something in such a block once, you have to remember to change the other occurrences too.

5.4. Prime function

Using a function, primality testing would look like:

```
bool isprime;
number = 13;
isprime = prime_test_function(number);
```

5.5. Anatomy of a function definition

- Result type: what's computed. `void` if no result
- Name: make it descriptive.
- Arguments: zero or more.
  `int i,double x,double y`
- Body: any length.
- Return statement: usually at the end, but can be anywhere; the computed result.

Loosely, a function takes input and computes some result which is then returned. Formally, a function consists of:

- *function result type*: you need to indicate the type of the result;
- name: you get to make this up;
- zero or more *function parameters* or *function arguments*: the data that the function operates on; and the
- *function body*: the statements that make up the function; and
- a *return* statement. Which doesn't have to be last, by the way.

Functions are defined before the main program, and used in that program: Here is a program with a function that doubles its input:

5.6. Program with function

```
#input <iostream>
using namespace std;

int twice_function(int n) {
  int twice_the_input = 2*n;
  return twice_the_input;
}

int main() {
  int number = 3;
  cout << "Twice three is: " <<
    twice_function(number) << endl;
  return 0;
}
```

5.7. Function call

The function call

1. causes the function body to be executed, and
2. the function call is replaced by whatever you `return`.
3. (If the function does not return anything, for instance because it only prints output, you declare the return type to be `void`.)

5.8. Functions without input, without return result

```
void print_header() {
  cout << "***************" << endl;
  cout << "* Ouput       *" << endl;
  cout << "***************" << endl;
  }
int main() {
```

```
  print_header();
  cout << "The results for day 25:" << endl;
  // code that prints results ....
  return 0;
}
```

5.9. Functions with input

```
void print_header(int day) {
  cout << "****************" << endl;
  cout << "* Ouput        *" << endl;
  cout << "****************" << endl;
  cout << "The results for day " << day << ":" << endl;
  }
int main() {
  print_header(25);
  // code that prints results ....
  return 0;
}
```

5.10. Functions with return result

```
#include <cmath>
double pi() {
  return 4*atan(1.0);
}
```

5.11. Scope

Function body is a *scope*: local variables.
No local functions.

A function body defines a *scope*: the local variables of the function calculation are invisible to the calling program.

Functions can not be nested: you can not define a function inside the body of another function.

5.2.1 Parameter passing

5.12. Mathematical type function

Pretty good design:

- pass data into a function,
- return result through `return` statement.
- Parameters are copied into the function.
- *pass by value*

Exercise 5.1. Early computers had no hardware for computing a square root. Instead, they used *Newton's method*. Suppose you want to compute

$$x = \sqrt{y}.$$

This is equivalent to finding the zero of

$$f(x) = x^2 - y.$$

Newton's method does this by evaluating

$$x_{\text{next}} = x - f(x)/f'(x)$$

until the guess is accurate enough.

- Write functions `f(x,y)` and `deriv(x,y)`, and a function `newton_root` that uses `f` and `deriv` to iterate to some precision.
- Take an initial guess for `x`, not zero.
- As a stopping test, use $|\texttt{f}(\texttt{x},\texttt{y})| < 10^{-5}$.
- Use `double` for all your variables.

5.13. Results other than through return

Also good design:

- Return no function result,
- or return (0 is success, nonzero various informative statuses), and
- return other information by changing the parameters.
- *pass by reference*

5.14. Pass by reference example

```
bool can_read_value( int &value ) {
  int file_status = try_open_file();
  if (file_status==0)
    value = read_value_from_file();
  return file_status!=0;
}
...
if (!can_read_value(n))
  // if you can't read the value, set a default
  n = 10;
```

Exercise 5.2. Write a function `swap` of two parameters that exchanges the input values:

```
int i=2,j=3;
swap(i,j);
// now i==3 and j==2
```

Exercise 5.3. Write a function that tests divisibility and returns a remainder:

```
int number,divisor,remainder;
// get the number and divisor from the user
if ( is_divisible(number,divisor,remainder) )
  cout << number << " is divisible by " << divisor << endl;
else
  cout << number << "/" << divisor <<
      " has remainder " << remainder << endl;
```

5.2.2 Recursive functions

5.15. Recursion

Functions are allowed to call themselves, which is known as *recursion*. You can define factorial as

$$F(n) = n \times F(n-1) \qquad \text{if } n > 1, \text{ otherwise } 1$$

```
int factorial( int n ) {
  if (n==1)
    return 1;
  else
    return n*factorial(n-1);
}
```

Exercise 5.4. The sum of squares:

$$S_n = \sum_{n=1}^{N} n^2$$

can be defined recursively as

$$S_1 = 1, \qquad S_n = n^2 + S_{n-1}.$$

Write a recursive function that implements this second definition. Test it on numbers that are input by the user.
Then write a program that prints the first 100 sums of squares.

Exercise 5.5. Write a recursive function for computing Fibonacci numbers:

$$F_0 = 1, \qquad F_1 = 1, \qquad F_n = F_{n-1} + F_{n-2}$$

First write a program that computes F_n for a value n that is input by the user.
Then write a program that prints out a sequence of Fibonacci numbers; the user should input how many.

If you let your Fibonacci program print out each time it computes a value, you'll see that most values are computed several times. (Math question: how many times?) This is wasteful in running time. This problem is addressed in section 35.3.1.

5.2.3 Polymorphic functions

5.16. Polymorphic functions

You can have multiple functions with the same name:

```
double sum(double a,double b) {
  return a+b; }
double sum(double a,double b,double c) {
  return a+b+c; }
```

Distinguished by input parameters: can not differ only in return type.

5.2.4 Default arguments

5.17. Default arguments

Functions can have *default argument*(s):

```
double distance( double x, double y=0. ) {
  return sqrt( (x-y)*(x-y) );
}
```

Any default argument(s) should come last in the parameter list.

5.2.5 Static variables

Variables in a function have *lexical scope* limited to that function. Normally they also have *dynamic scope* limited to the function execution: after the function finishes they completely disappear. (Class objects have their *destructor* called.)

There is an exception: a *static variable* persists between function invocations.

```
void fun() {
  static int remember;
}
```

For example

```
int onemore() {
  static int remember++; return remember;
}
int main() {
  for ( ... )
    cout << onemore() << end;
  return 0;
}
```

gives a stream of integers.

Exercise 5.6. The static variable in the `onemore` function is never initialized. Can you find a mechanism for doing so? Can you do it with a default argument to the function?

Chapter 6

Structures

6.1 Why structures?

6.1. Bundling information

Sometimes a number of variables belong logically together. For instance two doubles can be the x, y components of a vector.
This can be captured in the `struct` construct.

```
struct vector { double x; double y; } ;
```

(This can go in the main program or before it.)
Initialize:

```
struct vector { double x=0.; double y=0.; } ;
```

The elements of a structure are usually called *members*.

6.2 The basics of structures

6.2. Using structures

Once you have defined a structure, you can make variables of that type. Setting and initializing them takes a new syntax:

```
struct vector p1,p2;

p1.x = 1.; p1.y = 2.;
p2 = {3.,4.};

p2 = p1;
```

6.3. Functions on structures

You can pass a structure to a function:

```
double distance( struct vector p1,struct vector p2 ) {
  double d1 = p1.x-p2.x, d2 = p1.y-p2.y;
  return sqrt( d1*d1 + d2*d2 );
}
```

6.4. Functions on structures'

Prevent copying cost by passing by reference, use `const` to prevent changes:

```
double distance( const struct vector &p1,const struct vector &p2 ) {
  double d1 = p1.x-p2.x, d2 = p1.y-p2.y;
  return sqrt( d1*d1 + d2*d2 );
}
```

6.5. Returning structures

You can return a structure from a function:

```
struct vector vector_add
      ( struct vector p1,struct vector p2 ) {
   struct vector p_add = {p1.x+p2.x,p1.y+p2.y};
   return p_add;
};
```

(Something weird here with scopes: the explanation is that the returned value is copied.)

Exercise 6.1. Write a function `inner_product` that takes two `vector` structures and computes the inner product.

Exercise 6.2. Write a 2×2 matrix class (that is, a structure storing 4 real numbers), and write a function `multiply` that multiplies a matrix times a vector.

Chapter 7

Classes and objects

7.1 What is an object?

7.1. Classes look a bit like objects

```
class Vector {
public:
  double x,y;
};

int main() {
  Vector p1;
  p1.x = 1.; p1.y = 2.;
```

We'll get to that '`public`' in a minute.

7.2. Class initialization and use

Use a *constructor*:

```
class Vector {
public:
  double x,y;
  Vector( double userx,double usery ) {
    x = userx; y = usery;
  }
};

int main() {
  Vector p1(1.,2.);
```

7.3. Member initialization

Other syntax for initialization:

```
class Vector {
public:
  double x,y;
  Vector( double userx,double usery ) : x(userx),y(usery) {
  }
};
```

7.4. Private data

```
class Vector {
private:
  double vx,vy;
public:
  Vector( double x,double y ) {
    vx = x; vy = y;
  };
  double x() { return vx; }; // 'accessor'
  double y() { return vy; };
};

int main() {
  Vector p1(1.,2.);
  cout << "p1 = " << p1.x() << "," << p1.y() << endl;
```

7.5. Functions on objects

```
class Vector {
private:
  double vx,vy;
public:
  Vector( double x,double y ) {
    vx = x; vy = y;
  };
  double length() { return sqrt(vx*vx + vy*vy); };
  double angle() { return 0.; /* something trig */; };
};

int main() {
  Vector p1(1.,2.);
  cout << "p1 has length " << p1.length() << endl;
```

We call such internal functions 'methods'

7.6. Methods that alter the object

```
class Vector {
  /* ... */
  void scaleby( double a ) {
    vx *= a; vy *= a; };
  /* ... */
};
  /* ... */
  Vector p1(1.,2.);
  cout << "p1 has length " << p1.length() << endl;
  p1.scaleby(2.);
  cout << "p1 has length " << p1.length() << endl;
```

7.7. Methods that create a new object

```
class Vector {
  /* ... */
  Vector scale( double a ) {
    return Vector( vx*a, vy*a ); };
  /* ... */
};
  /* ... */
  cout << "p1 has length " << p1.length() << endl;
  Vector p2 = p1.scale(2.);
  cout << "p2 has length " << p2.length() << endl;
```

7.8. Constructor

```
Vector p1(1.,2.), p2;
cout << "p1 has length " << p1.length() << endl;
p2 = p1.scale(2.);
cout << "p2 has length " << p2.length() << endl;
```

gives:

```
pointdefault.cxx: In function 'int main()':
pointdefault.cxx:32:21: error: no matching function for call to
                'Vector::Vector()'
   Vector p1(1.,2.), p2;
```

So:

```
Vector() {};
Vector( double x,double y ) {
  vx = x; vy = y;
};
```

7.1.1 Accessors

It is a good idea to make the data in an object private, to control outside access to it.

- Sometimes this private data is auxiliary, and there is no reason for outside access.
- Sometimes you do want outside access, but you want to precisely control by whom.

Accessor functions:

```
class thing {
private:
 float x;
public:
 float get_x() { return x; };
 void set_x(float v) { x = v; }
};
```

This has advantages:

- You can print out any time you get/set the value; great for debugging
- You can catch specific values: if `x` is always supposed to be positive, print an error (throw an exception) if nonpositive.

Better accessor:

```
class thing {
private:
 float x;
public:
 float &the_x() { return x; };
};
int main () {
  thing t;
  t.the_x() = 5;
  cout << t.the_x();
}
```

The function `the_x` returns a reference to the internal variable `x`.

If the internal variable is something indexable:

```
class thing {
private:
  vector<float> x;
public:
  operator[](int i) { return x[i]; };
};
```

You define the subscript operator `[]` for the object, in terms of indexing of the private vector.

7.2 Relations between classes

7.3 Inclusion relations between classes

7.9. Has-a relationship

A class usually contains data members. These can be simple types or other classes.
This allows you to make structured code.

```
class Course {
private:
  Person the_instructor;
  int year;
}
class Person {
  string name;
  ....
}
```

This is called the *has-a relation*.

At this time, do exercises in section 33.2.

7.10. Literal and figurative has-a

Compare:

```
class Segment {
private:
  Point starting_point,ending_point;
}
  ...
  Segment somesegment;
  Point somepoint = somesegment.get_the_end_point();
```

Versus:

```
class Segment {
private:
  Point starting_point;
  float length,angle;
}
```

Implementation vs API.

7.11. Polymorphism in constructors

You have to decide what to store and what to derive, but you can construct two ways:

```
class Segment {
private:
 // up to you how to implement!
public:
  Segment( Point start,float length,float angle )
    { .... }
  Segment( Point start,Point end ) { ... }
```

Advantage: with a good API you can change your mind about the implementation!

At this time, do the exercises in section 33.3

7.4 Inheritance

7.12. General case, special case

You can have classes where an object of one class is a special case of the other class.

