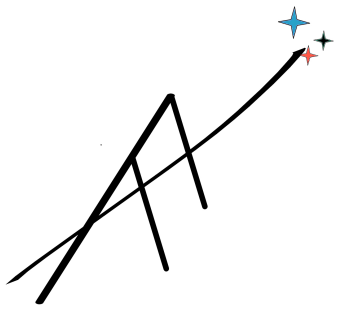
EE553 C++



Ad Astra Education

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Contents

1. Prerequisites

This course is a graduate-level introduction to C++ for students with little to no background programming. Accordingly it starts from the beginning and does not assume prior knowledge, but any prior programming experience is quite helpful.

2. C++ Programming Skills Overview

There are many topics you need to know to become a good programmer. This overview lists first the many individual topics you need to know. You will be asked during the course to evaluate how well you know each topic. Keep reviewing this section periodically to keep track of how far you have come, how much you have learned.

In addition, there are skills to master, such as how to use a debugger. These skills are also important, but many go beyond what we can assess during class. They are enumerated here so you can know what you need to learn to improve.

Each one of these skills is relatively limited and not a big deal. Cumulatively you can see in this section that C++ programming encompasses a huge body of knowledge and skills. One semester course will not suffice to learn this all, but at the end of this course, you will have the skills you need to continue learning and practicing.

Category	*Skill*	*Explanation*
integer data types	signed and unsigned behavior	Whole numbers used for counting, loops.
	constants	In order to use integers, you must be able to correctly store values
	arithmetic operators	Basic arithmetic in C-like languages is similar to math, but not quite the same. Learning the limitations and differences is key to programming correctly. If you do not know what the computer does, you cannot possibly write a program that requires computing with whole numbers
	overflow	Computers have a finite amount of memory, so every number is assigned a finite amount of space. If an answer is too big it will not fit, and an overflow error will result. Understanding this is essential because it is so easy to compute values that are too big. When computation goes wrong with integers, this is something we must suspect.
floating point data types	properties	How floating point numbers behave
	roundoff	How errors can accumulate in floating point answers
	Infinity and NaN	IEE 754 Floating Point Mathematics behavior involving infinity
	math library functions	The most frequently used functions in the math library
strings	literals	How string constants are embedded in C++ programs
	string data type	The C++ library contains a string object
	string operations	What can you do to strings?
C++ Syntax	identifiers	This is the generic name for entities that have names in C++
variables	initialization	How to put values into variables when they are created
	scope	Where an identifier is visible within the program
	lifetime	How long a variable lives.
Programming Logic	decision-making (comparison operators)	Used in many statements in C++

Statements	The syntax of statements in (C/C++/Java)	What all statements share in common
	Rules of curly braces and semicolons	Defining statements and blocks
	While loop	Statement that keeps going while true
	Analyzing how many times a loop will execute	You must be able to trace code and determine what it does
	Maximum and minimum number of times a loop will execute	Key skill to avoid bugs – thinking what could happen
	If statements	Decision making statement
	do...while	Loop that executes at least once
	break and continue	Breaking out of loops early, or skipping one iteration
	goto	Uncontrolled and dangerous, but useful for breaking out of multi-level loops
	switch	A multi-way if statement that works only for integral types
	Tracing through code: mental model of what is happening	You can use a debugger, but it is quicker if you can see what your code is doing
Arrays	declaration and initialization	How to create arrays and fill them with values
	Multi-dimensional arrays	Behavior of 2, 3, 4 and higher dimensional lists
IO	printing to the screen	The cout object
	reading from the keyboard	The cin object
	writing to error stream	understanding redirecting files and why there is an error stream
	opening/closing files	understanding buffers, and the fact that if you do not close the file it may not write out, or write incompletely
Standard Algorithmic Patterns	Writing a loop to count	Understanding variables, state, tracing through a basic loop
	Summation	Knowing to initialize to zero, and understanding that a second variable is needed
	Products	Computing a product requires initializing to 1
	Array processing	Being able to perform the same kind of computation but with an array
	Nested loops	Understanding what happens when one loop is inside another
	Convergence	Computing a summation until it converges, not a set number of times
	Reading input until a value is entered	A basic pattern that shows the advantage of a do... while

Statements	The syntax of statements in (C/C++/Java)	What all statements share in common
	Rules of curly braces and semicolons	Defining statements and blocks
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	switch	A multiway if statement that works only for integral types
	Tracing through code: mental model of what is happening	You can use a debugger, but it is quicker if you can see what your code is doing
each object's relationships		

3. Intro to C++

The hardest thing in learning to program a new technology is starting. Everything is new and unknown. Nothing works at first.

A C++ program starts with a function called main. The name main is not a keyword in the language, it is just a name. But the name main is special. It is the symbol that Unix tries to execute when starting a program. Windows uses this also for text applications to be compatible, but for graphical programs it calls the starting (entry) point WinMain. Using WinMain is non-standard C or C++ and will only work on windows.

The following program is the smallest legal program possible in C++. The program runs and returns the value zero to the caller, which is the operating system. The returned 0 means that everything went well. Returning a different number is used to tell that something went wrong.

The parentheses after main means that it is a function, or a named section of program. The code is contained within curly braces { }.

The keyword **int** is a reserved word in C++ meaning a whole number. The type int before main means that main returns a whole number to whoever calls it.

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

The second program we write prints out a message. To print, we send a sequence of characters, called a "string" to std::cout which represents the output. The operator << means print to the entity on the left, in this case std::cout.

```
#include <iostream>
int main() {
  std::cout << "hello";
  return 0;
}
```

C++ has a very complicated syntax. Over the years, features have been added into the language, and today it is a mess. As long as you learn the correct syntax, this is not a problem. As a programming language, C++ is unambiguous and precise in its grammar. The problem is, if you type anything wrong, since the language was not designed

cleanly but evolved, it is very difficult to tell what you mean. The error messages resulting from small errors can be wildly confusing.

For example, all simple statements must end in a semicolon. C++ does not care about the end of a line, or white space. So the following program is exactly the same as the one above:

```
#include <iostream>
int main() {
  std
    ::
        cout


<<
"hello"
;
  return 0;
}
```

However, miss the semicolon, and compile the program:

```
#include <iostream>
int main() {
  std::cout << "hello";
  return 0;
}
```

results in the error:

```
test.cpp: In function ‘int main()’:
test.cpp:3:23: error: expected ‘;’ before ‘return’
    3 |   std::cout << "hello"
      |                       ^
      |                       ;
    4 |   return 0;
      |   ~~~~~~
```

The above error seems quite reasonable, but unfortunately they are not all that good. Miss the semicolon in the following program (in the for they are replaced by commas) and three errors appear. They aren't completely misleading. Notice that the first one tells you exactly what is wrong, the comma needs to be a semicolon:

```
#include <iostream>
int main() {
  for (int i = 0, i < 10, i++);
    std::cout << "test"
  return 0;
```

```
}
```

```
test.cpp: In function ‘int main()’:
test.cpp:3:20: error: expected ‘;’ before ‘<’ token
    3 |   for (int i = 0, i < 10, i++);
      |                    ^~
      |                    ;
test.cpp:3:21: error: expected primary-expression before ‘<’ token
    3 |   for (int i = 0, i < 10, i++);
      |                     ^
test.cpp:3:30: error: expected ‘;’ before ‘)’ token
    3 |   for (int i = 0, i < 10, i++);
```

Unfortunately as we go on, the errors will get progressively more cryptic. Experience will help. But one technique you should know is to search the internet for the error. Very often, you will be able to find an explanation.

In Java, everything is an object. You cannot write a program without writing a class to do it. C++ by contrast is objectcapable. You can still write C programs in C++ that do not use objects.

C++ code may only be written inside a function. The function has a name (in this case, main), parentheses after the name and then curly braces.

There is also a return type, in this case int, that will be discussed later.

Write the function main, which is the entry point in C and C++. The following program displays the classic message ”Hello World”. The\n character goes to a new line

```
int main() {
  cout << "Hello World\n";
}
```

The above program still is not quite right. The variable cout has not been defined. In order to use it, we must include a header file describing what it is.

To print in C++, include the iostream file using #include (more on this later)

```
#include <iostream>
int main() {
  std::cout << "Hello World\n";
}
```

This time, notice we are using the full name of cout, which is std::cout. This program will work.

Since it is annoying to type std:: in front of many varianles and functions, we can use a shortcut. The statement ”using namespace std” tells the compiler that any time it does not understand a symbol, it should try that symbol with std:: in front of it.

```
#include <iostream>
using namespace std;
int main() {
  std::cout << "Hello World\n";
}
```

There are many named entities that we use from the std library. Typing std:: all the time can be inconvenient. So we can declare that we wish to try any unknown symbol with a std:: in front of it to see if it is in the standard library. The following program prints to the standard output object std::cout, reads from the keyboard using std::cin without mentioning std:: due to the statement: using namespace std;

```
#include <iostream>
using namespace std;
int main() {
  cout << "Please type a number:";
  int x;
  cin >> x;
  cout << " doubling: " << x * 2 << "\n";
}
```

3.1 Compilers

A compiler is a program that reads in a program in a particular language and generates an executable that can run on a computer. In this course we use either g++ or clang++, two open source and very popular C++ compilers. You may also use Visual Studio on windows, but since it is non-standard, you must verify that your program will compile with g++ in order to guarantee your homework will not be rejected because it fails to compile.

If you use an Integrated Development Environment (IDE) like CLion, qtcreator, vscode, etc. it is possible to build the program without understanding what is happening. The IDE does all the work. But as you get more advanced it is important that you understand what is happening, primarily so you can troubleshoot when (not if) things go wrong. This section describes the low-level g++ commands that I use in class to show how the program builds. You can learn more options in `github.com/LinuxCrashCourse`.

Each language has its own rules. In C++, programs must be called .cc (the suffix defined by the original AT&T compiler), or .cpp or .cxx (used by microsoft). Today all three are acceptable to all compilers.Anything else will not work; the compiler will not know the program is C++.

To build C++ programs using g++ from the command line:

g++ HelloWorld.cc

will generate a program called a.out on Linux and MacOSX, and a.exe on Windows. To run the program on linux type:

```
./a.out
```

On windows, either of the following commands works:

```
a
a.exe
```

To generate an executable with the same name as the source code, use the command:

```
g++ HelloWorld.cc -o HelloWorld
```

4. File I/O

By default, C++ has three files open: cout which writes text to standard output, usually the terminal where the programmer is running the program, cin which reads in whatever is typed to the program, and cerr, which is the same as cout unless cout is redirected to a file. The cerr file is used to print to the screen even if the output is redirected. For example:

```
#include <iostream>
using namespace std;
int main() {
  cout << "hello\n";
  cerr << "this is going to cerr!\n";
}
```

if this program is run:

```
g++ output.cc
./a.out
```

the output is:

```
hello
this is going to cerr!
```

On the other hand if the program redirects output to a file

```
./a.out >test.txt
```

then only hello appears. The string "this is going to cerr!" is stored in test.txt.

For a more complete listing of compiler options, see
https://github.com/LinuxCrashCourse

5. C++ Data Types and constants

5.1 C++ Integer Data Types

C++supports multiple sizes of integer from small to large. The problem is, these have not been defined portably so the exact size differs depending on the computer. Also, types may be unsigned (only positive numbers) or signed (positive and negative numbers). This also affects the maximum size of the number that can be processed.

The following table shows how many bits are in each data type on a typical 64-bit computer today, and also on a small microcontroller such as Arduino (Atmel328).

Data Type	*Space (bits)*	*64-bit PC*	*Micro-controller*	*Description*
short or short int	$\geq$ 16 bits	16	16 bits	Typically signed by default.
int	$\geq$ short	32	16 bits	$\leq$ word width of machine for speed
long	$\geq$ int	64	32 bits	
long long	64 bits	64 bits	64	Guaranteed?
unsigned int	= int		32	Just like int, but unsigned so holds values twice as big
signed int				guaranteed to be signed, unlike int
char	8	8	8	Not guaranteed, but almost always 8 bits, one byte

The next table shows maximum and minimum values for each type on a 64-bit PC today. Note that there are no guarantees. The actual size is up to the compiler writer, but this is the size as reported by g++ which is what we use in this class.

