

Modern C++ Programming

20. ADVANCED TOPICS I

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Move Semantic

Move semantics refers in transferring ownership of resources from one object to another

Differently from *copy semantic*, *move semantic* does not duplicate the original resource

In C++ every expression is either an **rvalue** or an **lvalue**

- a **lvalue** (left) represents an expression that occupies some identifiable location in memory
- a **rvalue** (right) is an expression that does not represent an object occupying some identifiable location in memory

```
int x = 5;           // "x" is an lvalue, "5" is an rvalue  
int y = 10;          // "y" is an lvalue  
  
int z = (x * y);     // "z" is an lvalue, (x * y) is an rvalue
```

C++11 introduces a new kind of *reference* called **rvalue reference** `X&&`

- An **rvalue reference** only binds to an **rvalue**, that is a temporary
- An **lvalue reference** only binds to an **lvalue**
- A **const lvalue reference** binds to both **lvalue** and **rvalue**

```
int      x  = 5;           // "x" is an lvalue
int&     r1 = x;           // "r1" is an lvalue reference
// int&   r2 = 5;           // compile error, "5" is an rvalue
const int& cr = (x * y);   // "cr" is an const lvalue reference

int&&     rv = (x * y);     // "rv" is an rvalue reference, "(x * y)" is an rvalue
// int&&   rv1 = x;         // compile error, "x" is NOT an rvalue
```



```
struct A {};  
  
void f(A& a) {}           // lvalue reference  
  
void g(const A& a) {}     // const lvalue reference  
  
void h(A&& a) {}          // rvalue reference  
  
A a;  
f(a);      // ok, f() can modify "a"  
g(a);      // ok, f() cannot modify "a"  
// h(a);   // compile error f() does not accept lvalues  
  
// f(A{}); // compile error f() does not accept rvalues  
g(A{});    // ok, f() cannot modify the object A{}  
h(A{});    // ok, f() can modify the object A{}
```

```
#include <algorithm>

class Array { // Array Wrapper
public:
    Array() = default;

    Array(int size) : _size{size}, _array{new int[size]} {}

    Array(const Array& obj) : _size{obj._size}, _array{new int[obj._size]} {
        // EXPENSIVE COPY (deep copy)
        std::copy(obj._array, obj._array + _size, _array);
    }

    ~Array() { delete[] _array; }
private:
    int _size;
    int* _array;
};
```

```
#include <vector>

int main() {
    std::vector<Array> vector;
    vector.push_back( Array{1000} ); // call push_back(const Array&)
                                    // expensive copy
}
```

Before C++11: `Array{1000}` is created, passed by const-reference, copied, and then destroyed

Note: `Array{1000}` is no more used outside `push_back`

After C++11: `Array{1000}` is created, and moved to `vector` (fast!)

Class prototype with support for *move semantic*:

```
class X {  
public:  
    X();                // default constructor  
  
    X(const X& obj);    // copy constructor  
  
    X(X&& obj);         // move constructor  
  
    X& operator=(const X& obj); // copy assign operator  
  
    X& operator=(X&& obj);    // move assign operator  
  
    ~X();                // destructor  
};
```

Move constructor semantic

```
X(X&& obj);
```

- (1) *Shallow copy* of `obj` data members (in contrast to deep copy)
- (2) *Release* any `obj` resources and reset all data members (pointer to `nullptr`, size to 0, etc.)

Move assignment semantic

```
X& operator=(X&& obj);
```

- (1) *Release* any resources of `this`
- (2) *Shallow copy* of `obj` data members (in contrast to deep copy)
- (3) *Release* any `obj` resources and reset all data members (pointer to `nullptr`, size to 0, etc.)
- (4) Return `*this`

Move constructor

```
Array(Array&& obj) {  
    _size      = obj._size;  // (1) shallow copy  
    _array     = obj._array; // (1) shallow copy  
    obj._size  = 0;          // (2) release obj (no more valid)  
    obj._array = nullptr;    // (2) release obj  
}
```

Move assignment

```
Array& operator=(Array&& obj) {  
    delete[] _array;          // (1) release this  
    _size      = obj._size;  // (2) shallow copy  
    _array     = obj._array; // (2) shallow copy  
    obj._array = nullptr;    // (3) release obj  
    obj._size  = 0;          // (3) release obj  
    return *this;            // (4) return *this  
}
```

C++11 provides the method `std::move` (`<utility>`) to indicate that an object may be “moved from”

It allows to efficient transfer resources from an object to another one

```
#include <vector>

int main() {
    std::vector<Array> vector;
    vector.push_back( Array{1000} );    // call "push_back(Array&&)"

    Array arr{1000};
    vector.push_back( arr );            // call "push_back(const Array&)"

    vector.push_back( std::move(arr) ); // call "push_back(Array&&)"
                                        // efficient!!

    // "arr" is not more valid here
}
```

Move Semantic Notes

If an object requires the *copy constructor/assignment*, then it should also define the *move constructor/assignment*. The opposite could not be true

The *defaulted move constructor/assignment* `=default` recursively applies the move semantic to its *base class* and *data members*.