You declare that as

```
class General {
protected: // note!
 int g;
public:
 void general_method() {};
};
class Special : public General {
public:
  void special_method() { g = ... };
```

```
};
```

7.13. Inheritance: derived classes

Derived class `Special` *inherits inheritance* methods and data from *base class* `General`:

```
int main() {
  Special special_object;
  special_object.general_method();
```

Data needs to be `protected`, not `private`, to be inheritable.

7.14. Constructors

When you run the special case constructor, usually the general case needs to run too. By default the 'default constructor', but:

```
class General {
public:
  General( double x,double y ) {};
};
class Special : public General {
public:
  Special( double x ) : General(x,x+1) {};
};
```

7.15. More

- Multiple inheritance: an X is-a A, but also is-a B.
  This mechanism is somewhat dangerous.
- Virtual base class: you don't actually define a function in the base class, you only say 'any derived class has to define this function'.

7.4.1 Methods of base and derived classes

7.16. Overriding methods

- A derived class can inherit a method from the base class.
- A derived class can define a method that the base class does not have.
- A derived class *override* a base class method:

```
class Base {
public:
  virtual f() { ... };
};
class Deriv : public Base {
public:
  virtual f() override { ... };
};
```

7.17. Abstract classes

Special syntax for *abstract method*:

```
class Base {
public:
  virtual void f() = 0;
};
class Deriv {
public:
  virtual void f() { ... };
};
```

- The base class declares that every derived class has to define `f`
- The base class itself does not define this method: *abstract class*
- You can not make objects of the base class.

Chapter 8

Other

8.1 Output your own classes

See section 11.4.1.

Chapter 9

Arrays

9.1 Traditional arrays

Static allocation, initialization.

```
// basic/array.cxx
{
  int numbers[] = {5,4,3,2,1};
  cout << numbers[3] << endl;
}
{
  int numbers[5]{5,4,3,2,1};
  cout << numbers[3] << endl;
}
{
  int numbers[5] = {2};
  cout << numbers[3] << endl;
}
```

Disadvantage: no test on bounds.

Exercise 9.1. Check whether an array is sorted.

Exercise 9.2. Find the maximum element in an array.
Also report at what index the maximum occurs.

Arrays can be passed to a subprogram, but the bound is unknown there.

```
// basic/array.cxx
void print_first_index( int ar[] ) {
  cout << "First index: " << ar[0] << endl;
}
  {
    int numbers[] = {1,4,2,5,6};
    print_first_index(numbers);
  }
```

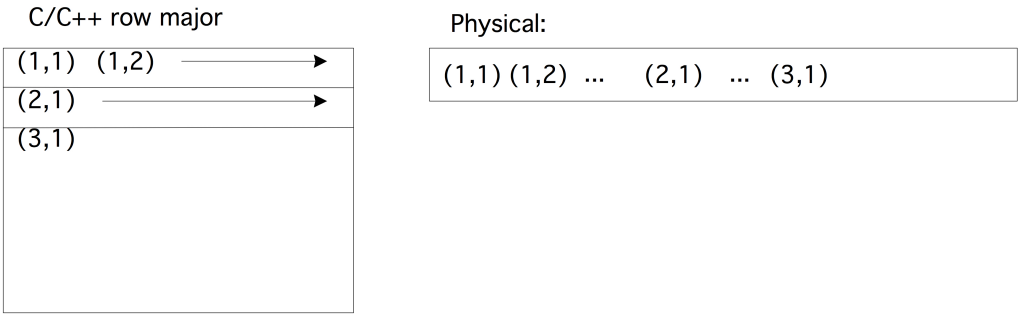
Exercise 9.3. Rewrite the above exercises where the sorting tester or the maximum finder is in a subprogram.

Subprograms can alter array elements. This was not possible with scalar arguments.

9.2 Multi-dimensional arrays

Declaration, pass to subprogram.

```
// array/contig.cxx
void print12( int ar[][6] ) {
  cout << "Array[1][2]: " << ar[1][2] << endl;
  return;
}
    int array[5][6];
    array[1][2] = 3;
    print12(array);
```



Memory layout: multi-dimensional arrays are actually contiguous and linear.

```
// array/contig.cxx
void print06( int ar[][6] ) {
  cout << "Array[0][6]: " << ar[0][6] << endl;
  return;
}
    int array[5][6];
    array[1][0] = 35;
    print06(array);
```

9.3 Other allocation mechanisms

A declaration

```
float ar[500];
```

is local to the scope it is in. This has some problems:

- Allocated on the *stack*; may lead to stack overflow.
- Can not be used as a class member:

```
class thing {
private:
  double array[ ???? ];
public:
  thing(int n) {
    array[ n ] ???? this does not work
  }
}
```

- Can not be returned from subprogram:

```
void make_array( double array[],int n ) {
  double array[n] ???? does not work
}
int main() {
  ....
  make_array(array,100);
}
```

Use of `new` uses the equivalence of array and reference.

```
// array/arraynew.cxx
void make_array( int **new_array, int length ) {
  *new_array = new int[length];
}
  int *the_array;
  make_array(&the_array,10000);
```

Since this is not scoped, you have to free the memory yourself:

```
// array/arraynew.cxx
class with_array{
private:
  int *array;
  int array_length;
public:
  with_array(int size) {
    array_length = size;
    array = new int[size];
  };
  ~with_array() {
    delete array;
  };
};
  with_array thing_with_array(12000);
```

Notice how you have to remember the array length yourself? This is all much easier by using a `std::vector`. See http://www.cplusplus.com/articles/37Mf92yv/.

Deprecated use of `malloc`.

9.4 Vector class for arrays

Syntax:

```
#include <vector>
using namespace std;

vector<type> name(size)
```

where

- `vector` is a keyword,
- `type` (in angle brackets) is any elementary type or class name,
- `name` is up to you, and
- `size` is the (initial size of the array). This is an integer, or more precisely, a `size_t` parameter.

A vector behaves like an array:

```
vector<double> x(25);
x[1] = 3.14;
cout << x[2];
```

Initialization:

```
vector<int> odd_array{1,3,5,7,9};
vector<int> even_array = {0,2,4,6,8};
```

(This syntax requires compilation with the `-std=c++11` option.)

There is a second way of accessing elements:

```
vector<double> x(5);
x[5] = 1.; // will probably work
x.at(5) = 1.; // runtime error!
```

Safer, but also slower; see below.

Method `size` gives the size of the vector:

```
vector<char> words(37);
cout << words.size(); // will print 37
```

The vector class is a template class: the type that it uses (int, float) is not predetermined, but you can make a vector object out of whatever type you like.

9.4.1 Vector methods

- Get elements with `ar[3]` (zero-based indexing).
- Get elements, including bound checking, with `ar.at(3)`.
- Size: `ar.size()`.
- Other functions: `front`, `back`.

9.4.2 Vectors are dynamic

Use `push_back` to add elements at end.

```
vector<int> array(5);
array.push_back(35);
cout << array.size(); // is now 6 !
```

Other methods that change the size: `insert`, `erase`.

9.4.3 Vector assignment

The limitation that you couldn't create an array in an object still holds:

```
class witharray {
private:
  vector<int> the_array( ???? );
public:
  witharray( int n ) {
    thearray( ???? n ???? );
  }
}
```

The following mechanism works:

```
class witharray {
private:
  vector<int> the_array;
public:
  witharray( int n ) {
    thearray = vector<int>(n);
  }
}
```

You could read this as

- `vector<int> the_array` declares a int-vector variable, and
- `thearray = vector<int>(n)` assigns an array to it.

However, technically, it actually does the following:

- The class object initially has a zero-size vector;
- the expression `vector<int>(n)` creates an anonymous vector of size `n`;
- which is then assigned to the variable `the_array`,
- so now you have an object with a vector of size `n` internally.

9.4.4 Vectors and functions

9.4.4.1 Vector as function return

You can have a vector as return type of a function:

```
vector<int> make_array(int n) {
  vector<int> x(n);
  x[0] = n;
  return x;
}
  /* ... */
  x1 = make_array(10);
```

9.4.4.2 Pass vector to function

You can pass a vector to a function:

```
void print0( vector v ) {
  cout << v[0] << endl;
};
```

Vectors, like any argument, are passed by value, so the vector is actually copied into the function.

```
void set0( vector<float> &v,float x ) {
  v[0] = x;
}
  /* ... */
  vector<float> v(1);
  v[0] = 3.5;
  set0(v,4.6);
  cout << v[0] << endl;
```

This means you have to pass by reference:

Exercise 9.4. Write functions `random_vector` and `sort` to make the following main program work:

```
int length = 99;
vec<float> values = random_floats(length);
sort(values);
```

(This creates a vector of random values of a specified length, and then sorts it.)

9.4.5 Dynamic size of vector

Writing

```
vector<int> iarray;
```

creates a vector of size zero. You can then

```
iarray.push_back(5);
iarray.push_back(32);
iarray.push_back(4);
```

to add elements to the vector, dynamically resizing it.

9.4.6 Timing

Different ways of acessing a vector can have drastically different timing cost.

You can push elements into a vector:

```
vector<int> flex;
point = std::chrono::system_clock::now();
for (int i=0; i<LENGTH; i++)
  flex.push_back(i);
```

If you allocate the vector statically, you can assign with `at`:

```
vector<int> stat(LENGTH);
point = std::chrono::system_clock::now();
for (int i=0; i<LENGTH; i++)
  stat.at(i) = i;
```

or with subscript:

```
vector<int> stat(LENGTH);
stat[0] = 0.;
point = std::chrono::system_clock::now();
for (int i=0; i<LENGTH; i++)
  stat[i] = i;
```

You can also use `new` to allocate:

```
int *stat = new int[LENGTH];
point = std::chrono::system_clock::now();
for (int i=0; i<LENGTH; i++)
  stat[i] = i;
```

Timings are partly predictable, partly surprising:

```
Flexible time: 2.445
Static at time: 1.177
Static assign time: 0.334
Static assign time to new: 0.467
```

The increased time for `new` is a mystery.

9.5 Wrapping a vector in an object

You may want to a create objects that contain a vector, for instance because you want to add some methods.

```
class printable {
private:
  vector<int> values;
public:
  printable(int n) {
    values = vector<int>(n);
  };
  string stringed() {
    string p("");
    for (int i=0; i<values.size(); i++)
      p += to_string(values[i])+" ";
    return p;
  };
};
```

Unfortunately this means you may have to recreate some methods:

```
int &at(int i) {
  return values.at(i);
};
```

9.6 Multi-dimensional cases

9.6.1 Matrix as vector of vectors

Multi-dimensional is harder with vectors:

```
vector<float> row(20);
vector<vector<float>> rows(10,row); // check on that >> syntax!
```

This is not contiguous.

9.6.2 Matrix class based on vector

Make sure you've studied classes; section **??**.

You can make a 'pretend' matrix by storing a long enough `vector` in an object:

```
// array/matrixclass.cxx
class matrix {
private:
  std::vector<double> the_matrix;
  int m,n;
```

```
public:
  matrix(int m,int n) {
    this->m = m; this->n = n;
    the_matrix.reserve(m*n);
  };
  void set(int i,int j,double v) {
    the_matrix[ i*n +j ] = v;
  };
  double get(int i,int j) {
    return the_matrix[ i*n +j ];
  };
  /* ... */
};
```

The syntax for `set` and `get` can be improved.

Exercise 9.5. Write a method `element` of type `double&`, so that you can write

```
A.element(2,3) = 7.24;
```

9.7 Exercises

Exercise 9.6. Program *bubble sort*: go through the array comparing successive pairs of elements, and swapping them if the second is smaller than the first. After you have gone through the array, the largest element is in the last location. Go through the array again, swapping elements, which puts the second largest element in the one-before-last location. Et cetera.

Exercise 9.7. Pascal's triangle contains binomial coefficients:

```
Row    1:                      1
Row    2:                    1   1
Row    3:                  1   2   1
Row    4:                1   3   3   1
Row    5:              1   4   6   4   1
Row    6:            1   5  10  10   5   1
Row    7:          1   6  15  20  15   6   1
Row    8:        1   7  21  35  35  21   7   1
Row    9:      1   8  28  56  70  56  28   8   1
Row   10:    1   9  36  84 126 126  84  36   9   1
```

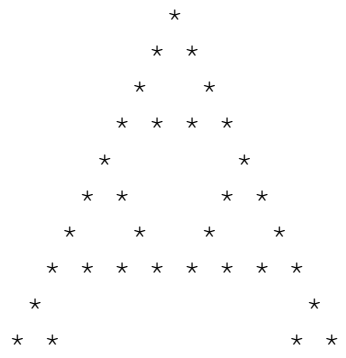
where

$$p_{rc} = \binom{r}{c} = \frac{r!}{c!(r-c)!}.$$

The coefficients can easily be computed from the recurrence

$$p_{rc} = \begin{cases} 1 & c \equiv 1 \vee c \equiv r \\ p_{r-1,c-1} + p_{r-1,c} & \end{cases}$$

- Write a class `pascal` so that `pascal(n)` is the object containing n rows of the above coefficients. Write a method `get(i,j)` that returns the (i, j) coefficient.
- Write a method `print` that prints the above display.
- Write a method `print(int m)` that prints a star if the coefficient modulo m is nonzero, and a space otherwise.



