Function Templates

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Before we dive in

- Preprocessing
- Compilation
- Linkage

Motivation

A useful routine to have is

```
void swap( int& a, int &b )
{
    int tmp = a;
    a = b;
    b = tmp;
}
```

Example

What happens if we want to swap a double ? or a string?

For each one, we need different function:

```
void swap( double& a, double &b )
{
   double tmp = a; a = b; b = tmp;
}
void swap( string& a, string &b )
{
   string tmp = a; a = b; b = tmp;
}
```

Generics Using void*

C approach:

```
void swap( void *a, void *b, size_t size )
{
    for (size_t i=0; i<size; i++) {
        char t = *(char *)(a+i);
        *(char *)(a+i) = *(char*)(b+i);
        *(char*)(b+i) = t;
    }
    // or can be done using malloc and memcpy
}
```

Function Templates

The `template` keyword defines “templates”

Piece of code that will be regenerated with different arguments each time

```
template<typename T> // T is a
                     //"type argument"
void swap( T& a, T& b )
{
   T tmp = a;
   a = b;
   b = tmp;
}
```

Template Instantiation

Explicit

```
double d1 = 4.5, d2 = 6.7;
swap<double>(d1, d2);
```

The compiler generates and compiles:

swap<double>(double&,double&)

Implicit

```
double d1 = 4.5, d2 = 6.7;
swap(d1, d2);
```

The compiler generates and compiles:

swap<double>(double&,double&)

Template Instantiation

Different instantiations of a template can be generated by the same program

```
int a = 2, b = 3;
swap( a, b ); // Compiler generates swap(int&,int&)
swap( b, a ); // No need to generate a new function

double x = 0.1, y = 1.0;
swap( x, y ); // Compiler generates swap(double&,double&)

char* s = “sss”, t = “ttt”;
swap( s, t ); // Compiler generates swap(char*&,char*&)

Member s, t;
swap( s, t ); // Compiler generates swap(Member&,Member&)
```

Technical comment

These two definitions are exactly the same, if we have both, we will have a compilation error:

```cpp
template <typename T>
void swap(T &a, T &b)
{
   T c = a;
   a = b;
   b = c;
}
```

```cpp
template <class P>
void swap(P &a, P &b)
{
   P c = a;
   a = b;
   b = c;
}
```

Template Instantiation – godbolt.org example

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

void swap (double& a, double& b) {
   a = a + b;   b = a - b;   a = a - b;
}

int main() {
   int a=4,b=5;
   swap(a,b);
   double c=4.1,d=5.1;
   swap(c,d);
   swap<double>(c,d);
}
```

Templates & Compilation

- A template is a **declaration**
- The compiler performs functions/operators calls checks only when a template is instantiated with specific arguments - then the generated code is compiled.

Not just the declaration

Implications:

1. Template **code** has to be visible by the code that uses it (i.e., appear in header *.h/.hpp* file)
2. Compilation errors can occur only in a specific instance

Template assumptions (folder 1)

```
// example of a uncopyable class
class Cookie
{
private:
   // private copy operations
   Cookie(const Cookie&);
   Cookie & operator=(const Cookie&);
public:
   Cookie() { };
};
...
 Cookie van, choc;
 swap(van, choc); /* compiler will try generate code for
swap(Cookie&,Cookie&), but will fail, claiming an error
somewhere at the declaration of swap*/
```

?Why

Another Example - max

```
template< typename T >
void max(T a, T b)
{
    return a > b ? a : b;
}
```

What are the template ?assumptions

Another Example - sort

```
// Inefficient generic sort
template< typename T >
void sort( T* begin, T* end )
{
    for( ; begin != end; begin++ )
        for( T* q = begin+1; q != end; q++ )
        {
            if( *q < *begin )
                swap( *q, *begin );
        }
}
```

What are the template ?assumptions

Another Example

