Generic Programming: Template

C++ Object Oriented Programming

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NTOU CS

polymorphism:
- static
- dynamic
- **parametric**

templates are code generators

default polymorphism for weak-typed languages

Contents

Generic Functions

- Suppose all you want to do is copy an array regardless of type

Generic Functions

- Suppose all you want to do is copy an array regardless of type

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void copy(int arrayTo[], int arrayFrom[], int n) {
   for (int i=0; i<n; i++)
      arrayTo[i] = arrayFrom[i];
}
```

Generic Functions

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The same function won't work on an array of doubles.

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- A traditional solution

```
typedef int genericType;
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
   for (int i=0; i<n; i++)
      arrayTo[i] = arrayFrom[i];
}
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Generic Functions

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This only works one type at a time.

Generic Functions

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- A C++ solution: overload the function

Generic Functions

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typedef int genericType;
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
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```

This only works one type at a time.

- A C++ solution: overload the function

```
void copy(int arrayTo[], int arrayFrom[], int n);
void copy(double arrayTo[], double arrayFrom[], int n);
```

Generic Functions

- Suppose all you want to do is copy an array regardless of type

```
void copy(int arrayTo[], int arrayFrom[], int n) {
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}
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- A traditional solution

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typedef int genericType;
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
   for (int i=0; i<n; i++)
      arrayTo[i] = arrayFrom[i];
}
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This only works one type at a time.

- A C++ solution: overload the function

```
void copy(int arrayTo[], int arrayFrom[], int n);
void copy(double arrayTo[], double arrayFrom[], int n);
```

You still have to write separate functions for each type.
You have to know in advance what types you need.

Using Template to Achieve Generality

✧ Template for toplevel functions

C++98/03

Using Template to Achieve Generality

- Template for toplevel functions C++98/03

```
template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
   for (int i=0; i<n; i++)
      arrayTo[i] = arrayFrom[i];
}
```

Using Template to Achieve Generality

✧ Template for toplevel functions C++98/03

keyword only → class

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template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
    for (int i=0; i<n; i++)
        arrayTo[i] = arrayFrom[i];
}
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Using Template to Achieve Generality

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C++98/03

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void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
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Using Template to Achieve Generality

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C++98/03

keyword only → class

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void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
    for (int i=0; i<n; i++)
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or equivalently,

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template <typename genericType>
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      arrayTo[i] = arrayFrom[i];
}
```

or equivalently,

```
template <typename genericType>
```

✧ Usage

```
void main() {
   int firstArray[] = {1, 2, 3};
   int secondArray[3];
   copy(secondArray, firstArray, 3);
}
```

Using Template to Achieve Generality

C++98/03

- Template for toplevel functions

keyword only → class; parameter → genericType

```
template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
    for (int i=0; i<n; i++)
        arrayTo[i] = arrayFrom[i];
}
```

or equivalently,

```
template <typename genericType>
```

- Usage

```
void main() {
    int firstArray[] = {1, 2, 3};
    int secondArray[3];
    copy(secondArray, firstArray, 3);
}
```

or explicitly

```
copy<int>(secondArray, firstArray, 3)
```

Using Template to Achieve Generality

- Template for toplevel functions

C++98/03

keyword only → class; parameter → genericType

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template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
   for (int i=0; i<n; i++)
      arrayTo[i] = arrayFrom[i];
}
```

or equivalently,

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template <typename genericType>
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- Usage

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void main() {
   int firstArray[] = {1, 2, 3};
   int secondArray[3];
   copy(secondArray, firstArray, 3);
}
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or explicitly

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copy<int>(secondArray, firstArray, 3)
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- What happens: the compiler instantiates the function with *int* as argument.

Using Template to Achieve Generality

- Template for toplevel functions

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keyword only — parameter

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template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
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or equivalently,

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template <typename genericType>
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- Usage

```
void main() {
    int firstArray[] = {1, 2, 3};
    int secondArray[3];
    copy(secondArray, firstArray, 3);
}
```

or explicitly

```
copy<int>(secondArray, firstArray, 3)
```

- What happens: the compiler instantiates the function with *int* as argument. Compiler derives the type from your statement.

Using Template to Achieve Generality

- Template for toplevel functions

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keyword only — parameter

```
template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
    for (int i=0; i<n; i++)
        arrayTo[i] = arrayFrom[i];
}
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or equivalently,

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template <typename genericType>
```

- Usage

