USC Viterbi School of Engineering

CSCI 104
Templates

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Overview

- C++ Templates allow alternate versions of the same code to be generated for various data **types**

FUNCTION TEMPLATES

Function Templates

- Example reproduced from: http://www.cplusplus.com/doc/tutorial/templates/
- Consider a max() function to return the max of two int's
- But what about two double's or two strings
- Define a generic function for any type, T
- Can then call it for any type, T, or let compiler try to implicitly figure out T

```
int max(int a, int b)
{
  if(a > b) return a;
  else return b;

}

double max(double a, double b)
{
  if(a > b) return a;
  else return b;
}
```

Non-Templated = Multiple code copies

```
template<typename T>
T max(const T& a, const T& b)
{
  if(a > b) return a;
  else return b;
}
int main()
{
  int x = max<int>(5, 9); //or
  x = max(5, 9); // implicit max< int > call
  double y = max<double>(3.4, 4.7);
  // y = max(3.4, 4.7);
}
```

Templated = One copy of code

CLASS TEMPLATES

Motivating Example

- We've built a list to store integers
- But what if we want a list of double's or string's or other objects
- We would have to define the same code but with **different types**
  - What a waste!
- Enter C++ Templates
  - Allows the one set of code to work for any type the programmer wants
  - The type of data becomes a parameter

```
#ifndef LIST_INT_H
#define LIST_INT_H
struct IntItem {
  int val; IntItem* next;
};
class ListInt{
 public:
   ListInt();  // Constructor
   ~ListInt();  // Destructor
   void push_back(int newval); ...
 private:
   IntItem* head_;
};
#endif
```

```
#ifndef LIST_DBL_H
#define LIST_DBL_H
struct DoubleItem {
  double val; DoubleItem* next;
};
class ListDouble{
 public:
   ListDouble();  // Constructor
   ~ListDouble();  // Destructor
   void push_back(double newval); ...
 private:
   DoubleItem* head_;
};
#endif
```

Templates

- Allows the type of variable in a class or function to be a parameter specified by the programmer
- Compiler will generate separate class/struct code versions for any type desired (i.e instantiated as an object)
  - LList<int> my_int_list causes an ‘int’ version of the code to be generated by the compiler
  - LList<double> my_dbl_list causes a ‘double’ version of the code to be generated by the compiler

```
// declaring templatized code
template <typename T>
struct Item {
  T val;
  Item<T>* next;
};

template <typename T>
class LList {
public:
   LList();  // Constructor
   ~LList();  // Destructor
   void push_back(const T& newval); ...
 private:
   Item<T>* head_;
};


// Using templatized code
//  (instantiating templatized objects)
int main()
{
  LList<int> my_int_list;
  LList<double> my_dbl_list;

  my_int_list.push_back(5);
  my_dbl_list.push_back(5.5125);

  double x = my_dbl_list.pop_front();
  int y = my_int_list.pop_front();
  return 0;
}
```

Template Mechanics (2)

- Writing a template
  - Precede class with:

