C and C++

1. Types — Variables — Expressions & Statements

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(with thanks to Alastair R. Beresford and Bjarne Stroustrup)

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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. (2000). The C++ Programming Language Special Edition (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
- 2008 Paper 3 Question 3   2008 Paper 10 Question 4
- 2009 Paper 3 Question 1
- 2010 Paper 3 Question 6

* 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)
- 201? C++0x - the next ISO C++ standard

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:

```
int i = 1234;
char c;
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

```
#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:
  - $\underline{\text{exp}}$ `?` $\underline{\text{exp}}$ `:` $\underline{\text{exp}}$
  - `if (`$\underline{\text{exp}}$`)` $stmt_1$ `else` $stmt_2$
  - `switch(`$\underline{\text{exp}}$`) {`
    `case` exp_1`:`
    $stmt_1$
    ...
    `default:`
    $stmt_{n+1}$
    `}`
  - `while (`$\underline{\text{exp}}$`)` $\underline{\text{stmt}}$
  - `for (` exp_1`;` exp_2`;` exp_3 `)` $\underline{\text{stmt}}$
  - `do` $\underline{\text{stmt}}$ `while (`$\underline{\text{exp}}$`);`
- 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 <u>required</u>
- 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:
```

<u>fix problem, or abort</u>

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:

```

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

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 "`<u>filename</u>`"`   `#include <`<u>filename</u>`>`

- Both forms replace the `#include ...` line in the source file with the contents of <u>filename</u>
- 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 `#define`d; `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 `#define`d 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:

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

```
#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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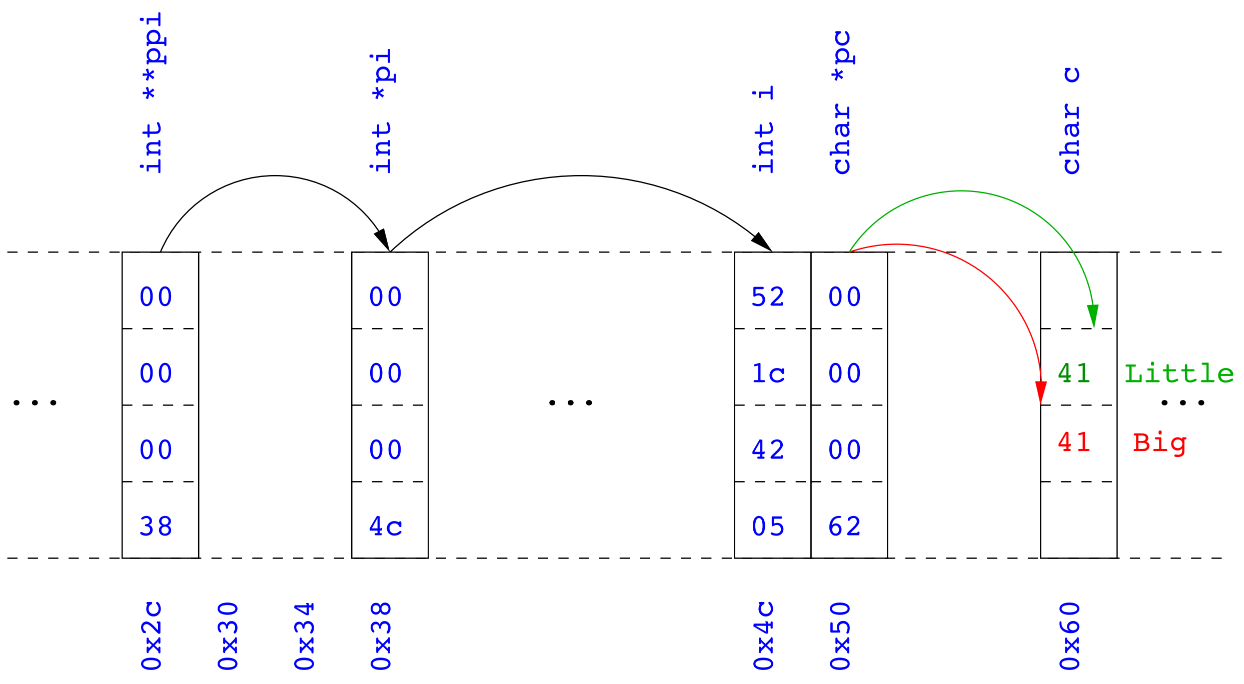
Pointers

- 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

