



Module 38

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Bhattacharya

Objectives &
Outline

What is a
Template?

Function
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Definition
Instantiation

Template Argument
Deduction

Example

typename

Summary

Module 38: Programming in C++

Template (Function Template): Part 1

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Slides taken from NPTEL course on Programming in C++
by **Prof. Partha Pratim Das**



Module Objectives

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What is a
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`typename`

Summary

- Understand Templates in C++



Module Outline

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`typename`

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- What is a Template?
- Function Template
 - Function Template Definition
 - Instantiation
 - Template Argument Deduction
 - Example
- `typename`
- Class Template
 - Class Template Definition
 - Instantiation
 - Partial Template Instantiation & Default Template Parameters
 - Inheritance



What is a Template?

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Summary

- Templates are specifications of a collection of functions or classes which are parameterized by types
- Examples:
 - Function search, min etc.
 - The basic algorithms in these functions are the same independent of types
 - Yet, we need to write different versions of these functions for strong type checking in C++
 - Classes list, queue etc.
 - The data members and the methods are almost the same for list of numbers, list of objects
 - Yet, we need to define different classes



Function Template: Code reuse in Algorithms

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- We need to compute the maximum of two values that can be of:
 - int
 - double
 - char * (C-String)
 - Complex (user-defined class for complex numbers)
 - ...

- We can do this with overloaded Max functions:

```
int Max(int x, int y);  
double Max(double x, double y);  
char *Max(char *x, char *y);  
Complex Max(Complex x, Complex y);
```

With every new type, we need to add an overloaded function in the library!

- **Issues in Max function**
 - **Same algorithm** (compare two value using the appropriate operator of the type and return the larger value)
 - **Different code versions** of these functions for strong type checking in C++



Max as Overload

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```
#include <iostream>
#include <cstring>
#include <cmath>
using namespace std;

// Overloads
int Max(int x, int y) { return x > y ? x : y; }
double Max(double x, double y) { return x > y ? x : y; }
char *Max(char *x, char *y) { return strcmp(x, y) > 0 ? x : y; }

int main() {
    int a = 3, b = 5, iMax;
    double c = 2.1, d = 3.7, dMax;

    cout << "Max(" << a << ", " << b << ") = " << Max(a, b) << endl;
    cout << "Max(" << c << ", " << d << ") = " << Max(c, d) << endl;

    char *s1 = new char[6], *s2 = new char[6];
    strcpy(s1, "black"); strcpy(s2, "white");
    cout << "Max(" << s1 << ", " << s2 << ") = " << Max(s1, s2) << endl;
    strcpy(s1, "white"); strcpy(s2, "black");
    cout << "Max(" << s1 << ", " << s2 << ") = " << Max(s1, s2) << endl;

    return 0;
}
```

- Overloaded solutions work
- In some cases (C-string), similar algorithms have exceptions
- With every new type, a new overloaded Max is needed
- Can we make Max generic and make a library to work with future types?
- How about macros?



Max as a Macro

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Summary

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

#define Max(x, y) (((x) > (y)) ? x : y)

int main() {
    int a = 3, b = 5;
    double c = 2.1, d = 3.7;

    cout << "Max(" << a << ", " << b << ") = " << Max(a, b) << endl;
    // Output: Max(3, 5) = 5

    cout << "Max(" << c << ", " << d << ") = " << Max(c, d) << endl;
    // Output: Max(2.1, 3.7) = 3.7

    return 0;
}
```

- Max, being a macro, is type oblivious – can be used for `int` as well as `double`, etc.
- Note the parentheses around parameters to protect precedence
- Note the parentheses around the whole expression to protect precedence
- Looks like a function – but does not behave as such



Max as a Macro: Pitfalls

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Summary

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

#define Max(x, y) (((x) > (y)) ? x : y)

int main() {
    int a = 3, b = 5;
    double c = 2.1, d = 3.7;

    // Side Effects
    cout << "Max(" << a << ", " << b << ") = ";    // Output: Max(3, 5) = 6
    cout << Max(a++, b++) << endl;
    cout << "a = " << a << ", b = " << b << endl; // Output: a = 4, b = 7