Data Type	*Space (bits)*	*M*	*Micro-controller*	*Description*
short	16 bits	16	16 bits	Typically signed by default.
int	$\geq$ short	32	16 bits	$\leq$ word width of machine for speed
long	$\geq$ int	64	32 bits	
long long	64 bits	64 bits	64	Guaranteed?
unsigned int	= int		32	Just like int, but unsigned so holds values twice as big
signed int				guaranteed to be signed, unlike int

The limits for all data types are found in the header file climits. The following code illustrates:

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

int main() {
     cout << "number of bits in a byte:\t" << CHAR_BIT;
     cout << "\nsmallest number in a byte:\t" << SCHAR_MIN;
     cout << "\nlargest number in a byte:\t" << SCHAR_MAX;

     cout << "\nsmallest number in a short:\t" << SHRT_MIN;
     cout << "\nlargest number in a short:\t" << SHRT_MAX;

     cout << "\nsmallest number in an int:\t" << INT_MIN;
     cout << "\nlargest number in an int:\t" << INT_MAX;

     cout << "\nsmallest number in a long:\t" << LONG_MIN;
     cout << "\nlargest number in a long:\t" << LONG_MAX;

     cout << "\nlargest number in an unsigned long:\t" <<
        ULONG_MAX;

     cout << "\nsmallest number in a long long:\t" << LLONG_MIN;
     cout << "\nlargest number in a long long:\t" << LLONG_MAX;
}
```

The output on Ubuntu using g++ 5.4 is:

```
number of bits in a byte: 8
smallest number in a byte: -128
largest number in a byte: 127
smallest number in a short: -32768
largest number in a short: 32767
smallest number in an int: -2147483648
largest number in an int: 2147483647
smallest number in a long: -9223372036854775808
largest number in a long: 9223372036854775807
largest number in an unsigned long: 18446744073709551615
smallest number in a long long: -9223372036854775808
largest number in a long long: 9223372036854775807
```

6. How Signed and Unsigned Arithmetic Work

To make it manageable, consider a 3-bit computer. Each bit has two possibilities 0 and 1. So there are a total of 2^8 different combinations. How do these represent numbers? The following table shows for both signed and unsigned. If signed, the leading digit represents positive or negative so the biggest number that can be represented is half the size.

Bits	***unsigned***	***signed***
000	0	0
001	1	1
010	2	2
011	3	3
100	4	-4
101	5	-3
110	6	-2
111	7	-1

Note that for unsigned, there is no number bigger than 7, so adding 1 to 7 wraps around to 0. This is called overflow. For signed numbers, the largest positive number is 3, so adding 1 results in -4 (the biggest negative number).

For a 16 bit signed integer, this means that: $32767 + 1 \rightarrow -32768$ (overflow).
$-32768 - 2 \rightarrow 32766$ (underflow).

What does this mean for you? When writing a program, if you suddenly see a value that should be positive, but turns negative, that is an immediate sign that overflow has happened and the value is wrong. But even if you do not observe this, that does not mean that overflow has not occurred.

Be suspicious if a value should grow, and does not. And try to figure out, in advance, when you expect overflow to happen. In other words, do not way passively and wonder when your code is not working, try to compute the maximum number expected to work, and create a test plan to make sure you are correct.

6.1 C++ constants

int	2, -5	-2100000000 +2100000000
unsigned int	2U,	4200000000
long integer	2L -5L,	-2100000000 +2100000000
long long	123456789012345678LL	
short int	2h, -52h	
char n' (newline) ' t' (tab) ' '	'a' 'b' 'n' 'x0d' '	
string	"hello world"	

commas are not legal in numeric constants

```
cout << 2 << '\n';
cout << -5L << '\n';
cout << 5h << '\n';
cout << 241200000000000LL << '\n';
```

7. Arithmetic Operators and Overflow

7.1 Integer Arithmetic

There are five basic binary arithmetic operations in C++. Each takes two values (operands) and computes a result.

+	addition
-	subtraction
*	multiplication
/	division
%	modulo (integer remainder)

Computer integer math is the same as it is in theory, except that in theoretical mathematics, there is no limit to the size of numbers. On a computer, there is a finite amount of space devoted to storing the number, and therefore, a limit to the biggest number that can be stored.

Addition and subtraction pretty much work normally as long as the maximum sizes are not exceeded. For example

4 + 5

is 9, and

5 - 9

is -4. But when a number does not fit, the answer will not be correct. The biggest signed integer that can fit into 32 bits is 2147483647. So

```
2147483647 + 1
```
[1]

does not result in a number that is one bigger since that number cannot be represented. Instead it "wraps around" and becomes the smallest number possible: -2147483648

Similarly, if we multiply 2147483647 * 2, the result will wrap around. This is called an overflow. Sometimes the results of an overflow are obviously wrong. You know that if you keep adding, numbers do not become negative when they get big! But the result is not always obviously wrong. You must do two things: first, figure out whether the answers you intend to compute could become too big to represent, and second, be alert

to the possibility that results could be wrong. DO NOT ASSUME that your computation is correct. In fact, the opposite: a good programmer must assume that the results are wrong until proven otherwise, and design unit testing to prove that the code is correct.

```
int y = 5 / 2;
int x = 5 % 2;
int a = 52 % 5;

cout << 214 % 2 << 215 % 2 << '\n'
```

8. C++11 Portable Integer Data Types

In C++11, data types have been defined that are the same across all platforms. In order to use them, compile with a C++ compiler that support C++11, and include the library cstdint

The data types beginning with u are definitely unsigned. The size of each data type is specified in bits. Thus int8_t is a signed 8-bit integer, (-128..127) while uint64_t is an unsigned 64 bit integer. Sizes 8, 16, 32, and 64 are supported.

```
#include <cstdint>
uint64_t a;
int32_t b;
```

9. Type bool and Comparison Operators

The data type bool can have values false and true. It takes a single memory location (usually a byte on most computers). The value true is internally 1 and the value false is 0, but prefer using true and false for clarity.

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

int main() {
  bool b = false;
  cout << b;
  b = !b; // reverse the truth value of b
  cout << b;
  cout << (2 < 3);
  cout << (2 > 3);
  cout << (2 <= 3);
  cout << (2 >= 3);
  cout << (2 == 3);
  cout << (2 != 3);
}
```

10. Logical Operators

Boolean operations can be combined using logical operators. The not operator ! reverses the truth value, so for example:

```
bool b = ! (2 < 3);
```

is false because 2 is less than 3 (true), and the opposite of true is false.

The and operator can be written either with two ampersands && or as the word and. For example, in the following code snippet b1 is true because both conditions are true, while b2 is false because the second is false. Both conditions must be true for and to be true.

```
bool b1 = 2 < 3 && 3 < 4; // true
bool b2 = 2 < 3 && 5 < 2; // false
```

The logical operators in the C family of languages are short-circuiting. For an and operation, this means that if the first condition is false, the compiler knows the whole thing must be false, so it never tests the second condition at all. For an or operation, if the first condition is true, the compiler can infer the entire expression is false so the second condition is similarly never tested.

In the following example, the function f() and g() are never called because the first part of the and condition (for b1) and the or condition (b2) is true.

```
bool f(int x) {
  cout << "hello";
  return x % 2 == 0;
}

bool g() {
  cout << "test";
  return true;
}

int main() {
  bool b1 = 6 < 2 && f(4);
  bool b2 = 2 < 3 || g(5);
}
```

11. Floating Point Types

We have seen the whole number (integral) data types that C++ and other languages support. But computers also have to compute decimals. Decimal types are called floating point because the decimal place can move in this representation. Floating point has a sign (+/-), a fixed number of digits of precision (callled the mantissa), and an exponent that defines how big or small the number is.

```
float f = 1.5f;
double d = 2.5;
long double d2 = 1.2345678901234567890123456 7;
const double avogadro = 6.023e+23;
const double pi = 3.14159265358979;
const double massEarth = 5.96e+24; // in kg
```

Questions It is a warning in C++ to lose accuracy in a computation. Can you spot where this is happening in each example?

```
float f = 1.5 + 2.5;
long double PI = 3.14159265358979L;
double pi = PI;
```

12. C++ Data Type Summary

In C++:

Data Type	*Space (bits)*	*PC*	*Micro-controller*	*Description*
short	$\geq$ 16 bits	16	16 bits	Typically signed by default.
int	$\geq$ short	32	16 bits	$\leq$ word width of machine for speed
long	$\geq$ int	32	32 bits	
long long	64 bits	64 bits	64	Guaranteed?
unsigned int	= int		32	Just like int, but unsigned so holds magnitudes twice as big
signed int				guaranteed to be signed, unlike int
float	32 bits	IEEE754		about 7 digits precision
double	64 bits	IEEE754		about 15 digits precision
long double				optional and size depends on platform

In practice, on "normal" pc: short=16, int=32, long=64
on small, embedded processors (Arduino) short=16, int=16, long=32

long long = 64 bits (8 bytes)

char is one byte typically, but always 1 minimal addressing unit.

float single precision

double double precision (except on Arduino, where double=float)

long double (more precision, not specified)

13. Variables

The result of computations can be stored in variables.

Variables must be declared.

A declaration consists of a type, a variable name and (optionally) initialization. You should almost always initialize variables.

Variables declared within functions that are uninitialized have undefined (somewhat random) values.

Variable names must begin with a letter or underscore. They may continue with a letter, number or underscore

Examples of legal variable names

```
pi
hello
ThisIsALongVariableName
Charlie48
x
amountOfVegetables
underscore_style_name
```

Variables may not contain other characters aside from those mentioned above, may not start with a digit, and may not be a reserved word in the language. A complete list of reserved words (or keywords) is here:

alignas (C++11)	alignof (C++11)	and	and_eq
asm	auto	bitand	bitor
bool	break	case	catch
char	char16_t (C++11)	char32_t (C++11)	class
compl	concept (concepts TS)	const	constexpr (C++11)
const_cast	continue	decltype (C++11)	default
delete	do	double	dynamic_cast
else	enum	explicit	export
extern	false	float	for
friend	goto	if	inline
int	long	mutable	namespace
new	noexcept (C++11)	not	not_eq
nullptr (C++11)	operator	or	or_eq
private	protected	public	register
reinterpret_cast	requires (concepts TS)	return	short
signed	sizeof	static	static_assert (C++11)
static_cast	struct	switch	template
this	thread_local (C++11)	throw	true
try	typedef	typeid	typename
union	unsigned	using	virtual
void	volatile	wchar_t	while
xor	xor_eq		

The following names are not legal

```
4pi
for
if
$xyz
ILoveC++!
```

Good Declarations

```
int x = 5;
long long y = 5000;
char c = 97; // int will automatically convert to anything
   smaller
short int s = 256; // int --> short is not a problem
```

Bad declarations

```
int z = 500000000000000LL; // losing information (warning)
```

13.1 Divide By Zero

For integers, a divide by zero results in a hardware exception. The processor actually sends a special message to the operating system, terminating the program. This is pretty bad, since the program stops dead. If the program is a word processor, for example, then it dies without saving. If the program is running a pacemaker or other lifesaving equipment, the results could be catastrophic. For this reason, it is possible to write code to trap the failure and recover, but the best defense is whenever a division is computed that could result in a divide by zero, test the denominator first, and do not do the division if the denominator is zero.

In order to handle an integer divide by zero, use signal handling (https://man7.org/linux/man-pages/man2/signal.2.html on Linux, and under msys2 on windows).

14. Introduction to C++ Statements

A statement is a grammatical entity. In C++ it can span multiple lines. Simple statements are terminated by a semicolon. For example:

```
x = 1 + 3 * 5;
```

is a simple statement.

Anywhere a simple statement may exist, a compound statement may be substituted. Compound statements are multiple statements surrounded by curly braces. Thus the following is gramatically a single statement:

```
c = a + b;
b = a;
a = c;
```

In this context, we now must add the ability to instruct the computer to conditionally execute code (an if statement) and to execute code repeatedly (in a loop). C++ has multiple ways of creating loops: **while**, **for**, and **do**.. **while**. As a programmer, it is possible to use only one of these forms most of the time, but to be a competent C++ programmer you must know all the forms, for the simple reason that you have no control over what other programmers will use, and you must be able to read their work.

15. Rules of Semicolon and Curly Braces

Every simple statement ends in a semicolon. This is because statements can span multiple lines.

Example:

```
int main() {
  x = 365.2425 * 24 * 60 * 60;
  double x = 1 + 3 / (1*2*3) + 3*3 / (1*2*3*4) +
     3*3*3/(1*2*3*4*5) +
    3*3*3*3/(1*2*3*4*5*6);s
}
```

Curly braces are used to combine multiple statements into a single compound statement. For example, the following compound statement combines three assignments:

```
{
  temp = a;
  a = b;
  b = temp;
}
```

Anywhere a single statement can go, a compound statement may be placed. Therefore, since an if statement executes a singlel statement conditionally, it can be used to execute a number of statements conditionally using curly braces.

16. if statements

The if statement allows a statement to be executed if a condition is true (conditionally) or to execute either one or another with the else clause.

```
int x = 2;
if (x == 2)
  cout << "A"; // this is printed
```

```
int x = 3;
if (x == 2)
  cout << "B\n";
else
  cout << "C\n"; // this is printed
```

To execute more than a single line in an if statement or else clause, surround by curly braces:

```
int main() {
  int x;
  cin >> x;
  if (x >= 2) {
    x = x * 3 + 5;
    cout << x << '\n';
  } else {
    x = x / 2 + 3;
    cout << x << '\n';
  }
}
```

17. if Statement

An if statement checks whether a condition is true or false. If the condition is true, it executes the statement immediately after the if statement. If the statement is false, it either executes nothing, or if there is an else clause with a second statement, it executes that one.

Example:

```
if (c)
  statement1;

if (c2)
  statement1;
else
  statement2;
```

In the following example, the program prints ”yes” and ”no” because the first if statement is true and the second is false.

18. while Loop

18.1 Structure

The while loop looks almost like an if statement. It too has the parentheses surrounding the condition. If the condition is true, it executes the statement immediately after the while statement. However, in addition it then checks if the condition is true again. While loops will go forever if nothing changes the condition. They can also execute zero times if the condition is initially false.

```
while (2 < 3)
  cout << "Yes"; // this always prints "yes" in an infinite
    loop (2 is always < 3)
```

The following while loop never executes because the condition is initially false:

```
while (3 < 2)
  cout << "Yes"; // nothing is printed
```

18.2 Counting Loops

In order to count, use a variable and add until it reaches the desired number

```
int count = 0;
while (count < 10) {
  cout << count;
  count++;
}
```

The above loop first checks whether $0 < 10$ (it is). Then it prints 0 and count becomes 1. The last value printed is 9.