```
#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)`:

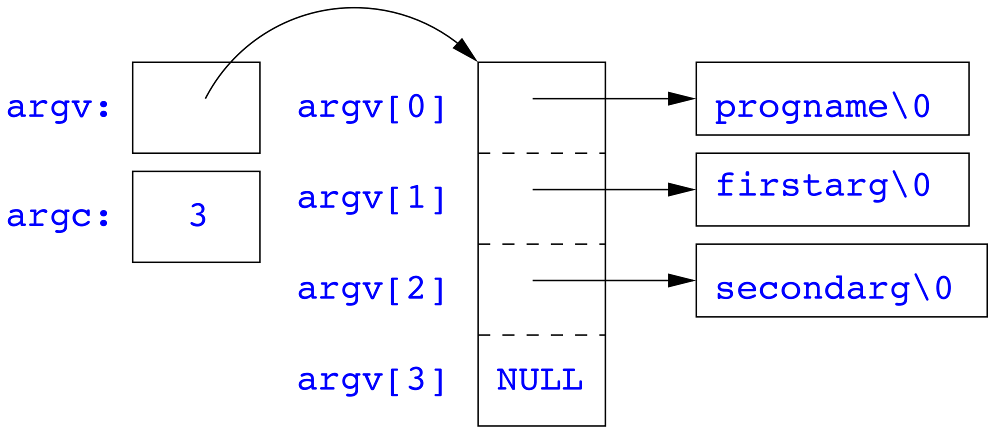
```
void swp1(int x,int y)
{
  int temp = x;
  x = y;
  y = temp;
}
```

```
void swp2(int *px,int *py)
{
  int temp = *px;
  *px = *py;
  *py = temp;
}
```

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

```
void sort(int a[], const int len,
          int (*compare)(int, int))
{
  int i,j,tmp;
  for(i=0;i<len-1;i++)
    for(j=0;j<len-1-i;j++)
      if ((*compare)(a[j],a[j+1]))
       tmp=a[j], a[j]=a[j+1], a[j+1]=tmp;
}

int inc(int a, int b) {
  return a > b ? 1 : 0;
}
```

Example

```c
#include <stdio.h>
#include "example8.h"

int main(void) {
  int a[] = {1,4,3,2,5};
  unsigned int len = 5;
  sort(a,len,inc); //or sort(a,len,&inc);

  int *pa = a; //C99
  printf("[");
  while (len--)
    printf("%d%s",*pa++,len?" ":"");
  printf("]\n");

  return 0;
}
```

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:

```c
sort(void *p, const unsigned int len,
     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:

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