- The object needs to have an array internally. The easiest solution is to make an array of size $n \times n$. When you have that code working, optimize your code to use precisely enough space for the coefficients.

Exercise 9.8. A knight on the chess board moves by going two steps horizontally or vertically, and one step either way in the orthogonal direction. Given a starting position, find a sequence of moves that brings a knight back to its starting position. Are there starting positions for which such a cycle doesn't exist?

Exercise 9.9. Put eight queens on a chessboard so that none threatens any other.

Exercise 9.10. From the 'Keeping it REAL' book, exercise 3.6 about Markov chains.

Chapter 10

Strings

10.1 Basic string stuff

10.1. String declaration

```
#include <string>
using namespace std;

// .. and now you can use 'string'
```

10.2. String creation

A *string* variable contains a string of characters.

```
string txt;
```

You can initialize the string variable, or assign it dynamically:

```
string txt{"this is text"};
string moretxt("this is also text");
txt = "and now it is another text";
```

10.3. Concatenation

Strings can be *concatenated*:

```
txt = txt1+txt2;
txt += txt3;
```

10.4. String is like vector

You can query the *size*:

```
int txtlen = txt.size();
```

or use subscripts:

```
cout << "The second character is <<" <<
        txt[1] << ">>" << endl;
```

10.5. More vector methods

Other methods for the vector class apply: `insert`, `empty`, `erase`, `push_back`, et cetera.

http://en.cppreference.com/w/cpp/string/basic_string

Exercise 10.1. Write a function to print out the digits of a number: `156` should print `one five six`. Use a vector of strings.
Hint: it is easiest to generate the digits last-to-first. Then figure out how to print them reversed.

Exercise 10.2. Write a function to convert an integer to a string: the input `205` should give `two hundred fifteen`, et cetera.

Exercise 10.3. Write a pattern matcher, where a period `.` matches any one character, and `x*` matches any number of 'x' characters.
For example:

- The string `abc` matches `a.c` but `abbc` doesn't.
- The string `abbc` matches `ab*c`, as does `ac`, but `abzbc` doesn't.

10.2 Conversion

`to_string`

Chapter 11

Input/output

11.1 Formatted output

11.1. Default output

Normally, output of numbers takes up precisely the space that it needs:

```
cout << "Unformatted:" << endl;
for (int i=1; i<200000000; i*=10)
  cout << "Number: " << i << endl;
cout << endl;
```

11.2. Output

```
Unformatted:
Number: 1
Number: 10
Number: 100
Number: 1000
Number: 10000
Number: 100000
Number: 1000000
Number: 10000000
Number: 100000000
```

11.3. Reserve space

You can specify the number of positions, and the output is right aligned in that space by default:

```
cout << "Width is 6:" << endl;
for (int i=1; i<200000000; i*=10)
  cout << "Number: " << setw(6) << i << endl;
cout << endl;
```

(Only applies to immediately following number)

11.4. Output

```
Width is 6:
Number:      1
Number:     10
```

```
Number:    100
Number:   1000
Number:  10000
Number: 100000
Number: 1000000
Number: 10000000
Number: 100000000
```

11.5. Padding character

Normally, padding is done with spaces, but you can specify other characters:

```
cout << "Padding:" << endl;
for (int i=1; i<200000000; i*=10)
  cout << "Number: "
       << left << setfill('.') << setw(6) << i << endl;
```

Note: single quotes denote characters, double quotes denote strings.

Note: many of these output modifiers need

```
#include <iomanip>
```

11.6. Output

```
Padding:
Number: .....1
Number: ....10
Number: ...100
Number: ..1000
Number: .10000
Number: 100000
Number: 1000000
Number: 10000000
Number: 100000000
```

11.7. Left alignment

Instead of right alignment you can do left:

```
cout << "Padding:" << endl;
for (int i=1; i<200000000; i*=10)
  cout << "Number: "
       << left << setfill('.') << setw(6) << i << endl;
cout << endl;
```

11.8. Output

```
Padding:
Number: 1.....
Number: 10....
Number: 100...
Number: 1000..
```

```
Number: 10000.
Number: 100000
Number: 1000000
Number: 10000000
Number: 100000000
```

11.9. Number base

Finally, you can print in different number bases than 10:

```
cout << "Base 16:" << endl;
cout << setbase(16) << setfill(' ');
for (int i=0; i<16; i++) {
  for (int j=0; j<16; j++)
    cout << i*16+j << " " ;
  cout << endl;
}
cout << endl;
```

11.10. Output

```
Base 16:
0 1 2 3 4 5 6 7 8 9 a b c d e f
10 11 12 13 14 15 16 17 18 19 1a 1b 1c 1d 1e 1f
20 21 22 23 24 25 26 27 28 29 2a 2b 2c 2d 2e 2f
30 31 32 33 34 35 36 37 38 39 3a 3b 3c 3d 3e 3f
etc
```

Exercise 11.1. Make the above output more nicely formatted:

```
00 01 02 03 04 05 06 07 08 09 0a 0b 0c 0d 0e 0f
10 11 12 13 14 15 16 17 18 19 1a 1b 1c 1d 1e 1f
20 21 22 23 24 25 26 27 28 29 2a 2b 2c 2d 2e 2f
```

Exercise 11.2. Use integer output to print fixed point numbers aligned on the decimal:

```
  1.345
 23.789
456.1234
```

Use four spaces for both the integer and fractional part.

11.2 Floating point output

11.11. Floating point precision

Use `setprecision` to set the number of digits before and after decimal point:

```
x = 1.234567;
for (int i=0; i<10; i++) {
  cout << setprecision(4) << x << endl;
```

```
  x *= 10;
}
```

11.12. Output

```
1.235
12.35
123.5
1235
1.235e+04
1.235e+05
1.235e+06
1.235e+07
1.235e+08
1.235e+09
```

(Notice the rounding)

11.13. Fixed point precision

Fixed precision applies to fractional part:

```
cout << "Fixed precision applies to fractional part:" << endl;
x = 1.234567;
cout << fixed;
for (int i=0; i<10; i++) {
  cout << setprecision(4) << x << endl;
  x *= 10;
}
```

11.14. Output

```
1.2346
12.3457
123.4567
1234.5670
12345.6700
123456.7000
1234567.0000
12345670.0000
123456700.0000
1234567000.0000
```

11.15. Aligned fixed point output

Combine width and precision:

```
x = 1.234567;
cout << fixed;
for (int i=0; i<10; i++) {
  cout << setw(10) << setprecision(4) << x << endl;
  x *= 10;
```

```
}
```

11.16. Output

```
    1.2346
   12.3457
  123.4567
 1234.5670
12345.6700
123456.7000
1234567.0000
12345670.0000
123456700.0000
1234567000.0000
```

11.17. Scientific notation

```
cout << "Combine width and precision:" << endl;
x = 1.234567;
cout << scientific;
for (int i=0; i<10; i++) {
  cout << setw(10) << setprecision(4) << x << endl;
  x *= 10;
}
```

11.18. Output

```
Combine width and precision:
1.2346e+00
1.2346e+01
1.2346e+02
1.2346e+03
1.2346e+04
1.2346e+05
1.2346e+06
1.2346e+07
1.2346e+08
1.2346e+09
```

11.3 Saving and restoring settings

```
ios::fmtflags old_settings = cout.flags();

cout.flags(old_settings);
```

```
int old_precision = cout.precision();

cout.precision(old_precision);
```

11.4 File output

11.19. Text output to file

Streams are general: work the same for console out and file out.

```
#include <fstream>
```

Use:

```
ofstream file_out;
file_out.open("fio_example.out");
/* ... */
file_out << number << endl;
file_out.close();
```

11.20. Binary output

```
ofstream file_out;
file_out.open("fio_binary.out",ios::binary);
```

11.4.1 Output your own classes

You have used statements like:

```
cout << ``My value is: `` << myvalue << endl;
```

How does this work? The 'double less' is an operator with a left operand that is a stream, and a right operand for which output is defined; the result of this operator is again a stream. Recursively, this means you can chain any number of applications of << together.

If you want to output a class that you wrote yourself, you have to define how the << operator deals with your class.

```
class container {
  /* ... */
  int value() const {
  /* ... */
  };
  /* ... */
std::ostream &operator<<(std::ostream &os,const container &i) {
  os << "Container: " << i.value();
  return os;
```

```
};
  /* ... */
  container eye(5);
  cout << eye << endl;
```

11.5 Input streams

Test, mostly for file streams: `is_eof is_open`

Chapter 12

References and addresses

12.1 Reference

This section contains further facts about parameter passing. Make sure you study section 5.2.1 first.

Passing a variable to a routine passes the value; in the routine, the variable is local.

```
// basic/arraypass.cxx
void change_scalar(int i) { i += 1; }
```

You can indicate that this is unintended:

```
// basic/arraypass.cxx
/* This does not compile:
   void change_const_scalar(const int i) { i += 1; }
*/
```

If you do want to make the change visible in the *calling environment*, use a reference:

```
// basic/arraypass.cxx
void change_scalar_by_reference(int &i) { i += 1; }
```

There is no change to the calling program. (Some people find this bad, since you can not see from the use of a function whether it passes *by reference* or *by value*.)

Arrays are always pass by reference:

```
// basic/arraypass.cxx
void change_array_location( int ar[], int i ) { ar[i] += 1; }
  int numbers[5];
  numbers[2] = 3.;
  change_array_location(numbers,2);
```

The old-style way of doing things:

```
// basic/arraypass.cxx
void change_scalar_old_style(int *i) { *i += 1; }
  number = 3;
  change_scalar_old_style(&number);
```

Chapter 13

Polymorphism

13.1 The basic idea

Sometimes you want to have the same function name for two slightly different purposes. C++ allows you to define the same function twice, as long as their parameters are different enough.

For instance, here is the same ‘sum’ function defined for both integers and reals:

Chapter 14

Memory

14.1 Memory and scope

If a variable goes *out of scope*, its memory is deallocated.

Deallocating objects is slightly more complicated: an *object destructor* is called.

gives:

```
Before the nested scope
calling the constructor
Inside the nested scope
calling the destructor
After the nested scope
```

Chapter 15

Pointers

15.1 What is a pointer

The term pointer is used to denote a reference to a quantity. The reason that people like C++ and C as high performance languages is that pointers are actually memory addresses. So you're programming 'to the bare metal' and are in complete control over what your program does.

15.2 Pointers and addresses, C style

15.1. Memory addresses

If you have an

```
int i;
```

then `&i` is the address of `i`.
An address is a (long) integer, denoting a memory address. Usually it is rendered in *hexadecimal* notation:

```
int i;
printf("address of i: %ld\n",(long)(&i));
printf(" same in hex: %x\n",(long)(&i));
```

15.2. Address types

The type of '`&i`' is `int*`, pronounced 'int-star',
or more formally: 'pointer-to-int'.
You can create variables of this type:

```
int i;
int* addr = &i;
```

15.3. Star stuff

Equivalent:

- `int* addr`: `addr` is an int-star, or
- `int *addr`: `*addr` is an int.

The notion `int* addr` is equivalent to `int *addr`, and semantically they are also the same: you could say that `addr` is an int-star, or you could say that `*addr` is an int.

15.4. Dereferencing

Using `*addr` 'dereferences' the pointer: gives the thing it points to;
the value of what is in the memory location.

```
int i;
int* addr = &i;
i = 5;
cout << *addr;
i = 6;
cout << *addr;
```

This will print `5` and `6`:

- `addr` is the address of `i`.
- You set `i` to 5; nothing changes about `addr`. This has the effect of writing `5` in the memory location of `i`.
- The first `cout` line dereferences `addr`, that is, looks up what is in that memory location.
- Next you change `i` to `6`, that is, you write `6` in its memory location.
- The second `cout` looks in the same memory location as before, and now finds `6`.

15.5. Array and pointer equivalence

Array and memory locations are largely the same:

```
double array[5];
double *addr_of_second = &(array[1]);
array = (11,22,33,44,55);
cout << *addr_of_second;
```

15.6. Pointer arithmetic

pointer arithmetic uses the size of the objects it points at:

```
double *addr_of_element = array;
cout << *addr_of_element;
addr_of_element = addr_of_element+1;
cout << *addr_of_element;
```

Increment add size of the array element, 4 or 8 bytes, not one!

15.2.1 Parameter passing

15.7. C++ pass by reference

C++ style functions that alter their arguments:

```
void inc(int &i) { i += 1; }
int main() {
  int i=1;
  inc(i);
  cout << i << endl;
  return 0;
}
```

15.8. C-style pass by reference

In C you can not pass-by-reference like this. Instead, you pass the address of the variable `i` by value:

```
void inc(int *i) { *i += 1; }
int main() {
  int i=1;
  inc(&i);
  cout << i << endl;
  return 0;
}
```

Now the function gets an argument that is a memory address: `i` is an int-star. It then increases `*i`, which is an int variable, by one.

