

Modern C++ Programming

5. BASIC CONCEPTS IV

FUNCTIONS AND PREPROCESSING

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Declaration and Definition

Declaration/Definition

Declaration/Prototype

A **declaration** (or *prototype*) of an entity is an identifier describing its type

A declaration is what the compiler and the linker needs to accept references (usage) to that identifier

C++ entities (class, functions, etc.) can be declared multiple times (with the same signature)

Definition/Implementation

An entity **definition** is the implementation of a declaration

For each entity, only a single *definition* is allowed

Declaration/Definition Function Example

```
void f(int a, char* b); // function declaration
```

```
void f(int a, char*) { // function definition  
    ...                // "b" can be omitted if not used  
}
```

```
void f(int a, char* b); // function declaration  
                        // multiple declarations is valid
```

```
f(3, "abc");           // usage
```

```
void g(); // function declaration
```

```
g(); // linking error "g" is not defined
```

Declaration/Definition struct Example

A declaration without a concrete implementation is an incomplete type (as `void`)

```
struct A;    // declaration 1
struct A;    // declaration 2 (ok)

struct B {   // declaration and definition
    int b;
// A  x;    // compile error incomplete type
    A* y;    // ok, pointer to incomplete type
};

struct A {   // definition
    char c;
}
```


Functions

A **function** (**procedure** or **routine**) is a piece of code that performs a *specific task*

Purpose:

- **Avoiding code duplication:** less code for the same functionality → less bugs
- **Readability:** better express what the code does
- **Organization:** break the code in separate modules

Function Parameter and Argument

Function Parameter [formal]

A **parameter** is the variable which is part of the method signature

Function Argument [actual]

An **argument** is the actual value (instance) of the variable that gets passed to the function

```
void f(int a, char* b); // parameters: int a, char* b
                        // return type: void

f(3, "abc");           // arguments: 3, "abc"
```

Call-by-value

The object is copied and assigned to input arguments of the method `f(T x)`

Advantages:

- Changes made to the parameter inside the function have no effect on the argument

Disadvantages:

- Performance penalty if the copied arguments are large (e.g. a structure with a large array)

When to use:

- Built-in data type and small objects (≤ 8 bytes)

When not to use:

- Fixed size arrays which decay into pointers
- Large objects

Pass by-Pointer

Call-by-pointer

The address of a variable is copied and assigned to input arguments of the method
`f(T* x)`

Advantages:

- Allows a function to change the value of the argument
- Copy of the argument is not made (fast)

Disadvantages:

- The argument may be null pointer
- Dereferencing a pointer is slower than accessing a value directly

When to use:

- Raw arrays (use `const T*` if read-only)

When not to use:

- All other cases

Pass by-Reference

Call-by-reference

The reference of a variable is copied and assigned to input arguments of the method
`f(T& x)`

Advantages:

- Allows a function to change the value of the argument (better readability compared with pointers)
- Copy of the argument is not made (fast)
- References must be initialized (no null pointer)
- Avoid implicit conversion (without `const T&`)

When to use:

- All cases except raw pointers

When not to use:

- Pass by-value *could* give performance advantages and improve the readability with built-in data type and small objects

Examples

```
struct MyStruct;

void f1(int a);           // pass by-value
void f2(int& a);          // pass by-reference
void f3(const int& a);    // pass by-const reference
void f4(MyStruct& a);     // pass by-reference

void f5(int* a);          // pass by-pointer
void f6(const int* a);    // pass by-const pointer
void f7(MyStruct* a);     // pass by-pointer

void f8(int*& a);          // pass a pointer by-reference
//-----

char c = 'a';
f1(c);    // ok, pass by-value (implicit conversion)
// f2(c); // compile error different types
f3(c);    // ok, pass by-value (implicit conversion)
```

Signature

Function signature defines the *input types* for a (specialized) function and the *inputs + outputs types* for a template function

A function signature includes the number of arguments, the types of arguments, and the order of the arguments

- The C++ standard prohibits a function declaration that only differs in the return type
- Function declarations with different signatures can have distinct return types

