

EDAF30 – Programming in C++

9. *Generic programming*

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Outline

- 1 **Function templates**
 - Template arguments
 - Function objects
- 2 **Class templates**
 - Class templates
- 3 **Some details**
 - Using type deduction
 - Variadic templates

Function templates

Example: compare

```
template<class T>
int compare(const T& a, const T& b) {
    if (a < b) return -1;
    if (b < a) return 1;
    return 0;
}
```

Can be instantiated for all types that have an **operator<**

Function templates

Requirements on types

Example: another compare template

```
template<class T>
int compare(T a, T b) {
    if (a < b) return -1;
    if (a == b) return 0;
    return 1;
}
```

More requirements on the type T:

- ▶ call-by-value: T must be copy constructible
- ▶ needs both `operator<` and `operator==`

Try to minimize the requirements on T

Templates

Concepts

- ▶ A concept is a named set of requirements (on a type)
- ▶ for template arguments
- ▶ Not yet part of the C++ language

Some example concepts

DefaultConstructible Objects can be constructed without explicit initialization

CopyConstructible, CopyAssignable Objects (of type X) can be copied and assigned.

LessThanComparable $a < b$ is defined

EqualityComparable $a == b$ and $a != b$ is defined

Iterator and the more specific `InputIterator`, `OutputIterator`, `ForwardIterator`, `RandomAccessIterator`, etc.

Function templates

Example: type deduction

```
template <typename T>
int compare(const T& a, const T& b)
{
    if(a < b) return -1;
    if(b < a) return 1;
    return 0;
}

void example()
{
    int x{4};
    int y{2};
    cout << "compare(x,y): " << compare(x,y) << endl;
    string s{"Hello"};
    string t{"World"};
    cout << "compare(s,t): " << compare(s,t) << endl;
}
```

T is int

T is string

The compiler can (often) infer the template parameters from the function arguments.

Function templates

Parameters must match

```
template <typename T>  
int compare(const T& a, const T& b);
```

Example: compare

```
int i{5};  
double d{5.5};  
  
cout << compare(i,d) << endl;
```

error: no matching function for call to 'compare(int&, double&)'

- ▶ First argument gives: T is **int**
- ▶ Second argument gives: T is **double**
- ▶ Template is not instantiated (not an error)
- ▶ There is no function `compare(int, double)` (error)

Types must match exactly. No implicit conversions are performed.

Substitution Failure Is Not An Error

If a template instantiation produces ill-formed code

- ▶ it is considered not viable
- ▶ and is silently discarded.

If *no viable instantiation* is found it is an error
("no such class/function")

Function templates

Explicit instantiation

```
template <typename T>  
int compare(const T& a, const T& b);
```

Example: compare with explicit instantiation

```
int i{5};  
double d{5.5};  
  
cout << compare<double>(i,d) << endl;    // -1  
cout << compare<int>(i,d) << endl;      // 0
```

*An explicitly instantiated function template is just a function.
⇒ implicit type conversion of arguments*

Function templates

Prefer type casts to be clear about type conversions

```
template <typename T>  
int compare(const T& a, const T& b);
```

Example: compare with explicit type conversion

```
int i{5};  
double d{5.5};  
  
cout << compare(static_cast<double>(i),d) << endl; // -1  
cout << compare(i,static_cast<int>(d)) << endl; // 0
```

For readability, it is often better to be explicit about type conversions than to rely on implicit type conversion of arguments

Function templates

Example: two template parameters

```
template <typename T, typename U>
int compare2(const T& a, const U& b)
{
    if(a < b) return -1;
    if(b < a) return 1;
    return 0;
}

void example3()
{
    int i{5};
    double d{5.5};

    cout << compare2(i,d) << endl; // -1
}
```

- ▶ First argument gives: T is **int**
- ▶ Second argument gives: U is **double**

OK!

Example: the minimum function

```
template<class T>
const T& minimum(const T& a, const T& b) {
    if (a < b)
        return a;
    else
        return b;
}
```

Can be instantiated for all types that have the operator <

Function templates

Overloading with a normal function

```
struct Name{  
    string s;  
    //...  
};
```

Overload for Name&

```
const Name& minimum(const Name& a, const Name& b)  
{  
    if(a.s < b.s)  
        return a;  
    else  
        return b;  
}
```

Function templates

Trailing return type (c++11)

```
template <typename T, typename U>
T minimum(const T& a, const U& b);
```

Would not always work, as the return type is always that of the first argument.

```
template <typename T, typename U>
auto minimum(const T& a, const U& b) -> decltype(a+b)
```

```
{
    return (a < b) ? a : b;
}
```

