Modern C++ Programming

19. Advanced Topics I

Federico Busato

2025-01-19

Table of Contents

Table of Contents

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
```

```cpp
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{}
```

Move Semantic - The Problem 1/2

```cpp
#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;
};
```

```cpp
#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
}
```

Class Declaration Semantic - Compiler Implicit

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

Class Declaration Semantic

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

Universal Reference


```cpp
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
```

```cpp
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*)

```cpp
#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**

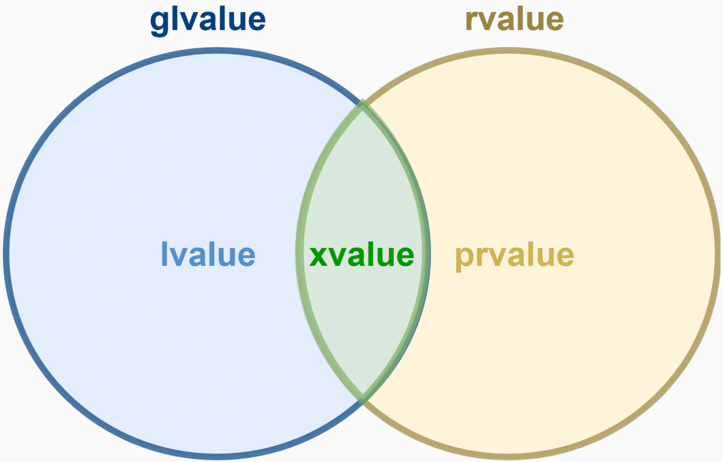
xvalue (*eXpiring*) has an identity and it is movable. It is a **glvalue** that denotes an object whose resources can be reused. An *unnamed rvalue reference* is a **xvalue**

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**

`en.cppreference.com/w/cpp/language/value_category`

Taxonomy 2/2



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 *creation, destruction, copying, and moving* of temporary objects

Copy elision can be also applied to avoid *unnecessary object copies when returning objects* from functions. Such optimizations are:

- **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;
};

// sigle 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
```

RVO Example - Where it does NOT work

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 NVRO 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

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
```

```cpp
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)
```

Type Deduction - Pass by-Value


```
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 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*
```

```cpp
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);             // call add(T, T)
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
```

Type Deduction - Conflicts


```
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-refernce
- `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

`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?

Basic Rules 1/2

- `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

```cpp
   const int const_value = 3;

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

```cpp
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; }
};
```