Important: *it does not release the resources*. It is very dangerous for classes with manual resource management

```
// Suppose: Array(Array&&) = default;
Array x{10};
Array y = std::move(x); // call the move constructor
// "x" calls ~Array() when it is out of scope, but now the internal pointer
// "_array" is NOT nullptr -> double free or corruption!!
```


Move Semantic and Code Reuse

Some operations can be expressed as a function of the move semantic

```
A& operator=(const A& other) {  
    *this = A{other}; // copy constructor + move assignment  
    return *this;  
}
```

```
void init(... /* any paramters */) {  
    *this = A{...}; // user-declared constructor + move assignment  
}
```

Special Members

compiler implicitly declares

user declares		default constructor	destructor	copy constructor	copy assignment	move constructor	move assignment
	Nothing	defaulted	defaulted	defaulted	defaulted	defaulted	defaulted
	Any constructor	not declared	defaulted	defaulted	defaulted	defaulted	defaulted
	default constructor	user declared	defaulted	defaulted	defaulted	defaulted	defaulted
	destructor	defaulted	user declared	defaulted	defaulted	not declared	not declared
	copy constructor	not declared	defaulted	user declared	defaulted	not declared	not declared
	copy assignment	defaulted	defaulted	defaulted	user declared	not declared	not declared
	move constructor	not declared	defaulted	deleted	deleted	user declared	not declared
	move assignment	defaulted	defaulted	deleted	deleted	not declared	user declared

Everything You Ever Wanted To Know About Move Semantics

A Quick Note of Copy and Move Control in C++

Class Declaration Semantic

User-declared Entity	Meaning / Implications
<code>non- static const</code> members	<i>Copy/Move constructors</i> are not trivial (not provided by the compiler). <i>Copy/move assignment</i> is not supported
reference members	<i>Copy/Move constructors/assignment</i> are not trivial (not provided by the compiler)
destructor	The resource management is not trivial. <i>Copy constructor/assignment</i> is very likely to be implemented
copy constructor/assignment	Resource management is not trivial. <i>Move constructors/assignment</i> need to be implemented by the user
move constructor/assignment	There is an efficient way to move the object. <i>Copy constructor/assignment</i> cannot fall back safely to <i>copy constructors/assignment</i> , so they are deleted

Universal Reference and Perfect Forwarding

The `&&` syntax has two different meanings depending on the context it is used

- **rvalue reference**
- **Universal reference**: Either **rvalue reference** or **lvalue reference**

Universal references (also called *forwarding references*) are **rvalues** that appear in a type-deducing context. `T&&`, `auto&&` accept any expression regardless it is an **lvalue** or **rvalue** and preserve the `const` property

```
void f1(int&& t) {} // rvalue reference

template<typename T>
void f2(T&& t) {}  // universal reference

int&& v1 = ...;    // rvalue reference
auto&& v2 = ...;   // universal reference
```

```
int          f_copy()           { return x; }
int&         f_ref(int& x)       { return x; }
const int&   f_const_ref(const int& x) { return x; }

auto         v1 = ...; // f_copy(), f_const_ref(), only lvalues
auto&        v2 = ...; // f_ref(), only lvalue ref
const auto&  v3 = ...; // f_copy(), f_ref(), f_const_ref()
               // only const lvalue ref (decay), cannot be modified
const auto&& v4 = ...; // f_copy(), only rvalues, cannot be modified

auto&&        v5 = ...; // everything
```

```
struct A {};  
void f1(A&& a) {} // rvalue only  
  
template<typename T>  
void f2(T&& t) {} // universal reference  
  
A a;  
f1(A{}); // ok  
// f1(a); // compile error (only rvalue)  
f2(A{}); // universal reference  
f2(a); // universal reference  
  
A&& a2 = A{}; // ok  
// A&& a3 = a; // compile error (only rvalue)  
auto&& a4 = A{}; // universal reference  
auto&& a5 = a; // universal reference
```

