

11.1. Motivation

11.2. Templates

11.3. Using templates, inheritance, friends

11.4. Templates and operator overloading

11.5. The Standard Template Library (STL)

11.1. Motivation: Revisiting the Queue class

The concept of a queue is characterized by its interface and behavior, independent of the type (or class) of elements stored inside.

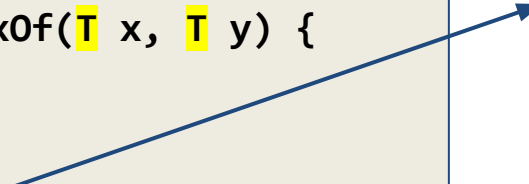
But: The **Queue** and **UQueue** classes in the previous chapter can only store integers; dealing with other types or objects in the queue would require re-writing the **QueueElement** and **Queue** or **UQueue** classes.

Templates allow implementing a container class independent of the type of data elements.


11.1. Motivation: Revisiting the Queue class

Templates are expanded at compile-time, where the compiler does type-checking before the template expansion happens. The source code contains only the function or class, the compiled code can afterwards contain multiple copies of the same function or class. For a function for example:

```
template <class T> T maxOf(T x, T y) {  
    return (x > y)? x : y;  
}  
  
int main() {  
    std::cout << maxOf<int>(12,24) << ' '  
    std::cout << maxOf<char>('d','e') << '\n';  
}
```



```
int maxOf(int x, int y) {  
    return (x > y)? x : y;  
}
```



```
char maxOf(char x, char y) {  
    return (x > y)? x : y;  
}
```

11.1. Motivation - Template Queue Example 00

`example00.cpp`

```
template <class Data> class Queue { // Template class for a queue
public:
    Queue(int size = 100) : maxSize(size), tail(0), head(0), filled(0) {items = new Data[size];}
    ~Queue() { delete[] items; items = nullptr; }
    void put(Data data);
    Data get();
    bool isFull() const { return filled == maxSize; }
    bool isEmpty() const { return filled == 0; }
    void clear() { filled = 0; head = 0; tail = 0; } // clear whole queue
private:
    Data *items; // array of Data
    int maxSize; // size of items
    int tail; // position in array to put
    int head; // position in array to get from
    int filled; // number of elements in queue
};
```

11.1. Motivation - Template Queue Example 00

example00.cpp

```
// put element at the tail of the queue, for example put(d) updates:
// items: [ ][ ][ ][ ][d][ ] ... [ ][ ]
//          head           tail→
template <class Data>
void Queue<Data>::put(Data data) { // put element data at tail
    if (!isFull()) {
        items[tail] = data;
        tail = (tail+1) % maxSize;
        filled++;
    } else {
        throw std::runtime_error("queue: full on put");
    }
}
```

11.1. Motivation - Template Queue Example 00

example00.cpp

```
// gets element at the head of the queue, for example get() updates.
// items: [ ][ ][ ][ ][ ][ ][ ] ... [ ][ ]
//           head→           tail
template <class Data>
Data Queue<Data>::get() { // get and remove element from head
    Data retval;
    if (!isEmpty()) {
        retval = items[head];
        head = (head+1) % maxSize;
        filled--;
    } else {
        throw std::runtime_error("queue: empty on get");
    }
    return retval;
}
```

11.1. Motivation - Template Queue Example 00

Queue are used while specifying the data type when creating the queue objects:

```
int main() {
    Queue<int> intQueue(127);
    Queue<char> charQueue(21);

    // fill int and char data in both queues:
    for (auto i = 1; i <= 9; i++) intQueue.put(i);
    for (auto i = '1'; i <= '9'; i++) charQueue.put(i);

    // get earliest data from both queues nine times:
    for (auto i = 0; i < 9; i++) {
        std::cout << intQueue.get() << ' ' << charQueue.get() << '\n';
    }
}
```

example00.cpp

11.1. Motivation - Template UQueue Example 01

`example01.cpp`

```
template <class Data> class QueueElement; // element class, hidden from users

template <class Data> class UQueue { // Template class for an unlimited queue
public:
    UQueue() { head = tail = nullptr; }
    ~UQueue() { clear(); };
    void put(Data data);
    Data get();
    bool isEmpty() const;
    void clear();
    Data get();
private:
    QueueElement<Data> * head; // pointer to element to put
    QueueElement<Data> * tail; // pointer to element to get from
};
```