```
void main() {
    int firstArray[] = {1, 2, 3};
    int secondArray[3];
    copy(secondArray, firstArray, 3);
}
```

or explicitly

```
copy<int>(secondArray, firstArray, 3)
```

- What happens: the compiler instantiates the function with *int* as argument. Compiler derives the type from your statement. If you call the same function with arrays of doubles, the compiler will instantiate a second overloaded function with *double* as argument.

Multiple Template Parameters

- A template parameter cannot represent more than one type

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template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
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template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
    for (int i=0; i<n; i++)
        arrayTo[i] = arrayFrom[i];
}
void main() {
    int firstArray[] = {1, 2, 3};
    double secondArray[3];
    copy(secondArray, firstArray, 3);
}
```

Multiple Template Parameters

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template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
    for (int i=0; i<n; i++)
        arrayTo[i] = arrayFrom[i];
}
void main() {
    int firstArray[] = {1, 2, 3};
    double secondArray[3];
    copy(secondArray, firstArray, 3);
}
```

error C2782: 'void __cdecl copy(genericType [],genericType [],int)' : template parameter 'genericType' is ambiguous could be 'int' or 'double'

Multiple Template Parameters

- A template parameter cannot represent more than one type

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template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
   for (int i=0; i<n; i++)
      arrayTo[i] = arrayFrom[i];
}
void main() {
   int firstArray[] = {1, 2, 3};
   double secondArray[3];
   copy(secondArray, firstArray, 3);
}
```

```
error C2782: 'void __cdecl copy(genericType [],genericType [],int)' :
template parameter 'genericType' is ambiguous could be 'int' or 'double'
```

```
copy<double,int>(secondArray, firstArray, 3)
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Multiple Template Parameters

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template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
   for (int i=0; i<n; i++)
      arrayTo[i] = arrayFrom[i];
}
void main() {
   int firstArray[] = {1, 2, 3};
   double secondArray[3];
   copy(secondArray, firstArray, 3);
}
```

```
error C2782: 'void __cdecl copy(genericType [],genericType [],int)' :
template parameter 'genericType' is ambiguous could be 'int' or 'double'
```

- **The solution**

```
copy<double,int>(secondArray, firstArray, 3)
```

Multiple Template Parameters

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template<class genericType>
void copy(genericType arrayTo[], genericType arrayFrom[], int n) {
    for (int i=0; i<n; i++)
        arrayTo[i] = arrayFrom[i];
}
void main() {
    int firstArray[] = {1, 2, 3};
    double secondArray[3];
    copy(secondArray, firstArray, 3);
}
```

> error C2782: 'void __cdecl copy(genericType [],genericType [],int)' : template parameter 'genericType' is ambiguous could be 'int' or 'double'

- **The solution**

```
copy<double,int>(secondArray, firstArray, 3)
```

```
template<class typeA, class typeB>
void copy(typeA arrayTo[], typeB arrayFrom[], int n) {
    for (int i=0; i<n; i++)
        arrayTo[i] = arrayFrom[i];
}
```

Template Errors

- You may not violate syntax rules in a template

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```
int array1[] = {1, 2, 3};
char *array2[3];
copy(array2, array1, 3);
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int array1[] = {1, 2, 3};
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error C2440: '=' : cannot convert from 'int' to 'char *'

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template<class type>
type add(type x, type y) {
   return x+y;
}
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int array1[] = {1, 2, 3};
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```
template<class type>
type add(type x, type y) {
   return x+y;
}
void main() {
   int int1=5, int2=6;
   double double1=7.2, double2=4.3;
   int array1[] = {1,2,3}, array2[] = {4,5,6};






}
```

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int array1[] = {1, 2, 3};
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template<class type>
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void main() {
   int int1=5, int2=6;
   double double1=7.2, double2=4.3;
   int array1[] = {1,2,3}, array2[] = {4,5,6};
   cout << add(int1, int2) << endl;


}
```

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int array1[] = {1, 2, 3};
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   int int1=5, int2=6;
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   int array1[] = {1,2,3}, array2[] = {4,5,6};
   cout << add(int1, int2) << endl;
   cout << add(double1, double2) << endl;


}
```

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   int int1=5, int2=6;
   double double1=7.2, double2=4.3;
   int array1[] = {1,2,3}, array2[] = {4,5,6};
   cout << add(int1, int2) << endl;
   cout << add(double1, double2) << endl;
   cout << add(int1, double2) << endl;