▶ **decltype** is an *unevaluated context*

```
void example()
{
```

▶ the expression `a + b` is not evaluated

```
    int a{3};
    int b{4};
```

▶ **decltype** gives the *type* of an expression

```
    double x{3.14};
```

▶ NB! Return-by-value as argument may need to be converted

```
    cout << "minimum(x,a); " << minimum(x,a) << endl;    // 3
    cout << "minimum(x,b); " << minimum(x,b) << endl;    // 3.14
```

```
}
```

Function templates

`min_element`: minimum element in iterator range

```
template<typename FwdIterator>
FwdIterator min_element(FwdIterator first, FwdIterator last)
{
    if(first==last) return last;

    FwdIterator res=first;

    auto it = first;
    while(++it != last){
        if(*it < *res) res = it;
    }
    return res;
}
```

Use:

```
int a[] {3,5,7,6,8,5,2,4};
auto ma = min_element(begin(a), end(a));
auto ma2 = min_element(a+2,a+4);

vector<int> v{3,5,7,6,8,5,2,4};
auto mv = min_element(v.begin(), v.end());
```

Function templates

`std::min_element` for types that don't have <

Overload with a second template parameter: Compare

```
template<class FwdIt, class Compare>
FwdIt min_element(FwdIt first, FwdIt last, Compare cmp)
{
    if(first==last) return last;

    FwdIt res=first;
    auto it = first;
    while(++it != last){
        if (cmp(*it, *res)) res = it;
    }
    return res;
}
```

Compare must have `operator()` and the types must match, e.g.,:

```
class Str_Less_Than {
public:
    bool operator () (const char *s1, const char *s2) {
        return strcmp(s1, s2) < 0;
    }
};
```


Function templates

`std::min_element` for types that don't have <

Example use on list of strings:

```
std::vector<const char*> tl = { "hej", "du", "glade" };
```

```
Str_Less_Than lt; // functor
```

```
cout << *min_element(tl.begin(), tl.end(), lt);
```

The `Str_Less_Than` object can be created directly in the argument list:

```
cout << *min_element(tl.begin(), tl.end(), Str_Less_Than());
```

(C++11) lambda: anonymous functor

```
auto cf= [](const char* s, const char* t){return strcmp(s,t)<0;};
```

```
cout << *min_element(tl.begin(), tl.end(), cf);
```

Class templates

- ▶ The container classes `vector`, `deque` and `list` are examples of *parameterized classes* or *class templates*
- ▶ The compiler uses the class template to *instantiate* a class with the given actual parameters
- ▶ No need to manually write a new class for every element type
- ▶ Classes can be parameterized
- ▶ Example: container classes in the standard library
 - ▶ `std::vector`
 - ▶ `std::deque`
 - ▶ `std::list`

“Container” is a generic concept, independent of the element type

Parameterized types

- ▶ Generalize Vector of doubles to Vector of anything.
- ▶ Class template with the element type as template parameter.

Example:

```
template <typename T>
class Vector{
private:
    T* elem;
    int sz;
public:
    explicit Vector(int s);
    ~Vector() {delete[] elem;}

    // copy and move ...

    T& operator[](int i);
    const T& operator[](int i) const;
    int size() const {return sz;}
};
```

The class template Vector

Member functions

► Invariant:

- $sz \geq 0$ (*NB! declared `int sz`, not `unsigned sz`*)
- `elem` pointer to a `T[sz]`;

```
template <typename T>
Vector<T>::Vector(int s){
    if(s < 0) throw invalid_argument("Negative size");
    sz = s;
    elem = new T[sz];
};
template <typename T>
const T& Vector<T>::operator[](int i) const
{
    if(i < 0 || size() <= i) throw range_error("Vector::operator[]");
    return elem[i];
}
template <typename T>
T& Vector<T>::operator[](int i)
{
    const auto& constme = *this;
    return const_cast<T&>(constme[i]);
}
```

Class templates

The Container classes

```
class Container {
public:
    virtual int size() const =0;
    virtual int& operator[](int o) =0;
    virtual ~Container() {}
    virtual void print() const =0;
};
```

► generalize on element type

```
class Vector :public Container {
public:
    explicit Vector(int l);
    ~Vector();
    int size() const override;
    int& operator[](int i) override;
    virtual void print() const override;
private:
    int *p;
    int sz;
};
```

Class templates

Generic Container and Vector

```
template <typename T>
class Container {
public:
    using value_type = T;
    virtual size_t size() const = 0;
    virtual T& operator[](size_t o) = 0;
    virtual ~Container() {}
    virtual void print() const = 0;
};
```

```
template <typename T>
class Vector : public Container<T> {
public:
    Vector(size_t l = 0) : elem{new T[l]}, sz{l} {}
    ~Vector() {delete[] elem;}
    size_t size() const override {return sz;}
    T& operator[](size_t i) override {return elem[i];}
    virtual void print() const override;
private:
    T *elem;
    size_t sz;
};
```