```
// Inefficient generic sort
template< typename T >
void sort( T* begin, T* end )
{
    for( ; begin != end; begin++ )
        for( T* q = begin+1; q != end; q++ )
        {
            if( *q < *begin )
                swap( *q, *begin );
        }
}
```

What are the template ?assumptions

Usage

Suppose we want to avoid writing operator != for new classes

```
template <typename T>
bool operator!= (T const& lhs, T const& rhs)
{
    return !(lhs == rhs);
}
```

When is this template used?

Usage

```
class MyClass
{
public:
    bool operator==
    (MyClass const & rhs) const;
};
int a, b;
if( a != b ) // uses built in
             // operator!=(int,int)
...
MyClass x,y;
if( x != y ) // uses template with
             // T= MyClass
```

Puzzle

Can you define all 6 operators

(<   >   ==   <=   >=   !=)

using only 1 of them?

Which one?

When Templates are Used? – overloads, again

When the compiler encounters

```
…
f( a, b )
…
```

1. Look for all functions named f.
2. Creates instances of all templates named f according to parameters.
3. Order them by matching quality (1..4).
4. **Within** same quality, prefer non-template over template.

Example 1

```
#include <iostream>
#include <typeinfo>
void foo(int x) {
    std::cout << "foo(int)\n";
}
void foo(double x) {
    std::cout << "foo(double)\n";
}
template<typename T> void foo(T* x) {
    std::cout << "foo<" << typeid(T).name() << ">(T*)\n";
}
int main() {
    foo(42);
    foo(42.2);
    foo("abcdef");
    return 0;
}
```

Example 1

```cpp
#include <iostream>
#include <typeinfo>
void foo(int x) {
    std::cout << "foo(int)\n";
}
void foo(double x) {
    std::cout << "foo(double)\n";
}
template<typename T> void foo(T* x) {
    std::cout << "foo<" << typeid(T).name() << ">(T*)\n";
}
int main() {
    foo(42);
    foo(42.2);
    foo("abcdef");
    return 0;
}
```

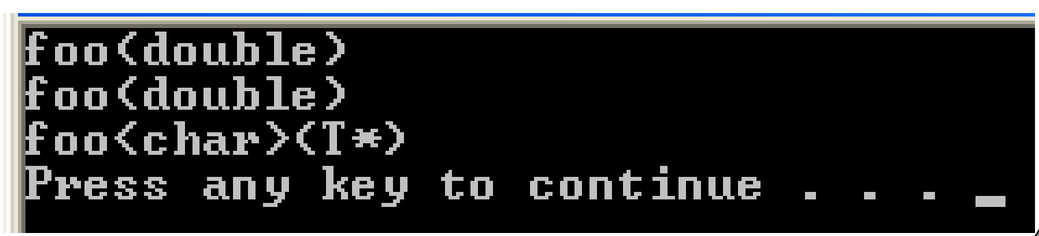
```
foo(int)
foo(double)
foo<char>(T*)
Press any key to continue . . .
```

Example 2

```cpp
#include <iostream>
#include <typeinfo>
//void foo(int x) {
//   std::cout << "foo(int)\n";
//}
void foo(double x) {
   std::cout << "foo(double)\n";
}
template<typename T> void foo(T* x) {
   std::cout << "foo<" << typeid(T).name() << ">(T*)\n";
}
int main() {
   foo(42);
   foo(42.2);
   foo("abcdef");
   return 0;
}
```

Example 2

```cpp
#include <iostream>
#include <typeinfo>
//void foo(int x) {
//   std::cout << "foo(int)\n";
//}
void foo(double x) {
   std::cout << "foo(double)\n";
}
template<typename T> void foo(T* x) {
   std::cout << "foo<" << typeid(T).name() << ">(T*)\n";
}
int main() {
   foo(42);
   foo(42.2);
   foo("abcdef");
   return 0;
}
```



Example 3