    // C-String Comparison
    char *s1 = new char[6], *s2 = new char[6];
    strcpy(s1, "black"); strcpy(s2, "white");
    cout << "Max(" << s1 << ", " << s2 << ") = " << Max(s1, s2) << endl;
    // Output: Max(black, white) = white

    strcpy(s1, "white"); strcpy(s2, "black");
    cout << "Max(" << s1 << ", " << s2 << ") = " << Max(s1, s2) << endl;
    // Output: Max(white, black) = black

    return 0;
}
```

- In "Side Effects" – the result is wrong, the larger values gets incremented twice
- In "C-String Comparison" – swapping parameters changes the result – actually compares pointers



Function Template

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- A **function template**
 - describes how a function should be built
 - supplies the definition of the function using some arbitrary types, (as place holders)
 - a **parameterized** definition
 - can be considered the definition for a **set of overloaded versions** of a function
 - is identified by the **keyword template**
 - followed by comma-separated list of **parameter** identifiers (each preceded by **keyword class** or **keyword typename**)
 - enclosed between **<** and **>** delimiters
 - followed by the signature the function
 - Note that every template parameter is a **built-in type** or **class** – type parameters



Max as a Function Template

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

```
template<class T>
T Max(T x, T y) {
    return x > y ? x : y;
}
```

```
int main() {
    int a = 3, b = 5, iMax;
    double c = 2.1, d = 3.7, dMax;
```

```
    iMax = Max<int>(a, b);
    cout << "Max(" << a << ", " << b << ") = " << iMax << endl;
    // Output: Max(3, 5) = 5
```

```
    dMax = Max<double>(c, d);
    cout << "Max(" << c << ", " << d << ") = " << dMax << endl;
    // Output: Max(2.1, 3.7) = 3.7
```

```
    return 0;
}
```

- Max, now, knows the type
- Template type parameter T explicitly specified in instantiation of `Max<int>`, `Max<double>`



Max as a Function Template: Pitfall "Side Effects" – Solved

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

template<class T>
T Max(T x, T y) {
    return x > y ? x : y;
}

int main() {
    int a = 3, b = 5, iMax;

    // Side Effects
    cout << "Max(" << a << ", " << b << ") = ";
    iMax = Max<int>(a++, b++);
    cout << iMax << endl;
    // Output: Max(3, 5) = 5

    cout << "a = " << a << ", b = " << b << endl;
    // Output: a = 4, b = 6

    return 0;
}
```

- Max is now a proper function call – no side effect



Max as a Function Template: Pitfall "C-String Comparison" – Solved

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

template<class T>
T Max(T x, T y) { return x > y ? x : y; }

template<> // Template specialization for 'char *' type
char *Max<char *>(char *x, char *y) { return strcmp(x, y) > 0 ? x : y; }

int main() {
    char *s1 = new char[6], *s2 = new char[6];

    strcpy(s1, "black"); strcpy(s2, "white");
    cout << "Max(" << s1 << ", " << s2 << ") = " << Max<char*>(s1, s2) << endl;
    // Output: Max(black, white) = white

    strcpy(s1, "white"); strcpy(s2, "black");
    cout << "Max(" << s1 << ", " << s2 << ") = " << Max<char*>(s1, s2) << endl;
    // Output: Max(black, white) = white

    return 0;
}
```

- Generic template code does not work for C-Strings as it compares pointers, not the strings pointed by them
- We provide a specialization to compare pointers using comparison of strings
- Need to specify type explicitly is bothersome
- *Type in code fixed at two places `Max<char>` → `Max<char*>`*



Max as a Function Template: Implicit Instantiation

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

template<class T>
T Max(T x, T y) {
    return x > y ? x : y;
}

int main() {
    int a = 3, b = 5, iMax;
    double c = 2.1, d = 3.7, dMax;

    iMax = Max(a, b); // Type 'int' inferred from 'a' and 'b' parameters types
    cout << "Max(" << a << ", " << b << ") = " << iMax << endl;
    // Output: Max(3, 5) = 5

    dMax = Max(c, d); // Type 'double' inferred from 'c' and 'd' parameters types
    cout << "Max(" << c << ", " << d << ") = " << dMax << endl;
    // Output: Max(2.1, 3.7) = 3.7

    return 0;
}
```

- Often template type parameter **T** may be inferred from the type of parameters in the instance
- If the compiler cannot infer or infers wrongly, we use explicit instantiation



