

2. C++ advanced (II): Templates

What do we learn today?

- templates of classes
- function templates
- Specialization
- templates with values

Motivation

Goal: generic vector class and functionality.

Examples

```
Vector<double> vd(10);
```

```
Vector<int> vi(10);
```

```
Vector<char> vi(20);
```

```
auto nd = vd * vd; // norm (vector of double)
```

```
auto ni = vi * vi; // norm (vector of int)
```

Types as Template Parameters

- 1 In the concrete implementation of a class replace the type that should become generic (in our example: `double`) by a representative element, e.g. `T`.
- 2 Put in front of the class the construct `template<typename T>`² (Replace `T` by the representative name).

The construct `template<typename T>` can be understood as “for all types `T`”.

²equally: `template<class T>`

Types as Template Parameters

```
template <typename ElementType>
class Vector{
    std::size_t size;
    ElementType* elem;
public:
    ...
    Vector(std::size_t s):
        size{s},
        elem{new ElementType[s]}{}
    ...
    ElementType& operator[](std::size_t pos){
        return elem[pos];
    }
    ...
}
```

Template Instances

`Vector<typeName>` generates a type instance `Vector` with `ElementType=typeName`.

Notation: **Instantiation**

Examples

```
Vector<double> x;           // vector of double
Vector<int> y;              // vector of int
Vector<Vector<double>> x;   // vector of vector of double
```

Type-checking

Templates are basically replacement rules at instantiation time and during compilation. The compiler always checks as little as necessary and as much as possible.

Example

```
template <typename T>
class Pair{
    T left; T right;
public:
    Pair(T l, T r):left{l}, right{r}{}
    T min(){
        return left < right ? left : right;
    }
};
```


Example

```
template <typename T>
class Pair{
    T left; T right;
public:
    Pair(T l, T r):left{l}, right{r}{}
    T min(){
        return left < right ? left : right;
    }
};
```

```
Pair<int> a(10,20); // ok
auto m = a.min(); // ok
Pair<Pair<int>> b(a,Pair<int>(20,30)); // ok
auto n = b.min(); no match for operator< !
```

Generic Programming

Generic components should be developed rather as a **generalization of one or more examples** than from first principles.

```
template <typename T>
class Vector{
public:
    Vector ();
    Vector(std :: size_t);
    ~Vector();
    Vector(const Vector&);
    Vector& operator=(const Vector&);
    Vector (Vector&&);
    Vector& operator=(Vector&&);
    const T& operator[] (std :: size_t) const;
    T& operator[] (std :: size_t);
    std :: size_t size() const;
    T* begin();
    T* end();
    const T* begin() const;
    const T* end() const;
}
```

Function Templates

- 1 In a concrete implementation of a function replace the type that should become generic by a replacement, .e.g **T**,
- 2 Put in front of the function the construct `template<typename T>`³(Replace **T** by the replacement name)

³equally: `template<class T>`

Function Templates

```
template <typename T>
void swap(T& x, T&y){
    T temp = x;
    x = y;
    y = temp;
}
```

Types of the parameter determine the version of the function that is (compiled) and used:

```
int x=5;
int y=6;
swap(x,y); // calls swap with T=int
```

Limits of Magic

```
template <typename T>
void swap(T& x, T&y){
    T temp = x;
    x = y;
    y = temp;
}
```

An inadmissible version of the function is not generated:

```
int x=5;
double y=6;
swap(x,y); // error: no matching function for ...
```

.. also with operators

```
template <typename T>
class Pair{
    T left; T right;
public:
    Pair(T l, T r):left{l}, right{r}{}
    T min(){ return left < right? left: right; }
    std::ostream& print (std::ostream& os) const{
        return os << "("<< left << "," << right<< ")";
    }
};

template <typename T>
std::ostream& operator<< (std::ostream& os, const Pair<T>& pair){
    return pair.print(os);
}
```

.. also with operators

```
template <typename T>
class Pair{
    T left; T right;
public:
    Pair(T l, T r):left{l}, right{r}{}
    T min(){ return left < right? left: right; }
    std::ostream& print (std::ostream& os) const{
        return os << "("<< left << "," << right<< ")";
    }
};
```

```
Pair<int> a(10,20); // ok
std::cout << a; // ok
```

```
template <typename T>
std::ostream& operator<< (std::ostream& os, const Pair<T>& pair){
    return pair.print(os);
}
```

Useful!

```
// Output of an arbitrary container
template <typename T>
void output(const T& t){
    for (auto x: t)
        std::cout << x << " ";
    std::cout << "\n";
}

int main(){
    std::vector<int> v={1,2,3};
    output(v); // 1 2 3
}
```


Explicit Type

```
// input of an arbitrary pair
template <typename T>
Pair<T> read(){
    T left;
    T right;
    std::cin << left << right;
    return Pair<T>(left,right);
}
...

auto p = read<double>();
```

Explicit Type

```
// input of an arbitrary pair
template <typename T>
Pair<T> read(){
    T left;
    T right;
    std::cin << left << right;
    return Pair<T>(left,right);
}
...
```

```
auto p = read<double>();
```

If the type of a template instantiation cannot be inferred, it has to be provided explicitly.