Overloading

Function overloading allows to have distinct functions with the same name but with different *signatures*


```
void f(int a, char* b);           // signature: (int, char*)

// char f(int a, char* b);       // compile error same signature
//                               // but different return types

void f(const int a, char* b);     // same signature, ok
//                               // const int == int

void f(int a, const char* b);     // overloading with signature: (int, const char*)

int f(float);                     // overloading with signature: (float)
//                               // the return type is different
```

Overloading Resolution Rules

- An exact match
- A promotion (e.g. char to int)
- A standard type conversion (e.g. float and int)
- A constructor or user-defined type conversion

```
void f(int a);  
void f(float b);           // overload  
void f(float b, char c);  // overload  
//-----  
    f(0);                 // ok  
// f('a');               // compile error ambiguous match  
    f(2.3f);              // ok  
// f(2.3);               // compile error ambiguous match  
    f(2.3, 'a');          // ok, standard type conversion
```

Function Default Parameters

Default/Optional parameter

A **default parameter** is a function parameter that has a default value

- If the user does not supply a value for this parameter, the default value will be used
- All default parameters must be the rightmost parameters
- Default parameters must be declared only once
- Default parameters can improve compile time and avoid redundant code because they avoid defining other overloaded functions

```
void f(int a, int b = 20);           // declaration

//void f(int a, int b = 10) { ... } // compile error, already set in the declaration

void f(int a, int b) { ... }         // definition, default value of "b" is already set

f(5); // b is 20
```

C++ allows to mark functions with standard properties to better express their intent:

- C++11 `[[noreturn]]` indicates that the function does not return
- C++14 `[[deprecated]]` , `[[deprecated("reason")]]` indicates the use of a function is discouraged (for some reason). It issues a warning if used
- C++17 `[[nodiscard]]`
C++20 `[[nodiscard("reason")]]` issues a warning if the return value is discarded
- C++17 `[[maybe_unused]]` suppresses compiler warnings on unused functions, if any (it applies also to other entities)

```
[[noreturn]] void f() { std::exit(0); }
```

```
[[deprecated]] void my_rand() { ... }
```

```
[[nodiscard]] bool g(int& x) {  
    update(x);  
    bool status = ...;  
    return status;  
}
```

```
void h([[maybe_unused]] x) {  
    #if !defined(SKIP_COMPUTATION)  
        ... use x ...  
    #endif  
}
```

```
//-----
```

```
my_rand();    // WARNING "deprecated"
```

```
g(y);         // WARNING "discard return value"
```

```
int z = g();  // no warning
```

```
h(3);         // no warning if SKIP_COMPUTATION is defined
```

Function Objects and Lambda Expressions

Standard C achieves generic programming capabilities and composability through the concept of **function pointer**

A function can be passed as a pointer to another function and behaves as an “*indirect call*”

```
#include <stdlib.h>

int descending(const void* a, const void* b) {
    return *((const int*) a) > *((const int*) b);
}

int array[] = {7, 2, 5, 1};
qsort(array, 4, sizeof(int), descending);
// array: { 7, 5, 2, 1 }
```

```
int eval(int a, int b, int (*f)(int, int)) {  
    return f(a, b);  
}  
  
// type: int (*)(int, int)  
int add(int a, int b) { return a + b; }  
int sub(int a, int b) { return a - b; }  
  
cout << eval(4, 3, add); // print 7  
cout << eval(4, 3, sub); // print 1
```

Problems:

Safety There is no check of the argument type in the generic case (e.g. `qsort`)

Performance Any operation requires an indirect call to the original function. Function inlining is not possible

Function Object

A **function object**, or **functor**, is a *callable* object that can be treated as a parameter

C++ provides a more efficient and convenience way to pass “*procedure*” to other functions called **function object**

```
#include <algorithm> // for std::sort

struct Descending { // <-- function object
    bool operator()(int a, int b) {
        return a > b;
    }
};

int array[] = {7, 2, 5, 1};
std::sort(array, array + 4, Descending{});
// array: { 7, 5, 2, 1 }
```

Advantages:

Safety Argument type checking is always possible. It could involves templates

Performance The compiler injects `operator()` in the code of the destination function and then compile the routine. Operator inlining is the standard behavior

C++11 simplifies the concept by providing less verbose `function` objects called **lambda expressions**