The next loop is similar, but x starts with 1 and counts to 10.

```
int x = 1;
while (x <= 10) {
```

```
  cout << x;
  x++;
}
```

There are four ways of adding 1 to a variable in C++. Get to know all four because they are commonly used.

```
  x = x + 1;
  x += 1;
  x++;
  ++x;
```

19. for Loop

The for loop is shorthand for a while loop with built-in place to put the code to initialize a variable, and to change it to the next value. The following while loop is exactly equivalent to the for loop. The for loop is more compact and has other advantages, so is generally better to use for typical counting loops.

The for statement has three expressions within the parentheses:

```
for (init-expr; while-condition; next-expr)
   statement
```

The init-expr is executed once. The while-condition is tested each time before the statement (the body of the loop) is executed. The next-expr is executed each time at the end of the loop.

A for loop is more compact than a while loop, but it is exactly equivalent. Here are two loops, a for and a while, both of which count from 0 to 9.

```
for (int x = 0; x < 10; x = x + 1)
   cout << x;
```

```
int x = 0;
while (x < 10) {
   cout << x;
   x = x + 1;
}
```

Loops do not have to count up linearly. The expressions just change the values of the variables until they end. See if you can following the logic of the following loops.

```
for (int x = 10; x > 0; x--)
   cout << x;
```

```
for (int x = 1; x  < 100; x *= 2)
   cout << x;
```

```
for (int x = 1; x  < 10; x += 2)
   cout << x;
```

```
for (int x = 1; x  < 10; x -= 2) // not an infinite loop, but very, very long!!! 1, -1, -3, -5, -7, ... -MAXINT, overflow, positive (stops)
    cout << x;
```

20. do ... while Loop

A while loop checks the condition at the beginning, so it is possible to execute the loop zero times (the condition fails immediate). For example, the following while loop does nothing:

```
   while (false)
      cout << "print nothing";
```

The do... while loop checks the condition at the end rather than the beginning like the while loop. It is not used as much as the while loop, but it is useful whenever you need to do something first, then go back if it is not done correctly. For example, read in a number from the keyboard, and go back and read again if the number is not acceptable. The following example keeps reading in values until one is greater than or equal to 10.

```
int main() {
  int x;
  do {
    cin >> x;
  } while (x < 10);
 // by the time control reaches this point, x must be bigger than
     10
}
```

21. break Statement

The break statement is used to break out of a statement. In this section we will just look at using it to break out of loops from the middle. Note that it is easy to construct weird logic that is difficult to understand. Ideally, a loop has a single exit condition (the while clause) but it is not always possible.

```
int n = 17;
for (int i = 2; i  < n; i++)
  if (n % i == 0) {
    cout << n << " is divisible by " << i < "\n";
    break; // get out of the loop if we find a divisor
 }
```

Note that if the goal is merely to get out of the loop, this could be written into the for as follows:

```
int n = 17;
for (int i = 2; i  < n && n % i != 0; i++)
  ;
```

22. continue statement

The continue statement skips the current iteration of a loop and keeps going with the next one. A loop containing an if statement with an if statement which executes continue is the same as executing the remainder of the loop inside an if statement with the inverse condition, as shown below:

```
for (int i = 0; i  < 10; i++) {
  if (i == 5)
    continue;
  cout << i << ' ';
}
```

is exactly the same as:

```
for (int i = 0; i  < 10; i++) {
  if (i != 5)
    cout << i << ' ';
}
```

23. goto statement

At the lowest level, computers implement loops by determining whether a condition is true and jumping to a different place in the program. The while and for loops are higher level ways of looking at loops that are clearer. C++ does provide a goto statement mirroring the low-level assembler code that computers really run. While goto can do things that structured loops cannot do, it is extremely confusing and easy to write completely unreadable code. The following example shows a simple loop created using an if statement and a goto. This may not look too bad, but never, ever use this.

```
  int x = 0;
loop:
  cout << x << ' ';
  if (x < 10)
    goto loop;
```

To illustrate how confusing gotos can be, consider the following spaghetti code, so called because there are gotos in multiple directions, and it is hard to see where one strand begins and the other ends.

```
  int x = 0;
start:
  cout << x << ' ';
  x--;
middle:
  if (x % 2 == 0)
    goto cond;
  cout << x+1 << ' ';
  if (x % 3 == 0) {
    x += 4;
    goto start;
  }
cond:
  if (x < 10)
    goto loop;
```

Essentially, there is only one case where goto should be used in C++. That is when you have a nested loop and want to break out of the middle. There is nothing else that does that as cleanly as goto. The following example shows a prime number loop which is

repeatedly testing a number n mod i. If a divisor that evenly multiplies n is found, then the number is definitely not prime. However, if the entire inner loop executes and none of the numbers are divisors of n, then n is prime. The goto in this case skips the prime check in a simple, clean way. Any other method is more complicated.

```
int count = 0; // so far, we have found no prime numbers
for (int n = 2; n <= 1000; n++) { // find all numbers from 2 to
   100 which are prime...
  for (int i = 2; i < n; i++)
    if (n % i == 0)
      goto notPrime;
  count++; // if the entire inner loop passes, then the number
     must be prime
notPrime:
  ; // this empty statement is where the test jumps to if the
     number is NOT prime
}
```

Note that in languages like java where the continue statement can be labelled to apply to the outer loop, this particular example is not needed either. Here is a way of writing this in C++ without the goto. Note that we require a flag to remember whether we successfully divided the number or not. It's slightly slower, which is not a big deal, but also less clear.

```
int count = 0; // so far, we have found no prime numbers
for (int n = 2; n <= 1000; n++) { // find all numbers from 2 to
   100 which are prime...
  bool prime = true; // let's assume for the moment that n is
     prime
  for (int i = 2; i < n; i++)
    if (n % i == 0) {
      prime = false;
      break;
    }
  if (prime) // at the end of the loop, check whether the flag is
      true or not.
    count++;
}
```

24. switch statement

The switch statement is a weird multi-way if statement with some odd properties. First, it is equivalent to testing for equality with each case.

```
int x;
cin >> x;
switch(x) {
case 1:
  cout << "one ";
  break;
case 2:
  cout << "two ";
  break;
case 5:
  cout << "five ";
  break;
default:
  cout << "something else";
  break;
}
```

The above code is equivalent to an if...else chain as follows:

```
int x;
cin >> x;
if (x == 1) {
  cout << "one ";
} else if (x == 2) {
 cout << "two ";
} else if (x == 5) {
  cout << "five ";
} else {
  cout << "something else";
}
```

The break statements are necessary in the switch statement. If not, control would continue downwards. So without the break:

```
int x;
cin >> x;
switch(x) {
case 1:  cout << "one ";
case 2:  cout << "two ";
case 5:  cout << "five ";
default:  cout << "something else";
}
```

```
float x = 1;
switch (x) { // ILLEGAL!!! switch value must be integral type
case 1: cout << x;
}
```

the above code, which tests whether $x == 1$ would first print "one ", and then print "two " and then "five ", and finally, "something else ". In other words, it does not get out after each case, it keeps on going from that point. Each case is actually a goto label.

The other odd quirk of the switch statement is that it tests for equality, so it is illegal to use a floating point value because (as we have learned with roundoff error) floating point values are rarely equal to anything. For example, the following code adds 0.1 to sum 100 times. This should be 10.0. But because of roundoff error, it is not quote 10.0, and therefore a test for equality would fail. Knowing that this is almost never a good idea, the switch statement only supports integer types (short/long, uint64_t, char, etc, but not float, double, or long double).

25. Recursive Functions

A function that calls itself is recursive. All recursive functions must contain an if statement to terminate the recursion. Otherwise, they will keep calling themselves, taking more memory until the computer runs out.

The simplest kind of recursion is called tail recursion because the call happens at the end. Here is a recursive definition of factorial which is based on the rule that 0! = 1 and for all n, n! = n * (n-1)!

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

More complicate recursions can involve the function calling itself multiple times. In this case, because fibonacci calls itself twice, as the parameter n grows, the function is called 2^n times.

```
int fibo(int n) {
  if (n <= 2)
     return 1;
  return fibo(n-1) + fibo(n-2);
}
```

26. Floating Point Calculations and Roundoff Error

C++ supports decimal calculations. These are called floating point. There are three suported types: float, double, long double.

Single precision has 7 digits precision and can range from +/- 10^38 Double precision has 15 digits precision and can range from +/- 10^328 It is stored in 64 bits (8 bytes). long double is bigger, and depends on the architecture of the machine.

The IEEE 754 standard defines the behavior of single and double precision.

You can read more detail about IEEE floating point on Wikipedia: IEEE Floating Point

```
float f = 1.0f;
double d = 1.5;
long double big = 1.5000000000000000000000000000000000123L;

float g = 12345.67;
float h = 1.234567e+20;

const double AVOGADRO = 6.022e+23; // it is conventional to use
   all CAPS for constants
const double PI = 3.14159265358979;
const double G = 6.6711e-11;
const double earthMass = 5.96e+24; // mass of the earth in kg
```

26.1 General Principles

In general, always use double. Single precision float has too few digits, and the answer can end up completely wrong.

26.2 Printing out Floating Point Values

By default, floating point values will print as whole numbers if the fraction is zero, or with 5 digits precision if there are digits after the decimal. For more control, include the iomanip header file. This provides two objects to control output: setprecision, which controls the number of digits displayed, and setw which controls the width of the field displayed. Whenever more digits are specified than width to display them, the digits will overflow the field rather than display the wrong number. For example:

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

int main() {
     cout << 5 << '\n';
     cout << 1.234567f << '\n';

     cout << setprecision(12) << 1.234567f << '\n';
     cout << setprecision(15) << 1.234567 << '\n';

     cout << setw(30) << 1.23 << setw(30) << 2.34 << '\n';
     cout << 1.23 << 2.34 << '\n';
}
```

26.3 Roundoff error

Floating point is inherently inaccurate. It can represent huge ranges of values, but accuracy is only relative. For example, in a 32-bit float there is 1 bit for sign, 10 bits for the position of the binary point, leaving 22 for the digits in the number (called the mantissa). Due to a hardware trick, we get an extra bit, so it is effectively 23 bits for the mantissa.

Floating point numbers are expressed in base 2 because they are stored on a digital computer where each bit is 1 or 0. This means that the mantissa contains powers:

2^{-1},2^{-2},2^{-3},2^{-4}...

The first digit of the number is $\frac{1}{2}$, the second is $\frac{1}{4}$, the third is $\frac{1}{8}$, and so on. So for a floating point number with the following mantissa:

10100000000000000

the number is $\frac{1}{2} + \frac{1}{8} = 0.625$.

There are a number of problems. You know from basic arithmetic that there is no way for you to express the fraction $\frac{1}{3}$. That is because we use base 10, and 3 does not divide

evenly into 10. The same is true in base 2, $\frac{1}{3}$ is a repeating fraction. However, you are used to the fact that $\frac{1}{10}$ is a "nice" fraction, and in base 10 we write it as: 0.1.

In binary, however, $\frac{1}{10}$ is a repeating fraction: $\frac{1}{16} + \frac{1}{64} + \frac{1}{256} + ...$ so internally the fraction is represented as: 0.0001101010101010101...

The following program illustrates the problem. Print out numbers from 0 to 10 stepping 0.1 and very soon, they start to be wrong, and they get worse the longer you go.

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

int main() {
     for (float x = 0; x < 10; x += 0.1)
          cout << x << ' ';
}
```

```
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2
2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3 3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 4
4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 4.9 5 5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 6
6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 6.9 7 7.1 7.2 7.3 7.4 7.5 7.6 7.7 7.79999 7.89999 7.9999
8.09999 8.2 8.3 8.4 8.5 8.6 8.7 8.8 8.9 9 9.1 9.2 9.3 9.4 9.5 9.6 9.7 9.8 9.9
```

26.4 Roundoff Error

Some numbers are "nice" in decimal. Fractions like 1/2 = 0.5 or 1/10 = 0.1 can be exactly represented. Computers represent fractions in binary. Floating point fractions are sums of 1/2, 1/4, 1/8, ... Some fractions we think of as "nice" like 1/10 cannot be exactly represented in binary.

1/10 in decimal is 0.000101010101..... in other words, 1/10 = 1/16 + 1/64 + 1/256 + ...

You can see this by counting from 0 to 10 by 0.1. Very quickly, the numbers get a little off. They get more and more wrong the more is added. This is called roundoff error.

