Templates

Giuseppe Lipari
http://retis.sssup.it

Scuola Superiore Sant'Anna – Pisa

June 8, 2009

Reuse

- One of the most important keywords in OO programming is code reuse
- If you have a piece of code that works correctly, you want to reuse it as much as you can:
  - because it has been tested and used, so there is more probability that it contains less bugs
  - because you do not need to redo the same thing again (so you save time and production cost)
- We have already seen that reusing software is far from being trivial (see the LSP section in the 04.inher.pdf).
- However, it is the *lapis philosophorum* (Philosopher's Stone) of all programmers

Reuse though inheritance

- In the previous slides, we have seen one particular OO technique for reusing code: inheritance
  - it achieves reuse through abstraction
  - a concept is abstracted, and then a hierarchy of concepts are linked togheter through inheritance
  - however, inheritance may not be the best approach to reuse!

Containers

- Consider the problem of providing a generic container of objects
- Example
  - We designed and developed a Stack class container
  - it is an object that *contains* other objects, and provides operations for inserting, extracting, finding object, and visiting them in a certain order
  - Our stack class contains integers
  - However, the code is generic enough and depends only in minimal part from the fact that it contains integers
- Problem:
  - How to extend it to contains other types of objects?
  - for example, Shapes

Cut & Paste

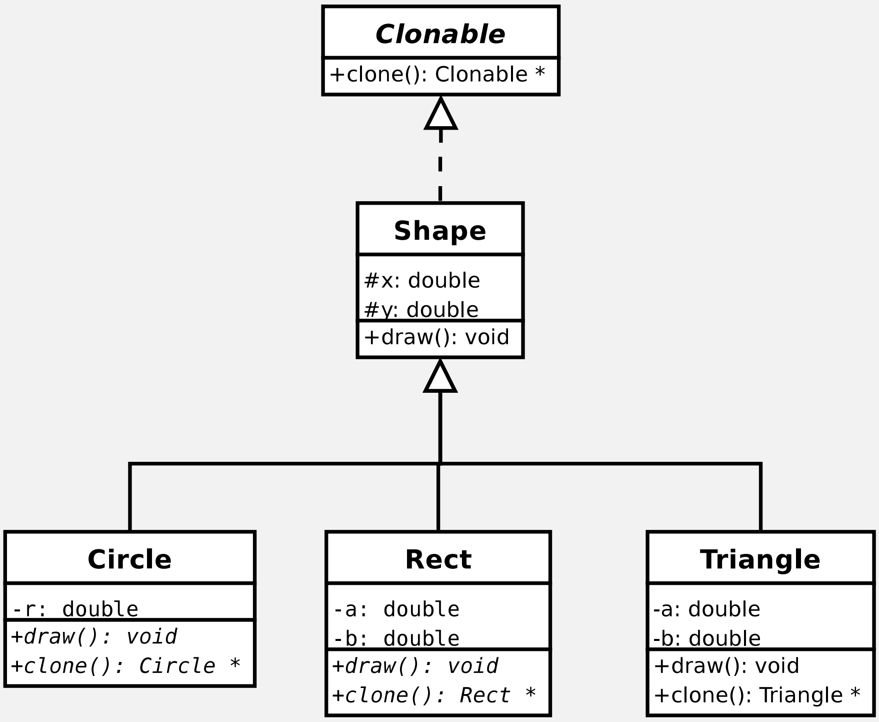
- In the early days of programming the solution would have been:
  - Copy and paste the code
  - modify it to use Shape instead of int
- Can you enumerate the problems with this approach?

