C and C++

1. Types — Variables — Expressions & Statements

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Structure of this course

Programming in C:

- types, variables, expressions & statements
- functions, compilation, pre-processor
- pointers, structures
- extended examples, tick hints 'n' tips

Programming in C++:

- references, overloading, namespaces,C/C++ interaction
- operator overloading, streams, inheritence
- exceptions and templates
- standard template library

Text books

There are literally hundreds of books written about C and C++; five you might find useful include:

- Eckel, B. (2000). Thinking in C++, Volume 1: Introduction to Standard C++ (2nd edition). Prentice-Hall. (`http://www.mindview.net/Books/TICPP/ThinkingInCPP2e.html`)
- Kernighan, B.W. & Ritchie, D.M. (1988). The C programming language (2nd edition). Prentice-Hall.
- Stroustrup, B. (1997). The C++ Programming Language (3rd edition). Addison Wesley Longman
- Stroustrup, B. (1994). The design and evolution of C++. Addison-Wesley.
- Lippman, S.B. (1996). Inside the C++ object model. Addison-Wesley.

Past Exam Questions

- 1993 Paper 5 Question 5 1993 Paper 6 Question 5
- 1994 Paper 5 Question 5 1994 Paper 6 Question 5
- 1995 Paper 5 Question 5 1995 Paper 6 Question 5
- 1996 Paper 5 Question 5 (except part (f) `setjmp`)
- 1996 Paper 6 Question 5
- 1997 Paper 5 Question 5 1997 Paper 6 Question 5
- 1998 Paper 6 Question 6 *
- 1999 Paper 5 Question 5 * (first two sections only)
- 2000 Paper 5 Question 5 *
- 2006 Paper 3 Question 4 *
- 2007 Paper 3 Question 4 2007 Paper 11 Question 3

* denotes CPL questions relevant to this course.

Context: from BCPL to Java

- *1966* Martin Richards developed BCPL
- *1969* Ken Thompson designed B
- *1972* Dennis Ritchie's C
- *1979* Bjarne Stroustrup created C with Classes
- *1983* C with Classes becomes C++
- *1989* Original C90 ANSI C standard (ISO adoption 1990)
- *1990* James Gosling started Java (initially called Oak)
- *1998* ISO C++ standard
- *1999* C99 standard (ISO adoption 1999, ANSI, 2000)

C is a "low-level" language

- C uses low-level features: characters, numbers & addresses
- Operators work on these fundamental types
- No C operators work on "composite types"
  e.g. strings, arrays, sets
- Only static definition and stack-based local variables
  heap-based storage is implemented as a library
- There are no `read` and `write` primitives
  instead, these are implemented by library routines
- There is only a single control-flow
  no threads, synchronisation or coroutines

Classic first example

```c
#include <stdio.h>

int main(void)
{
  printf("Hello, world\n");
  return 0;
}
```

Compile with:

```
$ cc example1.c
```

Execute program with:

```
$  ./a.out
Hello, world
$
```


Basic types

- C has a small and limited set of basic types:

type	description (size)
`char`	characters ($\geq$ 8 bits)
`int`	integer values ($\geq$ 16 bits, commonly one word)
`float`	single-precision floating point number
`double`	double-precision floating point number

- Precise size of types is architecture dependent
- Various *type operators* for altering type meaning, including:
  `unsigned`, `long`, `short`, `const`, `static`
- This means we can have types such as `long int` and `unsigned char`

Constants

- Numeric constants can be written in a number of ways:

type	style	example
`char`	*none*	*none*
`int`	number, character or escape seq.	`12 'A' '\n' '\007'`
`long int`	number w/suffix `l` or `L`	`1234L`
`float`	number with '`.`', '`e`' or '`E`' and suffix `f` or `F`	`1.234e3F` or `1234.0f`
`double`	number with '`.`', '`e`' or '`E`'	`1.234e3 1234.0`
`long double`	number '`.`', '`e`' or '`E`' and suffix `l` or `L`	`1.234E3l` or `1234.0L`

- Numbers can be expressed in octal by prefixing with a '`0`' and hexadecimal with '`0x`'; for example: `52=064=0x34`

Defining constant values

- An *enumeration* can be used to specify a set of constants; e.g.:
  `enum boolean {FALSE, TRUE};`
- By default enumerations allocate successive integer values from zero
- It is possible to assign values to constants; for example:
  `enum months {JAN=1,FEB,MAR}`
  `enum boolean {F,T,FALSE=0,TRUE,N=0,Y}`
- Names for constants in different `enum`s must be distinct; values in the same `enum` need not
- The preprocessor can also be used (more on this later)

Variables

- Variables must be *defined* (i.e. storage set aside) exactly once
- A variable name can be composed of letters, digits and underscore (_); a name must begin with a letter or underscore
- Variables are defined by prefixing a name with a type, and can optionally be initialised; for example: `long int i = 28L;`
- Multiple variables of the same basic type can be defined together; for example: `char c,d,e;`

Operators

- All operators (including assignment) return a result
- Most operators are similar to those found in Java:

type	operators
arithmetic	`+ - * / ++ -- %`
logic	`== != > >= < <= || && !`
bitwise	`| & << >> ^ ~`
assignment	`= += -= *= /= %= <<= >>= &= |= ^=`
other	`sizeof`

Type conversion

- Automatic type conversion may occur when two operands to a binary operator are of a different type
- Generally, conversion "widens" a variable (e.g. `short` → `int`)
- However "narrowing" is possible and may not generate a compiler warning; for example:

```
1 int i = 1234;
2 char c;
3 c = i+1; /* i overflows c */
```

- Type conversion can be forced by using a *cast*, which is written as: `(`*type*`)` *exp*; for example: `c = (char) 1234L;`

Expressions and statements

- An *expression* is created when one or more operators are combined; for example `x *= y % z`
- Every expression (even assignment) has a type and a result
- Operator precedence provides an unambiguous interpretation for every expression
- An expression (e.g. `x=0`) becomes a *statement* when followed by a semicolon (i.e. `x=0;`)
- Several expressions can be separated using a comma ',' ; expressions are then evaluated left to right; for example: `x=0,y=1.0`
- The type and value of a comma-separated expression is the type and value of the result of the right-most expression

Blocks or compound statements

- A *block* or *compound statement* is formed when multiple statements are surrounded with braces (`{ }`)
- A block of statements is then equivalent to a single statement
- In ANSI/ISO C90, variables can only be declared or defined at the start of a block (this restriction was lifted in ANSI/ISO C99)
- Blocks are typically associated with a function definition or a control flow statement, but can be used anywhere

Variable scope

- Variables can be defined outside any function, in which case they:
  - are often called *global* or *static* variables
  - have global scope and can be used anywhere in the program
  - consume storage for the entire run-time of the program
  - are initialised to zero by default
- Variables defined within a block (e.g. function):
  - are often called *local* or *automatic* variables
  - can only be accessed from definition until the end of the block
  - are only allocated storage for the duration of block execution
  - are only initialised if given a value; otherwise their value is undefined

Variable definition versus declaration

- A variable can be *declared* but not defined using the `extern` keyword; for example `extern int a;`
- The declaration tells the compiler that storage has been allocated elsewhere (usually in another source file)
- If a variable is declared and used in a program, but not defined, this will result in a *link error* (more on this later)

Scope and type example

```c
#include <stdio.h>

int a;                          /*what value does a have? */
unsigned char b = 'A';
extern int alpha;               /* safe to use this?      */

int main(void) {
  extern unsigned char b;       /* is this needed?        */
  double a = 3.4;
  {
    extern a;                   /*why is this sloppy?     */
    printf("%d %d\n",b,a+1); /*what will this print?   */
  }

  return 0;
}
```


Arrays and strings

- One or more items of the same type can be grouped into an array; for example: `long int i[10];`
- The compiler will allocate a contiguous block of memory for the relevant number of values
- Array items are indexed from zero, and there is no bounds checking
- Strings in C are usually represented as an array of `char`s, terminated with a special character `'\0'`
- There is compiler support for string constants using the '`"`' character; for example:
  `char str[]="two strs mer"  "ged and terminated"`
- String support is available in the `string.h` library

Control flow

- Control flow is similar to Java:
  - *exp* `?` *exp* `:` *exp*
  - `if (`*exp*`)` $stmt_1$ `else` $stmt_2$
  - `switch(`*exp*`) {`
    `case` exp_1`:`
    $stmt_1$
    ...
    `default:`
    $stmt_{n+1}$
    `}`
  - `while (`*exp*`)` *stmt*
  - `for (` exp_1`;` exp_2`;` exp_3 `)` *stmt*
  - `do` *stmt* `while (`*exp*`);`
- The jump statements `break` and `continue` also exist

Control flow and string example

```c
#include <stdio.h>
#include <string.h>

char s[]="University of Cambridge Computer Laboratory";

int main(void) {

  char c;
  int i, j;
  for (i=0,j=strlen(s)-1;i<j;i++,j--) /* strlen(s)-1 ? */
    c=s[i], s[i]=s[j], s[j]=c;

  printf("%s\n",s);
  return 0;
}
```


Goto (considered harmful)

- The `goto` statement is never *required*
- It often results in code which is hard to understand and maintain
- Exception handling (where you wish to exit or `break` from two or more loops) may be one case where a `goto` is justified:

```c
for (...) {
 for (...) {
   ...
   if (critical_problem)
    goto error;
  }
 }
 ...
error:
```

fix problem, or abort

Exercises

1. What is the difference between `'a'` and `"a"`?
2. Will `char i,j; for(i=0;i<10,j<5;i++,j++) ;` terminate? If so, under what circumstances?
3. Write an implementation of bubble sort for a fixed array of integers. (An array of integers can be defined as `int i[] = {1,2,3,4};` the 2nd integer in an array can be printed using `printf("%d\n",i[1]);`.)
4. Modify your answer to (3) to sort characters into lexicographical order. (The 2nd character in a character array `i` can be printed using `printf("%c\n",i[1]);`.)