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

int main() {
  for (double x = 0; x < 10; x += 0.1)
    cout << x << '\n';
}
```

When printing the numbers from 0 to 1 stepping by 0.1, we can do this two ways:

```
#include <iostream>
```

```
using namespace std;
for (double x = 0; x <= 1.0; x += 0.1)
  cout << x << ' ';
cout << '\n';
for (int i = 0; i <= 10; i++, x += 0.1)
  cout << x << ' ';
}
```

The output of the above program is:

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2

For a great example of how roundoff affects real life, see this article on the Patriot missile software problem.

27. The C++ Math Library

The C++ math library is in cstdlib. Older C++ and C used math.h, but this is now obsolete. The following table shows the most common functions in the math library

All functions are computed in double precision unless otherwise specified

sin(x)	sine
cos(x)	cosine
tan(x)	tangent
atan(x)	arctangent
atan2(y,x)	arctangent(y/x)
sqrt(x)	square root
exp(x)	e^x
log(x)	$log_e(x)$
pow(x,y)	x^y

Incredibly, the math library does not have a standard definition for pi, which boggles the mind after all these years. Instead, define:

const double PI = 3.14159265358979;

and use that for most purposes.

The functions above are the most commonly-used in cmath. All trigonometric functions are in radians, so for angles in degrees, convert the angles to radians.

```
const double DEG2RAD = PI/180; // see above for PI!
double y = sin(x * DEG2RAD);
```

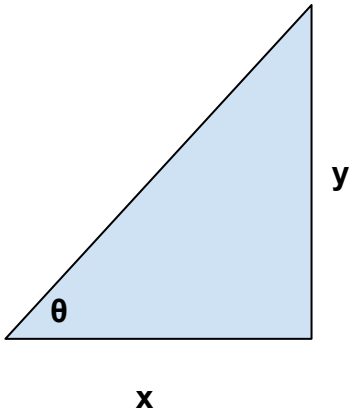
to convert from a function returning an angle, do the opposite:

```
const double RAD2DEG = 180/PI; // see above for PI!
double y = atan(x) * RAD2DEG;
```

27.1 Special Cases

One very common trigonometry problem is computing the angle when x and y are known. It comes up in robotics when the computer knows the destination (or target)

coordinate, and its own coordinate, and needs to compute at what angle to head.



In the case above, the equation of the angle is $\theta = tan^{-1}(\frac{y}{x})$. However, never use this on a computer, because there are many special cases starting with the one where x = 0. Instead, C++ (and most other languages) have a library function called atan2 which takes y and x as separate parameters and correctly handles all cases:

```
double y = atan2(y, x);
```

[1]

As usual, if the answer is to be in degrees, convert it back from radians.

28. IEEE Floating Point: Infinity and NaN

Floating point values can perform operations like divide by zero. Rather than crashing the program (as integer operations do by default) the IEEE standard defines results that makes sense numerically and in calculus. As the denominator approaches zero, the result of a division tends toward infinity. Therefore, the IEEE standard defines a special value, infinity to represent the result of this calculations.

Infinity is not like other values. Infinity + 1 is still infinity. Infinity * 2 is still infinity. And when infinite values battle it out, we cannot tell what the result will be, so Infinity - Infinity is not zero. In such cases, the IEEE standard defines another value: NaN (Not a Number). The NaN value is used when the value of a computation is indeterminate.

The following cases all generate positive and negative infinity:

```
#include <iostream>
using namespace std;
int main() {
  double x = 0.0;
  double y = 1 / x;
  double z = -1 / x;
  cout << y << z << '\n';
  cout << (y+1) << '\n';
  cout << (z*1) << '\n';
}
```

Dividing a finite value by infinity yields zero. Since there is positive and negative infinity, this leads to the concept of positive and negative zero. Even though the sign shows that they come from opposite infinities, if they are compared, they are equal to each other.

```
  double y = 1 / x;
  double z = -1 / x;
  cout << 5 / y << '\n';
  cout << 5 / z << '\n';
  cout << "positive zero and negative zero: " << (5/y == 5/z) <<
     '\n';
```

Last, when two opposing infinite forces meet, we don't know what the result is. Whether this is because of a zero in the numerator battling with a zero in the

denominator, or +infinity fighting with -infinity, all the results below are NaN.

```
#include <iostream>
#include <cmath>
using namespace std;
int main() {
  double x = 0.0;
  double y = 1 / x;
  double z = -1 / x;
  cout << (y+z) << '\n';
  cout << x / x << '\n';
  cout << sin(y) << '\n';
  cout << sqrt(-1) << '\n';
}
```

29. Arrays

Arrays are variables that hold lists of numbers indexed by position. Every element in a C++ array must be the same type. The size is declared with square brackets. For example, the folllowing declares an array a of 10 integers, and an array b of 5 doubles.

```
int a[10];
double b[20];
```

Just like variables with a single value, arrays declared in a function are not initiaized (they are random junk). To initialize an array, use the equal sign, but enclose the values within curly braces. If even one value is specified, all the remaining values in the array will automatically be initialized with 0.

```
int a[10] = {1,2};
double b[20] = {1.5, 3.5, 7.2 };
```

The first element of a C++ array is located at position 0. The following program prints out 1.5, then 1 then 0.

```
int main() {
  int a[10] = {1,2};
  double b[20] = {1.5, 3.5, 7.2 };
  cout << b[0] << '\n';
  cout << a[0] << '\n';
  cout << a[3] << '\n';
```

In order to process an array in a loop, use a for loop that goes from 0 to one less than the size. Remember that since the array starts with element 0, the last element is not n but n-1. It is also useful to declare a constant so that the size of the array and the loop are guaranteed to be the same, as shown in the followig example:

```
#include <iostream>
using namespace std;
int main() {
  const int SIZE = 5;
  int a[SIZE] = {9, 8, 5, 2, 6};
  for (int i = 0; i < SIZE; i++)
    cout << a[i] <<  ' ';
```

*** Need more problems to compute!

30. Functions

Functions are named chunks of program. They are used to break up programs into manageable sections. Every c++ program we have written has a function called main(), which is the standard entry point (where C++ starts). But you can write functions to break up a big complicated program.

The first example function will just print out something.

```
void f() {
  cout << "hello";
}
```

Notice that a function has a name (in this case, f) but it has parentheses after the name to indicate that it is a function not a variable. So with two declarations:

```
int x;
int y();
```

x is an integer variable, while y is a function (that returns a value of type int). The body of the function is written within curly braces. If just specifying the function name, there can be just a semicolon as shown above, without writing the code.

In order to call the function from main we type the name followed by parentheses. The function must be known before the compiler sees the call, or there will be an error. In the example bellow, the function is defined above main so the compiler knows what the name f is:

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

void f() {
  cout << "hello";
}

int main() {
  f();
}
```

Functions can also be written after they are called. If so, they must first be declared so that the compiler knows what is coming later:

```
#include <iostream>
using namespace std;
void f(); // function prototype for f

int main() {
  f();
}

void f() { // definition of the function f
  cout << "hello";
}
```

The above function is not that useful because it always prints the same thing every time. In order to make functions more useful we add parameters, values that can be sent to the function. The parameters are specified within the parentheses. Each parameter must have a data type, and a name. The following example shows a function f that accepts an integer parameter, and a function square that accepts a double parameter.

```
void f(int x) {
  cout << "The value passed in is: " << x << '\n';
}
void square(double v) {
  cout << v * v;
}

int main() {
  f(2);
  f(3);
  square(4);
}
```

31. inline Functions and Performance

In C++, unlike Java, almost everything must be declared before used. double f(double x); // there is a function, somewhere, called f

```
int main() {
  cout << f(2); // this will work provided f(x) actually exists.
}
```

The C calling convention: In order to call a function:

1. push the parameters
2. jsr (jump to subroutine)
3. in the function, pull the values off the stack. do computation
4. rts (return from subroutine)
5. caller copies the return value somewhere
6. add to stack pointer (pop the parameters off the stack)

Calling lots of subroutines is slow because the processor must push parameters on the stack, go somewhere, then pull them off the stack. Only then is the computation performed.

Object-oriented code typically contains many function calls so reducing this overhead can dramatically improve performance. inline code optimizes some of this out of existence inline is just a suggestion, but the compiler will try.

When a function is declared with the keyword inline the compiler will attempt to inject the body of the function at the call site instead of callling anything. In other words, instead of going somewhere, a copy of the code is pasted every time the function is called. For small functions this can be dramatically faster. The following is an extreme case. The code below defines a function f that takes a single parameter and returns the square. For the case of passing 2, this would result in about 10 machine language instructions. However, because it is inline, the compiler replaces the call to f(2) by 2*2. Since this is a constant expression, the compiler replaces it by 4. In other words, with an inline function there is no computation at all.

```
inline double f(double x) { return x*x; }

int main() {
 cout << f(2); // HUGE win, this turns into 4 (no computation!)
}
```

Good general rules for painless performance optimization

1. always use inline for one-liners, function that just calls another function with minimal computation.
2. don't request inline if the code >3 lines, if there is a huge loop, anything where the percentage of time to get in and out is tiny, and the code is bigger if generated inline.
3. if your code does not call the function more than once, inlining can't hurt.
4. functions cannot be inlined if the compiler does not have the code. For a function prototype, which just has the function parameters and a semicolon, inline is meaningless.

```
inline double f(double x); // cannot inline, do not know what to
   do
```

32. Pass by Reference

Parameters by default are passed by value. That means no matter what you do to a parameter, it does not change the original.

New notation to pass by reference. Looks like pointers, but it's different. Reuses the & symbol in a different context.

Problem: Rect to polar conversion requires r and theta back. You can only return one value Instead, use references:

```
void rect2polar(double x, double y, double& r, double &theta) {
  r = sqrt(x*x+y*y);
  theta = atan2(y,x);
}

int main() {
  double x = 3, y = 4;
  double r, theta;
  rect2polar(x, y, r, theta);
  cout << r << "," << theta << "\n";
}
```

1. Write the following function to compute the maximum, minimum, mean and variance

```
void stats(double[] x, int n, double& max, double& min,
   double& mean, double& var);
```

2. Write a second version of the stats code that computes the result in a single loop (see equation in wikipedia, how to calculate variance)

3. **Wikipedia also mentions a more numerically stable way that is a bit more complicated

33. Classes and Objects in C++

A class in C++ is a specification of an object. To create an object, we say we are instantiating or creating an instance. Classes are a single, big declaration, and must end in a semicolon. The following is an empty class definition.

```
class A {
};
```

All outer level classes are public, no need to say public. Anything inside a class is private by default and cannot be seen outside the class. The dot operator is used to look at symbols within a class.

```


class A {
  int x; // not specified privacy, so it's private
private:
  int y; // y is also private, so x and y cannot be seen by the
     outside world
public:
  int z; // z can be seen by everyone
};

A a1; // create an object of type A
a1.z = 5;
```

```
a1.x = 3; // illegal, private variables are not accessible
   outside the class
a1.y = 4; // illegal, private variables are not accessible
   outside the class
```

private, protected, public are sections followed by colons

```
int x; // declaration, ends in a semicolon

class A {
private:
  int x, y;
```

```
public:
  void f();
  void g();
}; // declaration, ends in a semicolon
```

The three ways to create an object (instantiate a class):

```
int main() {
  A a1; // declare a variable of type A.  a1 contains x and y
  A* p = new A(); // create an object of type A on the heap and
     return a pointer
  A(); // calling the constructor creates an unnamed, temporary
     object which disappears by the semicolon
}
```

Example:

```
class Fraction {
private:
  int num, den;
public:
  Fraction(int n, int d) { num = n; den = d; } // methods in the
     class are automatically inline
  Fraction add(Fraction right) {
    Fraction ans(                ,                    );
    return ans;
  }
};
```

```
class Fraction {
private:
  int num, den;
public:
  Fraction(int n, int d) { num = n; den = d; } // methods in the
     class are automatically inline
  Fraction add(Fraction right) {
    return Fraction(                ,                    );
  }
};
```

1. Implement the following class Fraction. Read in numerators and denominators in the following format and write the code to print out the sums

```
2
1 2    1 3          should print out 5/6
1 2    1 2          should print out 1/1
```

```
class Fraction {
private:
  int num, den;
public:
  Fraction(int n, int d) { num = n; den = d; } // methods in
     the class are automatically inline
  Fraction add(Fraction right) ;
  Fraction sub(Fraction right) ;
  Fraction mult(Fraction right) ;
  void print() const ; // this method is READONLY.  It
     promises not to change the object
};
```

This highlights an important object-oriented principle: never let bad state in the object. In this case, never let the object hold an unsimplified fraction, fix it as it is being built.

34. Constructors and Destructors

34.1 Constructors

The constructor in C++ is a special function with the same name as the class. Constructors are automatically called when objects are created to ensure that objects are correctly initialized.