Lambda Expression

Lambda Expression

A **C++11 lambda expression** is an *inline local-scope* function object

```
auto x = [capture clause] (parameters) { body }
```

- The **[capture clause]** marks the declaration of the lambda and how the local scope arguments are captured (by-value, by-reference, etc.)
- The **parameters** of the lambda are normal function parameters (optional)
- The **body** of the lambda is a normal function body

*The expression to the right of the **=** is the **lambda expression**, and the runtime object **x** created by that expression is the **closure***

Lambda Expression

```
#include <algorithm> // for std::sort

int array[] = {7, 2, 5, 1};
auto lambda = [](int a, int b){ return a > b; }; // named lambda

std::sort(array, array + 4, lambda);
// array: { 7, 5, 2, 1 }

// in alternative, in one line of code:           // unnamed lambda
std::sort(array, array + 4, [](int a, int b){ return a > b; });
// array: { 7, 5, 2, 1 }
```

Capture List

Lambda expressions *capture* external variables used in the body of the lambda in two ways:

- Capture *by-value*
- Capture *by-reference* (can modify external variable values)

Capture list can be passed as follows

- `[]` no capture
- `[=]` captures all variables *by-value*
- `[&]` captures all variables *by-reference*
- `[var1]` captures only `var1` *by-value*
- `[&var2]` captures only `var2` *by-reference*
- `[var1, &var2]` captures `var1` *by-value* and `var2` *by-reference*

Capture List Examples

```
// GOAL: find the first element greater than "limit"
#include <algorithm> // for std::find_if
int limit = ...

auto lambda1 = [=](int value)      { return value > limit; }; // by-value
auto lambda2 = [&](int value)      { return value > limit; }; // by-reference
auto lambda3 = [limit](int value) { return value > limit; }; // "limit" by-value
auto lambda4 = [&limit](int value) { return value > limit; }; // "limit" by-reference
// auto lambda5 = [] (int value)    { return value > limit; }; // no capture
//                                     // compile error

int array[] = {7, 2, 5, 1};
std::find_if(array, array + 4, lambda1);
```

Capture List - Other Cases

- `[=, &var1]` captures all variables used in the body of the lambda **by-value**, except `var1` that is captured **by-reference**
- `[&, var1]` captures all variables used in the body of the lambda **by-reference**, except `var1` that is captured **by-value**
- A lambda expression can read a variable without capturing it if the variable is `constexpr`

```
constexpr int limit = 5;
int var1 = 3, var2 = 4;

auto lambda1 = [](int value){ return value > limit; };

auto lambda2 = [=, &var2]() { return var1 > var2;  };
```

C++14 Lambda expression parameters can be automatically deduced

```
auto x = [](auto value) { return value + 4; };
```

C++14 Lambda expression parameters can be initialized

```
auto x = [](int i = 6) { return i + 4; };
```


Lambda expressions can be composed

```
auto lambda1 = [](int value){ return value + 4; };  
auto lambda2 = [](int value){ return value * 2; };  
  
auto lambda3 = [&](int value){ return lambda2(lambda1(value)); };  
// returns (value + 4) * 2
```

A function can return a lambda (dynamic dispatch is also possible)

```
auto f() {  
    return [](int value){ return value + 4; };  
}  
  
auto lambda = f();  
cout << lambda(2); // print "6"
```

constexpr/consteval Lambda Expression

C++17 Lambda expression supports `constexpr`

C++20 Lambda expression supports `consteval`

```
// constexpr lambda
constexpr auto factorial = [](int value) constexpr {
    int ret = 1;
    for (int i = 2; i <= value; i++)
        ret *= i;
    return ret;
};

constexpr int v1 = factorial(4); // '24'

constexpr int f() {
    return factorial(3); // 6
}
```

template Lambda Expression ~→

C++20 Lambda expression supports `template` and `requires` clause

```
auto lambda = []<typename T>(T value)
    requires std::is_arithmetic<T> {
    return value * 2;
};

auto v = lambda(3.4); // v: 6.8 (double)

struct A{} a;
// auto v = lambda(a); // compiler error
```

mutable Lambda Expression

Lambda capture is *by-const-value*

mutable specifier allows the lambda to modify the parameters captured *by-value*

```
int var = 1;

auto lambda1 = [&]() { var = 4; };           // ok
lambda1();
cout << var; // print '4'

// auto lambda2 = [=]() { var = 3; };      // compile error
// lambda operator() is const

auto lambda3 = [=]() mutable { var = 3; }; // ok
lambda3();
cout << var; // print '4', lambda3 captures by-value
```