11.1. Motivation - Template UQueue Example 01

`example01.cpp`

```
template <class Data> class QueueElement { // element class, hidden from users
public:
    QueueElement(Data data) : data(data) , next(nullptr) {}
    Data data;
    QueueElement<Data> * next;
};

template <class Data>
void UQueue<Data>::clear() { // iteratively clear the queue of all elements
    QueueElement<Data> * elem, * elem_next;
    for (elem = head; elem != nullptr; elem = elem_next) {
        elem_next = elem->next;
        delete elem;
    }
    head = tail = nullptr;
}
```

11.1. Motivation - Template UQueue Example 01

`example01.cpp`

```
template <class Data>
bool UQueue<Data>::isEmpty() const { // check whether the queue is empty
    return head == nullptr;
}

template <class Data>
void UQueue<Data>::put(Data data) { // put in new data element at tail
    QueueElement<Data> * node = new QueueElement<Data>(data);
    if (isEmpty()) {
        head = tail = node;
    } else {
        tail = tail->next = node; // tail is guaranteed to be valid
    }
}
```

11.1. Motivation - Template UQueue Example 01

`example01.cpp`

```
template <class Data>
Data UQueue<Data>::get() { // get and remove element from head
    Data retVal;
    if (!isEmpty()) {
        retVal = head->data;
        QueueElement<Data> * second = head->next;
        delete head;
        head = second;
    } else {
        throw std::runtime_error("uqueue: empty on get");
    }
    return retVal;
}
```

11.1. Motivation - Template UQueue Example 01

UQueue is used while specifying the data type when creating the queue objects:

```
int main() {  
    Queue<int> intQueue(127);  
    Queue<char> charQueue(21);  
  
    // fill int and char data in both queues:  
    for (auto i = 1; i <= 9; i++) intQueue.put(i);  
    for (auto i = '1'; i <= '9'; i++) charQueue.put(i);  
  
    // get earliest data from both queues nine times:  
    for (auto i = 0; i < 9; i++) {  
        std::cout << intQueue.get() << ' ' << charQueue.get() << '\n';  
    }  
}
```

example01.cpp

11.2. Templates

`template <class Data>` designates Data as the parameter. This is a placeholder for a type to be specified later, when an object of the class that follows this declaration of a template. `class` is almost interchangeable with `typename`.

The later use (e.g., instantiation) of a template is often called specialization:

```
UQueue<double> q; or Queue<Data> * n = new Queue<Data>(250);  
or int getSize( Queue<int> & q );
```

Templates tell the compiler that the class will use a type that is to be specified when the objects are created, which is why templates are *put in the header file*. The compiler will create the actual class only when it is specialized.

11.3. Using templates, inheritance, friends

Templates can have more than one parameter:

```
template <class XData, class YData>
```

Templates can have, like functions or methods, default parameters:

```
template <class XData, class YData = char>
```

Templates can have non-type parameters, too:

```
template <class XData, int max>
```

Inheritance is possible:

- Templates can inherit from other templates and from non-template classes

```
template <class x> class SortableQueue<x> : public UQueue<x> {
```

- Non-template classes can inherit from templates:

```
class IntQueue : public UQueue<int> {
```

11.3. Using templates, inheritance, friends

Template parameters for functions can be deduced by the compiler, i.e., without specifying the type. This is possible for template classes since C++17.

```
#include <iostream>
```

example06.cpp

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

```
int main() {  
    std::cout << maxOf<int>(12,24) << ' ';  
    std::cout << maxOf<char>('d','e') << '\n';  
    std::cout << maxOf(12,24) << ' ';           // these two lines have the same  
    std::cout << maxOf('d','e') << '\n';       // effect as above, types are deduced  
}
```

11.3. Using templates, inheritance, friends

Template classes can declare a non-template friend class or function, a general template friend class or function, or a type-specific template friend class or function:

```
template <class T> class A { //
public:
    template<class U> friend class B;
private:
    T data;
};
template<class U> class B {
public:
    B() { A<U> a; std::cout << "A's data: " << a.data << '\n'; };
};

int main() {
    B<int> b;
}
```


11.4. Templates and operator overloading

Overloading operators allows to customize the C++ operators (such as `+`, `-`, `*`, `/`, `%`, `^`, `&`, `|`, `~`, `!`, `=`, `<`, `>`, `+=`, `-=`, `*=`, `/=`, `%=`, `^=`, `&=`, `|=`, `<<`, `>>`, `>>=`, `<<=`, `==`, `!=`, `<=`, `>=`, `&&`, `||`, `++`, `--`, `,`, `->*`, `->`, `()`, `[]`, `<=>`(since C++20)) for operands of user-defined types. Example:

```
#include <iostream>
class A {
public:
    char a;
    A(char a): a(a) {}
};
std::string operator + (const A & a1, const A & a2) {
    std::string s;
    s += a1.a; s += a2.a;
    return s;
}
// A a1('a'), a2('b'); std::cout << a1+a2 << '\n';
```