Exercise 15.1. Write another version of the `swap` function:

```
void swap( /* something with i and j */ {
  /* your code */
}
int main() {
  int i=1,j=2;
  swap( /* something with i and j */ );
  cout << "check that i is 2: " << i << endl;
  cout << "check that j is 1: " << i << endl;
  return 0;
}
```

15.2.2 Allocation

In section 9.1 you learned how to create arrays that are local to a scope:

15.9. Problem with static arrays

```
if ( something ) {
  double ar[25];
} else {
  double ar[26];
}
ar[0] = // there is no array!
```

The array `ar` is created depending on if the condition is true, but after the conditional it disappears again. The mechanism of using `new` (section 9.3) allows you to allocate storage that transcends its scope:

15.10. Declaration and allocation

```
double *array;
if (something) {
  array = new double[25];
} else {
  array = new double[26];
```

```
}
```

15.11. De-allocation

Memory allocated with `new` does not disappear when you leave a scope. Therefore you have to delete the memory explicitly:

```
delete(array);
```

15.2.2.1 Malloc

The keywords `new` and `delete` are in the spirit of C style programming, but don't exist in C. Instead, you use `malloc`, which creates a memory area with a size expressed in bytes. Use the function `sizeof` to translate from types to bytes:

15.12. Allocation in C

```
int n;
double *array;
array = malloc( n*sizeof(double) );
if (!array)
  // allocation failed!
```

15.2.2.2 Allocation in a function

The mechanism of creating memory, and assigning it to a 'star' variable can be used to allocate data in a function and return it from the function.

15.13. Allocation in a function

```
void make_array( double **a, int n ) {
  *a = new double[n];
}
int main() {
  double *array;
  make_array(&array,17);
}
```

Note that this requires a 'double-star' or 'star-star' argument:

- The variable `a` will contain an array, so it needs to be of type `double*`;
- but it needs to be passed by reference to the function, making the argument type `double**`;
- inside the function you then assign the new storage to the `double*` variable, which is `*a`.

Tricky, I know.

15.2.3 Memory leaks

Pointers can lead to a problem called *memory leaking*: there is memory that you have reserved, but you have lost the ability to access it.

In this example:

```
double *array = new double[100];
// ...
array = new double[105];
```

memory is allocated twice. The memory that was allocated first is never release, because in the intervening code another pointer to it may have been set. However, if that doesn't happen, the memory is both allocated, and unreachable. That's what memory leaks are about.

15.3 Safer pointers in C++

Section 15.2.3 showed how how memory can become unreachable. The *C++11* standard has mechanisms that can help solve this problem[1].

A 'shared pointer' is a pointer that keeps count of how many times the object is pointed to. If one of these pointers starts pointing elsewhere, the shared pointer decreases this 'reference count'. If the reference count reaches zero, the object is deallocated or destroyed.

```
#include <memory>

auto array = std::shared_ptr<double>( new double[100] );
```

As an illustration:

```
cout << "set pointer1" << endl;
auto thing_ptr1 = shared_ptr<thing>( new thing );
cout << "overwrite pointer" << endl;
thing_ptr1 = nullptr;
```

creates an object and overwrites the pointer, causing the object to be destroyed:

```
set pointer1
calling constructor
overwrite pointer
calling destructor
```

Illustrating how the object is not destroyed until all references are gone:

```
cout << "set pointer2" << endl;
auto thing_ptr2 = shared_ptr<thing>( new thing );
cout << "set pointer3 by copy" << endl;
auto thing_ptr3 = thing_ptr2;
cout << "overwrite pointer2" << endl;
thing_ptr2 = nullptr;
cout << "overwrite pointer3" << endl;
thing_ptr3 = nullptr;
```

1. A mechanism along these lines already existed in the 'weak pointer', but it was all but unusable.

gives:

```
set pointer2
calling constructor
set pointer3 by copy
overwrite pointer2
overwrite pointer3
calling destructor
```

Chapter 16

Prototypes

16.1 Prototypes for functions

In most of the programs you have written in this course, you put any functions or classes above the main program, so that the compiler could inspect the definition before it encountered the use. However, the compiler does not actually need the whole definition, say of a function: it is enough to know its name, the types of the input parameters, and the return type.

Such a minimal specification of a function is known as function *prototype*; for instance

```
int tester(float);
```

A first use of prototypes is *forward declaration*:

```
int f(int);
int g(int i) { return f(i); }
int f(int i) { return g(i); }
```

Prototypes are useful if you spread your program over multiple files. You would put your functions in one file:

```
// file: def.cxx
int tester(float x) {
  .....
}
```

and the main program in another:

```
// file : main.cxx
int tester(float);

int main() {
  int t = tester(...);
  return 0;
}
```

Or you could use your function in multiple programs and you would have to write it only once.

16.1.1 Header files

Even better than writing the prototype every time you need the function is to have a *header file*:

```
// file: def.h
int tester(float);
```

The definitions file would include this:

```
// file: def.cxx
#include "def.h"
int tester(float x) {
  .....
}
```

and so does the main program

```
// file : main.cxx
#include "def.h"

int main() {
  int t = tester(...);
  return 0;
}
```

Having a header file is an important safety measure:

- Suppose you change your function definition, changing its return type:
- The compiler will complain when you compile the definitions file;
- So you change the prototype in the header file;
- Now the compiler will complain about the main program, so you edit that too.

Remark 1 *By the way, why does that compiler even recompile the main program, even though it was not changed? Well, that's because you used a* makefile. *See the tutorial.*

Remark 2 *Header files were able to catch more errors in C than they do in C++. With polymorphism of functions, it is no longer an error to have*

```
// header.h
int somefunction(int);
```

and

```
#include "header.h"

int somefunction( float x ) { .... }
```

16.1.2 C and C++ headers

You have seen the following syntaxes for including header files:

```
#include <header.h>
#include "header.h"
```

The first is typically used for system files, with the second typically for files in your own project. There are some header files that come from the C standard library such as `math.h`; the idiomatic way of including them in C++ is

```
#include <cmath>
```

16.2 Global variables

If you have a variable that you want known everywhere, you can make it global:

```
int processnumber;
int main() {
  processnumber = // some system call
};
```

It is then defined in functions defined in your program file.

If your program has multiple files, you should not put '`int processnumber`' in the other files, because that would create a new variable, that is only known to the functions in that file. Instead use:

```
extern int processnumber;
```

which says that the global variable `processnumber` is defined in some other file.

What happens if you put that variable in a *header file*? Since the *preprocessor* acts as if the header is textually inserted, this again leads to a separate global variable per file. The solution then is more complicated:

```
//file: header.h
#ifndef HEADER_H
#define HEADER_H
#ifndef EXTERN
#define EXTERN extern
#fi
EXTERN int processnumber
#fi

//file: aux.cc
#include "header.h"

//file: main.cc
#define EXTERN
```

```
#include "header.h"
```

This also prevents recursive inclusion of header files.

16.3 Prototypes for class methods

Header file:

```
class something {
public:
  double somedo(vector);
};
```

Implementation file:

```
double something::somedo(vector v) {
   .... something with v ....
};
```

16.4 Header files and templates

The use of *templates* often make separate compilation impossible: in order to compile the templated definitions the compiler needs to know with what types they will be used.

16.5 Namespaces and header files

Never put `using namespace` in a header file.

Chapter 17

Preprocessor

In your source files you have seen lines starting with a hash sign, like

```
#include <iostream>
```

Such lines are interpreted by the *C preprocessor*.

Your source file is transformed to another source file, in a source-to-source translation stage, and only that second file is actually compiled by the *compiler*. In the case of an `#include` statement, the preprocessing stage takes form of literaly inserting another file, here a *header file* into your source.

There are more sophisticated uses of the preprocessor.

17.1 Textual substitution

Suppose your program has a number of arrays and loop bounds that are all identical. To make sure the same number is used, you can create a variable, and pass that to routines as necessary.

```
void dosomething(int n) {
  for (int i=0; i<n; i++) ....
}

int main() {
  int n=100000;

  double array[n];

  dosomething(n);
```

You can also use a *preprocessor macro*:

```
#define N 100000
void dosomething() {
  for (int i=0; i<N; i++) ....
}

int main() {
```

```
  double array[N];

  dosomething();
```

It is traditional to use all uppercase for such macros.

17.2 Parametrized macros

Instead of simple text substitution, you can have *parametrized preprocessor macros*

```
#define CHECK_FOR_ERROR(i) if (i!=0) return i
...
ierr = some_function(a,b,c); CHECK_FOR_ERROR(ierr);
```

When you introduce parameters, it's a good idea to use lots of parentheses:

```
// the next definition is bad!
#define MULTIPLY(a,b) a*b
...
x = MULTIPLY(1+2,3+4);
```

Better

```
#define MULTIPLY(a,b) (a)*(b)
...
x = MULTIPLY(1+2,3+4);
```

Another popular use of macros is to simulate multi-dimensional indexing:

```
#define INDEX2D(i,j,n) (i)*(n)+j
...
double array[m,n];
for (int i=0; i<m; i++)
  for (int j=0; j<n; j++)
    array[ INDEX2D(i,j,n) ] = ...
```

Exercise 17.1. Write a macro that simulates 1-based indexing:

```
#define INDEX2D1BASED(i,j,n)  ????
...
double array[m,n];
for (int i=1; i<=m; i++)
  for (int j=n; j<=n; j++)
    array[ INDEX2D1BASED(i,j,n) ] = ...
```

17.3 Conditionals

There are a couple of *preprocessor conditions*.

17.3.1 Check on a value

The `#if` macro tests on nonzero. A common application is to temporarily remove code from compilation:

```
#if 0
  bunch of code that needs to
  be disabled
#endif
```

17.3.2 Check for macros

The `#ifdef` test tests for a macro being defined. Conversely, `#ifndef` tests for a macro not being defined. For instance,

```
#ifndef N
#define N 100
#fi
```

Why would a macro already be defined? Well you can do that on the compile line:

```
icpc -c file.cc -DN=500
```

Another application for this test is in preventing recursive inclusion of header files; see section 16.2.

Chapter 18

Templates

Sometimes you want a function or a class based on more than one different datatypes. For instance, in chapter 9 you saw how you could create an array of ints as `vector<int>` and of doubles as `vector<double>`. Here you will learn the mechanism for that.

18.1. Templated type name

Basically, you want the type name to be a variable. Syntax:

```
template <typename yourtypevariable>
// ... stuff with yourtypevariable ...
```

18.2. Example: function

Definition:

```
template<typename T>
void function(T var) { cout << var << end; }
```

Usage:

```
int i; function(i);
double x; function(x);
```

and the code will behave as if you had defined `function` twice, once for `int` and once for `double`.

Exercise 18.1. Machine precision, or 'machine epsilon', is sometimes defined as the smallest number ϵ so that $1 + \epsilon > 1$ in computer arithmetic.
Write a templated function `epsilon` so that the following code prints out the values of the machine precision for the `float` and `double` type respectively:

```
float float_eps;
epsilon(float_eps);
cout << "For float, epsilon is " << float_eps << endl;

double double_eps;
epsilon(double_eps);
cout << "For double, epsilon is " << double_eps << endl;
```

18.1 Templating over non-types

THESE EXAMPLES ARE NOT GOOD.

See: https://www.codeproject.com/Articles/257589/An-Idiots-Guide-to-Cplusplus-Temp

18.3. Templating a value

Templeting over integral types, not double.

The templated quantity is a value:

```
template<int s>
std::vector<int> svector(s);
  /* ... */
  svector(3) threevector;
  cout << threevector.size();
```

Exercise 18.2. Write a class that contains an array. The length of the array should be templated.

Chapter 19

Error handling

19.1 General discussion

Sources or errors:

- Array indexing. See section 9.4.
- Null pointers
- Division by zero and other numerical errors.

Guarding against errors.

- Check preconditions.
- Catch results.
- Check postconditions.

Error reporting:

- Message
- Total abort
- Exception

Assertions:

```
#include <cassert>
...
assert( bool )
```

assertions are omitted with optimization

Function return values

19.2 Exception handling

Throwing an *exception* is one way of signalling an error or unexpected behaviour:

```
void do_something() {
  if ( oops )
    throw(5);
}
```

It now becomes possible to detect this unexpected behaviour by *catching* the exception:

```
throw {
  do_something();
} catch (int i) {
  cout << "doing something failed: error=" << i << endl;
}
```

You can throw integers to indicate an error code, a string with an actual error message. You could even make an error class: Sophisticated:

```
class MyError {
public :
  int error_no; string error_msg;
  MyError( int i,string msg )
  : error_no(i),error_msg(msg) {};
}

throw( MyError(27,"oops");

try {
  // something
} catch ( MyError &m ) {
  cout << "My error with code=" << m.error_no
    << " msg=" << m.error_msg << endl;
}
```

You can multiple `catch` statements to catch different types of errors:

```
try {
  // something
} catch ( int i ) {
  // handle int exception
} catch ( std:;string c ) {
  // handle string exception
}
```

Catch all exceptions:

```
try {
  // something
} catch ( ... ) { // literally: three dots
  cout << "Something went wrong!" << endl;
}
```

- Functions can define what exceptions they throw:

```
void func() throw( MyError, std::string );
void funk() throw();
```

- Predefined exceptions: `bad_alloc`, `bad_exception`
- An exception handler can throw an ecxeption; to rethrow the same exception use '`throw;`' without arguments.
- Exceptions delete all stack data, but not `new` data.