Template Argument Deduction: Implicit Instantiation

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- Each item in the template parameter list is a template argument
- When a template function is invoked, the values of the template arguments are determined by seeing the types of the function arguments

```
template<class T> T Max(T x, T y);
template<> char *Max<char *>(char *x, char *y);
template <class T, int size> T Max(T x[size]);

int a, b; Max(a, b); // Binds to Max<int>(int, int);
double c, d; Max(c, d); // Binds to Max<double>(double, double);
char *s1, *s2; Max(s1, s2); // Binds to Max<char*>(char*, char*);

int pval[9]; Max(pval); //Error!
```

- Three kinds of conversions are allowed
 - L-value transformation (for example, Array-to-pointer conversion)
 - Qualification conversion
 - Conversion to a base class instantiation from a class template
- If the same template parameter are found for more than one function argument, template argument deduction from each function argument must be the same

- Type in code fixed at one place* template <class T, int size> Type Max(T x[size]) →

```
template <class T, int size> T Max(T x[size])
```



Max as a Function Template: With User-Defined Class

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```
#include <iostream>
#include <cmath>
#include <cstring>
using namespace std;

class Complex { double re_; double im_;
public:
    Complex(double re = 0.0, double im = 0.0) : re_(re), im_(im) {};
    double norm() const { return sqrt(re_*re_+im_*im_); }
    friend bool operator>(const Complex& c1, const Complex& c2) {
        return c1.norm() > c2.norm();
    }
    friend ostream& operator<<(ostream& os, const Complex& c) {
        os << "(" << c.re_ << ", " << c.im_ << ")"; return os;
    }
};

template<class T> T Max(T x, T y) { return x > y ? x : y; }
template<> char *Max<char *>(char *x, char *y) { return strcmp(x, y) > 0 ? x : y; }

int main() { Complex c1(2.1, 3.2), c2(6.2, 7.2);

    cout << "Max(" << c1 << ", " << c2 << ") = " << Max(c1, c2) << endl;
        // Output: Max((2.1, 3.2), (6.2, 7.2)) = (6.2, 7.2)

    return 0;
}
```

- When Max is instantiated with class Complex, we need comparison operator for Complex
- The code, therefore, will not compile without bool operator>(const Complex&, const Complex&)
- Traits of type variable T include bool operator>(T, T) which the instantiating type must fulfill



Max as a Function Template: Overloads

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

template<class T> T Max(T x, T y) { return x > y ? x : y; }

template<> char *Max<char *>(char *x, char *y) { return strcmp(x, y) > 0 ? x : y; }

template<class T, int size> T Max(T x[size]) { T t = x[0];
    for (int i = 0; i < size; ++i) { if (x[i] > t) t = x[i]; }

    return t;
}

int main() {
    int arr[] = { 2, 5, 6, 3, 7, 9, 4 };
    cout << "Max(arr) = " << Max<int, 7>(arr) << endl; // Output: Max(arr) = 9

    return 0;
}
```

- Template function can be overloaded
- A template parameter can be non-type (int) constant



Swap as a Function Template

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

template<class T> void Swap(T& one, T& other)
{
    T temp;
    temp = one; one = other; other = temp;
}

int main() {
    int i = 10, j = 20;
    cout << "i = " << i << ", j = " << j << endl;
    Swap(i, j);
    cout << "i = " << i << ", j = " << j << endl;

    string s1("abc"), s2("def");

    cout << "s1 = " << s1 << ", s2 = " << s2 << endl;
    Swap(s1, s2);
    cout << "s1 = " << s1 << ", s2 = " << s2 << endl;

    return 0;
}
```

- The traits of type variable T include default constructor (T::T()) and copy assignment operator (T operator=(const T&))
- Our template function cannot be called swap, as std namespace has such a function



typename Keyword

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- Consider:

```
template <class T> f (T x) {  
    T::name * p;  
}
```

- What does it mean?

- T::name is a type and p is a pointer to that type
- T::name and p are variables and this is a multiplication

- To resolve, we use **keyword typename**:

```
template <class T> f (T x) { T::name * p; } // Multiplication
```

```
template <class T> f (T x) { typename T::name * p; } // Type
```

- The keywords **class** and **typename** have almost the same meaning in a template parameter
- typename** is also used to tell the compiler that an expression is a type expression



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Summary

- Introduced the templates in C++
- Discussed function templates as generic algorithmic solution for code reuse
- Explained templates argument deduction for implicit instantiation
- Illustrated with examples