11.4. Templates and operator overloading, reminder: friend methods

Friend methods can also be used for operators:

```
class Complex;
Complex operator + (const Complex & obj1, const Complex & obj2);

class Complex { // Class representing a complex number, e.g. 2.3 + 4.5 i
public:
    Complex() : real(0), img(0) {}
    Complex(double real, double imag) : real(real), imag(imag){}
    friend Complex operator + (const Complex & obj1, const Complex & obj2);
private:
    double real, imag;
};

Complex operator + (const Complex & obj1, const Complex & obj2) {
    Complex temp;
    temp.real = obj1.real + obj2.real;
    temp.imag = obj1.imag + obj2.imag;
    return temp;
}
```

example03.cpp

11.4. Templates and operator overloading, reminder: conversions

Conversion operators can be used to convert one type to another type:

```
#include <iostream>

// class representing a fraction through numerator and denominator, e.g. 7/9
class Fraction {
public:
    Fraction(int n, int d) : n(n), d(d) {}
    // note that conversion does not have a return type:
    operator double() const { return double(n)/double(d); }
private:
    int n, d;
};

int main() {
    Fraction frac(7, 9);
    double val = frac; // conversion to double, double val = (double) frac;
    std::cout << val << '\n';
}
```

example04.cpp

11.4. Templates and operator overloading

An operator with template, now:

```
#include <iostream>

template <class T> class MyClass { // a very basic template class
public:
    MyClass(T c) : c(c) {}
    T c;
};

template <class U>
std::ostream & operator<<(std::ostream & out, const MyClass<U> & classObj) {
    out.put(classObj.c);
    return out;
}

int main() {
    MyClass<char> t('?');
    std::cout << t << '\n';
}
```

example05.cpp

11.4. Templates and operator overloading

An operator with template, now:

```
#include <iostream>
template <class T> class MyClass;
template <class T> std::ostream & operator<<(std::ostream & out, const MyClass<T> & classObj);

template <class T> class MyClass { // a very basic template class with a friend operator:
    T c;
public:
    MyClass(T c) : c(c) {}
    // <> tells C++ this is a friend declaration of a function template instantiated for type T:
    friend std::ostream & operator<< <>(std::ostream & out, const MyClass<T> & classObj)
};

template <class T>
std::ostream & operator<<(std::ostream & out, const MyClass<T> & classObj) {
    out.put(classObj.c);
    return out;
}

int main() {
    MyClass<char> t('?');
    std::cout << t << '\n';
}
```

example06.cpp

11.5. Standard Template Library (STL)

STL is a set of C++ template classes that:

- implement most common data structures for *containers* (queues, vectors, lists, stacks, maps, arrays, etc.), *algorithms* (sorting, search, etc.), *iterators* (to go through containers) , and *function objects or functors*
- in the form of a library of container classes, algorithms, and iterators,
- using components that are parameterized through templates.

11.5. The Standard Template Library (STL) - Vector

Dynamic array that resizes when elements are added or removed

```
std::vector<double> myVector( { 2.0, 4.0, 7.0 } );  
std::vector<double> largeVector( 200, 1.0 ); // 200 elements, all ones  
std::vector<double> copiedVector( myVector ); // exact copy of myVector
```

```
#include <iostream>  
#include <vector>  
int main() {  
    std::vector<std::string> name( {"John", "George", "Paul", "Smith"} );  
    std::cout << "name size=" << name.size() << " of " << name.max_size();  
    std::cout << " capacity=" << name.capacity() << '\n';  
    for (auto i = name.begin(); i < name.end(); i++) // use iterators  
        std::cout << *i << '\n';  
    name.insert(name.begin()+2, "Tom"); // insert another name at third element  
    for (auto i : name) // use range based for loop  
        std::cout << i << '\n';  
}
```

example07.cpp

11.5. The Standard Template Library (STL) - Map

Container for (key value, mapped value) pairs. Mapped values cannot have the same key values. Initialization can be done (since C++11) with initializer lists:

```
std::map<int, std::string> names = {{1, "Ann"}, {2, "Ames"}, {9, "Asa"}};
```

```
std::map<std::string, int> students;  
students["Aaron"] = 173923;    // insert two new map elements  
students["Zachary"] = 183211;
```

```
for (auto const & x : names)    // since C++11  
    std::cout << "key:" << x.first << ",val:" << x.second << "\n";
```

```
for (auto const & [key, val] : students)    // since C++17  
    std::cout << "key:" << key << ",val:" << val << "\n";
```