C and C++

2. Functions — Preprocessor

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Functions

- C does not have objects, but does have function support
- A function *definition* has a *return type*, *parameter specification*, and a body or *statement*; for example:
  `int power(int base, int n) { stmt }`
- A function *declaration* has a return type and parameter specification followed by a semicolon; for example:
  `int power(int base, int n);`
  - The use of the `extern` keyword for function declarations is optional
- All arguments to a function are copied, i.e. *passed-by-value*; modification of the local value does not affect the original
- Just as for variables, a function must have exactly one definition and can have multiple declarations
- A function which is used but only has a declaration, and no definition, results in a link error (more on this later)
- Functions cannot be nested

Function type-system nasties

- A function definition with no values (e.g. `power()`) is not an empty parameter specification, rather it means that its arguments should not be type-checked! (this is not the case in C++)
- Instead, a function with no arguments is declared using `void`
- An ellipsis (`...`) can be used for partial parameter specification, for example:
  `int printf(char* fmt,...) { stmt }`
- The ellipsis is useful for defining functions with variable length arguments, but leaves a hole in the type system (`stdarg.h`)
- In comparison, C++ uses operator overloading to provide better I/O type safety (more on this later)

Recursion

- Functions can call themselves recursively
- On each call, a new set of local variables are created
- Therefore, a function recursion of depth n has n sets of variables
- Recursion can be useful when dealing with recursively defined data structures, like trees (more on such data structures later)
- Recursion can also be used as you would in ML:

```
1
2 unsigned int fact(unsigned int n) {
3  return n ? n*fact(n-1) : 1;
4 }
```

Compilation

- A compiler transforms a C source file or *execution unit* into an *object* file
- An object file consists of machine code, and a list of:
  - *defined* or *exported* symbols representing defined function names and global variables
  - *undefined* or *imported* symbols for functions and global variables which are declared but not defined
- A *linker* combines several object files into an *executable* by:
  - combining all object code into a single file
  - adjusting the absolute addresses from each object file
  - resolving all undefined symbols

The Part 1B Compiler Course describes how to build a compiler and linker in more detail

Handling code in multiple files in C

- C separates declaration from definition for both variables and functions
- This allows portions of code to be split across multiple files
- Code in different files can then be compiled at different times
  - This allows libraries to be compiled once, but used many times
  - It also allows companies to sell binary-only libraries
- In order to use code written in another file we still need a declaration
- A *header* file can be used to:
  - supply the declarations of function and variable definitions in another file
  - provide preprocessor macros (more on this later)
  - avoid duplication (and ∴ errors) that would otherwise occur
- You might find the Unix tool `nm` useful for inspecting symbol tables

Multi-source file example

Header File — example4.h

```c
/*reverse a string in place */
void reverse(char str[]);
```

Source File — example4a.c

```c
#include <string.h>
#include "example4.h"

/*reverse a string in place */
void reverse(char s[]) {
  int c, i, j;
  for (i=0,j=strlen(s)-1;
                  i<j;i++,j--)
    c=s[i], s[i]=s[j], s[j]=c;
}
```

Source File — example4b.c

```c
#include <stdio.h>
#include "example4.h"


int main(void) {
  char s[] = "Reverse me";
  reverse(s);
  printf("%s\n",s);
  return 0;
}
```


Variable and function scope with static

- The `static` keyword limits the scope of a variable or function
- In the global scope, `static` does not export the function or variable symbol
  - This prevents the variable or function from being called externally
- In the local scope, a `static` variable retains its value between function calls
  - A single static variable exists even if a function call is recursive

C Preprocessor

- The preprocessor is executed before any compilation takes place
- It manipulates the textual content of the source file in a single pass
- Amongst other things, the preprocessor:
  - deletes each occurrence of a backslash followed by a newline;
  - replaces comments by a single space;
  - replaces definitions, obeys conditional preprocessing directives and expands macros; and
  - it replaces escaped sequences in character constants and string literals and concatenates adjacent string literals

Controlling the preprocessor programmatically

- The preprocessor can be used by the programmer to rewrite source code
- This is a powerful (and, at times, useful) feature, but can be hard to debug (more on this later)
- The preprocessor interprets lines starting with `#` with a special meaning
- Two text substitution directives: `#include` and `#define`
- Conditional directives: `#if`, `#elif`, `#else` and `#endif`

The #include directive

- The `#include` directive performs text substitution
- It is written in one of two forms:

  `#include "`*filename*`"` `#include <`*filename*`>`

- Both forms replace the `#include ...` line in the source file with the contents of *filename*
- The quote (") form searches for the file in the same location as the source file, then searches a predefined set of directories
- The angle (<) form searches a predefined set of directories
- When a `#include`d file is changed, all source files which depend on it should be recompiled

The #define directive

- The `#define` directive has the form:
  `#define` *name replacement text*
- The directive performs a direct text substitution of all future examples of *name* with the *replacement text* for the remainder of the source file
- The *name* has the same constraints as a standard C variable name
- Replacement does not take place if *name* is found inside a quoted string
- By convention, *name* tends to be written in upper case to distinguish it from a normal variable name

Defining macros

- The `#define` directive can be used to define *macros* as well; for example: `#define MAX(A,B) ((A)>(B)?(A):(B))`
- In the body of the macro:
  - prefixing a parameter in the replacement text with '`#`' places the parameter value inside string quotes (`"`)
  - placing '`##`' between two parameters in the replacement text removes any whitespace between the variables in generated output
- Remember: the preprocessor only performs text substitution
  - This means that syntax analysis and type checking doesn't occur until the compilation stage
  - This can, initially at least, generate some confusing compiler warnings on line numbers where the macro is used, rather than when it is defined; for example:
    `#define JOIN(A,B) (A ## B))`

Example

```c
#include <stdio.h>

#define PI 3.141592654
#define MAX(A,B) ((A)>(B)?(A):(B))
#define PERCENT(D) (100*D)              /* Wrong? */
#define DPRINT(D) printf(#D " = %g\n",D)
#define JOIN(A,B) (A ## B)

int main(void) {
  const unsigned int a1=3;
  const unsigned int i = JOIN(a,1);
  printf("%u %g\n",i, MAX(PI,3.14));
  DPRINT(MAX(PERCENT(0.32+0.16),PERCENT(0.15+0.48)));

  return 0;
}
```


Conditional preprocessor directives

Conditional directives: `#if`, `#ifdef`, `#ifndef`, `#elif` and `#endif`

- The preprocessor can use conditional statements to include or exclude code in later phases of compilation
- `#if` accepts a (somewhat limited) integer *expression* as an argument and only retains the code between `#if` and `#endif` (or `#elif`) if the expression evaluates to a non-zero value; for example:
  `#if SOME_DEF > 8 && OTHER_DEF != THIRD_DEF`
- The built-in preprocessor function `defined` accepts a name as it's sole argument and returns `1L` if the name has been `#defined`; `0L` otherwise
- `#ifdef N` and `#ifndef N` are equivalent to `#if defined(N)` and `#if !defined(N)` respectively
- `#undef` can be used to remove a `#defined` name from the preprocessor macro and variable namespace.

Example

Conditional directives have several uses, including preventing double definitions in header files and enabling code to function on several different architectures; for example:

```c
#if SYSTEM_SYSV
#define HDR "sysv.h"
#elif SYSTEM_BSD
#define HDR "bsd.h"
#else
#define HDR "default.h"
#endif
#include HDR
```

```c
#ifndef MYHEADER_H
#define MYHEADER_H 1
...
/* declarations & defns */
...
#endif /* !MYHEADER_H */
```

Error control

- To help other compilers which generate C code (rather than machine code) as output, compiler line and filename warnings can be overridden with:
  `#line` *constant* `"`*filename*`"`
- The compiler then adjusts its internal value for the next line in the source file as *constant* and the current name of the file being processed as *filename* (`"`*filename*`"` may be omitted)
- The statement "`#error` *some text*" causes the preprocessor to write a diagnostic message containing *some text*
- There are several predefined identifiers that produce special information: `__LINE__`, `__FILE__`, `__DATE__`, and `__TIME__`.