```
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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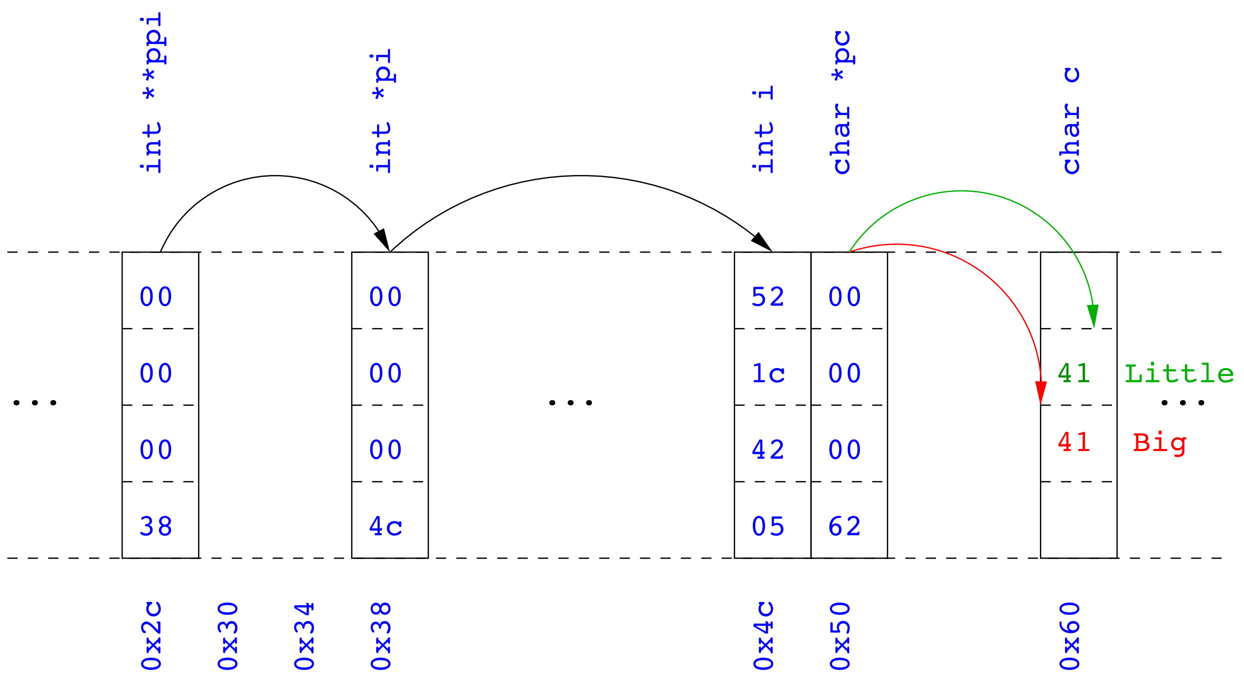
Michaelmas Term 2010

Example



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

```c
int main(void) {
  int i = 42;
  int j = 28;

  const int *pc = &i;         //Also: "int const *pc"
  *pc = 41;                   //Wrong
  pc = &j;

  int *const cp = &i;
  *cp = 41;
  cp = &j;                    //Wrong

  const int *const cpc = &i;
  *cpc = 41;                  //Wrong
  cpc = &j;                   //Wrong
  return 0;
}
```

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:

```c
typedef struct llist *llptr;
typedef struct llist {
  int val;
  llptr next;
} linklist;
```

In-line functions

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

```c
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, ...);
```

```c
#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

```c
#include<stdio.h>

struct test {int i;};
typedef struct test test_t;

int main(void) {

  test_t a,b;
  test_t *p[] = {&a,&b};
  p[0]->i=0;
  p[1]->i=0;
  test_t *q = p[0];

  printf("%d\n",++q->i); //What does this do?

  return 0;
}
```

Gotchas: `i++`

```c
#include <stdio.h>

int main(void) {

  int i=2;
  int j=i++ + ++i;
  printf("%d %d\n",i,j); //What does this print?

  return 0;
}
```

Gotchas: local stack

```c
#include <stdio.h>

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

int main(void) {

  printf("%s\n",unary(6)); //What does this print?

  return 0;
}
```

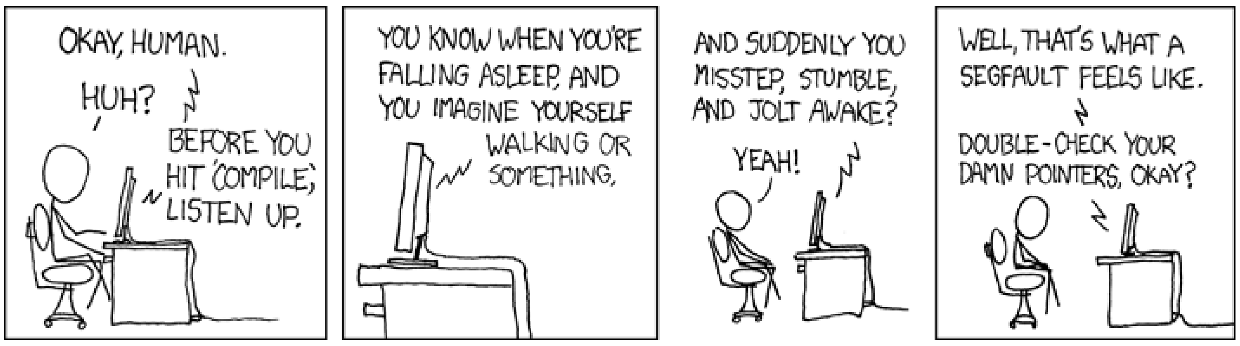
Gotchas: local stack (contd.)