Chapter 20

Standard Template Library

The C++ language has a *Standard Template Library* (STL), which contains functionality that is considered standard, but that is actualy implemented in terms of already existing language mechanisms. The STL is enormous, so we just highlight a couple of parts.

You have already seen

- arrays (chapter 9),
- strings (chapter 10),
- streams (chapter 11).

20.1 Containers

Vectors (section 9.4) and strings (chapter 10) are special cases of a STL *container*. Methods such as `push_back` and `insert` apply to all containers.

20.1.1 Iterators

The container class has a subclass *iterator* that can be used to iterate through all elements of a container.

```
for (vector::iterator element=myvector.begin();
                element!=myvector.end(); elements++) {
  // do something with element
}
```

You would hope that, if `myvector` is a vector of `int`, `element` would be an int, but it is actually a pointer-to-int; section 15.2. So you could write

```
for (vector::iterator elt=myvector.begin();
                elt!=myvector.end(); elt++) {
  int element = *elt;
  // do something with element
}
```

This looks cumbersome, and you can at least simplify it by letting C++ deduce the type:

```
for (auto elt=myvector.begin(); ..... ) {
 .....
}
```

In the C++11/14 standard the iterator notation has been simplified to *range-based* iteration:

```
for ( int element : myvector ) {
 ...
}
```

20.2 Complex numbers

```
#include <complex>
complex<float> f;
f.re = 1.; f.im = 2.;

complex<double> d(1.,3.);
```

Math operator like `+`, `*` are defined, as are math functions.

20.3 About the 'using' keyword

Only use this internally, not in header files that the user sees.

Chapter 21

Obscure stuff

21.1 Casts

C++ pointers are really memory addresses, with no type information to it. With a *cast* it becomes possible change your mind about what a pointer is.

The syntax 'open parenthesis, type, closing parenthesis' means:

- take whatever you have here,
- and interpret it as the specified type.

Example:

```
int i[2];
double *point_at_real = (double*)i;
cout << "Print two integers as double: " << *point_at_real << endl;
```

This is very dangerous. In C++ there are two safer cast mechanisms.

21.1.1 Static cast

21.1.2 Dynamic cast

If we have a pointer to a derived object, stored in a pointer to a base class object, it's possible to turn it safely into a derived pointer again:

```
derived_object *derived_pointer;
basic_class *basic_pointer;
derived_pointer = dynamic_cast<derived_object*>(basic_pointer);
if (derived_pointer==nullptr)
  // cast failed
```

Chapter 22

More exercises

22.1 cplusplus

http://www.cplusplus.com/forum/articles/12974/

Dungeon crawl.

22.2 world best learning center

http://www.worldbestlearningcenter.com/index_files/cpp-tutorial-variables_datatypes_exercises.htm

PART III

FORTRAN

Chapter 23

Basics of Fortran

23.1 Main program

A Fortran program needs to start with a `Program` line, and end with `End Program`. The program needs to have a name on both lines:

```
Program SomeProgram
  ! stuff goes here
End Program SomeProgram
```

and you can not use that name for any entities in the program.

23.1.1 Program structure

Unlike C++, Fortran can not mix variable declarations and executable statements, so both the main program and any subprograms have roughtly a structure:

```
Program foo
  < declarations >
  < statements >
End Program foo
```

23.1.2 Statements

Let's say a word about layout. Fortran has a 'one line, one statement' principle.

- As long as a statement fits on one line, you don't have to terminate it explicitly with something like a semicolon:
  ```
  x = 1
  y = 2
  ```
- If you want to put two statements on one line, you have to terminate the first one:
  ```
  x = 1; y = 2
  ```
- If a statement spans more than one line, all but the first line need to have an explicit *continuation character*, the ampersand:

```
x = very &
  long &
  expression
```

(This is different between *free format* and *fixed format*, where it's the lines after the first that are marked a continuation, but we don't teach that here.)

23.1.3 Comments

Fortran knows only single-line *comments*, indicated by an exclamation point:

```
x = 1 ! set x to one
```

23.2 Variables

23.2.1 Data types

Fortran has a somewhat unusual treatment of data types: if you don't specify what data type a variable is, Fortran will deduce it from some default or user rules. This is a very dangerous practice, so we advocate putting a line

```
implicit none
```

immediately after any program or subprogram header.

23.1. Floating point types

Indicate number of bytes:

```
integer(2) :: i2
integer(4) :: i4
integer(8) :: i8

real(4) :: r4
real(8) :: r8
real(16) :: r16

complex(8) :: c8
complex(16) :: c16
complex*32 :: c32
```

23.2. Storage size

F08: `storage_size` reports number of bits.
F95: `bit_size` works on integers only.
`c_sizeof` reports number of bytes, requires `iso_c_binding` module.

23.2.2 Constants

Force a constant to be `real(8)`:

```
1.d0
```

23.2.3 Initialization

Variables can be initialized in their declaration:

```
integer :: i=2
real(4) :: x = 1.5
```

That this is done at compile time, leading to a common error:

```
subroutine foo()
  integer :: i=2
  cout << i << endl;
  i = 3
end subroutine foo
```

On the first subroutine call `i` is printed with its initialized value, but on the second call this initialization is not repeated, and the previous value of `3` is remembered.

Chapter 24

Loop constructs

24.1 Loop types

Indexed do loop:

```
do i=1,10,2
  print *,i
end do
```

While:

```
do
  print *,i
  i = i*2
while (i<1000)
```

F77 note: Do not use label-terminated loops.

24.2 Interruptions of the control flow

You can have a do loop without index or `while` test. In that case you need the `exit` statement to stop the iteration.

```
do
  x = randomvalue()
  if (x>.9) exit
  print *,"Nine out of ten exes agree"
end do
```

Skip rest of iteration:

```
do i=1,100
  if (isprime(i)) cycle
  ! do something with non-prime
end do
```

Cycle and exit can apply to multiple levels, if the do-statements are labeled.

24.3 Implied do-loops

Iterate an item:

```
print *,(2*i,i=1,20)
```

Multiple items:

```
print *,(2*i,2*i+1,i=1,20)
```

Nested:

```
print *,( (i*j,i=1,20), j=1,20 )
```

Useful in I/O, especially of arrays.

Chapter 25

Scope, subprograms, modules

25.1 Scope

Fortran 'has no curly brackets': you not easily create nested scopes. The range between `do` and `end do` is not a scope.

However, see modules below 25.3.

25.2 Procedures

Programs can have procedures: parts of code that for some reason you want to separate from the main program. If you structure your code in a single file, this is the recommended structure:

```
Program foo
  < declarations>
  < executable statements >
  Contains
    < procedure definitions >
End Program foo
```

That is, procedures are placed after the main program statements, separated by a `contains` clause.

25.2.1 Subroutines and functions

Fortran has two types of procedures:

- Subroutines, which are somewhat like `void` functions in C++: they can be used to structure the code, and they can only return information to the calling environment through their parameters.
- Functions, which are like C++ functions with a return type.

Both types have the same structure, which is roughly the same as of the main program:

```
subroutine foo( <parameters> )
<variable declarations>
<executable statements>
end subroutine foo
```

Exit from a procedure can happen two ways:

1. the flow of control reaches the end of the procedure body, or
2. execution is finished by an explicit `return` statement.

```
subroutine foo()
  print *,"foo"
  if (something) return
  print *,"bar"
end subroutine foo
```

The `return` statement is optional in the first case.

A subroutine is invoked with a `call` statement:

```
call foo()
```

25.2.2 Return results

While a `subroutine` can only return information through its parameters, a *function* procedure returns an explicit result:

```
logical function test(x)
  implicit none
  real :: x

  test = some_test_on(x)
  return ! optional, see above
end function test
```

You see that the result is not returned in the `return` statement, but rather through assignment to the function name. The `return` statement, as before, is optional and only indicates where the flow of control ends.

A function is not invoked with `call`, but rather through being used in an expression:

```
if (test(3.0) .and. something_else) ...
```

You now have the following cases to make the function known in the main program:

- If the function is in a `contains` section, its type is known in the main program.
- If the function is in a module (see section 25.3 below), it becomes known through a `use` statement.

  F77 note: Without modules and `contains` sections, you need to declare the function type explitly in the calling program.

25.2.3 Types of procedures

Procedures that are in the main program (or another type of program unit), separated by a `contains` clause, are known as *internal procedures*. This is as opposed to *module procedures*.

There are also *statement functions*, which are single-statement functions, usually to identify commonly used complicated expressions in a program unit. Presumably the compiler will *inline* them for efficiency.

The `entry` statement is so bizarre that I refuse to discuss it.

25.2.4 Optional arguments

25.3 Modules

A module is a container for variables and functions, but it is not a class or object: there is only one instance.

```
Module FunctionsAndValues
  implicit none

  real(8),parameter :: pi = 3.14

contains
  subroutine SayHi()
    print *,"Hi!"
  end subroutine SayHi

End Module FunctionsAndValues
```

Any routines come after the `contains`

A module is made available with the `use` keyword, which needs to go before the `implicit none`.

```
Program ModProgram
  use FunctionsAndValues
  implicit none

  print *,"Pi is:",pi
  call SayHi()

End Program ModProgram
```

If you compile a module, you will find a `.mod` file in your directory. (This is little like a `.h` file in C++.) If this file is not present, you can not use the module in another program unit.

Chapter 26

Structures, eh, types

26.1. Structures: `type`

The Fortran name for structures is `type` or *derived type*.

26.2. Type definition

`Type name` / `End Type` block. Variable declarations inside the block

```
type mytype
  integer :: number
  character :: name
  real(4) :: value
end type mytype
```

26.3. Creating a type structure

Declare a typed object in the main program:

```
Type(mytype) :: typed_object,object2
```

Initialize with type name:

```
typed_object = mytype( 1, 'my_name', 3.7 )
object2 = typed_object
```

26.4. Member access

Access structure members with `%`

```
Type(mytype) :: typed_object
type_object%member = ....
```

26.5. Example

```
type point
   real :: x,y
end type point

type(point) :: p1,p2
p1 = point(2.5, 3.7)

p2 = p1
print *,p2%x,p2%y
```

Chapter 27

Classes and objects

27.1 Classes

27.1. Classes and objects

Fortran classes are based on `type` objects, a little like the analogy between C++ `struct` and `class` constructs.
New syntax for specifying methods.