Exercises

1. Write a function definition which matches the declaration `int cntlower(char str[]);`. The implementation should return the number of lower-case letters in a string
2. Use function recursion to write an implementation of merge sort for a fixed array of integers; how much memory does your program use for a list of length n?
3. Define a macro `SWAP(t,x,y)` that exchanges two arguments of type `t`
   (K&R, Exercise 4-14)
4. Define a macro `SWAP(x,y)` that exchanges two arguments of the same type (e.g. `int` or `char`) *without using a temporary*

C and C++

3. Pointers — Structures

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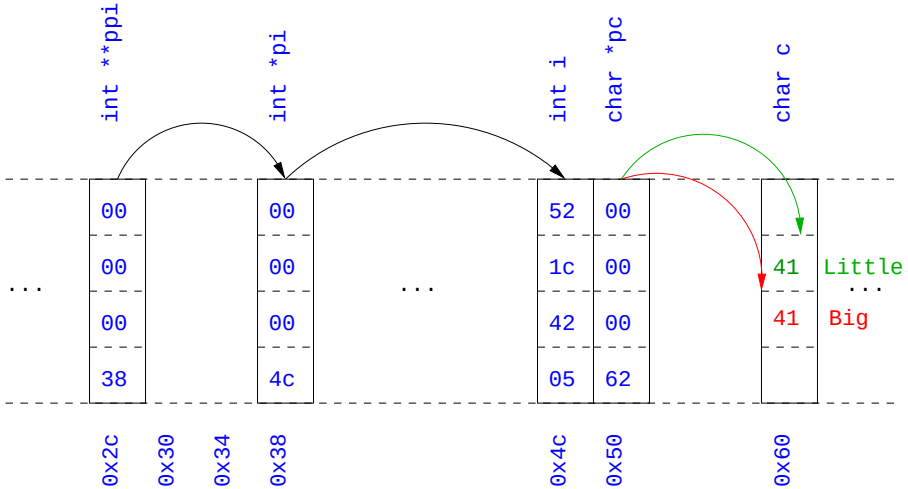
Pointers

- Computer memory is often abstracted as a sequence of bytes, grouped into words
- Each byte has a unique address or index into this sequence
- The size of a word (and byte!) determines the size of addressable memory in the machine
- A *pointer* in C is a variable which contains the memory address of another variable (this can, itself, be a pointer)
- Pointers are declared or defined using an asterisk(`*`); for example: `char *pc;` or `int **ppi;`
- The asterisk binds to the variable name, not the type definition; for example `char *pc,c;`
- A pointer does *not* necessarily take the same amount of storage space as the type it points to

Example



Manipulating pointers

- The value "pointed to" by a pointer can be "retrieved" or *dereferenced* by using the unary `*` operator; for example:
  ```
  int *p = ...
  int x = *p;
  ```
- The memory address of a variable is returned with the unary ampersand (`&`) operator; for example
  ```
  int *p = &x;
  ```
- Dereferenced pointer values can be used in normal expressions; for example: `*pi += 5;` or `(*pi)++`

Example

```c
#include <stdio.h>

int main(void) {
  int x=1,y=2;
  int *pi;
  int **ppi;

  pi = &x; ppi = &pi;
  printf("%p, %p, %d=%d=%d\n",ppi,pi,x,*pi,**ppi);
  pi = &y;
  printf("%p, %p, %d=%d=%d\n",ppi,pi,y,*pi,**ppi);

  return 0;
}
```


Pointers and arrays

- A C array uses consecutive memory addresses without padding to store data
- An array name (without an index) represents the memory address of the beginning of the array; for example:
  `char c[10];`
  `char *pc = c;`
- Pointers can be used to "index" into any element of an array; for example:
  `int i[10];`
  `int *pi = &i[5];`

Pointer arithmetic

- *Pointer arithmetic* can be used to adjust where a pointer points; for example, if `pc` points to the first element of an array, after executing `pc+=3;` then `pc` points to the fourth element
- A pointer can even be dereferenced using array notation; for example `pc[2]` represents the value of the array element which is two elements beyond the array element currently pointed to by `pc`
- In summary, for an array `c`, `*(c+i)`≡`c[i]` and `c+i`≡`&c[i]`
- A pointer is a variable, but an array name is not; therefore `pc=c` and `pc++` are valid, but `c=pc` and `c++` are not

Example

```c
#include <stdio.h>

int main(void) {
  char str[] = "A string.";
  char *pc = str;

  printf("%c %c %c\n",str[0],*pc,pc[3]);
  pc += 2;
  printf("%c %c %c\n",*pc, pc[2], pc[5]);

  return 0;
}
```

Pointers as function arguments

- Recall that all arguments to a function are copied, i.e. *passed-by-value*; modification of the local value does not affect the original
- In the second lecture we defined functions which took an array as an argument; for example `void reverse(char s[])`
- Why, then, does `reverse` affect the values of the array after the function returns (i.e. the array values haven't been copied)?
  - because `s` is a pointer to the start of the array
- Pointers of any type can be passed as parameters and return types of functions
- Pointers allow a function to alter parameters passed to it

Example

- Compare `swp1(a,b)` with `swp2(&a,&b)`:

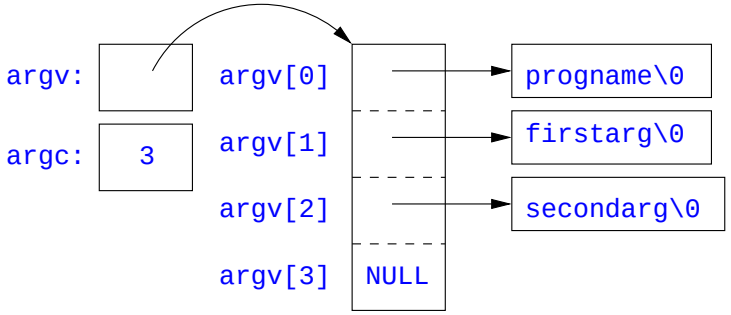
```
1 void swp1(int x,int y)
2 {
3   int temp = x;
4   x = y;
5   y = temp;
6 }
```

```
1 void swp2(int *px,int *py)
2 {
3   int temp = *px;
4   *px = *py;
5   *py = temp;
6 }
```


Arrays of pointers

- C allows the creation of arrays of pointers; for example `int *a[5];`
- Arrays of pointers are particularly useful with strings
- An example is C support of command line arguments: `int main(int argc, char *argv[]) { ... }`
- In this case `argv` is an array of character pointers, and `argc` tells the programmer the length of the array

Example



Multi-dimensional arrays

- Multi-dimensional arrays can be declared in C; for example:
  `int i[5][10];`
- Values of the array can be accessed using square brackets; for example: `i[3][2]`
- When passing a two dimensional array to a function, the first dimension is not needed; for example, the following are equivalent:
  ```
  void f(int i[5][10]) { ... }
  void f(int i[][10])  { ... }
  void f(int (*i)[10]) { ... }
  ```
- In arrays with higher dimensionality, all but the first dimension must be specified

Pointers to functions

- C allows the programmer to use pointers to functions
- This allows functions to be passed as arguments to functions
- For example, we may wish to parameterise a sort algorithm on different comparison operators (e.g. lexicographically or numerically)
- If the sort routine accepts a pointer to a function, the sort routine can call this function when deciding how to order values

Example

```
1  void sort(int a[], const int len,
2            int (*compare)(int, int))
3  {
4    int i,j,tmp;
5    for(i=0;i<len-1;i++)
6      for(j=0;j<len-1-i;j++)
7        if ((*compare)(a[j],a[j+1]))
8         tmp=a[j], a[j]=a[j+1], a[j+1]=tmp;
9  }
10
11 int inc(int a, int b) {
12   return a > b ? 1 : 0;
13 }
```


Example

```
1  #include <stdio.h>
2  #include "example8.h"
3
4  int main(void) {
5    int a[] = {1,4,3,2,5};
6    unsigned int len = 5;
7    sort(a,len,inc); //or sort(a,len,&inc);
8
9    int *pa = a; //C99
10   printf("[");
11   while (len--)
12     printf("%d%s",*pa++,len?" ":"");
13   printf("]\n");
14
15   return 0;
16 }
```

The void * pointer

- C has a "typeless" or "generic" pointer: `void *p`
- This can be a pointer to anything
- This can be useful when dealing with dynamic memory
- Enables "polymorphic" code; for example:

```
1 sort(void *p, const unsigned int len,
2       int (*comp)(void *,void *));
```

- However this is also a big "hole" in the type system
- Therefore `void *` pointers should only be used where necessary

Structure declaration

- A structure is a collection of one or more variables
- It provides a simple method of abstraction and grouping
- A structure may itself contain structures
- A structure can be assigned to, as well as passed to, and returned from functions
- We declare a structure using the keyword `struct`
- For example, to declare a structure `circle` we write
  `struct circle {int x; int y; unsigned int r;};`
- Once declared, a structure creates a new type