```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;
}
```

Gotchas: XKCD pointers


OKAY, HUMAN.
HUH?
BEFORE YOU HIT 'COMPILE,' LISTEN UP.
YOU KNOW WHEN YOU'RE FALLING ASLEEP, AND YOU IMAGINE YOURSELF WALKING OR SOMETHING,
AND SUDDENLY YOU MISSTEP, STUMBLE, AND JOLT AWAKE?
YEAH!
WELL, THAT'S WHAT A SEGFAULT FEELS LIKE.
DOUBLE-CHECK YOUR DAMN POINTERS, OKAY?

Tricks: Duff's device

```
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 21st January 2011
- Sign-up sheet removed midday on 21st January 2011
- Viva examinations 1300-1600 on 3rd February 2011
- Viva examinations 1300-1600 on 4th February 2011
- 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
- Comprehending man pages

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

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Version|  IHL  |Type of Service|          Total Length         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Identification        |Flags|      Fragment Offset    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Time to Live |    Protocol   |         Header Checksum       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Source Address                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination Address                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Options                    |    Padding    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

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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Michaelmas Term 2010

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:

```
float fun1(float&);
float fun2(const float&);
void test() {
  double v=3.141592654;
  fun1(v); //Wrong
  fun2(v);
}
```

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:

```
void f(double);
void f(long);
void test() {
  f(1L);  //f(long)
  f(1.0); //f(double)
  f(1);   //Wrong: f(long(1)) or f(double(1)) ?
```

Scoping and overloading

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

```
void f(int);

void example() {
  void f(double);
  f(1); //calls f(double);
}
```

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

```
namespace Module1 {int x;}

namespace Module2 {
  inline int sqr(const int& i) {return i*i;}
  inline int halve(const int& i) {return i/2;}
}

using namespace Module1; //"import" everything

int main() {
  using Module2::halve;  //"import" the halve function
  x = halve(x);
  sqr(x);                //Wrong
}
```

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:

```
extern "C" {
  int globalvar; //definition
  int f();
  void g(int);
}
```

Linking C and C++ code

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

```
extern "C" void qsort(void* p, \
                size_t nmemb, size_t size, \
                int (*compar)(const void*, const void*));

int compare(const void*,const void*);

char s[] = "some chars";
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

```
class Complex {
  double re,im;
 public:
  Complex(double r=0.0L, double i=0.0L);
};

Complex::Complex(double r,double i) {
  re=r,im=i;
}

int main() {
  Complex c(2.0), d(), e(1,5.0L);
  return 0;
}
```

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:

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

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

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

Constant member functions

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

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

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:

```
Complex* c = new Complex[5];
  ...
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:

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

Hint: heap allocation & deallocation should occur exactly once!

C and C++

6. Operators — Inheritance — Virtual

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(with thanks to Alastair R. Beresford and Bjarne Stroustrup)

Michaelmas Term 2010

From last lecture . . .

```
class Complex {
  double re,im;
 public:
  Complex(double r=0.0L, double i=0.0L);
};

Complex::Complex(double r,double i) {
  re=r,im=i;
}

int main() {
  Complex c(2.0), d(), e(1,5.0L);
  return 0;
}
```

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 *s1 = a.c_str();     //Okay
const char *s2 = (a+b).c_str(); //Wrong
 ...
//s still in scope here, but the temporary holding
//"a+b" has been deallocated
 ...
string tmp = a+b;
const char *s3 = tmp.c_str();   //Okay
```

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:

```
class vehicle {
  int wheels;
public:
  vehicle(int w=4):wheels(w) {}
  int maxSpeed() {return 60;}
};

class bicycle : public vehicle {
  int panniers;
public:
  bicycle(bool p=true):vehicle(2),panniers(p) {}
  int maxSpeed() {return panniers ? 12 : 15;}
};
```

Example