}
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int array1[] = {1, 2, 3};
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template<class type>
type add(type x, type y) {
   return x+y;
}
void main() {
   int int1=5, int2=6;
   double double1=7.2, double2=4.3;
   int array1[] = {1,2,3}, array2[] = {4,5,6};
   cout << add(int1, int2) << endl; // OK
   cout << add(double1, double2) << endl;
   cout << add(int1, double2) << endl;

}
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int array1[] = {1, 2, 3};
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copy(array2, array1, 3);
```

error C2440: '=' : cannot convert from 'int' to 'char *'

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   int int1=5, int2=6;
   double double1=7.2, double2=4.3;
   int array1[] = {1,2,3}, array2[] = {4,5,6};
   cout << add(int1, int2) << endl; // OK
   cout << add(double1, double2) << endl;
   cout << add(int1, double2) << endl;
   cout << add(array1, array2) << endl;
}
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Template Errors

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int array1[] = {1, 2, 3};
char *array2[3];
copy(array2, array1, 3);
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template<class type>
type add(type x, type y) {
    return x+y;
}
void main() {
    int int1=5, int2=6;
    double double1=7.2, double2=4.3;
    int array1[] = {1,2,3}, array2[] = {4,5,6};
    cout << add(int1, int2) << endl;  // OK
    cout << add(double1, double2) << endl;  // OK
    cout << add(int1, double2) << endl;
    cout << add(array1, array2) << endl;
}
```

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int array1[] = {1, 2, 3};
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copy(array2, array1, 3);
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error C2440: '=' : cannot convert from 'int' to 'char *'

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template<class type>
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   return x+y;
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void main() {
   int int1=5, int2=6;
   double double1=7.2, double2=4.3;
   int array1[] = {1,2,3}, array2[] = {4,5,6};
   cout << add(int1, int2) << endl;  // OK
   cout << add(double1, double2) << endl;  // OK
   cout << add(int1, double2) << endl;  // bad syntax
   cout << add(array1, array2) << endl;
}
```

error C2782: 'type __cdecl add(type,type)' :
template parameter 'type' is ambiguous
could be 'double' or 'int'

Template Errors

- You may not violate syntax rules in a template

```
int array1[] = {1, 2, 3};
char *array2[3];
copy(array2, array1, 3);
```

error C2440: '=' : cannot convert from 'int' to 'char *'

- You may not violate semantics

```
template<class type>
type add(type x, type y) {
   return x+y;
}
void main() {
   int int1=5, int2=6;
   double double1=7.2, double2=4.3;
   int array1[] = {1,2,3}, array2[] = {4,5,6};
   cout << add(int1, int2) << endl; // OK
   cout << add(double1, double2) << endl; // OK
   cout << add(int1, double2) << endl; // bad syntax
   cout << add(array1, array2) << endl; //error C2110: cannot add two pointers
}
```

error C2782: 'type __cdecl add(type,type)' :
template parameter 'type' is ambiguous
could be 'double' or 'int'

Improving the Semantics

```
template<class type>
type add(type x, type y) {
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Improving the Semantics

```
template<class type>
type add(type x, type y) {
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}
class Array {
public:
   Array();
   void insert(int slot, double element);
   double get(int slot) const;
   void display() const;
   Array operator+(const Array &rhs) const;
private:
   double m_array[cArraySize];
};
```

Improving the Semantics

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template<class type>
type add(type x, type y) {
   return x+y;
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public:
   Array();
   void insert(int slot, double element);
   double get(int slot) const;
   void display() const;
   Array operator+(const Array &rhs) const;
private:
   double m_array[cArraySize];
};
void main() {
   Array array1, array2, array3;
   array1.insert(0, 2.2); array2.insert(0, 4.5);
   array3 = add(array1, array2);
   array3.display();
}
```

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type add(type x, type y) {
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class Array {
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   void insert(int slot, double element);
   double get(int slot) const;
   void display() const;
   Array operator+(const Array &rhs) const;
private:
   double m_array[cArraySize];
};
void main() {
   Array array1, array2, array3;
   array1.insert(0, 2.2); array2.insert(0, 4.5);
   array3 = add(array1, array2);
   array3.display();
}
```

```
Array Array::operator+(const Array &rhs) const {
   Array tmp;
   for (int i=0; i<cArraySize; i++)
      tmp.m_array[i] = m_array[i] + rhs.m_array[i];
   return tmp;
}
```