Use inheritance

- OO languages that do not have templates, use inheritance for implementing such containers
  - For example, in Smalltalk (and in Java), all classes derive from a common ancestor: Object
  - The containers will contain pointers to Object
  - however, the type is lost when you insert an object in a container
  - The user has to perform an appropriate downcast to get back to the original type
- We can do something similar in C++, by using multiple interface inheritance

Using interfaces

- The following interface specifies that an object can be cloned



Using interfaces with Stack

- Stack now contains pointers to Clonable objects (i.e. objects that possess the Clonable interface)

```
class Clonable {
public:
    virtual Clonable * clone() = 0;
    virtual ~Clonable();
};

class Stack {
  class Elem {...};
 public:
  class Iterator {...};

  Stack();
  ~Stack();

  void push(Clonable *d);
  Clonable * pop();
  int size();
  ...
};
```

Exercise

1. Extend the previous Stack class by providing a copy constructor that actually copies all elements (using the clone() virtual function)
   - To show that they are actually different, first implement a static id counter in the Shape class, so that every object has its own id
2. Now, write a "OrderedList" class that contains objects with Interface Comparable
   - The objects in the list must be inserted according to an order decided by a function lessThan() that returns true is the object is "less" than the object passed as argumkent:

```
class Comparable {
public:
    virtual bool lessThan(Comparable *obj) = 0;
    virtual ~Comparable() {}
};
```

   - Extend class hierarchy shapes to also derive from Comparable, and shapes must be ordered by their x position

Problems with this approach

The problems with this approach are the following:

- It is necessary to modify the code for the objects (they must derive from the appropriate interfaces)
  - A possible solution is to write a *wrapper* object that derives from the contained object and from the interface
- It is necessary to downcast at least once
  - Type safety is lost, the compiler cannot check anything meaningful during compilation time
  - For example, it is not possible to avoid that different types of objects are inserted in the same contaneir by mistake

Templates

- Templates are used for generic programming
- The general idea is: what we want to reuse is not only the abstract concept, but the code itself
- we templates we reuse algorithms by making them general
- As an example, consider the code needed to swap two objects of the same type (i.e. two pointers)

```
void swap(int &a, int &b)
{
    int tmp;
    tmp = a;
    a = b;
    b = tmp;
}
...
int x=5, y=8;
swap(x, y);
```

- Can we make it generic?

Solution

- By using templates, we can write

```
template<class T>
void swap(T &a, T &b)
{
    T tmp;
    tmp = a;
    a = b;
    b = tmp;
}
...

int x=5, y=8;
swap<int>(x, y);
```

- Apart from the first line, we have just substituted the type int with a generic type T

How it works

- The template mechanism resembles the macro mechanism in C
  - We can do the same in C by using pre-processing macros:

```
#define swap(type, a, b) { type tmp; tmp=a; a=b; b=tmp; }
...
int x = 5; int y = 8;

swap(int, x, y);
```

- in this case, the C preprocessor substitutes the code
  - it works only if the programmer knows what he is doing
- The template mechanism does something similar
  - but the compiler performs all necessary type checking

Code duplicates

- the compiler will instantiate a version of swap() with integer as a internal type
- if you call swap() with a different type, the compiler will generate a new version of swap
  - Only when a template is instantiated, the code is generated
    - If we do not use swap(), the code is never generated, even if we include it!
    - if there is some error in swap(), the compiler will never find it until it tries to generate the code
- Looking from a different point of view:
  - the template mechanism is like cut&paste done by the compiler at compiling time

Swap for other types

- What happens if we call swap for a different type:

```
class A { ... };
A x;
A y;
...

swap<A>(x, y);
```

- A new version of swap is automatically generated
  - Of course, the class A must support the assignment operator, otherwise the generation fails to compile
  - see template/swap/swap.cpp

- Parameters can be automatically implied by the compiler

```
int a = 5, b = 8;

swap(a, b);   // equivalent to swap<int>(a, b);
```

- Sometimes, this is not so straightforward ...