Powerful!

```
template <typename T> // square number
T sq(T x){
    return x*x;
}
template <typename Container, typename F>
void apply(Container& c, F f){ // x ← f(x) forall x in c
    for(auto& x: c)
        x = f(x);
}
int main(){
    std::vector<int> v={1,2,3};
    apply(v,sq<int>);
    output(v); // 1 4 9
}
```

Specialization

```
template <>
class Pair<bool>{
    short both;
public:
    Pair(bool l, bool r):both{(l?1:0) + (r?2:0)} {};
    std::ostream& print (std::ostream& os) const{
        return os << "(" << both % 2 << ", " << both /2 << ")";
    }
};
```

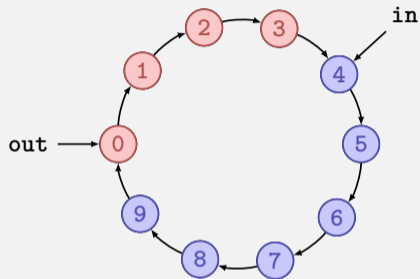
Specialization

```
template <>
class Pair<bool>{
    short both;
public:
    Pair(bool l, bool r):both{(l?1:0) + (r?2:0)} {};
    std::ostream& print (std::ostream& os) const{
        return os << "(" << both % 2 << ", " << both / 2 << ")";
    }
};

Pair<int> i(10,20); // ok -- generic template
std::cout << i << std::endl; // (10,20);
Pair<bool> b(true, false); // ok -- special bool version
std::cout << b << std::endl; // (1,0)
```

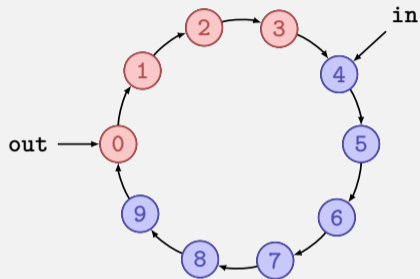
Template Parameterization with Values

```
template <typename T, int size>  
class CircularBuffer{  
    T buf[size] ;  
    int in; int out;
```



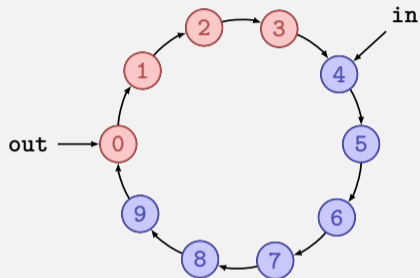
Template Parameterization with Values

```
template <typename T, int size>
class CircularBuffer{
    T buf[size] ;
    int in; int out;
public:
    CircularBuffer():in{0},out{0}{};
    bool empty(){
        return in == out;
    }
    bool full(){
        return (in + 1) % size == out;
    }
}
```



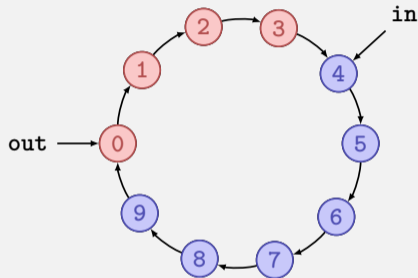
Template Parameterization with Values

```
template <typename T, int size>
class CircularBuffer{
    T buf[size] ;
    int in; int out;
public:
    CircularBuffer():in{0},out{0}{};
    bool empty(){
        return in == out;
    }
    bool full(){
        return (in + 1) % size == out;
    }
    void put(T x); // declaration
    T get();      // declaration
};
```



Template Parameterization with Values

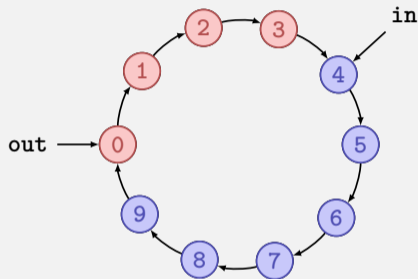
```
template <typename T, int size>
void CircularBuffer<T,size>::put(T x){
    assert(!full());
    buf[in] = x;
    in = (in + 1) % size;
}
```



Template Parameterization with Values

```
template <typename T, int size>
void CircularBuffer<T,size>::put(T x){
    assert(!full());
    buf[in] = x;
    in = (in + 1) % size;
}
```

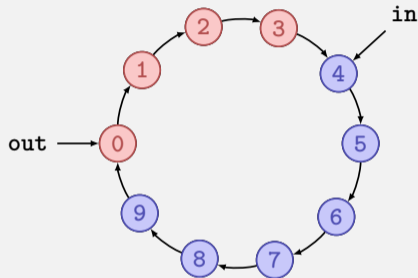
```
template <typename T, int size>
T CircularBuffer<T,size>::get(){
    assert(!empty());
    T x = buf[out];
    out = (out + 1) % size;
    return x;
}
```



Template Parameterization with Values

```
template <typename T, int size>
void CircularBuffer<T,size>::put(T x){
    assert(!full());
    buf[in] = x;
    in = (in + 1) % size;
}
```

```
template <typename T, int size>
T CircularBuffer<T,size>::get(){
    assert(!empty());
    T x = buf[out];
    out = (out + 1) % size; ← Potential for optimization if size = 2k.
    return x;
}
```



Today's exercise

- Implement a *generic* dynamic vector that offers subscript operators, features an efficient memory management and supports *Iteration*.
- Transform a sorting algorithm operating on indices of an int-vector into a *generic sorting algorithm working on an iterator*.