Improving the Semantics

```
template<class type>
type add(type x, type y) {
   return x+y;
}
class Array {
public:
   Array();
   void insert(int slot, double element);
   double get(int slot) const;
   void display() const;
   Array operator+(const Array &rhs) const;
private:
   double m_array[cArraySize];
};
void main() {
   Array array1, array2, array3;
   array1.insert(0, 2.2); array2.insert(0, 4.5);
   array3 = add(array1, array2);
   array3.display();
}
```

```
Array Array::operator+(const Array &rhs) const {
   Array tmp;
   for (int i=0; i<cArraySize; i++)
      tmp.m_array[i] = m_array[i] + rhs.m_array[i];
   return tmp;
}
```

```
Array::Array() {
   for (int i=0; i<cArraySize; i++)
      m_array[i] = 0;
}
```

Improving the Semantics

```
template<class type>
type add(type x, type y) {
   return x+y;
}
class Array {
public:
   Array();
   void insert(int slot, double element);
   double get(int slot) const;
   void display() const;
   Array operator+(const Array &rhs) const;
private:
   double m_array[cArraySize];
};
void main() {
   Array array1, array2, array3;
   array1.insert(0, 2.2); array2.insert(0, 4.5);
   array3 = add(array1, array2);
   array3.display();
}
```

```
Array Array::operator+(const Array &rhs) const {
   Array tmp;
   for (int i=0; i<cArraySize; i++)
      tmp.m_array[i] = m_array[i] + rhs.m_array[i];
   return tmp;
}
```

```
Array::Array() {
   for (int i=0; i<cArraySize; i++)
      m_array[i] = 0;
}
```

Output
6.7 0 0

Templates and Overloading

- You can overload a template function with another template function

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```
template<class type>
type add(type x, type y) {
   return x+y;
}
template<class type>
type add(type x, type y, type z)
    {
   return x+y+z;
}
```

Templates and Overloading

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template<class type>
type add(type x, type y) {
   return x+y;
}
template<class type>
type add(type x, type y, type z)
   {
   return x+y+z;
}
void main() {
   int x = 5;
   int y = 4;
   int z = 1;
   cout << add(x, y) << endl;
   cout << add(x, y, z) << endl;
}
```

Templates and Overloading

- You can overload a template function with another template function

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```

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- Overloading is more commonly used to *avoid* a template, see next page

Template and Overloading (cont'd)

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But this template will fail with C char arrays.

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But this template will fail with C char arrays.

- The solution is to provide an overloaded non-template function in addition to the template function

```
template <class type>
bool greaterThan(type x, type y)
   {
   return x > y;
}
```

```
bool greaterThan(char *str1, char *str2) {
   return strcmp(str1, str2) > 0;
}
```

Template and Overloading (cont'd)

- The template below will work fine with integers, doubles and chars

```
template <class type>
bool greaterThan(type x, type y) {
   return x > y;
}
```

But this template will fail with C char arrays.

- The solution is to provide an overloaded non-template function in addition to the template function

```
template <class type>
bool greaterThan(type x, type y)
   {
   return x > y;
}
```

```
bool greaterThan(char *str1, char *str2) {
   return strcmp(str1, str2) > 0;
}
```

- Rule for "signature matching" with templates: **non-template functions have precedence over template functions in matching function calls**

Program Linkage Notes

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*.cpp ? **No**. we should put template definitions into ***.h** file.

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  - Remember that the compiler needs to instantiate the real function body according to the **template function call statement**.

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Which files should we put the **template function** into?

*.cpp ? **No**. we should put template definitions into ***.h** file.

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- In a multi-file C++ project, we
  - put function prototypes in *.h file and put the definitions of each function in *.cpp files
  - put class declarations in *.h file and put the member function definitions in *.cpp files

Which files should we put the **template function** into?

*.cpp ? **No**. we should put template definitions into ***.h** file.

  - Remember that the compiler needs to instantiate the real function body according to the **template function call statement**. Therefore, the compiler need to know the complete template definitions before it can instantiate a template function after seeing the function call statement.
  - Previously, the compiler only need to know the declaration of each class or function. The actual function codes are only required at linkage step.