Rules for constructors:

- Constructors cannot have a return value, not even void.
- If no constructor is written, a default constructor that doe nothing.
- If any constructor is written, no default constructor is generated.

```
class A {
private:
  int x;
public:
};
// automatically generates default constructor: A() {} above

A a1; // variables within a1 are uninitialized.
```

If a constructor is written, then the default constructor is not generated. The example below contains a constructor that takes a single integer parameter. It is therefore illegal to declare variable a1 with no parameters since a constructor was defined with an integer parameter.

```
class A {
private:
  int x;
public:
  A(int xin) { x = xin; }
};

A a1; // this is illegal, no default constructor
```

```
A a2(5); // this is ok, calls the constructor defined in the
    class
```

35. Initializer Lists

Initialization of data members in a class can happen in two ways. First, you could assign values. For example:

```
class A {
private:
  int x;
public:
  A() {  x = 3; }
}

int main() {
  A a1;
}
```

However, if the value is constant, even the constructor is not allowed to assign a value to it. In this case, the programmer must use initializer list syntax.

```
class A {
private:
  const int x;
public:
  A() : x(3) { }
}

int main() {
  A a1;
}
```

35.1 Destructors

Destructors have the name of the class preceded by a tilde ( ). There is no reason to write a destructor unless something is allocated during the lifetime of the object that must be given back. Later, with dynamic memory, you will do exactly that. For now, the destructor can be used to display a message every time an object is going away.

```
class A {
private:
  int x;
public:
  A(int x) : x(x) { cout << "An object of type A is being born\n"
      ; }
  ~A() { cout << "An object of type A is dying\n"; }
}

void f() {
  A a1;
}

int main() {
  A a1;
  f();
}
```

36. const Members and const Methods

A data member is a variable declared within a class that is in each object created. If it is declared const, this means that it can never change for the life of the object. For example, the following class definition contains an id. Every time an object of type Person is created, an id is generated. This id cannot be changed for the life of the person.

```
class Person {
private:
  const int id;
public:
  Person() : id(1) {}
};
```

Note that in this case, even if the constructor tries to assign id, it is illegal to do so. Once id is initialized, it can never be written again:

```
  Person() { ud = 1; } // illegal, id is const cannot be assigned
```

A const method promises not to change the object. For example, in the following example, the method print() while not written in the greatest style, is written so it does not change the object.

```
class Person {
private:
  const int id;
public:
  Person() : id(1) {}
  void print() const { cout << "Person, id=" << id; }
};
```

37. static Members

By default, symbols declared within a class refer to instances of that class. This means that a variable declared within a class exists within each object. A function (method) declared within the class can be called for each particular object. Putting the keyword **static** in front of a declaration means that it is shared by the entire class. For variables, that means there is only a single value no matter how many objects are created.

For example, the following class Zebra contains a declaration of a string name. This means that every Zebra object has a name. But the variable count is declared static, meaning that there is only one count shared by all Zebras.

Note that every occurrence of a static variable within a class turns into extern. Each variable must be defined outside the class. In the example below this is done immediately after the class definition.

```
class Zebra {
private:
  string name;
  static int count;
public:
  Zebra(const string& name) : name(name) {
    count++;
    cout << "Zebra born, count = " << count << '\n';
  }
  ~Zebra()  {
    count--;
    cout << "Zebra " << name << "dying, count = " << count << '\n
        ';
  }
  static int getCount() { return count; }
};

int Zebra::count = 0; // define the static counter

int main() {
  Zebra z1("Fred"); // created zebra named Fred, now there is 1
  Zebra Z2("Alice"); // create zebra named Alice, now there are 2
} // at the end of the program the destructors are called
```

38. Operator Overloading

C++ allows the programmer to overload existing operators that apply to new data types. This makes mathematical code look very natural.

C++ does not permit

1. Redefining operators for built-in types like int, float, double that already have operators. Operators cannot be changed once defined. For example, defining int + int is not legal because this is already defined.

2. Defining new operators that did not exist, for example '**'

The simplest syntax for C++ operators is to consider operators outside of classes. The syntax simply replaces the name of a function with the keyword operator following by the operator. A binary operator takes two parameters and a unary operator takes one. For example:

```
Fraction operator +(Fraction left, Fraction right); // a + b
Fraction operator -(Fraction op);                   // -b
ostream& operator <<(ostream& s, Fraction r);  // cout << r
```

would declare that when the compiler sees two fractions with a + operator between them, it should call operator +, and when it sees a fraction preceded by unary -, it should call operator -. The following shows this in code:

```
Fraction f1;
Fraction f2;

Fraction f3 = f1 + f2;
Fraction f4 = -f1;
```

The problem is that even though the syntax is simple, these functions will not be allowed to use the internal values from the fractions (num and den) which are needed to compute the results. Either they will have to use access methods getNum() and getDen() or we must declare them somehow special and allowed to access private components of the class. The second method is preferred, and inside the class, the operators are declared friend allowing the function outside to access the private symbols.

```
class Fraction {
private:
  int num, den;
public:
  Fraction(int n, int d) : num(n), den(d) {}
  friend Fraction operator +(const Fraction& left, const Fraction
    & right);
  friend Fraction operator -(const Fraction& a);
};

Fraction operator +(const Fraction& left, const Fraction& right)
   {
  return Fraction(left.num*right.den + right.num*left.den,
                  left.den*right.den);
}

Fraction operator -(const Fraction& a) {
  return Fraction(-a.num, a.den);
}
```

39. Member Operators vs. Friends

C++ provides an alternate way of writing operators, as member functions. Member functions are always applied to an object of the type of this class. The parameter is called this. There is no first parameter. Therefore, a binary operator will only mention the right parameter, because the left is this. A unary operator will have no parameters, because the only parameter is this.

```
class Fraction {
private:
  int num, den;
public:
  Fraction(int n, int d) : num(n), den(d) {}
  Fraction operator +(const Fraction& right);
  Fraction operator -();
};

Fraction Fraction::operator +(const Fraction& right) {
  return Fraction(left.num*right.den + right.num*left.den,
                  left.den*right.den);
}

Fraction Fraction::operator -() {
  return Fraction(-a.num, a.den);
}
```

40. C++ Operator Precedence

41. Type Ambiguity

If two conversions are defined for a class, there may be two alternate ways of evaluating an expression. For example, given that an operator + is defined fora class Fraction, and the class has a constructor that turns an integer into a Fraction, and an operator int() that converts the fraction back to an integer, a mixed-type expression with one integer and one Fraction could be handled two ways: either the integer is converted to a Fraction, or the Fraction is converted to an integer.

```
Fraction f1;
Fraction operator +(Fraction, Fraction)
Fraction(int);
operator int(Fraction);
```

The following expression is ambiguous and results in a compiler error. It is not clear whether to convert 1 to a fraction, or convert f1 to an integer.

```
f1 + 1
```

To resolve, manually convert. Either convert the integer to a Fraction or the Fraction to an integer.

```
Fraction f2 = f1 + Fraction(1)
int j = int(f1) + 1
```

42. C++ Classes, Containment, Initializer Lists

In C++, constructors can be written to assign values to data members.

```
class A {
private:
  int x;
public:
  A() { x = 0; }
};
```

However, there are circumstances when assignment will not work. In this case, with the variable declared const, it is not allowed to change.

```
class A {
private:
  const int x;
public:
  A() { x = 0; } // THIS IS ILLEGAL, x cannot be assigned!
};
```

In the above case, instead of writing the constructor to assign the value of x, we need to initialize the value of x. This uses a new syntax: the C++ initializer list.

```
  A() : x(0) {}
```

There are other reasons that a data member cannot be assigned. It may be an object that must have an appropriate constructor call. The following example shows a class Car which contains four Tires and an Engine. Each object must be initialized. In order to initialize the Car, it is necessary to initialize the four Tires, and then then Engine.

```
class Tire {
private:
  int pressure;
public:
  Tire(int p) : pressure(p) { }
};

class Engine {
private:
```

```
  const int horsePower;
public:
  Engine(int hp) : horsePower(hp) { }
// this would be illegal
//  void setHorsePower(int hp) { horsePower = hp; }
};

class Vehicle {
private:
  int speed;
public:
  Vehicle(int speed) : this->speed(speed) {}
};

class Car : public Vehicle {
private:
  Tire t1, t2, t3, t4;
  Engine e;
public:
  // assume all four tires get the same pressure, how to specify
     constructor?
  Car(int speed, int pressure, int hp) : Vehicle(speed), t1(
     pressure), t2(pressure), t3(pressure), t4(pressure), e(hp)
 {  }
}

int main() {
  Tire t1(28);
  Car c1(55, 28, 150);
}
```

What would this look like in java??? (build complete examples in both languages)

```
public class Car {
private Tire t1, t2, t3, t4;
private Engine e;
public Car(int pressure, int hp) { t1 = new Tire(pressure) ...}
}
```

43. virtual Functions

In Java, classes by default allow polymorphism, which means each object must identify what class it belongs to.

This in turn means that every object contains a pointer (4 bytes). In C++ this overhead does not exist unless specifcially requested.

```
class Vehicle {
public:
  virtual void payToll();
}
```

The keyword virtual instructs the compiler to add information to this class, and all descendents. There is no more overhead for two virtual functions than for one.

Calling a virtual function through a pointer or reference is slower than a regular function.

A regular function is called directly A virtual function first looks up the object type, and calls the appropriate

```
Car c1(35);
c1.payToll(); // this calls Car::payToll,known at compile time,
   no time penalty
Vehicle* vp = &c1;
vp->payToll(); // this call must look at the tag at the front of
   the object and call the appropriate function.
```

44. The C++ Standard Library (Formerly known as STL)

The C++ Standard Library is a collection of classes and functions that provide many resources that are important for writing programs in C++. There are many classes such as lists (vector and linked_list) trees (map), hashmaps (unordered_map) and others. There are also algorithms which are written in a portable way so that they can be applied to many data structures. For example, the sort algorithms in STL can be used on many kinds of lists.

45. vector

The vector class is a list that can grow and shrink. It requires including ¡vector¿ The following example shows how to build a list, adding to the end using the push_back method. It contains both methods that view and modify the list without checking, and also methods that check whether an element is out of bounds before getting it.

```
#include <iostream>
#include <vector>
using namespace std;
int main() {
  vector<int> a; // a is a list of integers
  for (int i = 0; i < 10; i++)
    a.push_back(i);
  // a now has size 10.  The first element is 0, the last is 9.
  for (int i = 0; i < a.size(); i++)
    cout << a[i] << ' ';                  // access the elements
       like an array
  return 0;
}
```

The class vector is a generic class, so in addition to typing vector, you must specify the parameter that defines "vector of what?" Example:

```
vector<int> a;  // a is a list of int
vector<double> b;  // b is a list of double
vector <Elephant> elephants; // elephants is a list of elephant
   objects.
```

The class vector is very fast for appending to the end, but due to its design it is very slow for adding values to the front of the list (or the middle).

46. Iterators

An iterator is a design pattern that keeps track of a position within something else. Iterators are the most-used design pattern. There are iterators to walk through lists (the topic here), iterators to keep track of the position within a database (called a cursor), the position on the screen (also called a cursor). The last example showed how to track position within a vector using an integer index, but in general, an integer position is not always efficient. For another list (called a linked list) using an int to keep track of a position would be very slow. General rule: always use an iterator to keep track of position, because it will be written to do so in the most efficient way possible.

To declare an iterator on a vector, use: vector¡type¿::iterator. There are two methods in vector to return the beginning and end of the list:

```
vector<int> a;
a.push_back(3);
a.push_back(1);
a.push_back(4); // a now contains 3,1,4
vector<int>::iterator i = a.begin(); // i now points to the
   beginning of the list.
cout << *i << ' '; // print out the value of the element pointed
   to by i (3)
++i; // move forward to the next element
cout << *i << ' '; // print the current element (1)

for (vector<int>::iterator j = a.begin(); j != a.end(); ++j) //
   print the whole list

cout << *j << ' '; // print each element
```

It is not always possible to go backwards, but in the case of vector, you can start at the end and work backwards:

```
for vector<int>::reverse_iterator i = a.rbegin(); rit!= myvector.
   rend(); ++rit)
  cout << *i << ' ';
```

It is also possible to modify the list with an iterator by writing to the iterator. The following code adds one to every element in the list:

```
for (vector<int>::iterator i = a.begin(); i != a.end(); ++i)
  ++*i;
```

Because of this, it is illegal to attach an iterator to a constant object (because it can change the object). For objects that are not supposed to change, there is a const_iterator that only supports looking (not changing) the value.

```
const vector<double> mylist = {1.5, 2.5, 3.5}; // list cannot
   change now.
for (vector<double>::const_iterator i = a.begin(); i != a.end();
   ++i)
  cout << *i;
```

47. map

The map class is designed to store a mapping of key to value (a dictionary). Very often, we need to lookup one value (the key) and find the corresponding value. For example, in the stock market, stocks are listed by symbol. In order to look up the price of AAPL (Apple Computer), we need a data structure that rapidly finds the record for AAPL. Since there are thousands of stocks, looking through all of them for AAPL is not an attractive option.

The map class is implemented using an RB-Tree, something studied in data structures classes. Here we are just concerned with using the map class to achieve a goal.