    template <typename T>

    Or

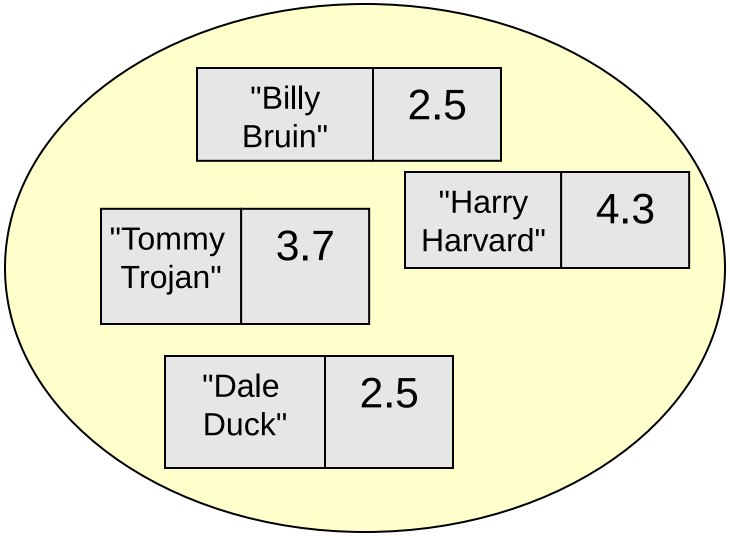
    template <class T>

    (in this context there is ABSOLUTELY no difference or implication for using typename vs. class)
  - Use T or other identifier where you want a generic type
  - Precede the definition of each function with template **<typename T>**
  - In the scope portion of the class member function, add **<T>**
  - Since Item and LList are now templated, you can never use Item and LList alone
    - **You must use Item<T> or LList<T>**

```
#ifndef LIST_H
#define LIST_H

template <typename T>
struct Item {
  T val; Item<T>* next;
};

template <typename T>
class LList{
 public:
   LList();  // Constructor
   ~LList();  // Destructor
   void push_back(const T& newval);
   T& at(int loc);
 private:
   Item<T>* head_;
};

template<typename T>
LList<T>::LList()
{ head_ = NULL;
}

template<typename T>
LList<T>::~LList()
{ }

template<typename T>
void LList<T>::push_back(T newval)
{  ... }

#endif
```

Exercise

- Recall that maps/dictionaries store key,value pairs
  - Example: Map student names to their GPA
- How many key,value type pairs are there?
  - string, int
  - int, double
  - Etc.
- Would be nice to create a generic data structure
- Define a Pair template with two generic type data members



Another Example

- A pair struct:

```
template<typename T1, typename T2>
struct pair {
  T1 first;
  T2 second;
  pair(const T1& f, const T2& s);
};

template<typename T1, typename T2>
pair<T1,T2>::pair(
   const T1& f,
   const T2& s);
    : first(f), second(s)
  { }
```

Templates

- Usually we want you to write the class definition in a separate header file (.h file) and the implementation in a .cpp file
- **Key Fact:** Templated classes must have the implementation **IN THE HEADER FILE!**
- **Corollary**: Since we don't compile .h files, you cannot compile a templated class separately
- Why? Because the compiler would have no idea what type of data to generate code for and thus what code to generate

```
#ifndef LIST_H
#define LIST_H

template <typename T>
struct Item {
  T val; Item<T>* next;
};

template <typename T>
class LList{
 public:
   LList();  // Constructor
   ~LList();  // Destructor
   void push_back(const T& newval);
private:
   Item<T>* head_;
};
#endif
```

List.h

```
#include "List.h"

template<typename T>
LList<T>::push_back(const T& newval)
{
  if(head_ = NULL){
    head_ = new Item<T>;
    // how much memory does an Item
    //  require?
  }
}
```

List.cpp

Templates

- The compiler will generate code for the type of data in the file where it is instantiated with a certain type

List.h

```
#ifndef LIST_H
#define LIST_H

template <typename T>
struct Item {
  T val; Item<T>* next;
};

template <typename T>
class LList{
 public:
   LList();  // Constructor
   ~LList();  // Destructor
   void push_back(const T& newval);
   T& at(int loc);
 private:
   Item<T>* head_;
};

template<typename T>
LList<T>::LList()
{ head_ = NULL;
}

template<typename T>
LList<T>::~LList()
{ }

template<typename T>
void LList<T>::push_back(const T& newval)
{  ... }

#endif
```

Main.cpp

```
#include "List.h"

int main()
{
  LList<int> my_int_list;
  LList<double> my_dbl_list;

  my_int_list.push_back(5);
  my_dbl_list.push_back(5.5125);

  double x = my_dbl_list.pop_front();
  int y = my_int_list.pop_front();
  return 0;
}

// Compiler will generate code for LList<int>
when compiling main.cpp
```

The devil in the details

C++ TEMPLATE ODDITIES

Templates & Inheritance

- For various reasons the compiler may have difficulty resolving members of a templated base class
- When accessing members of a templated base class provide the full scope or precede the member with this->

```
#include "llist.h"
template <typename T>
class Stack : private LList<T>{
 public:
   Stack();  // Constructor
   void push(const T& newval);
   T const & top() const;
};

template<typename T>
Stack<T>::Stack() : LList<T>()
{ }

template<typename T>
void Stack<T>::push(const T& newval)
{  // call inherited push_front()
   push_front(newval); // may not compile
   LList<T>::push_front(newval); // works
   this->push_front(newval);     // works
}

template<typename T>
void Stack<T>::push(const T& newval)
{ // assume head is a protected member
  if(head) return head->val; // may not work
  if(LList<T>::head)         // works
     return LList<T>::head->val;
  if(this->head)             // works
     return this->head->val;
}
```

"typename" & Nested members

- For various reasons the compiler will have difficulty resolving nested types of a templated class whose template argument is still generic (i.e. T vs. `int`)
- Precede the nested type with the keyword 'typename' when you are
  - Not in the scope of the templated class AND
  - The template type is still generic
- Why? Research template specialization and read https://en.wikipedia.org/wiki/Typename