Universal Reference - Misleading Cases

```
template<typename T>
void f(std::vector<T>&&) {} // rvalue reference

template<typename T>
void f(const T&&) {}      // rvalue reference (const)

const auto&& v = ...;    // const rvalue reference
```


Reference Collapsing Rules

Before C++11 (C++98, C++03), it was not allowed to take a reference to a reference (`A& &` causes a compile error)

C++11, by contrast, introduces the following **reference collapsing rules**:

```
template<typename T>
void f(T&) {} // compile error in C++98/03 (with gcc),
              // no errors in C++11 (and clang with C++98/03)

int a = 3;    //
f<int&>(a);    //
```

Type	Reference		Result
A&	&	→	A&
A&	&&	→	A&
A&&	&	→	A&
A&&	&&	→	A&&

Perfect Forwarding

Perfect forwarding allows preserving argument *value category* and `const/volatile` modifiers

`std::forward` (`<utility>`) forwards the argument to another function with the *value category* it had when passed to the calling function (*perfect forwarding*)

```
#include <utility> // std::forward
template<typename T> void f(T& t) { cout << "lvalue"; }
template<typename T> void f(T&& t) { cout << "rvalue"; } // overloading

template<typename T> void g1(T&& obj) { f(obj); } // call only f(T&)
template<typename T> void g2(T&& obj) { f(std::forward<T>(obj)); }

struct A{};
f ( A{10} ); // print "rvalue"
g1( A{10} ); // print "lvalue"!!
g2( A{10} ); // print "rvalue"
```

Value Categories

Taxonomy (simplified)

Every expression is either an **rvalue** or an **lvalue**

- An **lvalue** (*left* value of an assignment for historical reason or *locator* value) represents an expression that occupies an *identity*, namely a memory location (it has an address)
- An **rvalue** is movable; an **lvalue** is not

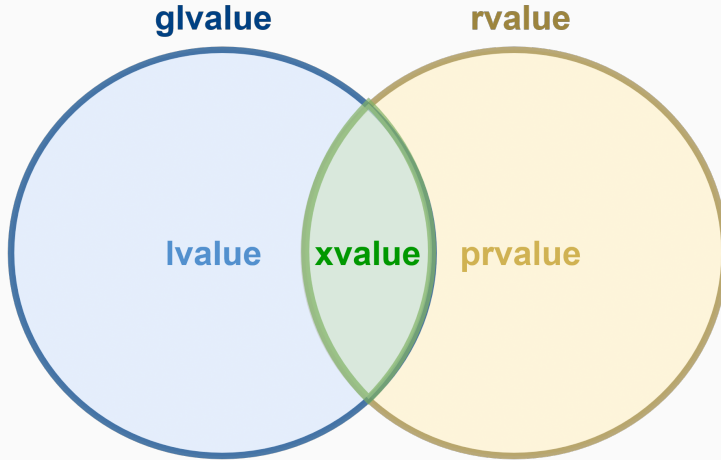
glvalue (*generalized lvalue*) is an expression that has an identity

lvalue is a **glvalue** but it is not movable (it is not an **xvalue**). An *named rvalue reference* is a **lvalue**

xvalue (*eXpiring*) has an identity and it is movable. It is a **glvalue** that denotes an object whose resources can be reused. An *unnamed rvalue reference* is a **xvalue**

prvalue (*pure rvalue*) doesn't have identity, but is movable. It is an expression whose evaluation initializes an object or computes the value of an operand of an operator

rvalue is movable. It is a **prvalue** or an **xvalue**



Examples

```
struct A {  
    int x;  
};  
  
void f(A&&) {}  
A&& g();  
//-----  
int a = 4;          // "a" is an lvalue, "4" is a prvalue  
f(A{4});            // "A{4}" is a prvalue  
  
A&& b = A{3};        // "A&& b" is a named rvalue reference → lvalue  
  
A c{4};  
f(std::move(c));     // "std::move(c)" is a xvalue  
f(A{}.x);            // "A{}.x" is a xvalue  
g();                 // "A&&" is a xvalue
```

&, && Ref-qualifiers and volatile Overloading

C++11 allows overloading member functions depending on the **lvalue/rvalue** property of their object. This is also known as **ref-qualifiers overloading** and can be useful for optimization purposes, namely, moving a variable instead of copying it

```
struct A {  
    // void f()    {} // already covered by "f() &"  
    void f() &    {}  
    void f() &&   {}  
};  
  
A a1;  
a1.f();           // call "f() &"  
  
A{}.f();          // call "f() &&"  
std::move(a1).f(); // call "f() &&"
```