To declare a map, decide what kind of value to use for the key and value. For example, for stocks we might look up a string and get a corresponding price which is a double. This would be declared as:

```
map<string, double> stocks;
```

There are three common operations needed with maps. First, we must be able to add new values into the map (or replace a value already in it). Second, we must be able to look up a key and find the corresponding value (if any). Finally, sometimes we want to iterate through the entire map. These three operations are shown below:

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

int main() {
  map<string, double> stocks;
  stocks["AAPL"] = 162; // this is one way to add a key, value
     pair

     // this is a second way to insert a new value that only
        works in C++11
  stocks.insert({"IBM", 108}); // another way to add a key,value
     pair


}
```

48. unordered_map

A map is pretty fast for looking up a single element, but the STL unordered_map is even faster. This class uses a hashmap to turn the key into the location where it may be found. It is not sorted, however, so while iterating through a map will traverse in sorted order, the traversal for an unordered_map will be random and can even change over time.

49. How References work

This section requires a knowledge of pointers. If you don't know pointers, read up on them first, then come back

Really, references ARE pointers. But C++ won't admit it. References are safer (not safe)

No pointer arithmetic.

References must be initialized

```
int main() {
  int a = 2;
  int& b; // error, b must be initialized
  int& b = a; // this is ok.  b is now an alias for a

  b = 3; // a is now 3 // b syntactically looks like the thing it
      points at.
// I know b is really a pointer, so...
  a = 4; // both b and a are now 4
  cout << b << '\n'; // prints the value of a
  cout << &b << "\n"; // prints the address of a
  cout << sizeof(b) << "\n"; // prints the size of a!!!
}
```

The reference b is locked to a (cannot change). This is analogous to the pointer:

```
int* const p = & a; // p is a pointer that can only point to a
```

except that with the pointer, casting could break it:

```
((int*)p)=0; // set pointer to null?  Probably compiler will stop
    me,
*(int**)&p = 0; // p now points to nothing.
```

50. Regular Expression Matcher

50.1 Regular Expressions

Regular expressions are patterns that can match strings. Using regular expressions is a way to search for very complicated strings without all the complexity. Still, regex is a topic (and a mini-language) in itself. In order to learn regular expressions interactively, go to a website like regexr.com

The basic rules of regular expressions are fairly simple. Here is a table of the simple rules:

abc	a followed by b followed by c
`[ace]`	one of the letters a c or e
`[a-z]`	one of the letters a through z
`[^aeiou]`	any letter that is not a e i o or u
.	any single letter that is not a newline (equivalent to [\^n]
ca?b	c followed by zero or one (optional) a followed by b
cab	c followed by zero or more a followed by b
ca+b	c followed by one or more a followed by b (equivalent to ca*ab)
\.	escape special character (in this case, a period)
a.*?n	find smallest match, not largest (not greedy)
hello—cat—dog	OR (any one word)
AZaz	any uppercase or lowercase letter (note: [Az] not the same!
\d	[0-9]
\s	[\t\n]
\w	[A-Za-z0-9]
( )	grouping (with capture)
(?:)	grouping (without capture)
hello$	string ends with hello
^hello	string starts with hello
^hello$	string is exactly hello with nothing else

https://stackoverflow.com/questions/3101366/regex-to-matc

There are other patterns, but even these simple rules can get far more complicated when combined. For example:

```
[0-9]{3}[\(\.\-][0-9]{3}[\(\.\-][0-9]{4}
```
[1]

matches phone numbers of the form: 212.866.3322, (212)866-3322 or 212-866-3322

In C++, the regex library is now built into C++11. Just include the ¡regex¿ header.

51. The C++-11 Random Number Generator

51.1 Random Numbers

Random numbers are a surprisingly hard subject. Most random numbers on computer are actually "pseudo-random" meaning the computer generates a sequence of numbers that looks random, but actually is deterministic if you understand the algorithm.

C traditionally supplied the rand() function which returned an integer. Unfortunately there is no standard on the algorithm used, and it often is not very good. Seeding the random number from the time with srand does not help. This kind of random number can be used in casual games where the answer is unimportant.

It is much better to use the new C++ random number generators, which have well-defined behavior and very strong numerics.

```
#include <random>
#include <iostream>
using namespace std;
int main()
{
    random_device rd;
    mt19937 gen(rd());
    uniform_int_distribution<> dis(1, 6);

    for (int n=0; n<10; ++n)
        std::cout << dis(gen) << ' ';
    cout << '\n';
}
```

See the following web page about randomness.

52. Dynamic Memory

52.1 Old C Memory Allocation

In C, memory can be allocated dynamically (from the heap) using malloc and returned using free(). In C++ these still work, but the new way of allocating memory is to use the operators new and delete. Both systems may be used in the same program, but may not mix and match.

For every pointer allocated with malloc, the memory must be returned to the system with free. The same is true of new and delete.

```
int* p = (int*)malloc(1000 * sizeof(int)); // allocate enough for 1000 integers
...
free(p); // give back the memory so it can be reused.
```

Memory must be returned, or it is "leaked." If leaked, it will be recovered when the task ends, but until then the memory is not available for use. Tasks that leak a lot of memory can impact performance of the computer, and may eventually crash.

52.2 The "New" Way

In C++, memory is allocated using operators **new** and **delete**. Both C and C++ memory operations can coexist in the same program, but memory allocated with malloc cannot be returned with delete, and memory allocated with new must not be returned with free().

```
int* p = new int; // new C++ way, allocate a single number dynamically
...
delete p;
```

If a block of numbers is allocated, it can be done using new[] and it must be deallocated using delete[] (with square brackets).

```
int* p = new int[1000]; // new C++ way
...
```

```
delete [] p;
```

It is illegal to:

- Allocate memory with new[] and delete it without the square brackets
- Delete memory that has not been allocated dynamically.
- Delete the same memory more than once.
- Not deallocate memory that was allocated with new.

Examples:

```
int a;
delete &a; // error, a was not declared with new
int* p = &a;
delete p; // error, p is not pointing to dynamically allocated
   memory
int* q = new int[1000];
delete q; // error, if allocated using new [], use delete[]
int* r = new int[100]; // error, this memory leaks because r is
   never deleted
int* s = new int[100];
s++;
delete[] s; // error, the pointer deleted must be the same as the
    one returned by new.  s has been changed to s+1.
```

53. Placement new syntax

54. Copy Semantics and Dynamic Memory

In Java, objects cannot be copied by default. If you want to copy, you must implements Cloneable.

```
public class Vector3D implements Cloneable {
}
...
Vector3D v1 = new Vector3D(1,2,3);
Vector3D v2 = v1; // not a copy, v2 points to same object
v2 = v1.clone(); // copy
```

In C++, copying objects works by default. A new object can be created that is an exact copy of an existing one.

```
int main() {
  Vector3D v1(1,2,3);
  Vector3D v2 = v1; // v2 is a copy of v1.  This is NOT the
     operator =
  Vector3D v3(v1); // alternate constructor syntax.
}
```

The default copy constructor copies each member bitwise. No guarantee is made about spaces between the data members. Example:

```
class A {
private:
  char x; // one byte, aligned to 8 bytes on a typical memory
     architecture
  int y; // your compiler will probably skip 3 bytes for speed
}
```

On a typical 64 bit machine the above is 8 bytes. The int is aligned to byte 4.

55. Copy Semantics

A class that allocates a resource (such as memory) in the constructor must give it back. To guarantee that the programmer does not forget, a destructor method is automatically called when the objects is about to die. The constructor has the same name as the class; the destructor has the same name with a tilde before it.

```
class A {
private:
  int* p;
public:
  A() {
    p = new int[5];
  }

  ~A() {
     delete[] p;
  }
};
```

The destructor does not need to be written unless the constructor allocates a resource that must be returned. If the constructor and destructor are written, then the problem is that C++ allows objects to be copied, and this creates a problem.

Instead, we override the default copy constructor and create one that correctly copies the logical object. There are two contexts where C++ copies an object. The first is when the programmer explicitly creates a new object that is a copy of the old:

```
  A a1;
  A a2 = a1; // a2 is a new object that is an exact copy of a1
  A a3(a1); // alternate syntax: a3 is also an exact copy of a1
```

The other circumstance is when a copy is made in order to pass by value into or out of a function:

```
void f(A a) { ... }
A g() { return A(); }
int main() {
  A a1;
  f(a1); // a1 is copied into the formal parameter a
```

```
  A a2 = g(); // the return value of g is copied into a2
}
```

As long as only values are in the object, it works. The following code creates a copy that does this correctly. This copy is completely unnecessary because the default behavior of the compiler does exactly the same thing.

```
class A {
private:
  int v;
public:
     A() : v(0) { }
     ~A() {  } //destructor does nothing, no dynamic memory
     A(const A& orig) : v(orig.v) { } // copy constructor
     A& operator =(const A& orig) {
          v = orig.v;
          return *this;
     }  // copy an object once it already exists
};
```

On the other hand, when the object contains a pointer that is dynamically allocated, the default copy is the incorrect semantics.

56. Pointer Ambiguity in C++

NULL is the old way of writing a pointer that does not point to anything. #define NULL ((void*)0L)

In C++, Stroustrup added the constant 0 as null

The problem is 0 is also an integer.

```
void f(int x) {

}
void f(char* p0) {

}


int a = 0;
char* p = 0;
f(a); // not ambiguous
f(p); // not ambiguous
f(0); // ambiguous
```

New C++11 way of writing null:

```
f(nullptr); // not ambiguous
```

57. Using the Optimizer

The optimizer is a powerful way to make programs faster. In C and C++, an optimizer is allowed to rewrite code as long as a correct program orks the same way with and without optimization. Note that this means if you write an incorrect program behavior could, in fact, change. Also, if the compiler itself has a bug (unlikely, but it happens) then optimizing coul change behavior of a correct program.

Consider the following program to count to 10 billion (10^10). This is a lot of operations even for a computer, so it will take some time.

```
int main() {
  for (long long  i = 0; i < 1000000000000L; i++)
    ;
  return 0;
}
```

On my laptop, when I use the time command in cygwin to measure how long the execution takes, it shows:

```
$ time ./a.exe

real    0m31.785s
user    0m31.750s
```

You will notice that the above program does nothing, so an optimizer, if it recognizes that fact, is free to get rid of the loop since it has no effect on the program (other than the time it takes). When compiled with the option:

g++ -O3 opt.cc

the time goes down to essentially zero:

```
$ time ./a.exe
real    0m0.019s
user    0m0.000s
sys     0m0.015s
```

In fact, increasing the loop count makes no difference, because the compiler is eliminating the loop.

Suppose the program is changed to sum the numbers from 1 to 10 billion. Now there is a purpose to the loop:

```
int main() {
  long long sum = 0;
  for (long long  i = 0; i < 10000000000L; i++)
    sum += i;
  return 0;
}
```

Yet when compiled with optimization, this program too runs instantly. The reason is that the program does nothing with the sum, and therefore the loop is again optimized away. However, if you print the result, then the program is affected by the loop, and it stays:

```
#include <iostream>
using namespace std;
int main() {
  long long sum = 0;
    for (long long  i = 0; i < 10000000000L; i++)
    sum += i;
  cout << sum << '\n';
  return 0;
}
```

Write a program to read in a number and determine all the primes up to that number. For example, if you enter the number 10, the answer should be 2 3 5 7.

It will be a little inefficient to print all the numbers, so to avoid ruining your timings, once you have the program working just add all the primes up and just print out the sum of all the primes. For example, the sum of all the primes below 10 is: 2+3+5+7 = 17.

Try running your program both with and without optimization. How much faster is it with optimization?

58. Preprocessor Directives

58.1 What is the Preprocessor?

The preprocessor is a separate language that runs before the C++ compiler analyzes code. Any line beginning in # invokes the preprocessor.

The preprocessor can modify the program in a number of ways:

- Remove comments so the compiler does not consider them
- Include a file whose contents is injected
- conditionally take some action based on the value of a symbol
- Define string macros which are replaced by their contents

The first three actions are most useful, while the third is now largely obsolete in C++.

When the preprocessor detects a comment, it turns it into a single space. Thus if your program looks like the following:

```
int x/*this is a comment*/=1;
```

the preprocessor turns it into this:

```
int x =1;
```

before the compiler looks at the program. To bring in a file, use the #include directive. We have always done this without discussing what it does.

The third major contribution is that the preprocessor can conditionally compile code. One use is in temporarily disabling some code without cutting it completely:

```
int main() {
  f();
#if 0 // everything from here to #endif will turn into a single
   space
  g(); // temporarily remove this call while we work on something
     ...
```

```
  h(); // this is all gone...
#endif
}
```

The ability of the preprocessor to conditionally eliminate code is useful in a number of cases. First, it is illegal to define the same symbol twice. For example:

```
int x;
int x;
class A {

};
class A {

};
```

is illegal because it defines x and A twice. But this can easily happen if these declarations are in a header file. Even though the programmer can make sure never to write:

```
#include "A.hh"
#include "A.hh"
```

it is impossible to stop the following situation:

```
//file B.hh
#include "A.hh"
class B {

};
```

```
//file C.hh
#include "A.hh"
class C {

};
```

In the above case, a programmer wanting to define both B and C must write:

```
#include "B.hh"
#include "C.hh"
```

yet this will bring in the definitions in A.hh twice. The solution is to use the preprocessor in file A.hh

```
#ifndef A_HH_ // the first time, A_HH_ is NOT DEFINED, so this is
    true
#define A_HH_ // now the symbol is defined, the 2nd time it will
   be FALSE
```

```
class A {
  ...
};
#endif
```

The above is the traditional (and still standard) technique to avoid this problem. Today, there is a new, non-standard technique that is more convenient but not yet supported by all compilers. Still, it is supported by g++ and clang, and will presumably become part of the standard soon.

```
#pragma once
\end{lstlsitng}

automatically prevents the file from being included twice without
    having to invnet a name.

\section{Macros: Mostly Obsolete}
The last use of the preprocessor is in defining macros. This is
   largely obsolete due to new features of C++ like inline
   functions and templates that provide the same capabilities in
   much more sophisticated and less error-prone ways.