Template Classes

- A template array example

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```
template <class type>
class Array {
public:
    Array(int arraySize);
    ~Array();
    void insert(int slot, type element);
    type get(int slot) const;
private:
    int m_arraySize;
    type *m_data;
};
```

Template Classes

✧ A template array example

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   type get(int slot) const;
private:
   int m_arraySize;
   type *m_data;
};

template<class type>
Array<type>::Array(int arraySize): m_arraySize(arraySize) {
   m_data = new type[arraySize];
}
```

Template Classes

- A template array example

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class Array {
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   Array(int arraySize);
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   int m_arraySize;
   type *m_data;
};
```

```
template<class type>
Array<type>::~Array() {
   delete[] m_data;
}
```

```
template<class type>
Array<type>::Array(int arraySize): m_arraySize(arraySize) {
   m_data = new type[arraySize];
}
```

Template Classes (cont’d)

```
template<class type>
void Array<type>::insert(int slot, type element) {
   if (slot<m_arraySize && slot>=0)
      m_data[slot] = element;
   else
      cout << "Warning, out of range!\n";
}
```

Template Classes (cont'd)

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template<class type>
void Array<type>::insert(int slot, type element) {
   if (slot<m_arraySize && slot>=0)
      m_data[slot] = element;
   else
      cout << "Warning, out of range!\n";
}

template<class type>
type Array<type>::get(int slot) const {
 if (slot<m_arraySize && slot>=0)
      return m_data[slot];
   else
      cout << "Warning, out of range!\n";
   return 0; // return something
}
```

Template Classes (cont’d)

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void Array<type>::insert(int slot, type element) {
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   else
      cout << "Warning, out of range!\n";
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}

void main() {
   Array<int> array(20);
   array.insert(0, 10);
   cout << array.get(0);
}
```

Template Classes (cont'd)

```
template<class type>
void Array<type>::insert(int slot, type element) {
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void main() {
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```

Now you have a configurable array class that can hold chars, ints, doubles, strings, and other classes

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private:
    type m_data[arraySize];
};
```

- Usage

```
void main() {
    Array<int, 100> array;
    array.insert(99, 123);
    cout << array.get(99) << endl;
}
```

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template<class type, int arraySize>
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```

also can be used to replace a **functor** in case a function requires compile time pre-configuration

- Usage

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void main() {
   Array<int, 100> array;
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   cout << array.get(99) << endl;
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Templates and Static Data Member

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   type *m_data;
   static type sDefault;
};
```

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template<class type>
type Array<type>::sDefault = 0;
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    Array(int arraySize);
    ~Array();
    void insert(int slot, type element);
    type get(int slot) const;
private:
    int m_arraySize;
    type *m_data;
    static type sDefault;
};
```

Or on a type by type basis (in .cpp file)

```
int Array<int>::sDefault = 0;
char Array<char>::sDefault = '#';
```

- Every static data member must be *defined* outside the class
  In the case of templates, we can do this generically (in .h file)

```
template<class type>
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```

Static Data Members (cont'd)

- The get() function returns the static data member

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```
template<class type>
type Array<type>::get(int slot) const {
   if (slot<m_arraySize && slot>=0)
        return m_data[slot];
   else {
        cout << "Warning, out of range!\n";
        return sDefault; // return something
   }
}
```

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        return sDefault; // return something
   }
}
```

- Usage

```
void main() {
   Array<char> array1(100);
   Array<int> array2(100);
   array1.insert(0, 'A');
   cout << array1.get(0) << endl;
   cout << array1.get(100) << endl; // out of range
   array2.insert(0, 5);
   cout << array2.get(0) << endl;
   cout << array2.get(100) << endl; // out of range
}
```

Static Data Members (cont'd)

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        cout << "Warning, out of range!\n";
        return sDefault; // return something
    }
}
```

- Usage

```
void main() {
    Array<char> array1(100);
    Array<int> array2(100);
    array1.insert(0, 'A');
    cout << array1.get(0) << endl;
    cout << array1.get(100) << endl; // out of range
    array2.insert(0, 5);
    cout << array2.get(0) << endl;
    cout << array2.get(100) << endl; // out of range
}
```

```
Output
A
Warning, out of range!
#
5
Warning, out of range!
0
```

Template Classes Working Together

- If a member object within a template class contains the parameterized variable, it must also be a template

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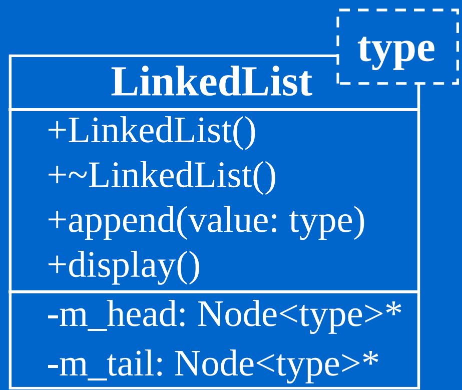
- Example (linked list)