Generalizing Stack

- Now, let's go back to our Stack class, and generalize it to contain any type of object

```
template<class T>
class Stack {
  class Elem {
  public:
    T data_;
    ...
  };
 public:
  class Iterator {
    friend class Stack<T>;
    ...
  public:
    inline T operator*() const { ... }
    ...
  };

  Stack() : head_(0), size_(0) {}
  ~Stack() {...}

  void push(const T &a) {...}
  T pop() {...}
  ...
```

Exercises

1. Write a program that inserts pointers to shapes into the stack
   - You will only need to modify the main!
2. Write a program that inserts only rectangles into a stack
3. Write a OrderedList container that makes use of operator<() to compare elements. Insert shapes into it, and order by increasing x coordinate

Advantages of this solution

- We do not need to modify the original code (i.e. the Shape hierarchy should not be modified)
- The code is polymorfic to the right level (no extra downcast is necessary)
- Can be applied not only to containers but also to any function

Inlines

- It is possible to define the members of a template class later on
  - Must be preceded by keyword template

```
template<class T>
class Array {
  enum { size = 100 };
  T A[size];
public:
  T& operator[](int index);
};

template<class T>
T& Array<T>::operator[](int index) {
  require(index >= 0 && index < size,
    "Index out of range");
  return A[index];
}

int main() {
  Array<float> fa;
  fa[0] = 1.414;
} ///:~
```

Template instantiation

- The code for the template is not instantiated until the template is used
  - It works similarly to in-lines
  - The template code should go in the header file
- It is possible to have the template code in a separate cpp file
  - through the export keyword
  - not supported by gcc and by Visual C++
  - it is a candidate for deletion from the standard

Parameters

- A template can have any number of parameters
- A parameter can be:
  - a class, or any predefined type
  - a function
  - a constant value (a number, a pointer, etc.)

```
template<T, int sz>
class Buffer {
   T v[sz];
   int size_;
public:
   Buffer() : size_(i) {}
};
...
Buffer<char, 127> cbuf;
Buffer<Record, 8> rbuf;
int x = 16;
Buffer<char, x> ebuf; // error!
```

Default values

- Some parameter can have default value

```
template<class T, class Allocator = allocator<T> >
class vector;
```

Templates of templates

- The third type of parameter a template can accept is another class template

```
template<class T>
class Array {
  ...
};

template<class T, template<class> class Seq>
class Container {
  Seq<T> seq;
public:
  void append(const T& t) { seq.push_back(t); }
  T* begin() { return seq.begin(); }
  T* end() { return seq.end(); }
};

int main() {
  Container<int, Array> container;
  container.append(1);
  container.append(2);
  int* p = container.begin();
  while(p != container.end())
    cout << *p++ << endl;
} ///:~
```

Using standard containers

- If the container class is well-written, it is possible to use any container inside

```
template<class T, template<class U, class = allocator<U> >
         class Seq>
class Container {
  Seq<T> seq; // Default of allocator<T> applied implicitly
public:
  void push_back(const T& t) { seq.push_back(t); }
  typename Seq<T>::iterator begin() { return seq.begin(); }
  typename Seq<T>::iterator end() { return seq.end(); }
};

int main() {
  // Use a vector
  Container<int, vector> vContainer;
  vContainer.push_back(1);
  vContainer.push_back(2);
  for(vector<int>::iterator p = vContainer.begin();
      p != vContainer.end(); ++p) {
    cout << *p << endl;
  }
  // Use a list
  Container<int, list> lContainer;
  lContainer.push_back(3);
  lContainer.push_back(4);
  for(list<int>::iterator p2 = lContainer.begin();
      p2 != lContainer.end(); ++p2) {
    cout << *p2 << endl;
  }
} ///:~
```

The typename keyword

- The typename keyword is needed when we want to specify that an identifier is a type

```
template<class T> class X {
  typename T::id i;    // Without typename, it is an error:
public:
  void f() { i.g(); }
};

class Y {
public:
  class id {
  public:
    void g() {}
  };
};

int main() {
  X<Y> xy;
  xy.f();
} ///:~
```

General rule

- if a type referred to inside template code is qualified by a template type parameter, you must use the typename keyword as a prefix,
- unless it appears in a base class specification or initializer list in the same scope (in which case you must not).