The preprocessor allows defining a symbol:
\cpp
#define A blah
```

From that point on, every time the preprocessor encounters the symbol A it replaces it with blah. Note this is not every occurrence of the letter A. For example:

```
int A = 5;
int THISISATEST = 6;
```

becomes

```
int blah = 5;
int THISISATEST = 6;
```

Notice that the A embedded in THISISATEST does not change.

Occasionally it can be so hard to figure out what the preprocessor is doing that you want to see the results. Every compiler has a way of saving the output of the preprocessor. On g++ and clang++ for example, it is:

```
g++ -E myfile.cc
```

which does not compile but shows the preprocessor output that would go into the compiler.

59. Separate Compilation

A small program can be written in a singe file. The C++ compiler expects this kind of program to have a suffix of .cc or .cpp or .cxx to show that it is C++.

Bigger programs must be split into multiple files. This way, many programmers can work on the project at the same time without colliding with each other.

In order to split an object-oriented program, the classes are defined in header files. These files by convention end in .h or .hh or .hxx but the C++ compiler will work with any name. This is the #include directive that you have used from the very first program in C++. In fact, the libraries themselves do not use any extensions at all – for example iostream or string does not end in .h.

Now, in order to split the code, you are about to write your own header files. The following example shows how a class Fraction, written in one C++ file, would be split into three files. First, there is the header file Fraction.hh which contains the definition of the class, but not the code. Then, the code is written in Fraction.cc. Since the code is no longer inside the class, all the members of the class are decared with Fraction:: in front of the symbols, to show that they are part of the Fraction class. Finally, the code that uses the class is put into test.cc

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

class Fraction {
private:
  int num, den;
public:
  Fraction(int n, int d = 1) : num(n), den(d) {}
  friend Fraction operator +(const Fraction& left, const Fraction
     & right) {
    return Fraction(left.num*right.den + right.num*left.den, left
       .den*right.den);
  }
};
int main() {
  Fraction a(1,2);
  Fraction b(1,3);
  Fraction c = a + b;
```

```
}
```

The first step is to define the class in a header file.

```
#ifndef FRACTION_HH_
#define FRACTION_HH_

#include <iostream>

class Fraction {
private:
  int num, den;
public:
  Fraction(int n, int d = 1);
  friend Fraction operator +(const Fraction& left, const Fraction
    & right);
};

#endif
```

Notice that the #ifndef, #define and #endif preprocessor directives are used to cut out the code if it is ever included twice. More on this later.

The main program (in main.cc) must #include the header file in order to define the class Fraction.

```
#include "Fraction.hh"
int main() {
  Fraction a(1,2);
  Fraction b(1,3);
  Fraction c = a + b;
}
```

Finally, the program must define the functions of class Fraction. This is done only once in Fraction.cc. No matter how many times in the program Fraction.hh is included, there is only a single copy of the functions.

```
#include "Fraction.hh"

// read :: as inside class Fraction , the constructor Fraction
Fraction::Fraction(int n, int d) : num(n), den(d) {
}

Fraction operator +(const Fraction& left, const Fraction& right)
   {
  return Fraction(left.num*right.den + right.num*left.den,
                  left.den*right.den);
}
```

60. Linking

61. Using Libraries

62. Building a library

63. The Make Utility

63.1 Building Larger Programs

In order to build programs with multiple files efficiently, it is vital to avoid recompiling everything every time a change is made. Most small changes only affect a small part of the code.

The make utility in Unix is often used, on all platforms to build programs. It is old, but it works well. This guide is a quick introdution to make, and to build tools in general.

The make command by default reads a file in the current directory named Makefile. This file contains a list of rules to build targets. Typing make will attempt to build the first target. That target may in turn depend on other targets and trigger more rules.

The simplest Makefille is something like:

```
myprog: myprog.cc
	g++ myprog.cc -o myprog
```

The first line defines the dependency, that myprog depends on myprog.cc. The make program checks the timestamp on both files, and if myprog.cc iis newer than myprog, it executes the second line (the command) to build the program. The g++ command is indented with a tab, which is required. When executed, g++ compiles the program and generates the executable myprog (or on Windows, myprog.exe).

To build a program comosed of test.cc Fraction.h and Fraction.cc, the following makefile would work. This time, the program fraction depends on two .o files, which in turn depend on the .cc files and the .h file.

```
fraction: test.o Fraction.o
	g++ test.o Fraction.o -o fraction

Fraction.o: Fraction.cc Fraction.hh
	g++ -c $<

test.o: test.cc
	g++ -c $<
```

63.2 Handling Build Options

There are two options that are particularly important to programmers. The first is turning on debugging information, wiithout which the debugger will not function properly. Debugging information is added into compilation using the $-g$ option on g++. The second is optimization which makes the code much faster and more efficient. In some rare cases, optimized code can go 10 times faster. Moreover, using it can reduce use of memory, and since memory is shared by mutiplpe cores, there are algorithms that will be far more parallelizable if the code is optimized.

To compile with optimization, use the -O2 or -O3 option for g++. You could, of course, leave optimization on all the time, but it makes debugging the program more difficult. Similarly, if the program is full of debugging information it can be a lot bigger and slower to load. Therefore, we build these options into the Makefile so that a single change can rebuild the whole program using different options.

The following Makefile contains some of these standard features. The variable CPP is set to the current compiler being used. The variable DEBUG can be set to -g for debugging, or commented out #-g for no debugging. The variable OPT can be set to -O3 for the fastest code, or commented out for no optimization.

Last the target clean will delete the whole program if desired. Use something like this in your builds, and particularly, in your group project.

```
CPP=g++
DEBUG=#-g   # debugging is off for now, remove # before -g to
   enable
OPT=-O3

fraction: test.o Fraction.o
     $(CPP) $(DEBUG) test.o Fraction.o -o fraction

Fraction.o: Fraction.cc Fraction.hh
     $(CPP) $(DEBUG) $(OPT) -c

clean:
     rm *.o fraction          #remove all the binary files, clean
         up
```

The problem with Make is that it takes a lot of your work to figure out how to build a makefile properly, and every time the structure of the program changes, the makefile

must be changed as well. Additionally, if you want to turn on debugging, the makefile has no dependency built in to realize that you just changed every command from:

```
g++
```

to

```
g++ -g
```

In order to do so, you would have to manually force a rebuild by using make clean followed by make. There are variants of make such as gnu make that have commands designed to identify when the commands change and rebuild the makefile. These are more complicated and beyond the scope of this short guide. But rather than using a bandaid which can make the make utility a bit easier to use, the next level is to consider another tool that can automatically configure a Makefile so that you do not have to generate one. This would be the cmake utility.

64. cmake

The cmake utility is a meta-program that builds code. But instead of building it directly, like make, its job is to have a set of commands that define what your program is, and a set of back-end tools (like make) that actually build the code. Then, CMake automatically generates the more complicated commands that the back end tool like make uses.

You can use cmake to automatically maintain a makefile that builds your program. But you are not limited to make. Today, there are faster, more modern tools such as ninja that are much faster than make. The cmake tool is designed to use many different build tools, and is configurable.

The CLion IDE uses cmake to build code, and so for simple programs you do not even have to think about it. However, for more complicated applications you will have to know how to modify the script controlling the build, so you cannot simply rely on the IDE to take care of everything for you.

In order to use cmake, you will first need to install it. Search for how to install cmake on your system.

The cmake utility uses a file called CMakeLists.txt. This file must, at minimum list which files are needed to build, and what is being built.

The following CMakeLists.txt shows a simple CLion project.

```
cmake_minimum_required(VERSION 3.8)
project(session01)

set(CMAKE_CXX_STANDARD 11)

set(SOURCE_FILES 08summation.cc)
add_executable(session01 ${SOURCE_FILES})
```

The first line specifies which version of cmake is required. The second specifies the name of the project. The third defines a set of rules using c++ 11, which probably specifies a number of things, including which c++ compiler is being used, what version of the standard (c++11). No doubt this results in a command

```
g++ -std=c++11
```

The next to last line sets the list of all files needed to build the code. If a second file is added to the project, all that is necessary is to add it to SOURCE_FILES.

Notice that there is nothing special about the variable SOURCE_FILES, it could be called anything. It is used in the following command which defines how to build the executable. This last line defines that in order to build session01, use all the files in ${SOURCE_FILES} .

To build the program, get into a directory where you want to build it. Generally, you should create a directory where all the binaries will go. By default in CLion this is called cmake-build-debug and clearly from this name you can tell that you could create multiple directories, with code generated for debug and production.

So, assuming you are in the directory cmake-build-debug, with the file CMakeLists.txt in the directory above, execute the commands:

```
cmake ..
make
```

For more complicated projects, it is possible to specify multiple executables, multiple source files, building libraries, and many other options. The most important thing is that while a tool like make requires you to identify which files depend on other files, cmake is responsible to automatically figure out that list and generate the right makefile. So cmake does not actually build your program. Typically, it just generates the underlying makefile which we do not even see. The following example shows building two executables and a shared object library. The second executable requires the shared object library.

```
cmake_minimum_required(VERSION 3.0)
project(CSP)

SET(CMAKE_CXX_FLAGS "-g -Wall -Wunreachable-code")
set(CMAKE_CXX_STANDARD 11)
set(EXECUTABLE_OUTPUT_PATH ${PROJECT_SOURCE_DIR}/cmake-build-
    debug)

set (A_SRC
        src/a.cpp
        )
add_executable(a ${A_SRC})


set (B_SRC
        src/b.cpp
        )
add_executable(b ${B_SRC})
```

Finally, just a quick recommendation. Everything in the binary directory is generated by cmake or make, so the entire directory should be added to .gitignore because none of it should be added into the repository. Whenever you want to regenerate, just invoke cmake again. In fact, on different machines it may execute different compilers.

65. Templates and Generic Programming

Object-oriented programming offers a way to save effort by reusing code. Specifically, new objects can be created that inherit from or contain existing objects, thus reducing effort. However, not all code can be simplified using object-oriented techniques. Another method called generic programming allows reduction of effort in different situations.

The situation is where there is the same logic, yet it must be applied to different objects not related by inheritance. Generic programming allows the programmer to specify an agorithm or class, and pass the type of the object to it as a parameter.

Templates are very powerful, but they work only at compile time.

66. Templated Functions: Sorting

Consider a sort algorithm. The following example shows a traditional bubblesort that can sort an array of integers. In order to sort a different array, the programmer would have to write an almost identica function with a different type list:

```
void bubbleSort(int x[], int n) {
  for (int i = 0; i < n-1; i++)
    for (int j  0; j < n-1-i; j++)
      if (xj] > x[j+1]) {
        int temp = x[j];
        x[j] = x[j+1];
        x[j+1] = temp;
      }
}
```

The only thing that keeps the above code speciific to integers is the two uses of the keyword int, one in the parameter (the array itsellf) and the other for the type of the variable temp which is used to swap the elements of x if they are out of order.

In order to make this function templated, a single template command precedes the function, defining a typename T. Then the two uses of int instead reference T

```
template<typename T>
void bubbleSort(T x[], int n) {
  for (int i = 0; i < n-1; i++)
    for (int j  0; j < n-1-i; j++)
      if (xj] > x[j+1]) {
        T temp = x[j];
        x[j] = x[j+1];
        x[j+1] = temp;
      }
}
```

No code has been generated at this point. But the moment a caller wants to use the function, one must be generated. If the programmer creates an integer array and passes it to the bubbleSort function, the compiler figures out that T must be int, a process called type unification . Then, the compiler generates a function specifically for int. If the programmer then creates an array of a different type (like string) the compiler generates

another copy of the code, just for string. The following example shows each call to bubbelSort which look just like they are calling a function written specifically for them:

```
int main() {
  int a[] = {9. 8, 7, 5};
  bubbleSort(a, 4); // generates an integer sort function

  string b[] = {"this", "is" "a" test", "of", "strings"};
  bubbleSort(b, 6);
}
```

67. Templated Classes

A template declaration applies to the definition immediately following. The previous section describes a template function. To define a template class:

```
template<typename T>
class A {
};
```

The template applies to all the methods and friends declared within the class:

```
template<typename T>
class A {
private:
  T x;
public:
  A(T x) : x(x) {}
  friend A operator + (A left, A right) {
    return A(left.x + right.x);
  }
  A operator -() const {
    return A(-x);
  }
};
```

To create an instance of the object, use angle brackets:

```
A<int> a1(5);
A<int> a2(6);
A<int> a3 = a1 + a2;
A<double> a4(2.5);
A<double>a5(3.2);
A<double> a6 = a4 + a5;
```

Note that trying to mix these types will result in a compile error:

```
A<int> a1(5);
A<double> a4(2.5);
A<double> a6 = a1 + a4;
```

68. Exception Handling

Exception handling is a superior method of breaking out when code has gone wrong. It was invented long ago in a lisp dialect, long before C++, but it was adopted for use in C++. The metaphor is throwing a ball. The code that discovers the error creates an object (the exception) and throws it. Whoever catches it handles the error.

In C++ the throw keyword creates the exception and try...catch handles it.

```
int main() {
  int x = 1, y = 0;
  x / y;  // error, divide by zero
}
```

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

int main() {
  try {
    int x = 1, y = 0;
    if (y == 0)
      throw "Divide by zero!";
     x / y;  // error, divide by zero
  } catch (const char* msg) {
    cout << msg << '\n';
  }
}
```

If the error is not caught, C++ calls terminate() which calls abort() which ends the program.

