

# Modern C++ Programming

## 11. TEMPLATES AND META-PROGRAMMING I

FUNCTION TEMPLATES AND COMPILE-TIME UTILITIES

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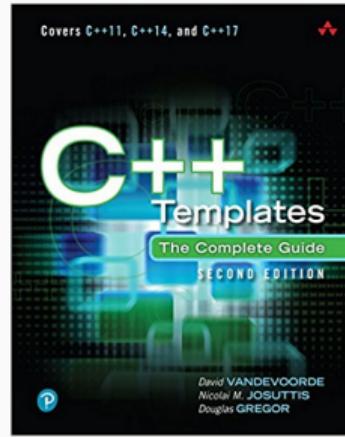
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# Template Books



## C++ Templates: The Complete Guide (2nd)

*D. Vandevoorde, N. M. Josuttis,  
D. Gregor, 2017*

# Function Template

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# Template Overview

## Template

A **template** is a mechanism for generic programming to provide a “*schema*” (or *placeholders*) to represent the structure of an entity

In C++, *templates* are a compile-time functionality to represent:

- A family of **functions**
- A family of **classes**
- A family of **variables** C++14

**The problem:** We want to define a function to handle different types

```
int add(int a, int b) {  
    return a + b;  
}  
  
float add(float a, float b) { // overloading  
    return a + b;  
}  
  
char add(char a, char b) { ... } // overloading  
ClassX add(ClassX a, ClassX b) { ... } // overloading
```

- Redundant code!!
- How many functions we have to write!?
- If the user introduces a new type we have to write another function!!

## Function Template

A **function template** is a function schema that operates with *generic* types (independent of any particular type) or concrete values

A function template works with multiple types without repeating the entire code for each of them

```
template<typename T> // or template<class T>
T add(T a, T b) {
    return a + b;
}

int    c1 = add(3, 4);      // c1 = 7
float  c2 = add(3.0f, 4.0f); // c2 = 7.0f
```

## Benefits

- **Generic Programming:** Less code and reusable. Reduce *redundancy*, better *maintainability* and *flexibility*
- **Performance.** Computation can be done/optimized at compile-time → *faster*

## Drawbacks

- **Readability.** “With respect to C++, the syntax and idioms of templates are *esoteric* compared to conventional C++ programming, and templates can be very difficult to understand” [wikipedia] → hard to read, cryptic error messages
- **Compile Time/Binary Size.** Templates are implicitly instantiated for every distinct parameters

# Template Instantiation

## Template Instantiation

The **template instantiation** is the substitution of template parameters with concrete values or types

The compiler *automatically* generates a **function implementation** for each template instantiation

```
template<typename T>
T add(T a, T b) {
    return a + b;
}
add(3, 4);           // generates: int    add(int, int)
add(3.0f, 4.0f);   // generates: float add(float, float)
add(2, 6);         // already generated
// other instances are not generated
// e.g. char add(char, char)
```

# Implicit and Explicit Template Instantiation

## Implicit Template Instantiation

**Implicit template instantiation** occurs when the compiler generates code depending on the *deduced argument types* or the *explicit template arguments* and only when the definition is needed

## Explicit Template Instantiation

**Explicit template instantiation** occurs when the compiler generates code depending only on the *explicit template arguments* specified in the declaration. Useful when dealing with multiple translation units to reduce the binary size

## Implicit and Explicit Template Instantiation

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

void g() {
    f(3);                      // generates: void f(int) → implicit
    f<short>(3.0);            // generates: void f(short) → implicit
}

template void f<int>(int); // generates: void f(int) → explicit
```

# Template Parameters

## Template Parameters

**Template Parameters** are the names following the template keyword

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

`typename T` is the **template parameter**

`int` is the **template argument**

A **template parameter** can be a generic type, i.e. `typename`, as well as a non-type template parameters (NTTP), e.g. `int`, `enum`, etc.

The **template argument** of a generic type is a built-in or user-declared type, while a concrete value for a non-type template parameter

**int parameter**