27.2. Object is type with methods

You define a type as before, with its data members, but now the type has a `contains`.

```
% -*- latex -*-
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%
%%%% This TeX file is part of the course
%%%% Introduction to Scientific Programming in C++/Fortran2003
%%%% copyright 2017 Victor Eijkhout eijkhout@tacc.utexas.edu
%%%%
%%%% pointf.tex : arrays in Fortran
%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Pointers in C++ were largely the same as memory addresses (until you
got to smart pointers). Fortran pointers on the other hand, are more
abstract.

\Level 0 {Basic pointer operations}

\begin{block}{Pointers are aliases}
  \begin{itemize}
  \item Pointer points at an object
  \item Access object through pointer
  \item You can change what object the pointer points at.
  \end{itemize}
\begin{verbatim}
real,pointer :: point_at_real
```

```
\end{verbatim}
\end{block}

Pointers could also be called 'aliases': they act like an alias for
object of elementary or derived data type. You can access the object
through the alias. The difference with actually using the object, is
that you can decide what object the pointer points at.

The \indextermtt{pointer} definition
\begin{verbatim}
real,pointer :: point_at_real
\end{verbatim}
defined a pointer that can point at a real variable.

\begin{block}{Setting the pointer}
  \begin{itemize}
  \item You have to declare that a variable is pointable:
\begin{verbatim}
real,target :: x
\end{verbatim}
\item Set the pointer with \verb+=>+ notation:
\begin{verbatim}
point_at_real => x
\end{verbatim}
\item Now using \n{point_at_real} is the same as using~\n{x}.
  \end{itemize}
\end{block}

Pointers can not just point at anything: the thing pointed at needs
be declared as \indextermtt{target}
\begin{verbatim}
real,target :: x
\end{verbatim}
and you use the \verb+=>+ operator to let a pointer point at a targe
\begin{verbatim}
point_at_real => x
\end{verbatim}

If you use a pointer, for instance to print it
\begin{verbatim}
print *,point_at_real
\end{verbatim}
it behaves as if you were using the value of what it points at.

\begin{block}{Pointer example}
  \verbatimsnippet{pointatreal}
```

```
  %
  \begin{enumerate}
  \item The pointer points at~\n{x}, so the value of \n{x} is printe
  \item The pointer is set to point at~\n{y}, so its value is printe
  \item The value of \n{y} is changed, and since the pointer still
    points at~\n{y}, this changed value is printed.
  \end{enumerate}
\end{block}

\begin{block}{Assign pointer from other pointer}
\begin{verbatim}
real,pointer :: point_at_real,also_point
point_at_real => x
also_point => point_at_real
\end{verbatim}
  Now you have two pointers that point at~\n{x}.

  \textbf{Very important to use the \n{=>}, otherwise strange
    memory errors}
\end{block}

If you have two pointers
\begin{verbatim}
real,pointer :: point_at_real,also_point
\end{verbatim}
you can make the target of the one to also be the target of the othe
\begin{verbatim}
also_point => point_at_real
\end{verbatim}
This is not a pointer to a pointer: it assigns the target of the
right-hand side to be the target of the left-hand side.

\textbf{Using ordinary assignment does not work, and will give stran
  memory errors.}

\begin{exercise}
  Write a routine that accepts an array and a pointer, and on return
  has that pointer pointing at the largest array element.
\end{exercise}
\begin{answer}
  \verbatimsnippet{arraypointf}
\end{answer}

\Level 0 {Example: linked lists}

\begin{block}{Linked list}
```

```
  \begin{itemize}
  \item Linear data structure
  \item more flexible for insertion~/ deletion
  \item \ldots~but slower in access
  \end{itemize}
\end{block}

One of the standard examples of using pointers is the
\indexterm{linked list}. This is a dynamic one-dimensional structure
that is more flexible than an array. Dynamically extending an array
would require re-allocation, while in a list an element can be
inserted.

\begin{exercise}
  Using a linked list may be more flexible than using an array.
  On the other hand, accessing an element in a linked list is
  more expensive, both absolutely and as order-of-magnitude in the s
  of the list.

  Make this argument precise.
\end{exercise}

\begin{block}{Linked list datatypes}
  \begin{itemize}
  \item Node: value field, and pointer to next node.
  \item List: pointer to head node.
  \end{itemize}
  \verbatimsnippet{linklistf}
\end{block}

A list is based on a simple data structure, a node, which contains a
value field and a pointer to another node.

By way of example, we create a dynamic list of integers, sorted by
size. To maintain the sortedness, we need to append or insert nodes,
as required.

Here are the basic definitions of a node, and a list which is
basically a repository for the head node:
%
\verbatimsnippet{linklistf}

\begin{block}{List initialization}
  First element becomes the list head:

\verbatimsnippet{listheadf}
```

```
\end{block}

Initially, the list is empty, meaning that the 'head' pointer is
un-associated. The first time we add an element to the list, we crea
a node and assign it as the head of the list:
%
\verbatimsnippet{listheadf}

\begin{block}{Attaching a node}
  Keep the list sorted: new largest element attached at the end.

  \verbatimsnippet{listattachf}
\end{block}

Adding a value to a list can be done two ways. If the new element is
larger than all elements in the list, a new node needs to be appende
to the last one. Let's assume we have managed
to let \n{current} point at the last node of the list,
then here is how to
attaching a new node from it:
%
\verbatimsnippet{listattachf}

\begin{block}{Inserting 1}
  Find the insertion point:
\verbatimsnippet{listfindf}
\end{block}

Inserting an element in the list is harder.
First of all, you need to find the two nodes,
\n{previous} and \n{current}, between which to insert the new node:
%
\verbatimsnippet{listfindf}

\begin{block}{Inserting 2}
  The actual insertion requires rerouting some pointers:
  %
  \verbatimsnippet{listinsertf}
\end{block}
```

27.3. Methods have object as argument

You define functions that accept the type as first argument, but instead of declaring the argument as `type`, you define it as `class`.

The members of the class object have to be accessed through the `%` operator.

```
subroutine set(p,xu,yu)
```

```
    implicit none
    class(point) :: p
    real(8),intent(in) :: xu,yu
    p%x = xu; p%y = yu
  end subroutine set
```

27.4. Objects definition, method invocation

Class objects are defined as `type` objects, just as if there were no class functions on them. The class functions are accessed as

```
object%function(arg1,arg2)
```

where the arguments do not include the `class` argument.

```
use PointClass
implicit none
type(Point) :: p1,p2

call p1%set(1.d0,1.d0)
call p2%set(4.d0,5.d0)
```

27.5. Use modules!

It is of course best to put the type definition and method definitions in a module, so that you can `use` it.

Mark methods as `private` so that they can only be used as part of the `type`:

```
Module PointClass
  private
contains
  subroutine setzero(p)
    implicit none
    class(point) :: p
    p%x = 0.d0 ; p%y = 0.d0
  end subroutine setzero
End Module PointClass
```

Exercise 27.1. Take the point example program and add a distance function.

Chapter 28

Arrays

28.1 Static arrays

The preferred way for specifying an array size is:

```
real(8), dimension(100) :: x,y
```

Such an array, with size explicitly indicated, is called a *static array* or *automatic array*. (See section 28.1.3 for dynamic arrays.)

Array indexing in Fortran is 1-based:

```
real :: x(8)
do i=1,8
  ... x(i) ...
```

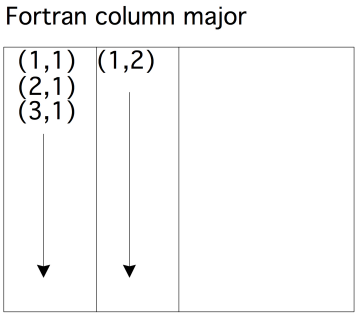
Unlike C++, Fortran can specify the lower bound explicitly:

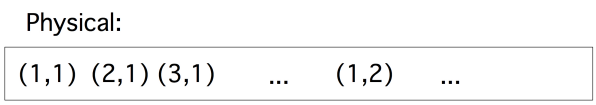
```
real :: x(-1:7)
do i=-1,7
  ... x(i) ...
```

Such array, as in C++, obey the scope: they disappear at the end of the program or subprogram.

28.1.1 Multi-dimensional

```
integer,dimension(20,30) :: array
```





28.1.2 Query the size of an array

Various query functions:

- Total number of elements (in a specified dimension) can be queried with `size`:

```
integer :: x(8), y(5,4)
size(x)
size(y,2)
```

- Lower and upper bound:

```
Lbound(x)
Ubound(x)
```

28.1.3 Allocatable arrays

Static arrays are fine at small sizes. However, there are two main arguments against using them at large sizes.

- Since the size is explicitly stated, it makes your program inflexible, requiring recompilation to run it with a different problem size.
- Since they are allocated on the so-called *stack*, making them too large can lead to *stack overflow*.

A better strategy is to indicate the shape of the array, and use `allocate` to specify the size later, presumably in terms of run-time program parameters.

```
real(8), dimension(:), allocatable :: x,y

n = 100
allocate(x(n), y(n))
```

You can `deallocate` the array when you don't need the space anymore.

If you are in danger of running out of memory, it can be a good idea to add a `stat=ierror` clause to the `allocate` statement:

```
integer :: ierr
allocate( x(n), stat=ierr )
if ( ierr/=0 ) ! report error
```

Has an array been allocated:

```
Allocated( x ) ! returns logical
```

28.2 Arrays to subroutines

Subprogram needs to know the shape of an array, not the actual bounds:

```
  real(8) function arraysum(x)
    implicit none
    real(8),intent(in),dimension(:) :: x
  /* ... */
    do i=1,size(x)
       tmp = tmp+x(i)
    end do
  /* ... */
Program ArrayComputations1D
    use ArrayFunction
    implicit none

    real(8),dimension(:) :: x(N)
  /* ... */
    print *,"Sum of one-based array:",arraysum(x)
```

28.3 Operating on a whole array

28.3.1 Arithmetic operations

Between arrays of the same shape:

```
A = B+C
D = D*E
```

(where the multiplication is by element).

28.3.2 Restricting with `where`

```
where ( A<0 ) B = 0
```

Full form:

```
WHERE ( logical argument )
  sequence of array statements
ELSEWHERE
  sequence of array statements
END WHERE
```

28.4 Array slicing

Chapter 29

Pointers

Pointers in C++ were largely the same as memory addresses (until you got to smart pointers). Fortran pointers on the other hand, are more abstract.

29.1 Basic pointer operations

29.1. Pointers are aliases

- Pointer points at an object
- Access object through pointer
- You can change what object the pointer points at.

```
real,pointer :: point_at_real
```

Pointers could also be called 'aliases': they act like an alias for an object of elementary or derived data type. You can access the object through the alias. The difference with actually using the object, is that you can decide what object the pointer points at.

The `pointer` definition

```
real,pointer :: point_at_real
```

defined a pointer that can point at a real variable.

29.2. Setting the pointer

- You have to declare that a variable is pointable:

```
real,target :: x
```

- Set the pointer with => notation:

```
point_at_real => x
```

- Now using `point_at_real` is the same as using `x`.

Pointers can not just point at anything: the thing pointed at needs to be declared as `target`

```
real,target :: x
```

and you use the => operator to let a pointer point at a target:

```
point_at_real => x
```

If you use a pointer, for instance to print it

```
print *,point_at_real
```

it behaves as if you were using the value of what it points at.

29.3. Pointer example

```
real,target :: x,y
real,pointer :: that_real

x = 1.2
y = 2.4
that_real => x
print *,that_real
that_real => y
print *,that_real
y = x
print *,that_real
```

1. The pointer points at `x`, so the value of `x` is printed.
2. The pointer is set to point at `y`, so its value is printed.
3. The value of `y` is changed, and since the pointer still points at `y`, this changed value is printed.

29.4. Assign pointer from other pointer

```
real,pointer :: point_at_real,also_point
point_at_real => x
also_point => point_at_real
```

Now you have two pointers that point at `x`.
Very important to use the `=>`, otherwise strange memory errors

If you have two pointers

```
real,pointer :: point_at_real,also_point
```

you can make the target of the one to also be the target of the other:

```
also_point => point_at_real
```

This is not a pointer to a pointer: it assigns the target of the right-hand side to be the target of the left-hand side.

Using ordinary assignment does not work, and will give strange memory errors.

Exercise 29.1. Write a routine that accepts an array and a pointer, and on return has that pointer pointing at the largest array element.

29.2 Example: linked lists

29.5. Linked list

- Linear data structure
- more flexible for insertion / deletion
- ... but slower in access

One of the standard examples of using pointers is the *linked list*. This is a dynamic one-dimensional structure that is more flexible than an array. Dynamically extending an array would require re-allocation, while in a list an element can be inserted.

Exercise 29.2. Using a linked list may be more flexible than using an array. On the other hand, accessing an element in a linked list is more expensive, both absolutely and as order-of-magnitude in the size of the list.
Make this argument precise.

29.6. Linked list datatypes

- Node: value field, and pointer to next node.
- List: pointer to head node.

```
type node
   integer :: value
   type(node),pointer :: next
end type node

type list
   type(node),pointer :: head
end type list

type(list) :: the_list
nullify(the_list%head)
```

A list is based on a simple data structure, a node, which contains a value field and a pointer to another node.

By way of example, we create a dynamic list of integers, sorted by size. To maintain the sortedness, we need to append or insert nodes, as required.

Here are the basic definitions of a node, and a list which is basically a repository for the head node:

```
type node
   integer :: value
   type(node),pointer :: next
end type node

type list
   type(node),pointer :: head
end type list

type(list) :: the_list
nullify(the_list%head)
```

29.7. List initialization

First element becomes the list head:

```
allocate(new_node)
new_node%value = value
nullify(new_node%next)
the_list%head => new_node
```

Initially, the list is empty, meaning that the 'head' pointer is un-associated. The first time we add an element to the list, we create a node and assign it as the head of the list:

```
allocate(new_node)
new_node%value = value
nullify(new_node%next)
the_list%head => new_node
```

29.8. Attaching a node

Keep the list sorted: new largest element attached at the end.

```
allocate(new_node)
new_node%value = value
nullify(new_node%next)
current%next => new_node
```

Adding a value to a list can be done two ways. If the new element is larger than all elements in the list, a new node needs to be appended to the last one. Let's assume we have managed to let `current` point at the last node of the list, then here is how to attaching a new node from it:

```
allocate(new_node)
new_node%value = value
nullify(new_node%next)
current%next => new_node
```

29.9. Inserting 1

Find the insertion point:

```
current => the_list%head ; nullify(previous)
do while ( current%value<value &
     .and. associated(current%next) )
   previous => current
   current => current%next
end do
```

Inserting an element in the list is harder. First of all, you need to find the two nodes, `previous` and `current`, between which to insert the new node:

```
current => the_list%head ; nullify(previous)
do while ( current%value<value &
     .and. associated(current%next) )
   previous => current
```

```
   current => current%next
end do
```

29.10. Inserting 2

The actual insertion requires rerouting some pointers:

```
allocate(new_node)
new_node%value = value
new_node%next => current
previous%next => new_node
```

PART IV

EXERCISES AND PROJECTS

Chapter 30

Simple exercises

30.1 Looping exercises

Exercise 30.1. Find all triples of integers u, v, w under 100 such that $u^2 + v^2 = w^2$. Make sure you omit duplicates of solutions you have already found.