```
template <class type>
class LinkedList {
public:
   LinkedList();
   ~LinkedList();
   void append(type value);
   void display();
private:
   Node<type> *m_head;
   Node<type> *m_tail;
};
```



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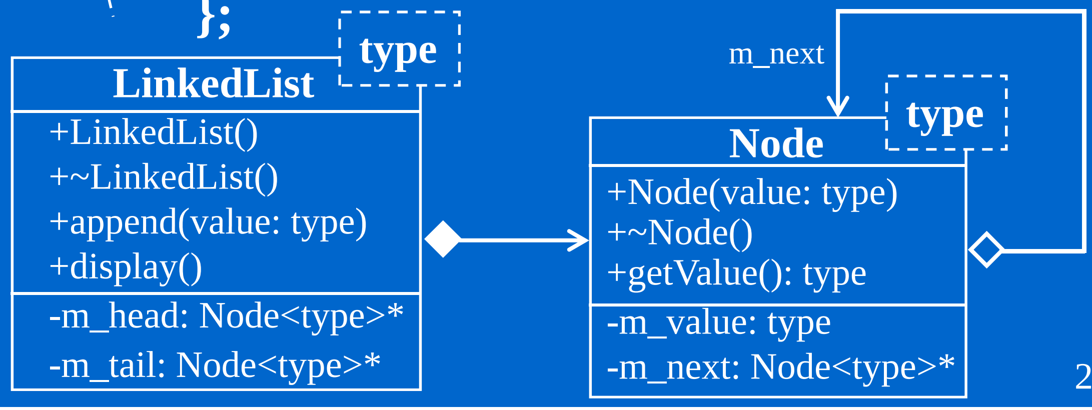
};
```

```
template <class type>
class Node {
   friend class LinkedList<type>;
private:
   Node(type value): m_value(value),
                     m_next(0) {}
   ~Node() { delete m_next; }
private:
   type m_value;
   Node<type> *m_next;
};
```



Templates and Friends

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```
template<class type>
void LinkedList<type>::append(type value) {
   Node<type> *tmp = new Node<type>(value);
   if (m_head == 0)
      m_head = tmp;
   else
      m_tail->m_next = tmp;
   m_tail = tmp;
}
```

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template <class type>
LinkedList<type>::LinkedList(): m_head(0), m_tail(0) {
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template <class type>
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      m_tail->m_next = tmp;
   m_tail = tmp;
}
```

- Usage

```
void main() {
   LinkedList<char> myLinkedList;
   myLinkedList.append('A');
}
```

Template Member Function

```
//------ MyClass.h -----
class MyClass {
public:
   MyClass(void);
   template <class T> void func(T x);
};
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};
```

```
template <class T>
void MyClass::func(T x) {
    std::cout << x << std::endl;
}
```

Template Member Function

```
//------ MyClass.h -----
class MyClass {
public:
    MyClass(void);
    template <class T> void func(T x);
};

#include <iostream>
template <class T>
void MyClass::func(T x) {
    std::cout << x << std::endl;
}
//------ end of MyClass.h -----
```

```
template <class T>
void MyClass::func(T x) {
    std::cout << x << std::endl;
}
```

Design Considerations

- Usage for templates: primarily for container classes, i.e. arrays, stacks, linked lists, map, etc
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- Examples:
  - a function that adds together two components
  - you can’t use the template on any class that doesn’t overload+
- Document the template thoroughly.
  State which types will not work with the template.
  State which functions you expect to be available, e.g., +

More Templates

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- **C++ Template Meta-programming (TMP, compile time programming, programming with types, see** https://en.wikibooks.org/wiki/C%2B%2B_Programming/Templates/Template_Meta-Programming**)** **For example**: factorial n! = n*(n-1)!

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template <unsigned n> struct factorial {
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More Templates

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int array[ factorial<7>::value ];
```

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7 * factorial<6>::value

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```

7 * factorial<6>::value

7 * 6 * factorial<5>::value

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int array[ factorial<7>::value ];  // compile-time constant
```

7 * factorial<6>::value
7 * 6 * factorial<5>::value
7 * 6 * 5 * factorial<4>::value
…

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```

7 * factorial<6>::value

7 * 6 * factorial<5>::value

7 * 6 * 5 * factorial<4>::value

. . .

7 * 6 * 5 * 4 * 3 * 2 * 1 * 1

References

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