Structure definition

- To define an instance of the structure `circle` we write
  `struct circle c;`
- A structure can also be initialised with values:
  `struct circle c = {12, 23, 5};`
- An automatic, or local, structure variable can be initialised by function call:
  `struct circle c = circle_init();`
- A structure can declared, and several instances defined in one go:
  `struct circle {int x; int y; unsigned int r;} a, b;`

Member access

- A structure member can be accessed using '`.`' notation: *structname*`.`*member*; for example: `pt.x`
- Comparison (e.g. `pt1 > pt2`) is undefined
- Pointers to structures may be defined; for example:
  `struct circle *pc`
- When using a pointer to a struct, member access can be achieved with the '.' operator, but can look clumsy; for example: `(*pc).x`
- Alternatively, the '`->`' operator can be used; for example: `pc->x`

Self-referential structures

- A structure declaration can contain a member which is a pointer whose type is the structure declaration itself
- This means we can build recursive data structures; for example:

```c
struct tree {
 int val;
 struct tree *left;
 struct tree *right;
}
```

```c
struct link {
 int val;
 struct link *next;
}
```


Unions

- A union variable is a single variable which can hold one of a number of different types
- A union variable is declared using a notation similar to structures; for example: `union u { int i; float f; char c;};`
- The size of a union variable is the size of its largest member
- The type held can change during program execution
- The type retrieved must be the type most recently stored
- Member access to unions is the same as for structures ('`.`' and '`->`')
- Unions can be nested inside structures, and vice versa

Bit fields

- Bit fields allow low-level access to individual bits of a word
- Useful when memory is limited, or to interact with hardware
- A bit field is specified inside a struct by appending a declaration with a colon (`:`) and number of bits; for example:
  `struct fields { int f1 : 2; int f2 : 3;};`
- Members are accessed in the same way as for structs and unions
- A bit field member does not have an address (no `&` operator)
- Lots of details about bit fields are implementation specific:
  - *word boundary overlap & alignment, assignment direction, etc.*

Example (adapted from K&R)

```c
struct { /* a compiler symbol table */
  char *name;
  struct {
   unsigned int is_keyword : 1;
   unsigned int is_extern : 1;
   unsigned int is_static : 1;
   ...
   } flags;
  int utype;
  union {
   int ival; /* accessed as symtab[i].u.ival */
   float fval;
   char *sval;
   } u;
} symtab[NSYM];
```

Exercises

1. If `p` is a pointer, what does `p[-2]` mean? When is this legal?
2. Write a string search function with a declaration of `char *strfind(const char *s, const char *f);` which returns a pointer to first occurrence of `s` in `f` (and `NULL` otherwise)
3. If `p` is a pointer to a structure, write some C code which uses all the following code snippets: "`++p->i`", "`p++->i`", "`*p->i`", "`*p->i++`", "`(*p->i)++`" and "`*p++->i`"; describe the action of each code snippet
4. Write a program `calc` which evaluates a reverse Polish expression given on the command line; for example

   ```
   $ calc 2 3 4 + *
   ```

   should print `14` (K&R Exercise 5-10)

C and C++

4. Misc. — Libary Features — Gotchas — Hints 'n' Tips

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Lent Term 2008

Uses of const and volatile

- Any declaration can be prefixed with `const` or `volatile`
- A `const` variable can only be assigned a value when it is defined
- The `const` declaration can also be used for parameters in a function definition
- The `volatile` keyword can be used to state that a variable may be changed by hardware, the kernel, another thread etc.
  - For example, the `volatile` keyword may prevent unsafe compiler optimisations for memory-mapped input/output
- The use of pointers and the `const` keyword is quite subtle:
  - `const int *p` is a pointer to a `const` int
  - `int const *p` is also a pointer to a `const` int
  - `int *const p` is a `const` pointer to an int
  - `const int *const p` is a `const` pointer to a `const` int

Example

```
1  int main(void) {
2    int i = 42;
3    int j = 28;
4
5    const int *pc = &i;       //Also: "int const *pc"
6    *pc = 41;                 //Wrong
7    pc = &j;
8
9    int *const cp = &i;
10   *cp = 41;
11   cp = &j;                  //Wrong
12
13   const int *const cpc = &i;
14   *cpc = 41;                //Wrong
15   cpc = &j;                 //Wrong
16   return 0;
17 }
```


Typedefs

- The `typedef` operator, creates new data type names;
  for example, `typedef unsigned int Radius;`
- Once a new data type has been created, it can be used in place of the usual type name in declarations and casts;
  for example, `Radius r = 5; ...; r = (Radius) rshort;`
- A `typedef` declaration does *not* create a new type
  - It just creates a synonym for an existing type
- A `typedef` is particularly useful with structures and unions:

```
1 typedef struct llist *llptr;
2 typedef struct llist {
3   int val;
4   llptr next;
5 } linklist;
```

In-line functions

- A function in C can be declared `inline`; for example:

```
inline fact(unsigned int n) {
    return n ? n*fact(n-1) : 1;
}
```

- The compiler will then try to "in-line" the function
  - A clever compiler might generate `120` for `fact(5)`
- A compiler might not always be able to "in-line" a function
- An `inline` function must be *defined* in the same execution unit as it is used
- The `inline` operator does not change function semantics
  - the in-line function itself still has a unique address
  - static variables of an in-line function still have a unique address

That's it!

- We have now explored most of the C language
- The language is quite subtle in places; in particular watch out for:
  - operator precedence
  - pointer assignment (particularly function pointers)
  - implicit casts between `int`s of different sizes and `char`s
- There is also extensive standard library support, including:
  - shell and file I/O (`stdio.h`)
  - dynamic memory allocation (`stdlib.h`)
  - string manipulation (`string.h`)
  - character class tests (`ctype.h`)
  - ...
  - (Read, for example, K&R Appendix B for a quick introduction)
  - (Or type "`man` *function*" at a Unix shell for details)

Library support: I/O

I/O is not managed directly by the compiler; support in `stdio.h`:

- `int printf(const char *format, ...);`
- `int sprintf(char *str, const char *format, ...);`
- `int scanf(const char *format, ...);`
- `FILE *fopen(const char *path, const char *mode);`
- `int fclose(FILE *fp);`
- `size_t fread(void *ptr, size_t size, size_t nmemb, FILE *stream);`
- `size_t fwrite(const void *ptr, size_t size, size_t nmemb, FILE *stream);`
- `int fprintf(FILE *stream, const char *format, ...);`
- `int fscanf(FILE *stream, const char *format, ...);`


```
#include<stdio.h>
#define BUFSIZE 1024

int main(void) {
  FILE *fp;
  char buffer[BUFSIZE];

  if ((fp=fopen("somefile.txt","rb")) == 0) {
    perror("fopen error:");
    return 1;
  }

  while(!feof(fp)) {
      int r = fread(buffer,sizeof(char),BUFSIZE,fp);
      fwrite(buffer,sizeof(char),r,stdout);
  }

  fclose(fp);
  return 0;
}
```

Library support: dynamic memory allocation

- Dynamic memory allocation is not managed directly by the C compiler
- Support is available in `stdlib.h`:
  - `void *malloc(size_t size)`
  - `void *calloc(size_t nobj, size_t size)`
  - `void *realloc(void *p, size_t size)`
  - `void free(void *p)`
- The C `sizeof` unary operator is handy when using `malloc`:
  `p = (char *) malloc(sizeof(char)*1000)`
- Any successfully allocated memory must be deallocated *manually*
  - Note: `free()` needs the pointer to the allocated memory
- Failure to deallocate will result in a *memory leak*

Gotchas: operator precedence

```
1  #include<stdio.h>
2
3  struct test {int i;};
4  typedef struct test test_t;
5
6  int main(void) {
7
8    test_t a,b;
9    test_t *p[] = {&a,&b};
10   p[0]->i=0;
11   p[1]->i=0;
12   test_t *q = p[0];
13
14   printf("%d\n",++q->i); //What does this do?
15
16   return 0;
17 }
```


Gotchas: `i++`

```
1  #include <stdio.h>
2
3  int main(void) {
4
5    int i=2;
6    int j=i++ + ++i;
7    printf("%d %d\n",i,j); //What does this print?
8
9    return 0;
10 }
```


Gotchas: local stack

```
1  #include <stdio.h>
2
3  char *unary(unsigned short s) {
4    char local[s+1];
5    int i;
6    for (i=0;i<s;i++) local[i]='1';
7    local[s]='\0';
8    return local;
9  }
10
11 int main(void) {
12
13   printf("%s\n",unary(6)); //What does this print?
14
15   return 0;
16 }
```

Gotchas: local stack (contd.)

```c
#include <stdio.h>

char global[10];

char *unary(unsigned short s) {
  char local[s+1];
  char *p = s%2 ? global : local;
  int i;
  for (i=0;i<s;i++) p[i]='1';
  p[s]='\0';
  return p;
}

int main(void) {
  printf("%s\n",unary(6)); //What does this print?
  return 0;
}
```