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

template <typename T>
class Stack {
public:
  ...
  const T& top();
private:
  std::vector<T> data;
};


template <typename T>
Const T& Stack<T>::top()
{
  vector<T>::iterator it = data.end();  // bad
  typename vector<T>::iterator it = data.end(); //good
  return *(it-1);
}

int main()
{
  Stack<int> s1;
  vector<int>::iterator it;
  s1.push(1); s1.push(2); s1.push(3);
  cout << s1.top() << endl;
  return 0;
}
```

When the template type is still generic and you scope a nested type, precede with `typename`

When the template type is specific there is no need to use `typename`

It's an object, it's a function…it's both rolled into one!

WHAT THE "FUNCTOR"

Who you gonna call?

- Functions are "called" by using parentheses () after the function name and passing some arguments
- Objects use the `.` or `->` operator to access methods of an object
- Calling an object doesn't make sense
  - You call functions not objects
  - Or can you?

```
class ObjA {
 public:
  ObjA();
  void action();
};

int main()
{
  ObjA a;
  ObjA *aptr = new ObjA;
  // This makes sense:
  a.action();
  aptr->action();

  // This doesn't make sense
  a();

  // a is already constructed, so
  // it can't be a constructor call
  // So is it illegal?


  return 0;
}
```

Operator()

- Calling an object does make sense when you realize that () is an operator that can be overloaded
- For most operators their number of arguments is implied
  - operator+ takes an LHS and RHS
  - operator-- takes no args
- You can overload operator() to take any number of arguments of your choosing
- **Def**. A **functor** or **function object** is a class/struct that defines an operator()

```
class ObjA {
 public:
  ObjA();
  void action();
  void operator()() {
    cout << "I'm a functor!";
    cout << endl;
  }
  void operator()(int &x) {
    return ++x;
  }
};
int main()
{
  ObjA a;
  int y = 5;
  // This does make sense!!
  a();
  // prints "I'm a functor!"

  // This also makes sense !!
  a(y);
  // y is now 6
  return 0;
}
// Don't get confused by the syntax:
// operator()(int& x)
// ^^^^^^^^^^ ^^^^^^
// <  name   >< args >
```

Purpose of Functors

- **The purpose of functors is to make code more generic so that the behavior of the same code template can be customized**
- Suppose I have a container of data and want to count how many elements meet a certain criteria but the criteria may change (negative values, even values, etc.)
  - Seems like a lot of work to keep repeating the same generic code
- How can I "genericize" the code?

```
int count_if_neg (
   vector<int>::iterator first,
   vector<int>::iterator last)
{
  int ret = 0;
  for( ; first != last; ++first){
    if ( *first < 0 )
      ++ret;
  }
  return ret;
}
int count_if_even (
   vector<int>::iterator first,
   vector<int>::iterator last)
{
  int ret = 0;
  for( ; first != last; ++first){
    if ( *first % 2 == 0 )
      ++ret;
  }
  return ret;
}
```

With Function Pointers

- We could make the `count_if` routine generic by passing in a function pointer (yes there are pointers to functions)
  - But the criteria may change generic behavior
- Function pointer types:
  - `bool (*funcPtr)(int);`
  - This declares a pointer named `funcPtr` which can point to any function that returns a `bool` and takes an `int` argument

```
bool isNeg(int x) { return x < 0; }
bool isEven(int x) { return x % 2 == 0; }


int count_if (vector<int>::iterator first,
              vector<int>::iterator last,
              bool (*funcPtr)(int) )
{ int ret = 0;
  for( ; first != last; ++first){
    if ( funcPtr(*first) )
      ++ret;
  }
  return ret;
}

int main()
{
  vector<int> v;
  // fill data somehow
  int neg = count_if(v.begin(), v.end(), isNeg);
  int even = count_if(v.begin(), v.end(), isEven);
  return 0;
}
```

With Functors

- We could also make the `count_if` routine generic by making it a template and use a functor object

```
struct isNeg {
 bool operator()(int x) { return x < 0; } };
struct isEven {
 bool operator()(int x) { return x % 2 == 0; } };


template <typename Comp>
int count_if (vector<int>::iterator first,
              vector<int>::iterator last,
              Comp c)
{ int ret = 0;
  for( ; first != last; ++first){
    if ( c(*first) )
      ++ret;
  }
  return ret;
}

int main()
{
  vector<int> v;   isNeg c1;   isEven c2;
  // fill data somehow
  int neg = count_if(v.begin(), v.end(), c1);
  int even = count_if(v.begin(), v.end(), c2);
  return 0;
}
```

std::count_if

- Functors can act as a user-defined "function" that can be passed as an argument and then called on other data items
- Below is a modified count_if template function (from STL <algorithm>) that counts how many items in a container meet some condition