```
#include <iostream>
using namespace std;
int main() {
  throw "testing!";
}
```

The error message is:

```
terminate called after throwing an instance of 'char const*'
Aborted (core dumped)
```

The old way of doing this would be to return a special value indicating failure. For example:

```
double hypot(double x, double y) {
  if (x < 0 || y < 0)
    return -1;
}
```

The problem with this approach is that the programmer calling must be aware of the possibility of a special value being returned. If they do not handle -1, the code will be wrong:

```
  double h = hypot(-1,-3); // length = -1, FAIL
}
```

Throwing exceptions is particularly useful in cases where there is no return value, like a constructor.

```
class Fraction {
public:
  Fraction(int n, int d) {
    if (d == 0)
      throw "Bad Fraction";
  }
};
```

The best defense against a bad value in the object is to never let the object be created in the first place. If an exception is thrown, the object construction fails (never happened).

```
int main() {
  Fraction f1(1,0); // breaks out
  Fraction f2(1,2); // never happens
  Fraction f3 = f1 + f2;
}
```

69. Passing Functions as Parameters

Functions can be passed as parameters, just as values can. A function name is a pointer to code. If referenced, C++ is forced to generate the code, since it is not possible to point to inline code.

The oldest method of passing a parameter is to define a pointer to code. The syntax is a bit tricky.

Here is are some examples showing the difficulty:

```
int * p1; // p1 is a pointer to int
int* p2(); // p2 is a function that returns pointer to int
int  *p3 (); // p3 is still a function retuning pointer to int,
   spaces don't matter

int (*p4)(); // p4 is a pointer to a function taking no
   parameters and returning int
void (*p5)(int,int); // p5 is a pointer to a function taking two
   integers
```

To pass a function as a parameter, just use its name. This does not invoke the function. Invoking a function requires the parentheses. Thus for example:

```
  f; // does nothing, f is a pointer to function
  f(); // call function f
```

Here is a simple example calling a function 10 times:

```
void hello() { cout << "hello"; }
void callme(void (*f)()) {
  for (int i = 0; i < 10; i++)
    f();
}
int main() {
  callme(hello); // prints hello 10 times
}
```

Note that it is illegal to call functions with a different signature. The function:

```
int sum(int a, int b) { return a +b; }
```
[1]

could not be passed to callme because the parameter of callme is a function with different parameters that do not match.

70. Multithreading

70.1 Introduction

Multithreading is an API giving the programmer control over multiple cooperating threads of execution. By using multiple threads, programs can complete operations in parallel. This can be more efficient even with only one CPU as computers often wait for I/O. Today, with multiple cores in most of our computers, and computers not gaining in speed due to limitations in clock speed due to power consumption, multithreading is one of the most important ways to speed up code.

Unfortunately, multithreading comes with a host of problems. As long as two threads are accessing different data, it is a simple, easy way to increase computational speed. When two or more threads need to write to the same data, subtle errors occur due to the order in which it happens. These errors will be random, non-repeatable, and they are among the hardest bugs to find. The next few chapters cover multithreading, and how to control them.

70.2 C++ Support for Threading

In C++11, multithreading became part of the language. Prior to that, each operating system had its own API, so multithreaded code was not portable.

To create a thread and start it running, include the thread header file, create a thread object passing it the name of a function to be executed in the background.

```
#include <thread>
void f() {
  for (int i = 0; i < 10; i++) {
    cout << "hello";
    sleep(1);
  }
}

void g() {
  for (int i = 0; i < 5; i++) {
    cout << "bye";
```

```
    sleep(1);
  }
}

int main() {
  thread t(f); // start executing function f in the background.
  g();
}
```

71. Mutexes

Computing in parallel works very well when the data being computed in each thread have nothing to do with each other. But when data is shared between threads, errors can be caused by two threads overwriting each other on the same data. This kind of error is called a race condition.

The following example shows a bank account where money can be deposited and withdrawn. To exaggerate the problem, we read the balance from the account, wait 1 second, then write back the modified amount. In reality, the interval between the computer reading the balance and writing back the modified value is measured in billionths of a second, but it does exist.

Suppose two threads A and B are reading the bank account, which is currently 100. Thread A deposits another 10. Thread B deposits 10. If both A and B read the current value at nearly the same time, then both believe it is 100. Suppose A gets in first. It adds 100 + 10 and computes the new balance which is 110. But B has already read 100, so it does the same thing. The result is that when B writes out its deposit, the balance is 100 + 10 = 110. In other words, two deposits have happened, yet only one has been recorded. This kind of error is called a race condition and can happen whenever two threads are accessing the same data in an uncontrolled manner.

To solve the problem, we create a mutex object which has two methods: lock and unlock. Whenever two threads are racing to be write to a value, one has to get in first. The mutex lock method will allow the first one to go through and make the second one wait until the first unlocks the mutex.

Here is the code which shows an exaggerated operation in which one second elapses between getting the old balance and storing the new one.

```
#include <iostream>
#include <thread>
#include <mutex>
#include <unistd.h>
using namespace std;

class Account {
private:
    double balance;
public:
```

```
    Account() : balance(0) {}
    void deposit(double amt) {
        double newBalance = balance + amt;
        sleep(1); // wait 1 second to amplify the possibility
            of race condition
        balance = newBalance;
    }
    double getBalance() const { return balance; }
};

void backgroundDeposit(Account* a) {
    a->deposit(10);
}

int main() {
    Account a;
    thread t[10];
    for (int i = 0; i < 10; i++) {
        t[i] = thread(backgroundDeposit, &a);
    }
    cout << "Before waiting for all threads, balance = " << a.
        getBalance() << '\n';
    for (int i = 0; i < 10; i++)
        t[i].join();
    cout << "After waiting for all threads, balance = " << a.
        getBalance() << '\n';
}
```

In order to make the code work properly, a mutex object must **mut**uallly **ex**clude each thread so that only one at a time has access to the balance. The code shown below replaces the Account object, all the rest of the program remains the same.

```
class Account {
private:
    double balance;
    mutex m;
public:
    Account() : balance(0) {}
    void deposit(double amt) {
        m.lock();
        double newBalance = balance + amt;
        sleep(1); // wait 1 second to amplify the possibility
            of race condition
        balance = newBalance;
        m.unlock();
    }
    double getBalance() const { return balance; }
```

```
};
```

Accessing a mutex is quite slow compared to the operation in this case. As a comparison, the multithreaded version of this code running 10 threads, each doing 100,000 deposits which lock and unlock the mutex took 4 seconds with maximum optimization under g++. Without optimization, the single threaded version of this code (without mutex) runs in under 0.03 seconds. Obviously, multithreading is only worthwhile when the overhead of checking for race conditions does not exceed the time saved by running the program in parallel!

72. unique_lock

73. condition_variable

74. POSIX Asynchronous I/O

75. OpenMP

Modern computers have multiple cores. This means they can compute faster in parallel, provided a program is able to run more than one thread. But multithreaded programming is hard as we have seen. So there is a library designed to automatically parallelize code with minimal human interaction. This library and standard is called OpenMP.

To build a c++ with OpenMP, compile with an option. For g++:

```
g++ -fopenmp test1.cc -o test1
```

This will link to the OpenMP library. When the program is run, it will read the state of an environment variable. To control the number of threads in a Unix shell:

```
export OMP_NUM_THREADS=4
```

then run the program, which will launch that many parallel threads.

The following simple code runs 10 iterations on a loop. Each one prints hello with a number and sleeps for one second. This would mean that the program would take 10 seconds to run. But if you run with OpenMP using the directive #pragma parallel the four threads set above will each get one and print out at the same time. This means that the order of completion is not guaranteed, so the output is a bit messy. It is still going to be necessary to be careful lest the threads corrupt some data. The threads must have their own private variables to work with, and typically share an array. The next section will show a simple prime number solver running in parallel.

```
#include <iostream>
#include <unistd.h>
using namespace std;

void f() {
#pragma omp parallel for
     for (int i = 0; i < 10; ++i) {
          cout << "hello" << i << '\n';
          sleep(1); // sleep for one second
     }
}
int main(int argc, char* argv[]) {
```

```
        f();
}
```

The above code does not run on Msys under Windows. It is tested only under Linux. Windows is capable of running OpenMP, but the threads in a Linux shell are not properly running. Either run a compiler native to windows (like Visual C++) or install Cygwin which has a more complete set of unix libraries.

The last thing to consider: memory bandwidth is limited. Each processor can read from local cache, but if multiple threads are writing to memory, processors will have to wait. One process is typically able to go at nearly 100% efficiency, barely waiting for memory if code is well written. With a second processor, there will be times when each processor is waiting for the other which is using the memory, so two processors typically do not go 100% faster than one. The second gets perhaps 80%. The next two get even less, so that running 4 processors, the result is often no more than 3 times faster, and may be far less.

76. Parallel Prime Number Search

In order to write a prime number solver that works in parallel, pick a loop that takes a long time to run, and add a directive in front of it instructing the OpenMP system to split it among the threads. The simplest directive to split is

```
#pragma omp parallel for
```
1

which tells the threads to take turns picking an iteration from the loop. This first approach is not very efficient because it takes time to start up threads and to assign them work, so it is most efficient to have a big unit of work for them to do. And whenever the threads are accessing common data, mutexes must be generated to prevent them from accessing the same data. In this case, when looking at a given number, the thread could immediately find that it is not prime because it is evenly divisible by 2, or 3, or the thread might have to go through all checks and discover that it is prime. This means that threads will finish at varying times and go back to get the next number to work on, wasting time.

In a second variant, we can try allocating a block of numbers for each thread to work on, but that is more complicated.

77. Tools

The modern programming world is very complex. Not only is C++ the language itself complicated, but there are many tools to master in a development environment.

There is no time to tackle these subjects in this course, but they are listed so you can know what you need to know, and study as you progress.

A debugger is a vital tool to step through code. In this course we have used gdb, and perhaps you have used a more sophisticated front end such as in CLion or qtcreator. While these IDEs using gdb or lldb as the underlying engine, the graphical front end means that you can see values changing as you go, which may improve your productivity. After all in gdb you must print the variables you want to see, whereas in a graphical debugger front end they constantly print everything, so it is easy to notice some variable changing that should not. Learning to use advanced features of debuggers like watching a variable or memory range to see when it changes, learning strategies to debug to avoid stepping when there are billions of instructions before the bug happens, all these take time.

A profiler shows how long code takes to execute. Usually profiling is done either by statistically sampling the code while it is running to see where it is, or by logging the time every time functions are entered and left, or every time lines are hit. Running a profiler takes extra time (the code runs slower) but it is the best way to find where in the code is taking the most time, which is the most productive way to figure out how to optimize code.

For g++ the profiler is called gprof. The following example shows how to compile a program using profiling:

```
g++ -pg test.cpp
```

The executable is run, then display the results with

```
gprof
```

A coverage tool analyzes which code has been tested in the same way as a profiler, by counting every time code is visited. Instead of measuring time, the coverage tool just tracks, for a set of tests, which lines of code have never been visited, because those lines

have not been tested. This is not perfect. A line of code may have been visited, but without a critical variable being set that yields a wrong answer. Nonetheless, code coverage is an important tool to catch bugs.

The code coverage tool for the gcc toolchain is called gcov.

The following compiler options set up code coverage on the executable a.out

```
g++ -fprofile-arcs -ftest-coverage test.cpp
```
[1]

The following article covers using it: https://medium.com/@naveen.maltesh/generating-code-coverage-report-using-gnu-gcov-lcov-ee54a4de3f11

Unit testing is an important discipline used to repeatably find errors every time code is changed. In the Java world, JUnit was a major milestone, and Google developed GTest as an analog for c++:

https://github.com/google/googletest

Working together in teams requires skills in communication, and tools to make sure that programmers can continue to work productively while changing code. A version control manager is crucial to coordinate work, and make sure that each programmer has access to a version that is stable so they can work on their part without being disturbed as others break the code. Git is the dominant version control system today, and many IDEs integrates tools making it easier to visualize differences in git. It is worth developing expertise in git itself, in visualization tools such as gitlens in vscode, and in utilities by hosts such as github or gitlab.

Continuous Integration (CI) is one major innovation over the last 10 years. Every time code is checked into a repository, a build in the cloud is automatically triggered. This means that it is possible to see the state of unit tests, in other words whether new code broke in any way.

There are a number of CI tools that are popular. Some are focused on a particular language. https://blog.conan.io/2017/03/14/Devops-and-Continouous-Integration-Challenges-in-C-C++-Projects.html

Finally, documentation is vital for the success of large projects. In Java there is a standard for how to weave documentation into code (JavaDoc). There is no equivalent standard in C++ but the default standard is doxygen https://doxygen.nl/.

78. Further Study

If you have read through this material, you now know a lot (though by no means all) of the C++ language. The language continues to evolve, with the latest at the time of writing being the C++22 draft standard. This course has some resources to let you fully assimilate this material, gain the equivalent of years of experience.

First, take the language summary quiz. This is a single C++ file containing many language features. Each function illustrates some feature. If you can predict what is output, then you understand that code. Compile and run to see what it really does output, and study anything you do not understand.

https://github.com/StevensDeptECE/CPE553-CPP/blob/master/languagesummaryquiz.cc

Second, there are a series of bugs of varying difficulty. They are easier than finding bugs in a program because each one is isolated, but studying these bugs is the best way you can gain experience quickly. By random chance it might take you years to encounter these errors, but by studying errors that have been deliberately created you can encounter them so you can hopefully recognize them if (by Murphy's law when!) they eventually happen to you.