Exercise 30.2. The integer sequence

$$u_{n+1} = \begin{cases} u_n/2 & \text{if } u_n \text{ is even} \\ 3u_n + 1 & \text{if } u_n \text{ is odd} \end{cases}$$

leads to the Collatz conjecture: no matter the starting guess u_1, the sequence $n \mapsto u_n$ will always terminate.
For $u_1 < 1000$ find the values that lead to the longest sequence: every time you find a sequence that is longer than the previous maximum, print out the starting number.

Exercise 30.3. Large integers are often printed with a comma (US usage) or a period (European usage) between all triples of digits. Write a program that accepts an integer such as 2542981 from the user, and prints it as `2,542,981`.

Exercise 30.4. **Root finding.** For many functions f, finding their zeros, that is, the values x for which $f(x) = 0$, can not be done analytically. You then have to resort to numerical *root finding* schemes. In this exercise you will implement a simple scheme.
Suppose x_-, x_+ are such that

$$x_- < x_+, \qquad f(x_-) \cdot f(x_+) < 0,$$

that is, the function values are of opposite sign. Then there is a zero in the interval (x_-, x_+). Try to find this zero by looking at the halfway point, and based on the function value there, considering the left or right interval.

- How do you find x_-, x_+? This is tricky in general; if you can find them in the interval $[-10^6, +10^6]$, halt the program.
- Finding the zero exactly may also be tricky or maybe impossible. Stop your program if $|x_- - x_+| < 10^{-10}$.

30.1.1 Further practice

The website http://www.codeforwin.in/2015/06/for-do-while-loop-programming-exercises.html lists the following exercises:

1. Write a C program to print all natural numbers from 1 to n. - using while loop
2. Write a C program to print all natural numbers in reverse (from n to 1). - using while loop
3. Write a C program to print all alphabets from a to z. - using while loop
4. Write a C program to print all even numbers between 1 to 100. - using while loop
5. Write a C program to print all odd number between 1 to 100.
6. Write a C program to print sum of all even numbers between 1 to n.
7. Write a C program to print sum of all odd numbers between 1 to n.
8. Write a C program to print table of any number.
9. Write a C program to enter any number and calculate sum of all natural numbers between 1 to n.
10. Write a C program to find first and last digit of any number.
11. Write a C program to count number of digits in any number.
12. Write a C program to calculate sum of digits of any number.
13. Write a C program to calculate product of digits of any number.
14. Write a C program to swap first and last digits of any number.
15. Write a C program to find sum of first and last digit of any number.
16. Write a C program to enter any number and print its reverse.
17. Write a C program to enter any number and check whether the number is palindrome or not.
18. Write a C program to find frequency of each digit in a given integer.
19. Write a C program to enter any number and print it in words.
20. Write a C program to print all ASCII character with their values.
21. Write a C program to find power of any number using for loop.
22. Write a C program to enter any number and print all factors of the number.
23. Write a C program to enter any number and calculate its factorial.
24. Write a C program to find HCF (GCD) of two numbers.
25. Write a C program to find LCM of two numbers.
26. Write a C program to check whether a number is Prime number or not.
27. Write a C program to check whether a number is Armstrong number or not.
28. Write a C program to check whether a number is Perfect number or not.
29. Write a C program to check whether a number is Strong number or not.
30. Write a C program to print all Prime numbers between 1 to n.
31. Write a C program to print all Armstrong numbers between 1 to n.
32. Write a C program to print all Perfect numbers between 1 to n.
33. Write a C program to print all Strong numbers between 1 to n.
34. Write a C program to enter any number and print its prime factors.
35. Write a C program to find sum of all prime numbers between 1 to n.
36. Write a C program to print Fibonacci series up to n terms.
37. Write a C program to find one's complement of a binary number.
38. Write a C program to find two's complement of a binary number.
39. Write a C program to convert Binary to Octal number system.
40. Write a C program to convert Binary to Decimal number system.
41. Write a C program to convert Binary to Hexadecimal number system.

42. Write a C program to convert Octal to Binary number system.
43. Write a C program to convert Octal to Decimal number system.
44. Write a C program to convert Octal to Hexadecimal number system.
45. Write a C program to convert Decimal to Binary number system.
46. Write a C program to convert Decimal to Octal number system.
47. Write a C program to convert Decimal to Hexadecimal number system.
48. Write a C program to convert Hexadecimal to Binary number system.
49. Write a C program to convert Hexadecimal to Octal number system.
50. Write a C program to convert Hexadecimal to Decimal number system.
51. Write a C program to print Pascal triangle upto n rows.

Chapter 31

Not-so simple exercises

31.1 List access

Exercise 31.1. Explore the efficiency of using an array versus a linked list.

1. Compare re-allocating the array versus adding elements to the linked list. Start with a simple case: add elements only at the end, and keep a pointer to the final element in the list.
2. Investigate access times: retrieve many (as in: thousands if not more) elements from the array. Do this as follows: allocate an array of indexes, and repeatedly retrieve those list/array elements, for instance adding them together. Does the access time for the array go up if the number of elements gets large?
3. Optimize allocation for the list: create an array of list nodes and use those. Does this make a difference in access times?

Chapter 32

Prime numbers

32.1 Preliminaries

Assuming you have learned about

- statements, section 3.1
- variables, section 3.2
- I/O, section 3.3

32.2 Arithmetic

Before doing this section, make sure you study section 3.4.

Exercise 32.1. Read two integers into two variables, and print their sum, product, quotient, modulus.

A less common operator is the modulo operator `%`.

Exercise 32.2. Read two numbers and print out their modulus. Two ways:

- use the `cout` function to print the expression, or
- assign the expression to a variable, and print that variable.

32.3 Conditionals

Before doing this section, make sure you study section 3.5.

Exercise 32.3. Read two numbers and print a message like

```
3 is a divisor of 9
```

if the first is an exact divisor of the second, and another message

```
4 is not a divisor of 9
```

if it is not.

32.4 Looping

Control structures such as loops; section 4.1.

Exercise 32.4. Read an integer and determine whether it is prime by testing for the smaller numbers whether they are a divisor of that number.
Print a final message

```
Your number is prime
```

or

```
Your number is not prime: it is divisible by ....
```

where you report just one found factor.

Exercise 32.5. Rewrite the previous exercise with a boolean variable to represent the primeness of the input number.

32.5 Functions

Before doing this section, make sure you study section 5.2.

Above you wrote several lines of code to test whether a number was prime.

Exercise 32.6. Write a function that takes an integer input, and return a boolean corresponding to whether the input was prime.

```
bool isprime;
isprime = prime_test_function(13);
```

Read the number in, and print the value of the boolean.

32.6 While loops

Before doing this section, make sure you study section 4.2.

Exercise 32.7. Take the prime number testing program, and modify it to read in how many prime numbers you want to print. Print that many successive primes. Keep a variable `number_of_primes_found` that is increased whenever a new prime is found.

32.7 Global variables: optional

Before doing this section, make sure you study section 5.1.

Exercise 32.8. Use global variables to rewrite exercise 32.7. Your main program should exactly be this:

```
int main() {
  int nprimes;
  cout << "How many primes do you want? " << endl;
  cin >> nprimes;
```

```
  while (numberfound<nprimes) {
    int number = nextprime();
    cout << "Number " << number << " is prime" << endl;
  }

  return 0;
}
```

The trick here is to write the function `nextprime` uses the remembered global information, calculates the next prime, and returns it.

32.8 Structures

Before doing this section, make sure you study section 6.1, 12.1.

A `struct` functions to bundle together a number of data item. We only discuss this as a preliminary to classes.

Exercise 32.9. Rewrite the exercise that found a predetermined number of primes, putting the `number_of_primes_found` and `last_number_tested` variables in a structure. Your main program should now look like:

```
struct primesequence sequence;
while (sequence.number_of_primes_found<nprimes) {
  int number = nextprime(sequence);
  cout << "Number " << number << " is prime" << endl;
}
```

32.9 Classes and objects

Before doing this section, make sure you study section 7.1, 27.1.

In exercise 32.9 you made a structure that contains the data for a primesequence, and you have separate functions that operate on that structure or on its members.

Exercise 32.10. Write a class `primesequence` that contains the members of the structure, and the functions `nextprime`, `isprime`. The function `nextprime` does not need the structure as argument, because the structure members are in the class, and therefore global to that function.
Your main program should look as follows:

```
primesequence sequence;
while (sequence.numberfound<nprimes) {
  int number = sequence.nextprime();
  cout << "Number " << number << " is prime" << endl;
}
```

In the previous exercise you defined the `primesequence` class, and you made one object of that class:

```
primesequence sequence;
```

But you can make multiple sequences, that all have their own internal data and are therefore independent of each other.

Exercise 32.11. The *Goldbach conjecture* says that every even number, from 4 on, is the sum of two primes $p+q$. Write a program to test this for the even numbers up to 20 million. Make an outer loop over the even numbers. In each iteration, make a `primesequence` object to generate p values. Then, for each p, make a second `primesequence` object to generate q values, and test with these.
For each even number, print out how it is the sum of two primes. If multiple possibilities exist, only print the first one you find.

Exercise 32.12. The *Goldbach conjecture* says that every even number $2n$ (starting at 4), is the sum of two primes $p + q$:

$$2n = p + q.$$

Equivalently, every number n is equidistant from two primes. In particular this holds for each prime number:

$$\forall_{p \text{ prime}} \exists_{q \text{ prime}} : r \equiv p + (p - q) \text{ is prime.}$$

Write a program that tests this. You need two prime number generators, one for the p-sequence and one for the q-sequence. For each p value, when the program finds the q value, print the q, p, r triple and move on to the next p.
Allocate an array where you record all the $p - q$ distances that you found. Print some elementary statistics, for instance: what is the average, do the distances increase or decrease with p?

32.10 Arrays

Another algorithm for finding prime numbers is the *Eratosthenes sieve*. It goes like this.

1. You take a range of integers, starting at 2.
2. Now look at the first number. That's a prime number.
3. Scratch out all of its multiples.
4. Find the next number that's not scratched out; since that's not a multiple of a previous number, it must be a prime number. Report it, and go back to the previous step.

The new mechanism you need for this is the data structure for storing all the integers.

```
int N = 1000;
vector<int> integers(N);
```

Exercise 32.13. Read in an integer that denotes the largest number you want to test. Make an array of integers that long. Set the elements to the successive integers.

Chapter 33

Geometry

In this set of exercises you will write a small 'geometry' package: code that manipulates points, lines, shapes. These exercises mostly use the material of section 7.

33.1 Point class

Before doing this section, make sure you study section 7.1.

A class can contain elementary data. In this section you will make a `Point` class that models cartesian coordinates and functions defined on coordinates.

Exercise 33.1. Make class `Point` with a constructor

```
Point( float xcoordinate, float ycoordinate );
```

Write a method `distance_to_origin` that returns a `float`.
Write a method `printout` that uses `cout` to display the point.
Write a function `distance` so that if `p,q` are `Point` objects,

```
p.distance(q)
```

computes the distance.

Exercise 33.2. Make a default constructor for the point class:

```
Point() { /* default code */ }
```

which you can use as:

```
Point p;
```

Exercise 33.3. Advanced. Can you make a `Point` class that can accomodate any number of space dimensions? Hint: use a `vector`; section 9.4. Can you make a constructor where you do not specify the space dimension explicitly?

33.2 Using one class in another

Before doing this section, make sure you study section 7.1.

Exercise 33.4. Make a class `LinearFunction` with a constructors:

```
LinearFunction( Point input_p1,Point input_p2 );
```

and a function

```
float evaluate_at( float x );
```

which you can use as:

```
LinearFunction line(p1,p2);
cout << "Value at 4.0: " << line.evaluate_at(4.0) << endl;
```

Exercise 33.5. Make a class `LinearFunction` with two constructors:

```
LinearFunction( Point input_p2 );
LinearFunction( Point input_p1,Point input_p2 );
```

where the first stands for a line through the origin.
Implement again the `evaluate` function so that

```
LinearFunction line(p1,p2);
cout << "Value at 4.0: " << line.evaluate_at(4.0) << endl;
```

33.3 Has-a relation

Before doing this section, make sure you study section 7.3.

Suppose you want to write a `Rectangle` class, which could have methods such as `float Rectangle::area()` or `bool Rectangle::contains(Point)`. Since rectangle has four corners, you could store four `Point` objects in each `Rectangle` object. However, there is redundancy there: you only need three points to infer the fourth. Let's consider the case of a rectangle with sides that are horizontal and vertical; then you need only two points.

33.1. Axi-parallel rectangle class

Intended API:

```
float Rectangle::area();
```

It would be convenient to store width and height; for

```
bool Rectangle::contains(Point);
```

it would be convenient to store bottomleft/topright points.