Ref-qualifiers overloading can be also combined with `const` methods

```
struct A {  
    // void f() const    {} // already covered by "f() const &"  
    void f() const &    {}  
    void f() const && {}  
};  
  
const A a1;  
a1.f();           // call "f() const &"  
  
std::move(a1).f(); // call "f() const &&"
```

A simple example where *ref-qualifiers overloading* is useful

```
struct ArrayWrapper {  
    ArrayWrapper(/*params*/) { /* something expensive */ }  
  
    ArrayWrapper copy() const & { /* expensive copy with std::copy() */ }  
    ArrayWrapper copy() const && { /* just move the pointer as the original  
                                   object is no more used */ }  
};
```

volatile Overloading

```
struct A {  
    void f()                {}  
    void f() volatile      {} // e.g. propagate volatile to data members  
    void f() const volatile {}  
    // void f() volatile &      {} // combining ref-qualifier and volatile  
    // void f() const volatile & {} // overloading is also fine  
    // void f() volatile &&      {}  
    // void f() const volatile && {}  
};  
  
volatile A a1;  
a1.f();    // call "f() volatile"  
  
const volatile A a2;  
a2.f();    // call "f() const volatile"
```

Copy Elision and RVO/NVRO

Copy Elision and RVO/NVRO

Copy elision is a compiler optimization technique that eliminates unnecessary copying/moving of objects (it is defined in the C++ standard)

A compiler avoids omitting copy/move operations with the following optimizations:

- **RVO (Return Value Optimization)** means the compiler is allowed to avoid creating *temporary* objects for return values
- **NRVO (Named Return Value Optimization)** means the compiler is allowed to return an object (with automatic storage duration) without invokes copy/move constructors

RVO Example

Returning an object from a function is *very expensive* without RVO/NVRO:

```
struct Obj {  
    Obj() = default;  
  
    Obj(const Obj&) { // non-trivial  
        cout << "copy constructor\n";  
    }  
};  
  
Obj f() { return Obj{}; } // first copy  
  
auto x1 = f();           // second copy (create "x")
```

If provided, the compiler uses the *move constructor* instead of *copy constructor*

RVO - Where it works

RVO Copy elision is always guaranteed if the operand is a **prvalue** of the same class type and the *copy constructor* is trivial and non-deleted

```
struct Trivial {  
    Trivial()           = default;  
    Trivial(const Trivial&) = default;  
};  
  
// single instance  
Trivial f1() {  
    return Trivial{}; // Guarantee RVO  
}  
  
// distinct instances and run-time selection  
Trivial f2(bool b) {  
    return b ? Trivial{} : Trivial{}; // Guarantee RVO  
}
```


Guaranteed Copy Elision (C++17)

In C++17, *RVO Copy elision* is always guaranteed if the operand is a `prvalue` of the same class type, even if the *copy constructor* is not trivial or deleted

```
struct S1 {
    S1()          = default;
    S1(const S1&) = delete; // deleted
};

struct S2 {
    S2()          = default;
    S2(const S2&) {}      // non-trivial
};

S1 f() { return S1{}; }
S2 g() { return S2{}; }

auto x1 = f(); // compile error in C++14
auto x2 = g(); // RVO only in C++17
```

NRVO is not always guarantee even in C++17

```
Obj f1() {  
    Obj a;  
    return a; // most compilers apply NRVO  
}  
  
Obj f2(bool v) {  
    Obj a;  
    if (v)  
        return a; // copy/move constructor  
    return Obj{}; // RVO  
}
```

GCC 14 adds the flag `-Wnvro` to diagnose when NRVO is not possible

```
Obj f3(bool v) {  
    Obj a, b;  
    return v ? a : b;    // copy/move constructor  
}  
  
Obj f4() {  
    Obj a;  
    return std::move(a); // force move constructor  
}  
  
Obj f5() {  
    static Obj a;  
    return a;           // only copy constructor is possible  
}
```

```
Obj f6(Obj& a) {  
    return a; // copy constructor (a reference cannot be elided)  
}  
  
Obj f7(const Obj& a) {  
    return a; // copy constructor (a reference cannot be elided)  
}  
  
Obj f8(const Obj a) {  
    return a; // copy constructor (a const object cannot be elided)  
}  
  
Obj f9(Obj&& a) {  
    return a; // copy constructor (the object is instantiated in the function)  
}
```