The Vector class template

Constructor with `std::initializer_list`

We want to initialize vectors with values:

```
Vector<int> vs{1,3,5,7,9};
```

```
template <typename T>
Vector<T>::Vector(std::initializer_list<T> l)
                :Vector<T>(static_cast<int>(l.size()))
{
    std::copy(l.begin(), l.end(), elem);
}
```

The pedantic `static_cast<int>` is used as `std::initializer_list<T>::size()` returns an unsigned type

Template parameters

Types or values

```
template <typename T, int N>
struct Buffer{
    using value_type = T;
    constexpr int size() {return N;}
    T buf[N];
};
```

- ▶ Buffer: like an array that knows its size
 - ▶ No overhead for heap allocation
 - ▶ Template parameters must be **constexpr**
 - cannot have variable size
 - ▶ cf. `std::array`
- ▶ The size as value parameter to the template
- ▶ An alias (`value_type`) and a **constexpr** function (`size()`)
 - ▶ Users can access (read) template parameter values

Template parameters and alias

All standard containers has an alias `value_type`

```
template <typename T>
class Container{
public:
    using value_type = T;
    ...
};

template <typename Cont>
typename Cont::value_type& get_first(Cont& t)
{
    return *t.begin(); // UB for empty container
}

void example()
{
    Vector<int> v{2,4,3,5,4,6};
    cout << "first element of v is " << get_first(v) << endl;
}
```

*Here **typename** is needed by the compiler to know that the name `value_type` is a type before the template is instantiated*

using can be used to create type aliases

```
using size_t = unsigned int;
```

including templates:

```
using IntVector = Vector<int>;
```

Class Templates

Definition of function members

```
template <typename T>
void Vector<T>::print() const
{
    for(size_t i = 0; i != sz; ++i)
        cout << p[i] << " ";
    cout << endl;
}
```

- ▶ Function members in a class template are function templates
- ▶ print() works for all types with an **operator<<**
- ▶ *“Duck typing”:*
if it walks like a duck and quacks like a duck, it is a duck

Class Templates

Definition of member functions

```
template <typename T>
void Vector<T>::print() const
{
    for(size_t i = 0; i != sz; ++i)
        cout << p[i] << " ";
    cout << endl;
}
```

► Works for all types with **operator<<**

► but not for elements of type

```
struct Foo{
    int x;

    Foo(int d=0) :x{d}{}
};
```

Template specialization for the type Foo:

```
template<> full specialization: no template arguments
void Vector<Foo>::print() const
{
    for(size_t i = 0; i != sz; ++i)
        cout << "Foo("<<p[i].x << ") ";
    cout << endl;
}
```

Template specialization

- ▶ Class Templates can be specialized
 - ▶ fully
 - ▶ partially
- ▶ Function templates can be specialized
 - ▶ fully
 - ▶ *but overloading is always preferable*

Templates, comments

- ▶ Templates have parameters
 - ▶ type parameters: declared with **class** or **typename**
 - ▶ value parameters: declared as usual, e.g., **int** N
- ▶ The compiler needs the template definition to instantiate
⇒ it must be in the *header file* (if used by others)
- ▶ Overloading:
 - ▶ Functions can be overloaded ⇒ function templates can be overloaded
 - ▶ Classes cannot be overloaded ⇒ class templates cannot be overloaded
- ▶ Template specialization:
 - ▶ Class templates can be specialized *partially* or *fully*
 - ▶ Function templates can only be *fully* specialized, *but*
 - ▶ Specializations are not overloaded
 - ▶ Often better/clearer to overload with a normal function (not a template) than to specialize

Iterator traits

Exempel: find

```
template <class InIt, class T>  
InIt find (InIt first, InIt last, const T& val);
```

Better way: the compiler knows the actual value type.

With `decltype` and `std::declval<T>`

```
template <class InIt, class T=decltype(* declval<InIt>())>  
InIt find (InIt first, InIt last, const T& val);
```

With `std::iterator_traits<Iterator>`

```
template <class InIt,  
          class T=typename iterator_traits<InIt>::value_type>  
InIt find (InIt first, InIt last, const T& val);
```

Variadic templates

A function template can take a variable number of arguments

```
void println() { base case: no argument
    cout << endl;
}

template <typename T, typename... Tail>
void println(const T& head, const Tail&... tail)
{
    cout << head << " ";    print the first element
    println(tail...);       recursion: print the rest
}

void test_variadic()
{
    string a{"Hej"};
    int b{10};
    double c{17.42};
    long d{100};

    println(a,b,c,d);
}
```


Suggested reading

References to sections in Lippman

Function templates 16.1.1

Class templates 16.1.2

Template arguments and deduction 16.2–16.2.2

Trailing return type 16.2.3

Templates and overloading 16.3