Usage

- The typical example of usage is for iterators

```
template<class T, template<class U, class = allocator<U> >
         class Seq>
void printSeq(Seq<T>& seq) {
  for(typename Seq<T>::iterator b = seq.begin();
       b != seq.end();)
    cout << *b++ << endl;
}

int main() {
  // Process a vector
  vector<int> v;
  v.push_back(1);
  v.push_back(2);
  printSeq(v);
  // Process a list
  list<int> lst;
  lst.push_back(3);
  lst.push_back(4);
  printSeq(lst);
} ///:~
```

Making a member template

- An example for the complex class

```
template<typename T> class complex {
public:
  template<class X> complex(const complex<X>&);
  ...
};

complex<float> z(1, 2);
complex<double> w(z);
```

- In the declaration of w, the complex template parameter T is double and X is float. Member templates make this kind of flexible conversion easy.

Another example

```
int data[5] = { 1, 2, 3, 4, 5 };
  vector<int> v1(data, data+5);
  vector<double> v2(v1.begin(), v1.end());
```

- As long as the elements in v1 are assignment-compatible with the elements in v2 (as double and int are here), all is well.
- The vector class template has the following member template constructor:

```
template<class InputIterator>
vector(InputIterator first, InputIterator last,
       const Allocator& = Allocator());
```

- InputIterator is interpreted as `vector<int>::iterator`

Another example

```
template<class T> class Outer {
public:
  template<class R> class Inner {
  public:
    void f();
  };
};

template<class T> template<class R>
void Outer<T>::Inner<R>::f() {
  cout << "Outer == " << typeid(T).name() << endl;
  cout << "Inner == " << typeid(R).name() << endl;
  cout << "Full Inner == " << typeid(*this).name() << endl;
}

int main() {
  Outer<int>::Inner<bool> inner;
  inner.f();
} ///:~
```

Restrictions

- Member template functions cannot be declared virtual.
  - Current compiler technology expects to be able to determine the size of a class's virtual function table when the class is parsed.
  - Allowing virtual member template functions would require knowing all calls to such member functions everywhere in the program ahead of time.
  - This is not feasible, especially for multi-file projects.

Function templates

- The standard template library defines many function templates in algorithm
  - sort, find, accumulate, fill, binary_search, copy, etc.
- An example:

```
#include <algorithm>
...
int i, j;
...
int z = min<int>(i, j);
```

Deduction

- Type can be deducted by the compiler
- But the compiler is smart until a certain point...

```
int z = min(x, j); // x is a double, error, not the same types

int z = min<double>(x, j); // this one works fine
```

Return type

```
template<typename T, typename U>
const T& min(const T& a, const U& b) {
  return (a < b) ? a : b;
}
```

- The problem is: which return value is the most correct? T or U?
- If the return type of a function template is an independent template parameter, you must always specify its type explicitly when you call it, since there is no argument from which to deduce it.

Example

```
template<typename T> T fromString(const std::string& s) {
  std::istringstream is(s);
  T t;
  is >> t;
  return t;
}
template<typename T> std::string toString(const T& t) {
  std::ostringstream s;
  s << t;
  return s.str();
}
int main() {
  int i = 1234;
  cout << "i == \"" << toString(i) << "\"" << endl;
  float x = 567.89;
  cout << "x == \"" << toString(x) << "\"" << endl;
  complex<float> c(1.0, 2.0);
  cout << "c == \"" << toString(c) << "\"" << endl;
  cout << endl;

  i = fromString<int>(string("1234"));
  cout << "i == " << i << endl;
  x = fromString<float>(string("567.89"));
  cout << "x == " << x << endl;
  c = fromString<complex<float> >(string("(1.0,2.0)"));
  cout << "c == " << c << endl;
} ///:~
```