Exercise 33.6. Make a class `Rectangle` (sides parallel to axes) with two constructors:

```
Rectangle(Point bl,Point tr);
Rectangle(Point bl,float w,float h);
```

and functions

```
float area(); float width(); float height();
```

Let the `Rectangle` object store two `Point` objects.
Then rewrite your exercise so that the `Rectangle` stores only one point (say, lower left), plus the width and height.

The previous exercise illustrates an important point: for well designed classes you can change the implementation (for instance motivated by efficiency) while the program that uses the class does not change.

33.4 Is-a relationship

Before doing this section, make sure you study section 7.4.

Exercise 33.7. Take your code where a `Rectangle` was defined from one point, width, and height.
Make a class `Square` that inherits from `Rectangle`. It should have the function `area` defined, inherited from `Rectangle`.
First ask yourself: what should the constructor of a `Square` look like?

Exercise 33.8. Revisit the `LinearFunction` class. Add methods `slope` and `intercept`.
Now generalize `LinearFunction` to `StraightLine` class. These two are almost the same except for vertical lines. The `slope` and `intercept` do not apply to vertical lines, so design `StraightLine` so that it stores the defining points internally. Let `LinearFunction` inherit.

Chapter 34

PageRank

34.1 Basic ideas

Assuming you have learned about arrays 9, in particular the use of `std::vector`.

The web can be represented as a matrix W of size N, the number of web pages, where $w_{ij} = 1$ if page i has a link to page j and zero otherwise. However, this representation is only conceptual; if you actually stored this matrix it would be gigantic and largely full of zeros. Therefore we use a *sparse matrix*: we store only the pairs (i, j) for which $w_{ij} \neq 0$. (In this case we can get away with storing only the indices; in a general sparse matrix you also need to store the actual w_{ij} value.)

Exercise 34.1. Store the sparse matrix representing the web as a

```
vector< vector<bool> >
```

structure.

1. At first, assume that the number of web pages is given and reserve the outer vector. Read in values for nonzero indices and add those to the matrix structure.
2. Then, assume that the number of pages is not pre-determined. Read in indices; now you need to create rows as they are needed. Suppose the requested indices are

   ```
   5,1
   3,5
   1,3
   ```

   Since your structure has only three rows, you also need to remeber their row numbers.

Now we want to model the behaviour of a person clicking on links.

PART V

ADVANCED TOPICS

Chapter 35

Tiniest of introductions to algorithms and data structures

35.1 Data structures

This really goes beyond this book.

- Arrays
- Lists
- Trees
- Graphs / DAGs
- Hashes

35.1.1 Linked lists

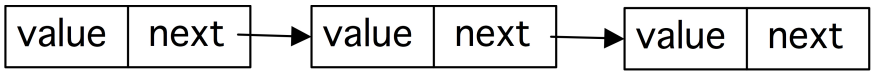
Before doing this section, make sure you study section 15.

Arrays are not flexible: you can not insert an element in the middle. Instead:

- Allocate larger array,
- copy data over (with insertion),
- delete old array storage

This is very expensive. (It's what happens in a C++ `vector`; section 9.4.2.)

If you need to do lots of insertions, make a *linked list*.




```
class Node {
private:
  int data{0},count{0};
  Node *next{nullptr};
public:
  Node() {}
  Node(int value) { data = value; count++; };
  bool hasnext() {
    return next!=nullptr; };
```

```
  Node *insert(int value) {
    if (value==this->data) {
      // we have already seen this value: just count
      count ++;
      return this;
    } else if (value>this->data) {
      // value belong in the tail
      if (!hasnext())
next = new Node(value);
      else
next = next->insert(value);
      return this;
    } else {
      // insert at the head of the list
      Node *newhead = new Node(value);
      newhead->next = this;
      return newhead;
    }
  };
```

35.1.2 Trees

Before doing this section, make sure you study section 15.

A tree can be defined recursively:

- A tree is empty, or
- a tree is a node with some number of children trees.

Let's design a tree that stores and counts integers: each node has a label, namely an integer, and a count value that records how often we have seen that integer.

Our basic data structure is the node, and we define it recursively to have up to two children. This is a problem: you can not write

```
class Node {
private:
  Node left,right;
}
```

because that would recursively need infinite memory. So instead we use pointers.

```
class Node {
private:
  int key{0},count{0};
  std::shared_ptr<Node> left,right;
  bool hasleft{false},hasright{false};
public:
  Node() {}
```

```
  Node(int i,int init=1 ) { key = i; count = 1; };
  void addleft( int value) {
    left = std::shared_ptr<Node>( new Node(value) );
    hasleft = true;
  };
  void addright( int value ) {
    right = std::shared_ptr<Node>( new Node(value) );
    hasright = true;
  };
};
```

and we record that we have seen the integer zero zero times.

Algorithms on a tree are typically recursive. For instance, the total number of nodes is computed from the root. At any given node, the number of nodes of that attached subtree is one plus the number of nodes of the left and right subtrees.

```
int number_of_nodes() {
  int count = 1;
  if (hasleft)
    count += left->number_of_nodes();
  if (hasright)
    count += right->number_of_nodes();
  return count;
};
```

Likewise, the depth of a tree is computed as a recursive max over the left and right subtrees:

```
int depth() {
  int d = 1, dl=0,dr=0;
  if (hasleft)
    dl = left->depth();
  if (hasright)
    dr = right->depth();
  d = max(d+dl,d+dr);
  return d;
};
```

Now we need to consider how actually to insert nodes. We write a function that inserts an item at a node. If the key of that node is the item, we increase the value of the counter. Otherwise we determine whether to add the item in the left or right subtree. If no such subtree exists, we create it; otherwise we descend in the appropriate subtree, and do a recursive insert call.

```
  void insert(int value) {
    if (key==value)
      count ++;
    else if (value<key) {
      if (hasleft)
```

```
left->insert(value);
      else
addleft(value);
    } else if (value>key) {
      if (hasright)
right->insert(value);
      else
addright(value);
    } else throw(1); // should not happen
  };
```

35.2 Algorithms

This *really* **really** goes beyond this book.

- Simple ones: numerical
- Connected to a data structure: search

35.2.1 Sorting

Unlike the tree algorithms above, which used a non-obvious data structure, sorting algorithms are a good example of the combination of very simple data structures (mostly just an array), and sophisticated analysis of the algorithm behaviour. We very briefly discuss two algorithms.

35.2.1.1 Bubble sort

An array a of length n is sorted if

$$\forall_{i<n-1}: a_i \leq a_{i+1}.$$

A simple sorting algorithm suggests itself immediately: if i is such that $a_i > a_{i+1}$, then reverse the i and $i+1$ locations in the array.

```
void swap( std::vector<int> &array,int i ) {
  int t = array[i];
  array[i] = array[i+1];
  array[i+1] = t;
}
```

(Why is the array argument passed by reference?)

If you go through the array once, swapping elements, the result is not sorted, but at least the largest element is at the end. You can now do another pass, putting the next-largest element in place, and so on.

This algorithm is known as *bubble sort*. It is generally not considered a good algorithm, because it has a time complexity (section 37.1.1) of $n^2/2$ swap operations. Sorting can be shown to need $O(n \log n)$ operations, and bubble sort is far above this limit.

35.2.1.2 Quicksort

A popular algorithm that can attain the optimal complexity (but need not; see below) is *quicksort*:

- Find an element, called the pivot, that is approximately equal to the median value.
- Rearrange the array elements to give three sets, consecutively stored: all elements less than, equal, and greater than the pivot respectively.
- Apply the quicksort algorithm to the first and third subarrays.

This algorithm is best programmed recursively, and you can even make a case for its parallel execution: every time you find a pivot you can double the number of active processors.

Exercise 35.1. Suppose that, by bad luck, your pivot turns out to be the smallest array element every time. What is the time complexity of the resulting algorithm?

35.3 Programming techniques

35.3.1 Memoization

In section 5.2.2 you saw some examples of recursion. The factorial example could be written in a loop, and there are both arguments for and against doing so.

The Fibonacci example is more subtle: it can not immediately be converted to an iterative formulation, but there is a clear need for eliminating some waste that comes with the simple recursive formulation. The technique we can use for this is known as *memoization*: store intermediate results to prevent them from being recomputed.

Here is an outline.

```
int fibonacci(int n) {
  std::vector<int> fibo_values(n);
  for (int i=0; i<n; i++)
    fibo_values[i] = 0;
  fibonacci_memoized(fibo_values,n-1);
  return fibo_values[n-1];
}
int fibonacci_memoized( std::vector<int> &values, int top ) {
  int minus1 = top-1, minus2 = top-2;
  if (top<2)
    return 1;
  if (values[minus1]==0)
    values[minus1] = fibonacci_memoized(values,minus1);
  if (values[minus2]==0)
    values[minus2] = fibonacci_memoized(values,minus2);
  values[top] = values[minus1]+values[minus2];
  //cout << "set f(" << top << ") to " << values[top] << endl;
  return values[top];
}
//codesnipet end
```

```
int main() {
  int fibo_n;
  cout << "What number? ";
  cin >> fibo_n;
  cout << "Fibo(" << fibo_n << ") = " << fibonacci(fibo_n) << endl;

  return 0;
}
```

Chapter 36

Programming strategies

36.1 Programming: top-down versus bottom up

The exercises in chapter 32 were in order of increasing complexity. You can imagine writing a program that way, which is formally known as *bottom-up* programming.

However, to write a sophisticated program this way you really need to have an overall conception of the structure of the whole program.

Maybe it makes more sense to go about it the other way: start with the highest level description and gradually refine it to the lowest level building blocks. This is known as *top-down* programming.

https://www.cs.fsu.edu/~myers/c++/notes/stepwise.html

Example:

Run a simulation

becomes

Run a simulation:
    Set up data and parameters
    Until convergence:
        Do a time step

becomes

Run a simulation:
    Set up data and parameters:
        Allocate data structures
        Set all values
    Until convergence:
        Do a time step:
            Calculate Jacobian
            Compute time step
            Update

You could do these refinement steps on paper and wind up with the finished program, but every step that is refined could also be a subprogram.

We already did some top-down programming, when the prime number exercises asked you to write functions and classes to implement a given program structure; see for instance exercise 32.10.

A problem with top-down programming is that you can not start testing until you have made your way down to the basic bits of code. With bottom-up it's easier to start testing. Which brings us to...

36.1.1 Worked out example

Take a look at exercise 30.2. We will solve this in steps.

1. State the problem:
```
// find the longest sequence
```

2. Refine by introducing a loop
```
// find the longest sequence:

// Try all starting points
// If it gives a longer sequence report
```

3. Introduce the actual loop:
```
// Try all starting points
for (int starting=2; starting<1000; starting++)
// If it gives a longer sequence report
```

4. Record the length:
```
// Try all starting points
int maximum_length=-1;
for (int starting=2; starting<1000; starting++) {
  // If the sequence gives a longer sequence report:
  int length=0;
  // compute the sequence
  if (length>maximum_length) {
    // Report this sequence as the longest
  }
}
```

5.
```
// Try all starting points
int maximum_length=-1;
for (int starting=2; starting<1000; starting++) {
  // If the sequence gives a longer sequence report:
  int length=0;
  // compute the sequence
  int current=starting;
  while (current!=1) {
    // update current value
    length++;
  }
  if (length>maximum_length) {
    // Report this sequence as the longest
  }
```

```
}
```

36.2 Coding style

After you write your code there is the issue of *code maintainance*: you may in the future have to update your code or fix something. You may even have to fix someone else's code or someone will have to work on your code. So it's a good idea to code cleanly.

Naming Use meaningful variable names: `record_number` instead `rn` or `n`. This is sometimes called 'self-documenting code'.

Comments Insert comments to explain non-trivial parts of code.

Reuse Do not write the same bit of code twice: use macros, functions, classes.

36.3 Documentation

Take a look at Doxygen.

36.4 Testing

If you write your program modularly, it is easy (or at least: easier) to test the components without having to wait for an all-or-nothing test of the whole program. In an extreme form of this you would write your code by *test-driven development*: for each part of the program you would first write the test that it would satisfy.

In a more moderate approach you would use *unit testing*: you write a test for each program bit, from the lowest to the highest level.

And always remember the old truism that 'by testing you can only prove the presence of errors, never the absence.

Chapter 37

Complexity

37.1 Order of complexity

37.1.1 Time complexity

Exercise 37.1. For each number n from 1 to 100, print the sum of all numbers 1 through n.

There are several possible solutions to this exercise. Let's assume you don't know the formula for the sum of the numbers $1 \ldots n$. You can have a solution that keeps a running sum, and a solution with an inner loop.

Exercise 37.2. How many operations, as a function of n, are performed in these two solutions?

37.1.2 Space complexity

Exercise 37.3. Read numbers that the user inputs; when the user inputs zero or negative, stop reading. Add up all the positive numbers and print their average.

This exercise can be solved by storing the numbers in a `std::vector`, but one can also keep a running sum and count.

Exercise 37.4. How much space do the two solutions require?

Chapter 38

Index