Type Deduction

When you call a template function, you may omit any template argument that the compiler can determine or deduce (inferred) by the usage and context of that template function call [IBM]

- The compiler tries to deduce a template argument by comparing the type of the corresponding template parameter with the type of the argument used in the function call
- Similar to function default parameters, (any) template parameters can be deduced only if they are at end of the parameter list

Full Story: IBM Knowledge Center

Example

```
template<typename T>
int add1(T a, T b) { return a + b; }

template<typename T, typename R>
int add2(T a, R b) { return a + b; }

template<typename T, int B>
int add3(T a) { return a + B; }

template<int B, typename T>
int add4(T a) { return a + B; }

add1(1, 2);           // ok
// add1(1, 2u);       // the compiler expects the same type
add2(1, 2u);          // ok (add2 is more generic)
add3<int, 2>(1);       // "int" cannot be deduced
add4<2>(1);           // ok
```

Type Deduction - Pass by-Reference

Type deduction with references

```
template<typename T>
```

```
void f(T& a) {}
```

```
template<typename T>
```

```
void g(const T& a) {}
```

```
int      x = 3;
```

```
int&     y = x;
```

```
const int& z = x;
```

```
f(x);    // T: int
```

```
f(y);    // T: int
```

```
f(z);    // T: const int // <-- !! it works...but it does not
```

```
g(x);    // T: int      //      for "f(int& a)"!!
```

```
g(y);    // T: int      //      (only non-const references)
```

```
g(z);    // T: int      // <-- note the difference
```


Type deduction with pointers

```
template<typename T>
void f(T* a) {}

template<typename T>
void g(const T* a) {}

int*      x = nullptr;
const int* y = nullptr;
auto      z = nullptr;
f(x);     // T: int
f(y);     // T: const int
// f(z);  // compile error!! z: "nullptr_t != T*"
g(x);     // T: int
g(y);     // T: int  <-- note the difference
```

```
template<typename T>
void f(const T* a) {} // pointer to const-values
```

```
template<typename T>
void g(T* const a) {} // const pointer
```

```
int*          x = nullptr;
const int*    y = nullptr;
int* const    z = nullptr;
const int* const w = nullptr;
f(x);         // T: int
f(y);         // T: int
f(z);         // T: int
g(x);         // T: int
g(y);         // T: const int
g(z);         // T: int
g(w);         // T: const int
```

Type deduction with values

```
template<typename T>
void f(T a) {}

template<typename T>
void g(const T a) {}

int      x = 2;
const int y = 3;
const int& z = y;
f(x);    // T: int
f(y);    // T: int!! (drop const)
f(z);    // T: int!! (drop const&)
g(x);    // T: int
g(y);    // T: int
g(z);    // T: int!! (drop reference)
```

```
template<typename T>
void f(T a) {}

int*      x = nullptr;
const int* y = nullptr;
int* const z = x;
f(x);    // T = int*
f(y);    // T = const int*
f(z);    // T = int* !! (const drop)
```

Type Deduction - Array

Type deduction with arrays

```
template<typename T, int N>
void f(T (&array)[N]) {}    // type and size deduced

template<typename T>
void g(T array) {}

int      x[3] = {};
const int y[3] = {};
f(x);    // T: int, N: 3
f(y);    // T: const int, N: 3
g(x);    // T: int*
g(y);    // T: const int*
```

```
template<typename T>
```

```
void add(T a, T b) {}
```

```
template<typename T, typename R>
```

```
void add(T a, R b) {}
```

```
template<typename T>
```

```
void add(T a, char b) {}
```

```
add(2, 3.0f);           // call add(T, R)
```

```
// add(2, 3);           // error!! ambiguous match
```

```
add<int>(2, 3);          // call add(T, T)
```

```
add<int, int>(2, 3);     // call add(T, R)
```

```
add(2, 'b');            // call add(T, char) -> nearest match
```

```
template<typename T, int N>
void f(T& array) {}

template<typename T>
void f(T* array) {}

int x[3];
f(x); // call f(T*) not f(T&) !!
```

```
template<typename T, int N>
void g(T& array) {}

template<typename T>
void g(T array) {}

int x[3];
g(x); // call g(T) not g(T&) !!
```

auto Deduction

- `auto x =` copy by-value/by-const value
- `auto& x =` copy by-reference/by-const-reference
- `auto* x =` copy by-pointer/by-const-pointer
- `auto&& x =` copy by-universal reference
- `decltype(auto) x =` automatic type deduction

```
int          f1(int& x) { return x; }
int&         f2(int& x) { return x; }
auto         f3(int& x) { return x; }
decltype(auto) f4(int& x) { return x; }
```

```
int  v  = 3;
int  x1 = f1(v);
int& x2 = f2(v);
// int& x3 = f3(v); // compile error 'x' is copied by-value
int& x4 = f4(v);
```


