Programming in C and C++

7. C++: Exceptions and 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:

```cpp
#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;
  }

};
```

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 practice to wrap any locks, open file handles, heap memory etc., inside stack-allocated object(s), with constructors doing allocation and destructors doing deallocation. This design pattern is analogous to Java's try-finally, and is often refered to as "RAII: Resource Allocation is Initialisation".

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 <u>generic</u> 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();       // should generally be virtual
  T pop();
  void push(T val);
  void append(T val);
};
```

```
#include "example16.hh"
#include <iostream>

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();
  s.push(10);
  return 0;
}
```

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;
}
```

Specialisation

- The `class T` template parameter will accept any type `T`
- We can define a specialisation for a particular type as well (effectively type comparison at compile-time)

```
#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:

```
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,3)`
- 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 in vtables)
  - larger binaries if `sort()` is used with data of many different types

```
#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

```
#include <iostream>

template<unsigned int N>
struct fact {
  static const long int value = N * fact<N-1>::value;
  char v[value];  // value is computed at compile time!
};

template<>
struct fact<0> {
  static const long int value = 1;
};

int v = 8;
struct fact<v> foo;  // struct with char v[5040] and a const.
int main() {
  std::cout << sizeof(foo) << ", " << foo.value << std::endl;
}
```

Templates are a Turing-complete compile-time programming language.

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?