```
template <class InputIterator, class Cond>
int count_if (InputIterator first,
              InputIterator last,
              Cond pred)
{ int ret = 0;
  for( ; first != last; ++first){
    if ( pred( *first ) )
      ++ret;
  }
  return ret;
}
```

```
struct NegCond {
  bool operator(int val)
   { return val < 0; }
};

int main()
{ std::vector<int> myv;

  // myvector: -5 -4 -3 ... 2 3 4
  for (int i=-5; i<5; i++)
     myvec.push_back(i);
  NegCond c;
  int mycnt =
     count_if(v.begin(), v.end(), c);
  cout << "myvec contains " << mycnt;
  cout << " negative values." << endl;
  return 0;
}
```

Functors for Maps and Sets

- Suppose I'd like to use a certain class as a key in a map or set
- Maps/sets require the key to have…
  - A less-than operator
- Guess I can't use Pt
  - Or can I?

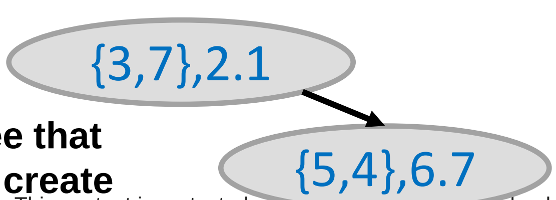
```
class Pt {
 public:
  Pt(...);
  void action() { /* do stuff */ }
  int getX() { return x; }
  int getY() { return y; }
 private:
  int x, y;
};
```

pt.h – Someone else wrote it

```
int main()
{
  // I'd like to use Pt as a key
  // Can I?
  map<Pt, double> mymap;

  Pt p1(4,5);
  mymap[p1] = 6.7;
  return 0;
}
```

Functors for Maps and Sets

- Map template takes in a third template parameter which is called a "Compare" functor
- It will use this type and assume it has a functor [i.e. operator()] defined which can take two key types and compare them
- In the map implementation:
  - It will never do `if(k1 < k2)` or `if(k1 > k2)`
  - But instead use the comparator: `if(c(k1,k2))` or `if(c(k2,k1))`



Internal tree that map would create

pt.h – Someone else wrote it

```
class Pt {
 public:
  Pt(...);
  void action() { /* do stuff */ }
  int getX() { return x; }
  int getY() { return y; }
 private:
  int x, y;
};
```

```
struct PtComparer
{
  bool operator()(const Pt& lhs, const Pt& rhs)
  { return (lhs.getX() < rhs.getX()) ||
      (lhs.getX() == rhs.getX() &&
       lhs.getY() < rhs.getY()); }
};

int main()
{ // Now we can use Pt as a key!!!!
  map<Pt, double, PtComparer> mymap;

  Pt a(4, 5), b(3, 7);
  mymap[a] = 6.7;   mymap[b] = 2.1;
  return 0;
}
```

Warm Up: Functor Exercise

Write a single function to find max by different criteria

```
template <typename T>
   T mymax(const T& a, const T& b)
{
   if(a > b) return a;
   return b;
}

struct SizeComp {
     bool operator()(const vector<int>& a, const vector<int>& b) const {

      }
};
struct SumComp {
    bool operator()(const vector<int>& a, const vector<int>& b) const {




   }
};
```

Warm Up: Functor Exercise Solution

Write a single function to find max by different criteria

```
template <typename T, typename comp>
   T mymax(const T& a, const T& b, comp test)
{
   if(test(a,b)) return a;
   return b;
}

 struct SizeComp {
      bool operator()(const vector<int>& a, const vector<int>& b) const {
         return a.size() > b.size();
      }
   };
 struct SumComp {
      bool operator()(const vector<int>& a, const vector<int>& b) const {
         int asum = std::accumulate(a.begin(),a.end(),0);
         int bsum = std::accumulate(b.begin(),b.end(),0);
         return asum > bsum;
      }
   };
```

Final Word

- Functors are all over the place in C++ and STL
- Look for them and use them where needed
- References
  - http://www.cprogramming.com/tutorial/functors-function-objects-in-c++.html
  - http://stackoverflow.com/questions/356950/c-functors-and-their-uses

Practice

- SlowMap
  - wget http://ee.usc.edu/~redekopp/cs104/slowmap.cpp
- Write a functor so you can use a set of string*'s and ensure that no duplicate strings are put in the set
  - http://bits.usc.edu/websheets/index.php?folder=cpp/templates
  - strset