```
template<int A, int B>
int add_int() {
    return A + B; // sum is computed at compile-time
}               // e.g. add_int<3, 4>();
```

**enum parameter**

```
enum class Enum { Left, Right };

template<Enum Z>
int add_enum(int a, int b) {
    return (Z == Enum::Left) ? a + b : a;
}               // e.g. add_enum<Enum::Left>(3, 4);
```

- Ceiling division

```
template<int DIV, typename T>
T ceil_div(T value) {
    return (value + DIV - 1) / DIV;
}
// e.g. ceil_div<5>(11); // returns 3
```

- Rounded division

```
template<int DIV, typename T>
T round_div(T value) {
    return (value + DIV / 2) / DIV;
}
// e.g. round_div<5>(11); // returns 2 (2.2)
```

Since DIV is known at compile-time, the compiler can heavily optimize the division  
(almost for every number, not just for power of two)

**C++11** Template parameters can have default values

```
template<int A = 3, int B = 4>
void print1() { cout << A << ", " << B; }

template<int A = 3, int B> // still possible, but little sense
void print2() { cout << A << ", " << B; }

print1<2, 5>(); // print 2, 5
print1<2>(); // print 2, 4 (B: default)
print1<>(); // print 3, 4 (A,B: default)
print1(); // print 3, 4 (A,B: default)

print2<2, 5>(); // print 2, 5
// print2<2>(); compile error
// print2<>(); compile error
// print2(); compile error
```

## Template parameters may have no name

```
void f() {}

template<typename = void>
void g() {}

int main() {
    g(); // generated
}
```

f() is always generated in the final code

g() is generated in the final code only if it is called

C++11 Unlike function parameters, template parameters can be initialized by previous values

```
template<int A, int B = A + 3>
void f() {
    cout << B;
}

template<typename T, int S = sizeof(T)>
void g(T) {
    cout << S;
}

f<3>(); // B is 6
g(3);   // S is 4
```

# Function Template Overloading

Template Functions can be *overloaded*

Concrete type overloading has higher precedence

```
template<typename T>
T add(T a, T b) { return a + b; }           // e.g add(3, 4);

template<typename T>
int add(int a, int b) { return a + b + 1; } // higher precedence over
                                            // the generic version

// different number of parameters
template<typename T>
T add(T a, T b, T c) { return a + b + c; } // e.g add(3, 4, 5);
```

Also, templates themselves can be *overloaded*

```
template<int C, typename T>          // it is not in conflict with
T add(T a, T b) { return a + b + C; } // T add(T a, T b)
                                         // "C" is part of the signature
```

## Template Specialization

**Template specialization** refers to the concrete implementation for a specific combination of template parameters

### The problem:

```
template<typename T>
bool compare(T a, T b) {
    return a < b;
}
```

The direct comparison between two floating-point values is dangerous due to rounding errors

**Solution:** Template specialization

```
template<>
bool compare<float>(float a, float b) {
    return ... // a better floating point implementation
}
```

Full Specialization: *Function templates can be specialized only if ALL template arguments are specialized*

# Template Variable

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## Template Variable

C++14 allows variables with templates

A template variable can be considered a special case of a *class template* (see next lecture)

```
template<typename T>
constexpr T pi{ 3.1415926535897932385 }; // variable template

template<typename T>
T circular_area(T r) {
    return pi<T> * r * r; // pi<T> is a variable template instantiation
}

circular_area(3.3f); // float
circular_area(3.3); // double
// circular_area(3); // compile error, narrowing conversion with "pi"
```

# Template Parameter Types

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# Template Parameter Types

Template parameters can be:

- *integral type*
- `enum`, `enum class`
- *floating-point type* C++20
- `auto` placeholder C++17
- *class literals and concepts* C++20
- *generic type* `typename`

and rarely:

- *function*
- *reference/pointer* to global `static` function or object
- *pointer to member type*
- `nullptr_t` C++14

# Generic Type Notes

## Pass multiple values and floating-point types