```
#include <iostream>
#include <typeinfo>
void foo(int x) {
    std::cout << "foo(int)\n";
}
//void foo(double x) {
//  std::cout << "foo(double)\n";
//}
template<typename T> void foo(T* x) {
    std::cout << "foo<" << typeid(T).name() << ">(T*)\n";
}
int main() {
    foo(42);
    foo(42.2);
    foo("abcdef");
    return 0;
}
```

Example 3

```cpp
#include <iostream>
#include <typeinfo>
void foo(int x) {
    std::cout << "foo(int)\n";
}
//void foo(double x) {
//  std::cout << "foo(double)\n";
//}
template<typename T> void foo(T* x) {
    std::cout << "foo<" << typeid(T).name() << ">(T*)\n";
}
int main() {
    foo(42);
    foo(42.2);
    foo("abcdef");
    return 0;
}
```

```
foo(int)
foo(int)
foo<char>(T*)
Press any key to continue . . . _
```

Example 3

```
#include <iostream>
#include <typeinfo>
void foo(int x) {
   std::cout << "foo(int)\n";
}
//void foo(double x) {
//  std::cout << "foo(double)\n";
//}
template<typename T> void foo(T* x) {
   std::cout << "foo<" << typeid(T).name() << ">(T*)\n";
}
int main() {
   foo(42);
   foo(42.2);
   foo("abcdef");
   return 0;
}
```

Won’t compile with the flag:
-Wconversion (forbids lossy conversions)

Example 4

```
#include <iostream>
#include <typeinfo>
//void foo(int x) {
//   std::cout << "foo(int)\n";
//}
void foo(double x) {
   std::cout << "foo(double)\n";
}
template<typename T> void foo(T* x) {
   std::cout << "foo<" << typeid(T).name() << ">(T*)\n";
}
int main() {
   foo(42);
   foo(42.0);
   foo("abcdef");
   return 0;
}
```

Will compile with the flag:
-Wconversion (allows lossless conversion)

Example 5

```
template<typename T>
void f(T x, T y)
{
   cout << "Template" << endl;
}

void f(int w, int z)
{
   cout << "Non-template" << endl;
}

int main(){
    f( 1 ,  2 );
    f('a', 'b');
    f( 1 , ’b’);
}
```

```
Non-template
Template
Non-template
Press any key to continue . . . _
```

Example 6

```
template<typename T>
void f(T x, T y)
{
   cout << "Template" << endl;
}

void f(int w, int z)
{
   cout << "Non-template" << endl;
}

int main(){
   f( 2 , 1.2);
   f( 2.2 , 1.2);
}
```

```
Non-template
Template
Press any key to continue . . .
```

Example 7

```
template <typename T> void f(T) { cout << "Less specialized";}    1
template <typename T> void f(T*) { cout<< "More specialized";}    2
int main() {
   int i =0;
   int *pi = &i;
   f(i); // Calls less specialized function.
   f(pi); // Calls more specialized function.
}
```

Is there a type that fits 1 and will not fit 2? If so, 2 is more specialized and should be preferred.

Variable Templates

Template variables

```
template<typename T> const T pi =
      T(3.1415926535897932385L);  // variable template

template<typename T> T circular_area(T r) {
    return pi<T> * r * r;
}

int main() {
   return circular_area(5);  // 75?
}
```

Class Templates

String Stack

```
class StrStk {
public:
  StrStk():m_first(nullptr) { }
  ~StrStk() { while (!isEmpty()) pop(); }
  void push (string const& s )  {m_first=new Node(s,m_first);}
  bool isEmpty() const {return m_first==nullptr;}
  const string& top () const {return m_first->m_value;}
  void pop ()
  {Node *n=m_first; m_first=m_first->m_next; delete n;}
private:
  StrStk(StrStk const& rhs);    StrStk& operator=(StrStk const& rhs);
  struct Node {
    string m_value;
    Node* m_next;
    Node(string const& v ,Node* n):m_value(v),m_next(n) { }
  };
  Node* m_first;
};
```

Generic Classes

- The actual code for maintaining the stack has nothing to do with the particulars of the string type.
- Can we have a generic implementation of stack?

Generic Stack (folder 2)