Gotchas: careful with pointers

```c
#include <stdio.h>

struct values { int a; int b; };

int main(void) {
 struct values  test2 = {2,3};
 struct values  test1 = {0,1};

 int *pi = &(test1.a);
 pi += 1; //Is this sensible?
 printf("%d\n",*pi);
 pi += 2; //What could this point at?
 printf("%d\n",*pi);

 return 0;
}
```


Tricks: Duff's device

```c
send(int *to, int *from, int count)
{
  int n=(count+7)/8;
  switch(count%8){
  case 0: do{ *to = *from++;
  case 7:     *to = *from++;
  case 6:     *to = *from++;
  case 5:     *to = *from++;
  case 4:     *to = *from++;
  case 3:     *to = *from++;
  case 2:     *to = *from++;
  case 1:     *to = *from++;
          } while(--n>0);
  }
}
```


Assessed exercise

- To be completed by midday on 25th April 2008
- Sign-up sheet removed midday on 25th April 2008
- Viva examinations 1300-1600 on 8th May 2008
- Viva examinations 1300-1600 on 9th May 2008
- Download the starter pack from:
  `http://www.cl.cam.ac.uk/Teaching/current/CandC++/`
- This should contain eight files:

`server.c`	`rfc0791.txt`	`message1`	`message3`
`client.c`	`rfc0793.txt`	`message2`	`message4`

Exercise aims

Demonstrate an ability to:

- Understand (simple) networking code
- Use control flow, functions, structures and pointers
- Use libraries, including reading and writing files
- Understand a specification
- Compile and test code

Task is split into three parts:

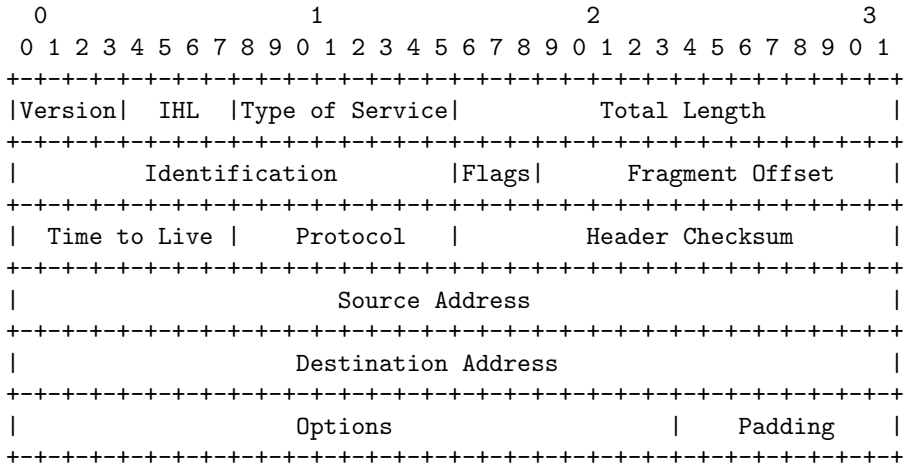
- Comprehension and debugging
- Preliminary analysis
- Completed code and testing

Exercise submission

- Assessment is in the form of a 'tick'
- There will be a short viva; remember to sign up!
- Submission is via email to `c-tick@cl.cam.ac.uk`
- Your submission should include seven files, packed in to a ZIP file called *crsid*`.zip` and attached to your submission email:

```
answers.txt   client1.c   summary.c   message1.txt
              server1.c   extract.c   message2.jpg
```


Hints: IP header



Hints: IP header (in C)

```c
#include <stdint.h>

struct ip {
  uint8_t hlenver;
  uint8_t tos;
  uint16_t len;
  uint16_t id;
  uint16_t off;
  uint8_t ttl;
  uint8_t p;
  uint16_t sum;
  uint32_t src;
  uint32_t dst;
};

#define IP_HLEN(lenver) (lenver & 0x0f)
#define IP_VER(lenver) (lenver >> 4)
```

Hints: network byte order

- The IP network is big-endian; x86 is little-endian
- Reading multi-byte values requires conversion
- The BSD API specifies:
  - `uint16_t ntohs(uint16_t netshort)`
  - `uint32_t ntohl(uint32_t netlong)`
  - `uint16_t htons(uint16_t hostshort)`
  - `uint32_t htonl(uint32_t hostlong)`

Exercises

1. What is the value of `i` after executing each of the following:
   1.1 `i = sizeof(char);`
   1.2 `i = sizeof(int);`
   1.3 `int a; i = sizeof a;`
   1.4 `char b[5]; i = sizeof(b);`
   1.5 `char *c=b; i = sizeof(c);`
   1.6 `struct {int d;char e;} s; i = sizeof s;`
   1.7 `void f(int j[5]) { i = sizeof j;}`
   1.8 `void f(int j[][10]) { i = sizeof j;}`
2. Use `struct` to define a data structure suitable for representing a binary tree of integers. Write a function `heapify()`, which takes a pointer to an integer array of values and a pointer to the head of an (empty) tree and builds a binary heap of the integer array values. (Hint: you'll need to use `malloc()`)
3. What other C data structure can be used to represent a heap? Would using this structure lead to a more efficient implementation of `heapify()`?

C and C++

5. Overloading — Namespaces — Classes

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C++

To quote Bjarne Stroustrup:

"C++ is a general-purpose programming language with a bias towards systems programming that:

- is a better C
- supports data abstraction
- supports object-oriented programming
- supports generic programming."

C++ fundamental types

- C++ has all the fundamental types C has
  - character literals (e.g. `'a'`) are now of type `char`
- In addition, C++ defines a new fundamental type, `bool`
- A bool has two values: `true` and `false`
- When cast to an integer, `true`→`1` and `false`→`0`
- When casting from an integer, non-zero values become `true` and `false` otherwise

C++ enumeration

- Unlike C, C++ enumerations define a new type; for example `enum flag {is_keyword=1, is_static=2, is_extern=4, ... }`
- When defining storage for an instance of an enumeration, you use its name; for example: `flag f = is_keyword`
- Implicit type conversion is not allowed:
  `f = 5; //wrong` `f = flag(5); //right`
- The maximum valid value of an enumeration is the enumeration's largest value rounded up to the nearest larger binary power minus one
- The minimum valid value of an enumeration with no negative values is zero
- The minimum valid value of an enumeration with negative values is the nearest least negative binary power

References

- C++ supports *references*, which provide an alternative name for a variable
- Generally used for specifying parameters to functions and return values as well as overloaded operators (more later)
- A reference is declared with the `&` operator; for example:
  `int i[] = {1,2}; int &refi = i[0];`
- A reference must be initialised when it is defined
- A variable referred to by a reference cannot be changed after it is initialised; for example:
  `refi++; //increments value referenced`

References in function arguments

- When used as a function parameter, a referenced value is not copied; for example:
  `void inc(int& i) { i++;} //bad style?`
- Declare a reference as `const` when no modification takes place
- It can be noticeably more efficient to pass a large struct by reference
- Implicit type conversion into a temporary takes place for a `const` reference but results in an error otherwise; for example:

```
1 float fun1(float&);
2 float fun2(const float&);
3 void test() {
4   double v=3.141592654;
5   fun1(v); //Wrong
6   fun2(v);
7 }
```


Overloaded functions

- Functions doing different things should have different names
- It is possible (and sometimes sensible!) to define two functions with the same name
- Functions sharing a name must differ in argument types
- Type conversion is used to find the "best" match
- A best match may not always be possible:

```
1 void f(double);
2 void f(long);
3 void test() {
4   f(1L);  //f(long)
5   f(1.0); //f(double)
6   f(1);   //Wrong: f(long(1)) or f(double(1)) ?
```


Scoping and overloading

- Functions in different scopes are not overloaded; for example:

```
1 void f(int);
2
3 void example() {
4   void f(double);
5   f(1); //calls f(double);
6 }
```

Default function arguments

- A function can have default arguments; for example:
  `double log(double v, double base=10.0);`
- A non-default argument cannot come after a default; for example:
  `double log(double base=10.0, double v); //wrong`
- A declaration does not need to name the variable; for example:
  `double log(double v, double=10.0);`
- Be careful of the interaction between `*` and `=`; for example:
  `void f(char*=0); //Wrong '*=' is assignment`

Namespaces

Related data can be grouped together in a *namespace*:

```
namespace Stack { //header file
void push(char);
char pop();
}
```

```
void f() { //usage
...
Stack::push('c');
...
}
```

```
namespace Stack { //implementation
const int max_size = 100;
char s[max_size];
int top = 0;

void push(char c) { ... }
char pop() { ... }
}
```


Using namespaces

- A namespace is a *scope* and expresses logical program structure
- It provides a way of collecting together related pieces of code
- A namespace without a name limits the scope of variables, functions and classes within it to the local execution unit
- The same namespace can be declared in several source files
- The global function `main()` cannot be inside a namespace
- The use of a variable or function name from a different namespace must be qualified with the appropriate namespace(s)
  - The keyword `using` allows this qualification to be stated once, thereby shortening names
  - Can also be used to generate a hybrid namespace
  - `typedef` can be used: `typedef Some::Thing thing;`
- A namespace can be defined more than once
  - Allows, for example, internal and external library definitions

