

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 templated 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 templated code
// (instantiating templated 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;
}

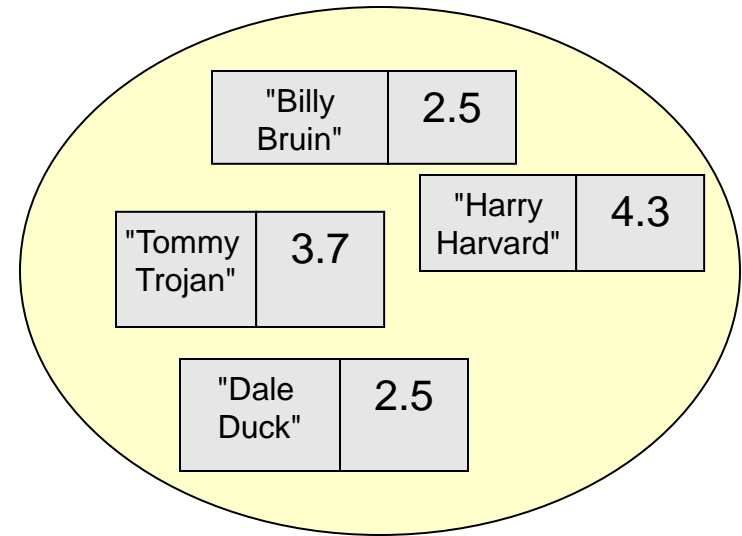
template<typename T>
LList<T>::~~LList()
{ }

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

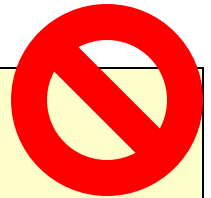
template <typename T>
struct Item {
    T val; Item<T>* next;
};

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

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
```

```
#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
```

List.h

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 "l1list.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;
}
```

Purpose of Functors

- **The purpose of functors is to genericize code so that the same template of code 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
- Is there a way to "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))`

{3,7},2.1

{5,4},6.7

Internal tree that
map would create

```
class Pt { pt.h – Someone else wrote it
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=c++/templates>
 - strset