The problem: implement a function to remove the first element of a container

```
template<typename T>
void pop_v1(T& x) {
    std::remove(x.begin(), x.end(), x.front()); // undefined behavior!!
}
```

This is *undefined behavior* because

- `x.front()` returns a reference
- `std::remove` takes the element to remove by-const-reference
- `std::remove` modifies the container, invalidating iterators and references. The reference must not be an element of the range `[first, last)`

Sub-optimal solutions:

```
template<typename T>
void pop_v2(T& x) {
    auto tmp = x.front();           // lvalue copy
    std::remove(x.begin(), x.end(), tmp); // ok
}
```

```
template<typename T>
void pop_v3(T& x) {
    using R = std::decay_t<decltype(x.front())>; // verbose/non-trivial solution
    std::remove(x.begin(), x.end(), R(x));       // ok, create a temporary (rvalue)
}                                                // copy
// decltype(x.front()) -> retrieve the type of x.front()
// std::decay_t         -> get the 'decay' type as pass by-value,
//                       e.g. 'const int' to 'int'
```

C++23 introduces `auto(x)` *decay-copy* utility to express the rvalue copy in a clear way

```
template<typename T>
void pop_v4(T& x) {
    std::remove(x.begin(), x.end(), auto(x.front())); // ok, rvalue copy
}                                                    // equivalent to R(x)
```

const **Correctness**

const correctness refers to guarantee object/variable const consistency throughout its lifetime and ensuring safety from unintentional modifications

References:

- Isocpp: `const-correctness`
- GotW: `Const-Correctness`
- Abseil: `Meaningful 'const' in Function Declarations`
- `const` is a contract
- `Why const Doesn't Make C Code Faster`
- `Constant Optimization?`

- `const` entities do not change their values at run-time. This does not imply that they are evaluated at compile-time
- `const T*` is different from `T* const`. The first case means “*the content does not change*”, while the later “*the value of the pointer does not change*”
- Pass *by-const-value* and *by-value* parameters imply the *same* function signature
- Return *by-const-value* and *by-value* have different meaning
- `const_cast` can *break* const-correctness

`const` and member functions:

- `const` member functions do not change the internal status of an object
- `mutable` fields can be modified by a `const` member function (they should not change the external view)

`const` and code optimization:

- `const` keyword purpose is for correctness (*type safety*), not for performance
- `const` may provide performance advantages in a few cases, e.g. non-trivial copy semantic

Function Declarations Example

```
void f(int);  
void f(const int); // the declaration is exactly the same of  
                  // "void f(int)"!!  
  
void f(int*);  
void f(const int*); // different declaration  
  
void f(int&);  
void f(const int&); // different declaration
```

```
int      f();  
// const int f(); // compile error conflicting declaration
```


const Return Example

```
const int const_value = 3;

const int& f2() { return const_value; }
// int&      f1() { return const_value; } // WRONG
int       f3() { return const_value; }   // ok
```

```
struct A {
    void f()      { cout << "non-const"; }
    void f() const { cout << "const";    }
};
```

```
const A getA() { return A{}; }
```

```
auto a = getA(); // "a" is a copy
a.f();           // print "non-const"
```

```
getA().f();      // print "const"
```

struct Example

```
struct A {           // struct A_const { // equal to "const A"
    int* ptr;        //      int* const ptr;
    int  value;      //      const int  value;
};                  // };

void f(A a) {
    a.value = 3;
    a.ptr[0] = 3;
}

void g(const A a) { // the same with g(const A&)
//  a.value = 3;    // compile error
    a.ptr[0] = 3;   // "const" does not apply to "ptr" content!!
}

A a{new int[10]};
f(a);
g(a);
```

Member Functions Example

```
struct A {  
    int value = 0;  
  
    int&      f1() { return value; }  
    const int& f2() { return value; }  
  
    // int&      f3() const { return value; } // WRONG  
    const int& f4() const { return value; }  
  
    int      f5() const { return value; } // ok  
    const int f6() const { return value; }  
};
```