Example

```
1  namespace Module1 {int x;}
2
3  namespace Module2 {
4    inline int sqr(const int& i) {return i*i;}
5    inline int halve(const int& i) {return i/2;}
6  }
7
8  using namespace Module1; //"import" everything
9
10 int main() {
11   using Module2::halve;  //"import" the halve function
12   x = halve(x);
13   sqr(x);                //Wrong
14 }
```

Linking C and C++ code

- The directive `extern "C"` specifies that the following declaration or definition should be linked as C, not C++ code:
  `extern "C" int f();`
- Multiple declarations and definitions can be grouped in curly brackets:

```
1 extern "C" {
2   int globalvar; //definition
3   int f();
4   void g(int);
5 }
```


Linking C and C++ code

- Care must be taken with pointers to functions and linkage:

```
1 extern "C" void qsort(void* p, \
2                 size_t nmemb, size_t size, \
3                 int (*compar)(const void*, const void*));
4
5 int compare(const void*,const void*);
6
7 char s[] = "some chars";
8 qsort(s,9,1,compare); //Wrong
```


User-defined types

- C++ provides a means of defining classes and instantiating objects
- Classes contain both data storage and functions which operate on storage
- Classes have access control:
  `private`, `protected` and `public`
- Classes are created with `class` or `struct` keywords
  - `struct` members default to `public` access; `class` to `private`
- A member function with the same name as a class is called a *constructor*
- A member function with the same name as the class, prefixed with a tilde (~), is called a *destructor*
- A constructor can be overloaded to provide multiple instantiation methods
- Can create `static` (i.e. per *class*) member variables

Example

```
1 class Complex {
2   double re,im;
3  public:
4   Complex(double r=0.0L, double i=0.0L);
5 };
6
7 Complex::Complex(double r,double i) {
8   re=r,im=i;
9 }
10
11 int main() {
12   Complex c(2.0), d(), e(1,5.0L);
13   return 0;
14 }
```

Constructors and destructors

- A default constructor is a function with no arguments (or only default arguments)
- If no constructor is specified, the compiler will generate one
- The programmer can specify one or more constructors
- Only one constructor is called when an object is created
- There can only be one destructor
  - This is called when a stack allocated object goes out of scope or when a heap allocated object is deallocated with `delete`; this also occurs for stack allocated objects during exception handling (more later)

Copy constructor

- A new class instance can defined by assignment; for example;

```
Complex c(1,2);
Complex d = c;
```

- In this case, the new class is initialised with copies of all the existing class' non-static member variables; no constructor is called
- This behaviour may not always be desirable (e.g. consider a class with a pointer as a member variable)
  - In which case, define an alternative *copy constructor*:
    `Complex::Complex(const Complex&) { ... }`
- If a copy constructor is not appropriate, make the copy constructor a private member function

Assignment operator

- By default a class is copied on assignment by over-writing all non-static member variables; for example:

```
1 Complex c(), d(1.0,2.3);
2 c = d; //assignment
```

- This behaviour may also not be desirable
- The assignment operator (`operator=`) can be defined explicitly:

```
1 Complex& Complex::operator=(const Complex& c) {
2   ...
3 }
```


Constant member functions

- Member functions can be declared `const`
- Prevents object members being modified by the function:

```
1 double Complex::real() const {
2   return re;
3 }
```

Arrays and the free store

- An array of class objects can be defined if a class has a default constructor
- C++ has a `new` operator to place items on the heap:
  `Complex* c = new Complex(3.4);`
- Items on the heap exist until they are explicity deleted:
  `delete c;`
- Since C++ (like C) doesn't distinguish between a pointer to an object and a pointer to an array of objects, array deletion is different:

```
1 Complex* c = new Complex[5];
2   ...
3 delete[] c; //Cannot use "delete" here
```

- When an object is deleted, the object destructor is invoked

Exercises

1. Write an implementation of a class `LinkList` which stores zero or more positive integers internally as a linked list *on the heap*. The class should provide appropriate constructors and destructors and a method `pop()` to remove items from the head of the list. The method `pop()` should return -1 if there are no remaining items. Your implementation should override the copy constructor and assignment operator to copy the linked-list structure between class instances. You might like to test your implementation with the following:

```
1 int main() {
2   int test[] = {1,2,3,4,5};
3   LinkList l1(test+1,4), l2(test,5);
4   LinkList l3=l2, l4;
5   l4=l1;
6   printf("%d %d %d\n",l1.pop(),l3.pop(),l4.pop());
7   return 0;
8 }
```

Hint: heap allocation & deallocation should occur exactly once!

C and C++

6. Operators — Inheritance — Virtual

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Operators

- C++ allows the programmer to overload the built-in operators
- For example, a new test for equality:

```
bool operator==(Complex a, Complex b) {
  return a.real()==b.real()
         && a.imag()==b.imag();
}
```

- An operator can be defined or declared within the body of a class, and in this case one fewer argument is required; for example:

```
bool Complex::operator==(Complex b) {
  return re==b.real() && im==b.imag();
}
```

- Almost all operators can be overloaded

Streams

- Overloaded operators also work with built-in types
- Overloading is used to define a C++ "`printf`"; for example:

```
#include <iostream>

int main() {
  const char* s = "char array";

  std::cout << s << std::endl;

  //Unexpected output; prints &s[0]
  std::cout.operator<<(s).operator<<(std::endl);

  //Expected output; prints s
  std::operator<<(std::cout,s);
  std::cout.operator<<(std::endl);
  return 0;
}
```


The 'this' pointer

- If an operator is defined in the body of a class, it may need to return a reference to the current object
  - The keyword `this` can be used
- For example:

```
Complex& Complex::operator+=(Complex b) {
  re += b.real();
  this->im += b.imag();
  return *this;
}
```

Class instances as member variables

- A class can have an instance of another class as a member variable
- How can we pass arguments to the class constructor?
- New notation for a constructor:

```
class X {
  Complex c;
  Complex d;
  X(double a, double b): c(a,b), d(b) {
    ...
  }
};
```

- This notation must be used to initialise const and reference members
- It can also be more efficient

Temporary objects

- Temporary objects are often created during execution
- A temporary which is not bound to a reference or named object exists only during evaluation of a *full expression*
- Example: the `string` class has a function `c_str()` which returns a pointer to a C representation of a string:

```
string a("A "), b("string");
const char *s = (a+b).c_str(); //Wrong
 ...
//s still in scope here, but the temporary holding
//"a+b" has been deallocated
 ...
```


Friends

- A (non-member) `friend` function can access the private members of a class instance it befriends
- This can be done by placing the function declaration inside the class definition and prefixing it with the keyword `friend`; for example:

```
class Matrix {
  ...
  friend Vector operator*(const Matrix&, \
                          const Vector&);
   ...
  };
}
```


Inheritance

- C++ allows a class to inherit features of another:

```
class vehicle {
  int wheels;
public:
  vehicle(int w=4):wheels(w) {}
};

class bicycle : public vehicle {
  bool panniers;
public:
  bicycle(bool p):vehicle(2),panniers(p) {}
};

int main() {
  bicycle(false);
}
```

Derived member function call

- Default derived member function call semantics differ from Java:

```
1 class vehicle {
2   int wheels;
3 public:
4   vehicle(int w=4):wheels(w) {}
5   int maxSpeed() {return 60;}
6 };
7
8 class bicycle : public vehicle {
9   int panniers;
10 public:
11   bicycle(bool p=true):vehicle(2),panniers(p) {}
12   int maxSpeed() {return panniers ? 12 : 15;}
13 };
```


Example

```
1 #include <iostream>
2 #include "example13.hh"
3
4 void print_speed(vehicle &v, bicycle &b) {
5   std::cout << v.maxSpeed() << " ";
6   std::cout << b.maxSpeed() << std::endl;
7 }
8
9 int main() {
10   bicycle b = bicycle(true);
11   print_speed(b,b); //prints "60 12"
12 }
```


Virtual functions

- Non-virtual member functions are called depending on the *static type* of the variable, pointer or reference
- Since a derived class can be cast to a base class, this prevents a derived class from overloading a function
- To get polymorphic behaviour, declare the function `virtual` in the superclass:

```
1 class vehicle {
2   int wheels;
3  public:
4   vehicle(int w=4):wheels(w) {}
5   virtual int maxSpeed() {return 60;}
6 };
```


Virtual functions

- In general, for a virtual function, selecting the right function has to be *run-time* decision; for example:

```
1 bicycle b;
2 vehicle v;
3 vehicle* pv;
4
5 user_input() ? pv = &b : pv = &v;
6
7 std::cout << pv->maxSpeed() << std::endl;
8 }
```

Enabling virtual functions

- To enable virtual functions, the compiler generates a *virtual function table* or *vtable*
- A vtable contains a pointer to the correct function for each object instance
- The vtable is an example of indirection
- The vtable introduces run-time overhead