Capture List and Classes ~→

- `[this]` captures the current object `(*this)` *by-reference* (implicit in C++17)
- `[x = x]` captures the current object member `x` *by-value* C++14
- `[&x = x]` captures the current object member `x` *by-reference* C++14
- `[=]` default capture of `this` pointer by value has been deprecated C++20

```
class A {  
    int data = 1;  
  
    void f() {  
        int var = 2; // <--  
        auto lambda1 = [=]() { int var = 3; return var; }; // return 3 (nearest scope)  
        auto lambda2 = [=]() { return var; }; // copy by-value, return 2  
        auto lambda3 = [this]() { return data; }; // copy by-reference, return 2  
        auto lambda3 = [*this]() { return data; }; // copy by-value, only C++17, return 2  
        // auto lambda4 = [data]() { return data; }; // compile error not visible  
        auto lambda5 = [data = data]() { return data; }; // return 1  
    }  
};
```

Preprocessing

Preprocessing and Macro

A **preprocessor directive** is any line preceded by a *hash* symbol (#) which tells the compiler how to interpret the source code before compiling it

Macro are preprocessor directives which substitute any occurrence of an *identifier* in the rest of the code by replacement

Macro are evil:

Do not use macro expansion!!

...or use as little as possible

- Macro cannot be directly debugged
- Macro expansions can have unexpected side effects
- Macro have no namespace or scope

All statements starting with

- `#include "my_file.h"`

Inject the code in the current file

- `#define MACRO <expression>`

Define a new macro

- `#undef MACRO`

Undefine a macro

(a macro should be undefined as early as possible for safety reasons)

Multi-line Preprocessing: `\` at the end of the line

Indent: `# define`

Conditional Compiling

- `#if <condition>`

code

`#elif <condition>`

code

`#else`

code

`#endif`

- `#if defined(MACRO)` equal to `#ifdef MACRO`

Check if a macro is defined

- `#if !defined(MACRO)` equal to `#ifndef MACRO`

Check if a macro is not defined

Common Error 1

A Do not define macro in header files and before includes!!

```
#include <iostream>

#define value    // very dangerous!!
#include "big_lib.hpp"

int main() {
    std::cout << f(4); // should print 7, but it prints always 3
}
```

big_lib.hpp:

```
int f(int value) {    // 'value' disappear
    return value + 3;
}
```

It is very hard to see this problem when the macro is in a header

Use parenthesis in macro definition!!

```
#include <iostream>

#define SUB1(a, b)  a - b           // WRONG
#define SUB2(a, b) (a - b)         // WRONG
#define SUB3(a, b) ((a) - (b))     // correct

int main() {
    std::cout << (5 * SUB1(2, 1));  // print 9 not 5!!
    std::cout << SUB2(3 + 3, 2 + 2); // print 6 not 2!!
    std::cout << SUB3(3 + 3, 2 + 2); // print 2
}
```

Common Error 3

Macros make hard to find compile errors!!

```
1: #include <iostream>
2:
3: #define F(a) {      \
4:     ...             \
5:     ...             \
6:     return v;
7:
8: int main() {
9:     F(3);    // compile error at line 9!!
10: }
```

- In which line is the error??!*

*modern compilers are able to roll out the macro

Common Error 4

Macro content is not always evaluated!!

```
#if defined(DEBUG)
#   define CHECK(EXPR)    // do something with EXPR
    void check(bool b) { /* do something with b */ }
#else
#   define CHECK(EXPR)    // do nothing
    void check(bool) {}  // do nothing
#endif
bool f() { /* return a boolean value */ }

check( f() )
CHECK( f() )
```

- What happens when `DEBUG` is not defined?