```
#include <iostream>
#include "example13.hh"

void print_speed(vehicle &v, bicycle &b) {
  std::cout << v.maxSpeed() << " ";
  std::cout << b.maxSpeed() << std::endl;
}

int main() {
  bicycle b = bicycle(true);
  print_speed(b,b); //prints "60 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:

```
class vehicle {
  int wheels;
 public:
  vehicle(int w=4):wheels(w) {}
  virtual int maxSpeed() {return 60;}
};
```

Virtual functions

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

```
bicycle b(true);
vehicle v;
vehicle* pv;

user_input() ? pv = &b : pv = &v;

std::cout << pv->maxSpeed() << std::endl;
}
```

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, public 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::var=3;
d.C::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:

```
void f() { ... throw MyError(); ... }
...
try {
  f();
}
catch (MyError) {
  //handle error
  throw; //re-throw error
}
```

Conveying information

- The “thrown” type can carry information:

```
struct MyError {
  int errorcode;
  MyError(i):errorcode(i) {}
};

void f() { ... throw MyError(5); ... }

try {
  f();
}
catch (MyError x) {
  //handle error (x.errorcode has the value 5)
  ...
}
```

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

```
template <class T,int i=128> struct Buffer{
  T buf[i];
};

int main() {
  Buffer<int> B; //i=128
  Buffer<int,256> C;
}
```

Specialization

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

```cpp
#include <iostream>
class A {};

template<class T> struct B {
  void print() { std::cout << "General" << std::endl;}
};
template<> struct B<A> {
  void print() { std::cout << "Special" << std::endl;}
};

int  main() {
  B<A> b1;
  B<int> b2;
  b1.print(); //Special
  b2.print(); //General
}
```

Templated functions

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

```cpp
template<class T> void sort(T a[],
                            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. JNI and STL

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JNI — Java Native Interface

Java Native Interface (JNI) is the Java interface to non-Java code.

- interoperate with applications and libraries writtern in other programming languages (e.g., C, C++, assembly)

Examples we will look at:

- Embedding C in Java
- Using Java from C

Why use JNI?

- Low-level specifics not provided by Java
- Performance (java is not famous for being fast)
- Legacy code wrapper

Justification

Pro:

- Reuse: allow access to useful native code
- Efficiency: use best language for the right task

Cons:

- Applets: mobility makes this painful
- Portability: native methods aren't portable
- Extra work: `javah`, creating shared library

Embedding C in Java

1. Declare the method using the keyword native (without implementatin)
2. (Make sure Java loads the required library)
3. Run `javah` to generate names & headers
4. Implement the method in C
5. Compile as a shared library

```
class HelloWorld
{
        public native void displayHelloWorld();
        static
     {
                        System.loadLibrary("hello");
        }
        public static void main(String[] args)
        {
                        new HelloWorld().displayHelloWorld();
        }
}
```

Generate JNI Header

Compile HelloWorld.java

```
$ javac HelloWorld.java
```

Create HelloWorld.h

```
$ javah HelloWorld
```

HelloWorld.h

```c
#include <jni.h>
/* Header for class HelloWorld */
#ifndef _Included_HelloWorld
#define _Included_HelloWorld
#ifdef __cplusplus
extern "C" {
#endif
/*
 * Class:     HelloWorld
 * Method:    displayHelloWorld
 * Signature: ()V
 */
JNIEXPORT void JNICALL Java_HelloWorld_displayHelloWorld
  (JNIEnv *, jobject);

#ifdef __cplusplus
}
#endif
#endif
```

HelloWorldImp.c

```c
#include <jni.h>
#include "HelloWorld.h"
#include <stdio.h>

JNIEXPORT void JNICALL
Java_HelloWorld_displayHelloWorld(JNIEnv *env, jobject obj)
{
    printf("Hello world!\n");
    return;
}
```

Create a Shared Library

```java
class HelloWorld
{
   . . .
                        System.loadLibrary("hello");
   . . .
}
```

Compile the native code into a shared library:

(on pwf, other OS may require the `-I` option)