Abstract classes

- Sometimes a base class is an un-implementable concept
- In this case we can create an abstract class:

```
class shape {
 public:
  virtual void draw() = 0;
}
```

- It is not possible to instantiate an abstract class:
  `shape s; //Wrong`
- A derived class can provide an implementation for some (or all) the abstract functions
- A derived class with no abstract functions can be instantiated

Example

```
class shape {
public:
  virtual void draw() = 0;
};

class circle : public shape {
public:
  //...
  void draw() { /* impl */ }
};
```


Multiple inheritance

- It is possible to inherit from multiple base classes; for example:

```
class ShapelyVehicle: public vehicle, public shape {
 ...
}
```

- Members from *both* base classes exist in the derived class
- If there is a name clash, explicit naming is required
- This is done by specifying the class name; for example:
  `ShapelyVehicle sv;`
  `sv.vehicle::maxSpeed();`

Multiple instances of a base class

- With multiple inheritance, we can build:

```
class A {};
class B : public A {};
class C : public A {};
class D : public B, C {};
```

- This means we have two instances of `A` even though we only have a single instance of `D`
- This is legal C++, but means all references to `A` must be stated explicitly:

```
D d;
d.B::A::var=3;
d.C::A::var=4;
```


Virtual base classes

- Alternatively, we can have a *single* instance of the base class
- Such a "virtual" base class is shared amongst all those deriving from it

```
class Vehicle {int VIN;};
class Boat : public virtual Vehicle { ... };
class Car : public virtual Vehicle { ... };
class JamesBondCar : public Boat, public Car { ... };
```


Exercises

1. If a function `f` has a static instance of a class as a local variable, when might the class constructor be called?
2. Write a class `Matrix` which allows a programmer to define two dimensional matrices. Overload the common operators (e.g. `+`, `-`, `*`, and `/`)
3. Write a class `Vector` which allows a programmer to define a vector of length two. Modify your `Matrix` and `Vector` classes so that they interoperate correctly (e.g. `v2 = m*v1` should work as expected)
4. Why should destructors in an abstract class almost always be declared `virtual`?

C and C++

7. Exceptions — Templates

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Exceptions

- Some code (e.g. a library module) may detect an error but not know what to do about it; other code (e.g. a user module) may know how to handle it
- C++ provides *exceptions* to allow an error to be communicated
- In C++ terminology, one portion of code *throws* an exception; another portion *catches* it.
- If an exception is thrown, the call stack is unwound until a function is found which catches the exception
- If an exception is not caught, the program terminates

Throwing exceptions

- Exceptions in C++ are just normal values, matched by type
- A class is often used to define a particular error type:
  `class MyError {};`
- An instance of this can then be thrown, caught and possibly re-thrown:

```
1 void f() { ... throw MyError(); ... }
2 ...
3 try {
4   f();
5 }
6 catch (MyError) {
7   //handle error
8   throw; //re-throw error
9 }
```


Conveying information

- The "thrown" type can carry information:

```
1  struct MyError {
2    int errorcode;
3    MyError(i):errorcode(i) {}
4  };
5
6  void f() { ... throw MyError(5); ... }
7
8  try {
9    f();
10 }
11 catch (MyError x) {
12   //handle error (x.errorcode has the value 5)
13   ...
14 }
```

Handling multiple errors

- Multiple catch blocks can be used to catch different errors:

```
try {
  ...
}
catch (MyError x) {
  //handle MyError
}
catch (YourError x) {
  //handle YourError
}
```

- Every exception will be caught with `catch(...)`
- Class hierarchies can be used to express exceptions:


```
#include <iostream>

struct SomeError {virtual void print() = 0;};
struct ThisError : public SomeError {
  virtual void print() {
    std::cout << "This Error" << std::endl;
  }
};
struct ThatError : public SomeError {
  virtual void print() {
    std::cout << "That Error" << std::endl;
  }
};
int main() {
  try { throw ThisError(); }
  catch (SomeError& e) { //reference, not value
    e.print();
  }
  return 0;
}
```


Exceptions and local variables

- When an exception is thrown, the stack is unwound
- The destructors of any local variables are called as this process continues
- Therefore it is good C++ design practise to wrap any locks, open file handles, heap memory etc., inside a stack-allocated class to ensure that the resources are released correctly

Templates

- Templates support *meta-programming*, where code can be evaluated at compile-time rather than run-time
- Templates support *generic programming* by allowing types to be parameters in a program
- Generic programming means we can write one set of algorithms and one set of data structures to work with objects of *any* type
- We can achieve some of this flexibility in C, by casting everything to `void *` (e.g. `sort` routine presented earlier)
- The C++ Standard Template Library (STL) makes extensive use of templates

An example: a stack

- The stack data structure is a useful data abstraction concept for objects of many different types
- In one program, we might like to store a stack of `int`s
- In another, a stack of `NetworkHeader` objects
- Templates allow us to write a single *generic* stack implementation for an unspecified type `T`
- What functionality would we like a stack to have?
  - `bool isEmpty();`
  - `void push(T item);`
  - `T pop();`
  - ...
- Many of these operations depend on the type `T`

Creating a stack template

- A class template is defined as:

```
template<class T> class Stack {
  ...
}
```

- Where `class T` can be any C++ type (e.g. `int`)
- When we wish to create an instance of a `Stack` (say to store `int`s) then we must specify the type of `T` in the declaration and definition of the object: `Stack<int> intstack;`
- We can then use the object as normal: `intstack.push(3);`
- So, how do we implement `Stack`?
  - Write `T` whenever you would normally use a concrete type


```
template<class T> class Stack {

  struct Item { //class with all public members
    T val;
    Item* next;
    Item(T v) : val(v), next(0) {}
  };

  Item* head;

  Stack(const Stack& s) {}            //private
  Stack& operator=(const Stack& s) {} //

public:
  Stack() : head(0) {}
  ~Stack();
  T pop();
  void push(T val);
  void append(T val);
};
```



```
#include "example16.hh"

template<class T> void Stack<T>::append(T val) {
  Item **pp = &head;
  while(*pp) {pp = &((*pp)->next);}
  *pp = new Item(val);
}

//Complete these as an exercise
template<class T> void Stack<T>::push(T) {/* ... */}
template<class T> T Stack<T>::pop() {/* ... */}
template<class T> Stack<T>::~Stack() {/* ... */}

int main() {
  Stack<char> s;
  s.push('a'), s.append('b'), s.pop();
}
```

Template details

- A template parameter can take an integer value instead of a type:
  `template<int i> class Buf { int b[i]; ... };`
- A template can take several parameters:
  `template<class T,int i> class Buf { T b[i]; ... };`
- A template can even use one template parameter in the definition of a subsequent parameter:
  `template<class T, T val> class A { ... };`
- A templated class is not type checked until the template is instantiated:
  `template<class T> class B {const static T a=3;};`
  - `B<int> b;` is fine, but what about `B<B<int> > bi;`?
- Template definitions often need to go in a header file, since the compiler needs the source to instantiate an object

Default parameters

- Template parameters may be given default values

```
1 template <class T,int i=128> struct Buffer{
2   T buf[i];
3 };
4
5 int main() {
6   Buffer<int> B; //i=128
7   Buffer<int,256> C;
8 }
```


Specialization

- The `class T` template parameter will accept any type `T`
- We can define a *specialization* for a particular type as well:

```
1 #include <iostream>
2 class A {};
3
4 template<class T> struct B {
5   void print() { std::cout << "General" << std::endl;}
6 };
7 template<> struct B<A> {
8   void print() { std::cout << "Special" << std::endl;}
9 };
10
11 int  main() {
12   B<A> b1;
13   B<int> b2;
14   b1.print(); //Special
15   b2.print(); //General
16 }
```


Templated functions

- A function definition can also be specified as a template; for example:

```
1 template<class T> void sort(T a[],
2                             const unsigned int& len);
```

- The type of the template is inferred from the argument types:
  `int a[] = {2,1,3}; sort(a,3);` $\Longrightarrow$ `T` is an `int`
- The type can also be expressed explicitly:
  `sort<int>(a)`
- There is no such type inference for templated classes
- Using templates in this way enables:
  - better type checking than using `void *`
  - potentially faster code (no function pointers)
  - larger binaries if `sort()` is used with data of many different types

```cpp
#include <iostream>

template<class T> void sort(T a[], const unsigned int& len) {
  T tmp;
  for(unsigned int i=0;i<len-1;i++)
    for(unsigned int j=0;j<len-1-i;j++)
      if (a[j] > a[j+1]) //type T must support "operator>"
       tmp = a[j], a[j] = a[j+1], a[j+1] = tmp;
}

int main() {
  const unsigned int len = 5;
  int a[len] = {1,4,3,2,5};
  float f[len] = {3.14,2.72,2.54,1.62,1.41};

  sort(a,len), sort(f,len);
  for(unsigned int i=0; i<len; i++)
    std::cout << a[i] << "\t" << f[i] << std::endl;
}
```


Overloading templated functions

- Templated functions can be overloaded with templated and non-templated functions
- Resolving an overloaded function call uses the "most specialised" function call
- If this is ambiguous, then an error is given, and the programmer must fix by:
  - being explicit with template parameters (e.g. `sort<int>(...)`)
  - re-writing definitions of overloaded functions
- Overloading templated functions enables meta-programming:

Meta-programming example

```cpp
#include <iostream>

template<unsigned int N> inline long long int fact() {
  return N*fact<N-1>();
}

template<> inline long long int fact<0>() {
  return 1;
}

int main() {
  std::cout << fact<20>() << std::endl;
}
```


Exercises

1. Provide an implementation for:
   `template<class T> T Stack<T>::pop();` and
   `template<class T> Stack<T>::~Stack();`
2. Provide an implementation for:
   `Stack(const Stack& s);` and
   `Stack& operator=(const Stack& s);`
3. Using meta programming, write a templated class `prime`, which evaluates whether a literal integer constant (e.g. 7) is prime or not at compile time.
4. How can you be sure that your implementation of class `prime` has been evaluated at compile time?