11.5. The Standard Template Library (STL) - Map

```
#include <iostream>
#include <map>

int main() {
    std::map<std::string, int> students;
    students["Aaron"] = 173923;    // insert new map elements
    students["Zachary"] = 183211;
    students.insert( {"Patrick", 172932} );
    students.insert( std::pair<std::string, int>("Arnold", 161010) );

    for (auto const & x : names)    // since C++11
        std::cout << "key:" << x.first << ",val:" << x.second << '\n';

    for (auto const & [key, val] : students)    // since C++17
        std::cout << "key:" << key << ",val:" << val << '\n';

}
```

example08.cpp

11.5. The Standard Template Library (STL) - transform

```
int increase(int x) { return (x+1); } // operation to execute
```

```
int array[] = {1, 2, 3}; // a simple container
```

```
// transform from [ array to array+3 ] to array, with increase:  
std::transform(array, array+3, array, increase);
```

```
for ( const int & i : array )  
    std::cout << i << ", "; // output: 2, 3, 4,
```

Apart from the unary use above, transform also allows two input containers to be used (e.g., summing up elements of two containers).

A [functor](#) can be passed for the given operation to be done on all elements of container, with the additional benefit of keeping its state.

11.5. The Standard Template Library (STL) - transform

```
#include <iostream>
#include <vector>

int main() {
    std::vector a( { 16.0, 17.0, 18.0 } ); // init. lists since C++17
    std::vector b( { 10.0, 30.0, 60.0 } );
    std::vector<double> c;
    double n = 2.7;
    std::transform(a.begin(), a.end(),           // iterators to input and
                  b.begin(), std::back_inserter(c), // output vector elements
                  [=](double x, double y) {return(x - y)/n; });
    // [=] : capture all external variables (n) in lambda by value
    // [&] : capture all external variables (n) in lambda by reference

    for (const double & i : c) {
        std::cout << i << '\n';
    }
}
```

example09.cpp

11.5. The Standard Template Library (STL) - functors

Example of a functor:

```
#include <cassert>
class addX { // this is a functor
public:
    addX(int val) : x(val) {} // Constructor sets how much to add
    int operator()(int y) const { return x + y; } // ()
private:
    int x;
};

int main() {
    addX add5(5); // create object of functor class
    int i = add5(3); // "call" it through the () operation
    assert(i == 8);
}
```

11.5. The Standard Template Library (STL) - functors

More quick examples of functors in standard library:

```
#include <random>
int main() {
    std::random_device r; // generate uniformly-distributed random integers
    auto n = r(); // calls operator(), returns a random integer
}
```

```
#include <iostream>
int main() {
    std::hash<std::string> h; // provide hash function for std::string
    std::cout << h("hello") << '\n'; // Output hash value of "hello"
}
```

```
#include <iostream>
int main() {
    std::function<int(int)> square = [](int x) { return x*x; };
    std::cout << square(11) << '\n'; // Outputs 121
}
```

11.5. The Standard Template Library (STL)

```
#include <iostream>
#include <random> // for generating random values in the data set

int main() {
    // we simulate a sensor data set, rawData, with 1M floats in [0,1023]:
    const size_t dataSize = 1'000'000;
    std::vector<float> rawData(dataSize);
    std::random_device rand;
    std::generate(rawData.begin(), rawData.end(),
        [&]() { return static_cast<float>(rand()) / rand.max() * 1000.0f; } );

    // normalize the data in rawData between 0 and 1, by first finding the maximum
    // value, creating a vector for the normalized data, and then using transform
    // using a lambda function that scales all rawData elements.
    // Bonus: time the transform by using std::chrono::high_resolution_clock::now()

}
```

example10.cpp

11.5. The Standard Template Library (STL)

`example11.cpp`

```
#include <iostream>

// Create a functor called 'Calibrate' for calibration of data, using two
// attributes 'scale' and 'offset', which are used to do the calibration
// through the () operator.

int main() {
    // A time series for temperature values in degrees Celcius:
    std::vector<float> rawTemps = {37.5f, 37.8f, 37.5f, 37.3f, 37.6f};

    // Create a vector 'calibratedTemps' of the same size as rawTemps, and
    // apply Calibrate in std::transform by scaling the temperatur values up
    // by 10% and then shifting the signal down by 2 degrees Celsius

}
```

11.5. The Standard Template Library (STL)

More reference information about the C++ STL is given at these locations:

https://en.cppreference.com/w/cpp/standard_library

<https://cplusplus.com/reference/stl/>