```
cc -shared HelloWorldImpl.c -o libhello.so
```

Run the Program

```
$ java HelloWorld
```

Sometimes:

```
Hello World!
```

Othertimes:

```
Exception in thread "main" java.lang.UnsatisfiedLinkError: no hello
       at java.lang.ClassLoader.loadLibrary(ClassLoader.java:1698)
       at java.lang.Runtime.loadLibrary0(Runtime.java:840)
       at java.lang.System.loadLibrary(System.java:1047)
       at HelloWorld.<clinit>(HelloWorld.java:6)
Could not find the main class: HelloWorld. Program will exit.
```

Problems? set your LD_LIBRARY_PATH:

```
export LD_LIBRARY_PATH=.
```

Primitive Types and Native Equivalents

Some examples:

```
typedef unsigned char   jboolean; // 8, unsigned
typedef unsigned short  jchar; // 16, unsigned
typedef short           jshort; // 16
typedef float           jfloat; // 32
typedef double          jdouble; // 64
```

Each Java language element must have a corresponding native equivalent

- Platform-specific implementation
- Generic programming interface

The JNIEnv *env argument

- passed to every native method as the first argument.
- contains function entries used by native code.
- organized like a C++ virtual function table.

In C: `(*env)->(env,foo);`

In C++: `env->(foo);`

Through JNI interface pointer, native code can:

- operate on classes (loading, checking, etc.)
- catch and throw exceptions
- access fields
- call methods
- manipulate strings and arrays
- enter/exit monitors

Accessing Java Strings

The jstring type is not equivalent to the C string type

```
/* Wrong way */
JNIEXPORT jstring JNICALL Java_Prompt_getLine(JNIEnv *env, \
jobject obj, jstring prompt)
{
printf("%s", prompt); ...
}
/* Right way */
JNIEXPORT jstring JNICALL Java_Prompt_getLine(JNIEnv *env,\
 jobject obj, jstring prompt)
{
char buf[128];
const char *str = (*env)->GetStringUTFChars(env, prompt, 0);
printf("%s", str);
/* release the memory allocated for the string operation */
(*env)->ReleaseStringUTFChars(env, prompt, str); ...
}
```

Accessing Java Array

```
/* Wrong way */
JNIEXPORT jint JNICALL Java_IntArray_sumArray(JNIEnv *env, \
jobject obj, jintArray arr) {
int i, sum = 0;
for (i=0; i<10; i++)  {
sum += arr[i];
} ...
/* Right way */
JNIEXPORT jint JNICALL Java_IntArray_sumArray(JNIEnv *env, \
jobject obj, jintArray arr) {
int i, sum = 0;
/* 1. obtain the length of the array */
jsize len = (*env)->GetArrayLength(env, arr);
/* 2. obtain a pointer to the elements of the array */
jint *body = (*env)->GetIntArrayElements(env, arr, 0);
/* 3. operate on each individual elements */
for (i=0; i<len; i++) { sum += body[i]; }
/* 4. release the memory allocated for array */
(*env)->ReleaseIntArrayElements(env, arr, body, 0);
```

Accessing Java Member Variables

```
class FieldAccess {
  static int si; /* signature is "si" */
  String s;      /* signature is "Ljava/lang/String;";
}   /* run javap -s -p FieldAccess to get the signature */

  /* 1. get the field ID */
fid = (*env)->GetStaticFieldID(env, cls, "si", "I");
  /* 2. find the field variable */
si = (*env)->GetStaticIntField(env, cls, fid);
  /* 3. perform operation on the primitive*/
(*env)->SetStaticIntField(env, cls, fid, 200);

  /* 1. get the field ID */
fid = (*env)->GetFieldID(env, cls, "s", "Ljava/lang/String;");
  /* 2. find the field variable */
jstr = (*env)->GetObjectField(env, obj, fid);
  /* 3. perform operation on the object */
jstr = (*env)->NewStringUTF(env, "123");
(*env)->SetObjectField(env, obj, fid, jstr);
```

Calling a Java Method

1. Find the class of the object
   Call GetObjectClass
2. Find the method ID of the object
   Call GetMethodID, which performs a lookup for the Java method in a given class
3. Call the method
   JNI provides an API for each method-type
   e.g., CallVoidMethod(), etc.
   You pass the object, method ID, and the actual arguments to the method (e.g., CallVoidMethod)