C and C++

8. The Standard Template Library

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The STL

Alexander Stepanov, designer of the Standard Template Library says:

"STL was designed with four fundamental ideas in mind:

- Abstractness
- Efficiency
- Von Neumann computational model
- Value semantics"

It's an example of *generic* programming; in other words reusable or "widely adaptable, but still efficient" code

Additional references

- Musser et al (2001). STL Tutorial and Reference Guide (Second Edition). Addison-Wesley.
- `http://gcc.gnu.org/onlinedocs/libstdc++/documentation.html`

Advantages of generic programming

- Traditional container libraries place algorithms as member functions of classes
  - Consider, for example, `"test".substring(1,2);` in Java
- So if you have m container types and n algorithms, that's nm pieces of code to write, test and document
- Also, a programmer may have to copy values between container types to execute an algorithm
- The STL does not make algorithms member functions of classes, but uses meta programming to allow programmers to link containers and algorithms in a more flexible way
- This means the library writer only has to produce $n + m$ pieces of code
- The STL, unsurprisingly, uses templates to do this

Plugging together storage and algorithms

Basic idea:

- define useful data storage components, called *containers*, to store a set of objects
- define a generic set of access methods, called *iterators*, to manipulate the values stored in containers of any type
- define a set of *algorithms* which use containers for storage, but only access data held in them through iterators

The time and space complexity of containers and algorithms is specified in the STL standard

A simple example

```
1 #include <iostream>
2 #include <vector>  //vector<T> template
3 #include <numeric> //required for accumulate
4
5 int  main() {
6   int i[] = {1,2,3,4,5};
7   std::vector<int> vi(&i[0],&i[5]);
8
9   std::vector<int>::iterator viter;
10
11  for(viter=vi.begin(); viter < vi.end(); ++viter)
12    std::cout << *viter << std::endl;
13
14  std::cout << accumulate(vi.begin(),vi.end(),0) << std::endl;
15 }
```


Containers

- The STL uses *containers* to store collections of objects
- Each container allows the programmer to store multiple objects of the same type
- Containers differ in a variety of ways:
  - memory efficiency
  - access time to arbitrary elements
  - arbitrary insertion cost
  - append and prepend cost
  - deletion cost
  - ...

Containers

- Container examples for storing sequences:
  - `vector<T>`
  - `deque<T>`
  - `list<T>`
- Container examples for storing associations:
  - `set<Key>`
  - `multiset<Key>`
  - `map<Key,T>`
  - `multimap<Key, T>`

Using containers

```
#include <string>
#include <map>
#include <iostream>

int main() {

  std::map<std::string,std::pair<int,int> > born_award;

  born_award["Perlis"] = std::pair<int,int>(1922,1966);
  born_award["Wilkes"] = std::pair<int,int>(1913,1967);
  born_award["Hamming"] = std::pair<int,int>(1915,1968);
  //Turing Award winners (from Wikipedia)

  std::cout << born_award["Wilkes"].first << std::endl;

  return 0;
}
```


std::string

- Built-in arrays and the `std::string` hold elements and can be considered as containers in most cases
- You can't call "`.begin()`" on an array however!
- Strings are designed to interact well with C char arrays
- String assignments, like containers, have value semantics:

```
#include <iostream>
#include <string>

int main() {
  char s[] = "A string ";
  std::string str1 = s, str2 = str1;

  str1[0]='a', str2[0]='B';
  std::cout << s << str1 << str2 << std::endl;
  return 0;
}
```


Iterators

- Containers support *iterators*, which allow access to values stored in a container
- Iterators have similar semantics to pointers
  - A compiler may represent an iterator as a pointer at run-time
- There are a number of different types of iterator
- Each container supports a subset of possible iterator operations
- Containers have a concept of a `begin`ning and `end`

Iterator types

Iterator type	Supported operators
Input	`== != ++ *`(read only)
Output	`== != ++ *`(write only)
Forward	`== != ++ *`
Bidirectional	`== != ++ * --`
Random Access	`== != ++ * -- + - += -= < > <= >=`

- Notice that, with the exception of input and output iterators, the relationship is hierarchical
- Whilst iterators are organised logically in a hierarchy, they do not do so formally through inheritence!
- There are also const iterators which prohibit writing to ref'd objects

Adaptors

- An adaptor modifies the interface of another component
- For example the `reverse_iterator` modifies the behaviour of an `iterator`

```
#include <vector>
#include <iostream>

int main() {
  int i[] = {1,3,2,2,3,5};
  std::vector<int> v(&i[0],&i[6]);

  for (std::vector<int>::reverse_iterator i = v.rbegin();
       i != v.rend(); ++i)
    std::cout << *i << std::endl;

  return 0;
}
```


Generic algorithms

- Generic algorithms make use of iterators to access data in a container
- This means an algorithm need only be written once, yet it can function on containers of many different types
- When implementing an algorithm, the library writer tries to use the most restrictive form of iterator, where practical
- Some algorithms (e.g. `sort`) cannot be written efficiently using anything other than random access iterators
- Other algorithms (e.g. `find`) can be written efficiently using only input iterators
- Lesson: use common sense when deciding what types of iterator to support
- Lesson: if a container type doesn't support the algorithm you want, you are probably using the wrong container type!

Algorithm example

- Algorithms usually take a `start` and `finish` iterator and assume the valid range is `start` to `finish-1`; if this isn't true the result is undefined

Here is an example routine `search` to find the first element of a storage container which contains the value `element`:

```
//search: similar to std::find
template<class I,class T> I search(I start, I finish, T element) {
  while (*start != element && start != finish)
    ++start;
  return start;
}
```


Algorithm example

```
#include "example23.hh"

#include "example23a.cc"

int main() {
  char s[] = "The quick brown fox jumps over the lazy dog";
  std::cout << search(&s[0],&s[strlen(s)],'d') << std::endl;

  int i[] = {1,2,3,4,5};
  std::vector<int> v(&i[0],&i[5]);
  std::cout << search(v.begin(),v.end(),3)-v.begin()
            << std::endl;

  std::list<int> l(&i[0],&i[5]);
  std::cout << (search(l.begin(),l.end(),4)!=l.end())
            << std::endl;

  return 0;
}
```

Heterogeneity of iterators

```
#include "example24.hh"

int main() {
  char one[] = {1,2,3,4,5};
  int two[] = {0,2,4,6,8};
  std::list<int> l (&two[0],&two[5]);
  std::deque<long> d(10);

  std::merge(&one[0],&one[5],l.begin(),l.end(),d.begin());

  for(std::deque<long>::iterator i=d.begin(); i!=d.end(); ++i)
    std::cout << *i << " ";
  std::cout << std::endl;

  return 0;
}
```


Function objects

- C++ allows the function call "`()`" to be overloaded
- This is useful if we want to pass functions as parameters in the STL
- More flexible than function pointers, since we can store per-instance object state inside the function
- Example:

```
struct binaccum {
  int operator()(int x, int y) const {return 2*x + y;}
};
```


Higher-order functions in C++

- In ML we can write: `foldl (fn (y,x) => 2*x+y) 0 [1,1,0];`
- Or in Python: `reduce(lambda x,y: 2*x+y, [1,1,0])`
- Or in C++:

```
#include<iostream>
#include<numeric>
#include<vector>

#include "example27a.cc"

int main() { //equivalent to foldl

  bool binary[] = {true,true,false};
  std::cout<< std::accumulate(&binary[0],&binary[3],0,binaccum())
           << std::endl; //output: 6

  return 0;
}
```


Higher-order functions in C++

- By using reverse iterators, we can also get foldr:

```
#include<iostream>
#include<numeric>
#include<vector>

#include "example27a.cc"

int main() { //equivalent to foldr

  bool binary[] = {true,true,false};
  std::vector<bool> v(&binary[0],&binary[3]);

  std::cout << std::accumulate(v.rbegin(),v.rend(),0,binaccum());
  std::cout << std::endl; //output: 3

  return 0;
}
```