`f()` is not evaluated the second time

Common Error 5

Use curly brackets in multi-lines macros!!

```
#include <iostream>
#include <nuclear_explosion.hpp>

#define NUCLEAR_EXPLOSION          \ // {
    std::cout << "start nuclear explosion"; \
    nuclear_explosion();
                                     // }

int main() {
    bool never_happen = false;
    if (never_happen)
        NUCLEAR_EXPLOSION
} // BOOM!! 💀
```

The second line is executed!!

Macros do not have scope!!

```
#include <iostream>

void f() {
    #define value 4
    std::cout << value;
}

int main() {
    f();                // 4
    std::cout << value; // 4
    #define value 3
    f();                // 4
    std::cout << value; // 3
}
```

Macros can have side effect!!

```
#define MIN(a, b) ((a) < (b) ? (a) : (b))

int main() {
    int array1[] = { 1, 5, 2 };
    int array2[] = { 6, 3, 4 };
    int i = 0;
    int j = 0;
    int v1 = MIN(array1[i++], array2[j++]); // v1 = 5!!
    int v2 = MIN(array1[i++], array2[j++]); // undefined behavior/segmentation fault 💀
}
```


When Preprocessors are Necessary

- **Conditional compiling:** different architectures, compiler features, etc.
- **Mixing different languages:** code generation (example: asm assembly)
- **Complex name replacing:** see template programming

Otherwise, prefer `const` and `constexpr` for constant values and functions

```
#define SIZE 3           // replaced with
const int SIZE = 3;     // only C++11 at global scope

#define SUB(a, b) ((a) - (b)) // replaced with
constexpr int sub(int a, int b) {
    return a - b;
}
```

`__LINE__` Integer value representing the current line in the source code file being compiled

`__FILE__` A string literal containing the presumed name of the source file being compiled

`__DATE__` A string literal in the form "MMM DD YYYY" containing the date in which the compilation process began

`__TIME__` A string literal in the form "hh:mm:ss" containing the time at which the compilation process began

main.cpp:

```
#include <iostream>
int main() {
    std::cout << __FILE__ << ":" << __LINE__; // print main.cpp:2
}
```

C++20 provides source location utilities for replacing macro-based approach

```
#include <source_location>
```

```
current()  get source location info (static)
```

```
line()     source code line
```

```
column()   line column
```

```
file_name() current file name
```

```
function_name() current function name
```

```
#include <source_location>
```

```
void f(std::source_location s = std::source_location::current()) {  
    std::cout << "line " << s.line();  
}
```

```
f(); // print: "line 6"
```

Select code depending on the C/C++ version

- `#if defined(__cplusplus)` C++ code
- `#if __cplusplus == 199711L` ISO C++ 1998/2003
- `#if __cplusplus == 201103L` ISO C++ 2011*
- `#if __cplusplus == 201402L` ISO C++ 2014*
- `#if __cplusplus == 201703L` ISO C++ 2017*

Select code depending on the compiler

- `#if defined(__GNUG__)` The compiler is gcc/g++ †
- `#if defined(__clang__)` The compiler is clang/clang++
- `#if defined(_MSC_VER)` The compiler is Microsoft Visual C++

* MSVC defines `__cplusplus == 199711L` even for C++11/14. Link: [MSVC now correctly reports __cplusplus](#) Avatar 47/57

Select code depending on the operation system or environment

- `#if defined(_WIN64)` OS is Windows 64-bit
- `#if defined(__linux__)` OS is Linux
- `#if defined(__APPLE__)` OS is Mac OS
- `#if defined(__MINGW32__)` OS is MinGW 32-bit
- ...and many others

Very Comprehensive Macro list:

- sourceforge.net/p/predef/wiki/Home/
- Compiler predefined macros
- Abseil platform macros

Feature Testing Macro

C++17 introduces `__has_include` keyword which returns `1` if header or source file with the specified name exists

```
#if __has_include(<iostream>)
#    include <iostream>
#endif
```

C++20 introduces a set of macro to evaluate if a given feature is supported by the compiler

```
#if __cpp_constexpr
constexpr int square(int x) { return x * x; }
#endif
```

Macros depend on compilers and environment!!

```
struct A {  
    int x; // enable C++11 code  
#if __cplusplus >= 201103  
    A() = default;  
#else  
    A() {}  
#endif  
};
```

```
// should return  $\approx 10.0f$   
float safe_function() {  
    A a{}; // zero-initialization  
    for (int i = 0; i < 10; i++)  
        a.x += 1.0f;  
    return a.x;  
}  
// what is the behavior ???
```