```
template <typename T> class Stk {
public:
  Stk():m_first(nullptr) { }
  ~Stk() { while (!isEmpty()) pop(); }
  void push (T const& s )  {m_first=new Node(s,m_first);}
  bool isEmpty() const {return m_first==nullptr;}
  const T& top () const {return m_first->m_value;}
  void pop ()
  {Node *n=m_first; m_first=m_first->m_next; delete n;}
private:
  Stk(Stk const& rhs); Stk& operator=(Stk const& rhs);
  struct Node {
    T m_value;
    Node* m_next;
    Node(T const& v ,Node* n):m_value(v),m_next(n) { }
  };
  Node* m_first;
};
```

Class Templates

```
template<typename T>
class Stk
{
   ...
};

Stk<int> intList; // T = int
Stk<string> stringList; // T = string
```

Class Templates

The code is similar to non-template code, but:

- Add `template<…>` statement before the class definition
- Use template argument as type in class definition
- To implement methods outside the class definition (but still in header: .h.hpp, not in a cpp file!):

```
template <typename T>
bool Stk<T>::isEmpty() const
{
  return m_first==nullptr;
}
```

Example of generic programming - Iterators

Constructing a List

- We want to initialize a stack from a primitive array.

- int arr[6];
- We can use a pointer to initial position and **one to the position after the last**:
- Stk<int> myStack(

```
Stk<int> myStack(
      arr,arr+sizeof(arr)/sizeof(*arr));
```

Constructing a List

```
// Fancy copy from array
template< typename T >
Stk<T>::Stk<T>(const T* begin, const T* end) {
    for(; begin!=end; ++begin) {
        push(*begin);
    }
}
```

Pointer Paradigm

Code like:

```
const T* begin=theList;
const T* end=
list+sizeof(theList)/sizeof(*theList);
for(; begin!=end; ++begin)
{
    // Do something with *begin
}
```

- Applies to all elements in [begin,end-1]
- Common in C/C++ programs
- Can we extend it to other containers?

Iterator

- **Object that behaves "almost" like a pointer**
- Allows to iterate over elements of a container

Example:

```
Stk<int> L;
...
Stk<int>::iterator i;
for( i = L.begin(); i != L.end(); ++i)
    cout << " " << *i << "\n";
```

Iterators

To emulate pointers, we need:

1. copy constructor
2. `operator= (copy)`
3. `operator== (compare)`
4. `operator* (access value)`
5. `operator++ (increment)`

And maybe:

6. `operator[] (random access)`
7. `operator+= / -= (random jump)`
8. ...

Stk<T> iterator (folder 2)

Create an inner class, keep a pointer to a node.

```
class iterator
{
private:
   Node *m_pointer;
};
```

Provides encapsulation, since through such an iterator we cannot change the structure of the list

Initializing a Stk

We now want to initialize a stack from using parts of another stack. Something like:

```
Stk(iterator begin, iterator end) {
    for(; begin!=end; ++begin) {
        push(*begin);
    }
}
```

Initializing a Stk

Compare:

```
Stk<T>::Stk<T>(iterator begin, iterator end) {
    for(; begin!=end; ++begin) {
        push(*begin);
    }
}
```

To:

```
Stk<T>::Stk<T>(const T* begin, const T* end) {
    for(; begin!=end; ++begin) {
        push(*begin);
    }
}
```

Generic Constructor

The code for copying using

- T*
- Stk<T>::iterator

are essentially identical on purpose --- iterators mimic pointers!

Can we write the code once?

Yes: template inside template (folder 2)

Another example of using iterators

Summing all elements of a container:

- Linked list;
- vector;
- native array;
- user defined...