```
jclass cls = (*env)->GetObjectClass(env, obj);
jmethodID mid = (*env)->GetMethodID(env,cls,''hello'',''(I)V'')
(*env)->CallVoidMethod(env,obj,mid,parm1);
```

Garbage Collection & Thread Issues

- Arrays and (explicit) global objects are *pinned* and must be explicitly released
- Everything else is released upon the native method returning

(JNIEnv *) is *only* valid in the current thread

- Interface pointer are not valid to pass between threads
- Local references are not valid to pass between threads
- Thread access to global variables requires locking

Synchronization

- Synchronize is availble as a C call
- Wait and Notify calls through JNIEnv do work and are safe to use

```
In Java:
synchronized(obj)
{ ...
   /* synchronized block */
... }
```

```
In C:
(*env)->MonitorEnter(env,obj);

/* synchronized block */

(*env)->MonitorExit(env,obj);
```

Embedding a JVM in C

- JDK ships JVM as a shared library
- This is handled as a special funcition-call from C
- Call does not return
- The call provides a pointer for access from native code

JVMinC.c

```c
#include <stdlib.h>
#include <jni.h>
int main(int argc, char *argv[]) {
    JNIEnv *env;
    JavaVM *jvm;
    jint res;
    jclass cls;
    jmethodID mid;
    jstring jstr;
    jobjectArray args;
    JavaVMInitArgs vm_args;
    JavaVMOption options[4];
/* disable JIT */
    options[0].optionString = "-Djava.compiler=NONE";
/* set user class and native library path */
    options[1].optionString = "-Djava.class.path=.";
    options[2].optionString = "-Djava.library.path=.";
/* print JNI-related messages */
    options[3].optionString = "-verbose:jni";
```

JVMinC.c (cont.)

```c
   vm_args.version = JNI_VERSION_1_4;
   vm_args.options = options;
   vm_args.nOptions = 4;
   vm_args.ignoreUnrecognized = 1;
/* spawn JVM, find class and the class entry-point */
   res = JNI_CreateJavaVM(&jvm, (void **)&env, &vm_args);
   cls = (*env)->FindClass(env, "JVMinCTest");
   mid = (*env)->GetStaticMethodID(env, cls, "main", \
      "([Ljava/lang/String;)V");
/* create a valid string to pass */
   jstr = (*env)->NewStringUTF(env, " from C!");
   args = (*env)->NewObjectArray(env, 1, \
      (*env)->FindClass(env, "java/lang/String"), jstr);
/* Run and cleanup */
   (*env)->CallStaticVoidMethod(env, cls, mid, args);
   (*jvm)->DestroyJavaVM(jvm);
   return 0;
}
```

Compiling Embedded JVM and C

```java
public class JVMinCTest
{
   public static void main(String [] args)
   {
      System.out.println("Hello from JVMinCTest");
      System.out.println("String passed from C: " + args[0]);
   }
}
```

To compile

```
$ javac JVMinCTest
$ cc JVMinC.c -o JVMinC -L
/usr/lib/jvm/java-1.6.0-openjdk-1.6.0/jre/lib/i386/client/
-ljvm
```

Running:

```
$ ./JVMinCTest Hello from JVMinCTest
String passed from C: from C!
$
```

Standard Template Library - bonus material

(Templates are examinable however, STL is NOT examinable for 2009/2010)

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

```cpp
#include <iostream>
#include <vector>  //vector<T> template
#include <numeric> //required for accumulate

int  main() {
  int i[] = {1,2,3,4,5};
  std::vector<int> vi(&i[0],&i[5]);

  std::vector<int>::iterator viter;

  for(viter=vi.begin(); viter < vi.end(); ++viter)
    std::cout << *viter << std::endl;

  std::cout << accumulate(vi.begin(),vi.end(),0) << std::endl;
}
```

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`

```cpp
#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;
}
```