The code works fine on Linux, but not under Windows MSVC. MSVC sets `__cplusplus` to `199711` even if C++11/14/17 flag is set!! in this case the code can return `NaN`

see Lecture “Object-Oriented Programming II - Zero Initialization” and MSVC now correctly reports `__cplusplus`

Stringizing Operator (#)

The **stringizing macro operator** (**#**) causes the corresponding actual argument to be enclosed in double quotation marks **"**

```
#define STRING_MACRO(string) #string
```

```
cout << STRING_MACRO(hello); // equivalent to "hello"
```

```
#define INFO_MACRO(my_func) \
{\
    my_func \
    cout << "call " << #my_func << " at " \
        << __FILE__ << ":" << __LINE__;\
}
```

```
void g(int) {}
```

```
INFO_MACRO( g(3) ) // print: "call g(3) at my_file.cpp:7"
```


Code injection

```
#include <stdio>

#define CHECK_ERROR(condition) \
{ \
    if (condition) { \
        std::printf("expr: " #condition " failed at line %d\n", \
                    __LINE__); \
    } \
}

int t = 6, s = 3;
CHECK_ERROR(t > s) // print "expr: t > s failed at line 13"
CHECK_ERROR(t % s == 0) // segmentation fault!!! 💀
// printf interprets "% s" as a format specifier
```

#error and #pragma

- `#error "text"` The directive emits a user-specified error message at compile time when the compiler parse the related instruction

The `#pragma` directive controls implementation-specific behavior of the compiler. In general, it is not portable

- `#pragma message "text"` Display informational messages at compile time (every time this instruction is parsed)
- `#pragma GCC diagnostic warning "-Wformat"`
Disable a GCC warning
- `_Pragma(<command>)` (C++11)

It is a keyword and can be embedded in a `#define`

```
#define MY_MESSAGE \  
    _Pragma("message(\"hello\")")
```

Token-Pasting Operator (##) ★

The **token-concatenation (or pasting) macro operator** (##) allows combining two tokens (without leaving no blank spaces)

```
#define FUNC_GEN_A(tokenA, tokenB) \  
    void tokenA##tokenB() {}
```

```
#define FUNC_GEN_B(tokenA, tokenB) \  
    void tokenA##_##tokenB() {}
```

```
FUNC_GEN_A(my, function)
```

```
FUNC_GEN_B(my, function)
```

```
myfunction(); // ok, from FUNC_GEN_A
```

```
my_function(); // ok, from FUNC_GEN_B
```

Variadic Macro ★

A **variadic macro** C++11 is a special macro accepting a variable number of arguments (separated by comma)

Each occurrence of the special identifier `__VA_ARGS__` in the macro replacement list is replaced by the passed arguments

Example:

```
void f(int a)           { printf("%d", a);           }
void f(int a, int b)    { printf("%d %d", a, b);     }
void f(int a, int b, int c) { printf("%d %d %d", a, b, c); }
```

```
#define PRINT(...) \
    f(__VA_ARGS__);
```

```
PRINT(1, 2)
```

```
PRINT(1, 2, 3)
```

Convert a number literal to a string literal

```
#define TO_LITERAL_AUX(x) #x  
#define TO_LITERAL(x)    TO_LITERAL_AUX(x)
```

Motivation: avoid integer to string conversion (performance)

```
int main() {  
    int  x1    = 3 * 10;  
    int  y1    = __LINE__ + 4;  
    char x2[] = TO_LITERAL(3);  
    char y2[] = TO_LITERAL(__LINE__);  
}
```

Avoid Unused Variable Warning `[[maybe_unused]]`

```
int f(int value) {  
    [[maybe_unused]] int x = value * 2;  
    #if defined(ENABLE_FAST_RETURN)  
        return x + 3;  
    #else defined(ENABLE_CUBE_RETURN)  
        return x * x * x;  
    #else  
        return 0;  
    #endif  
}
```

If the two macros are not defined, the compiler issues a warning because the variable `x` is unused. C++17 introduces `[[maybe_unused]]` attribute to prevent this warning