```
template<float V> // only in C++20
void print_float() {}

template<typename T>
void print() {
    cout << T::x << ", " << T::y;
}

struct Multi {
    static const int x = 1;
    static constexpr float y = 2.0f;
};

print<Multi>(); // print "1, 2"
```

## auto Placeholder

C++17 introduces automatic deduction of *non-type* template parameters with the `auto` keyword

```
template<int X, int Y>
void f() {}

template<typename T1, T1 X, typename T2, T2 Y>
void g1() {} // before C++17

template<auto X, auto Y>
void g2() {}

f<2u, 2u>();           // X: int, Y: int
g1<int, 2, char, 'a'>(); // X: int, Y: char
g2<2, 'a'>();          // X: int, Y: char
```

## Function

```
template<int (*F)(int, int)> // <-- signature of "f"
int apply1(int a, int b) {
    return F(a, b);
}

int f(int a, int b) { return a + b; }

int g(int a, int b) { return a * b; }

template<decltype(f) F> // alternative syntax
int apply2(int a, int b) {
    return F(a, b);
}

int main() {
    apply1<f>(2, 3); // return 5
    apply2<g>(2, 3); // return 6
}
```

# Compile-Time Utilities

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## static\_assert

C++11 `static_assert` is used to test an assertion at compile-time, e.g.

`sizeof`, literals, templates, `constexpr`

If the *static assertion* fails, the program does not compile

```
static_assert(2 + 2 == 4, "test1"); // ok, it compiles
static_assert(2 + 2 == 5, "test2"); // compile error, print "test2"
```

## C++17: assertions without messages

```
template<typename T, typename R>
void f() { static_assert(sizeof(T) == sizeof(R)); }
```

```
f<int, unsigned>(); // ok, it compiles
// f<int, char>(); // compile error
```

## C++26: assertions with text formatting

```
static_assert(sizeof(T) != 4, std::format("test1 with sizeof(T)={}{}", sizeof(T))); 26/47
```

## using keyword (C++11)

The `using` keyword introduces an *alias-declaration* or *alias-template*

- `using` is an enhanced version of `typedef` with a more readable syntax
- `using` can be combined with templates, as opposite to `typedef`
- `using` is useful to simplify complex template expression
- `using` allows introducing new names for partial and full specializations

```
typedef int distance_t; // equal to:  
  
typedef void (*function)(int, float); // equal to:  
  
using function = void (*)(int, float);
```

Full/Partial specialization alias:

```
template<typename T, int Size>
struct Vector {};
// see next lecture for further details
// on class template

template<int Size>
using Bitset = Vector<bool, Size>; // partial specialization alias

using IntV4 = Vector<int, 4>; // full specialization alias
```

Accessing a type within a structure:

```
struct A {
    using type = int;
};

using Alias = A::type;
```

## C++11 decltype keyword deduces the type of an *entity* or *expression*

- `decltype` is always evaluated at compile-type
- `decltype(entity)` returns the *declared type* of the entity
- `decltype(expression)` returns the type of the expression
  - A variable evaluated as an expression, i.e. `decltype((var))`, is deduced as an *lvalue*
  - A general expression, e.g. `decltype((a + b))`, is deduced as its final type

```
int      x = 3;
int&    y = x;
const int z = 4;
int      array[2];
void    f(int, float);

decltype(x);           // int
decltype(2 + 3.0);    // double
decltype(y);           // int&
decltype(z);           // const int
decltype(array);       // int[2]
decltype(f(1, 2.0f));  // void, i.e. the return type of 'f'
decltype(f);           // void (int, float), i.e. the signature of 'f'

decltype(x) y = 3;     // 'y' is int
using T      = y;      // T is int&
```

```
bool f(int);

struct A {
    int x;
};

int x = 3;
const A a{4};

decltype(x)      d1;      // int
decltype((x))   d2 = x; // int&

decltype(f)      d3;      // bool (int)
decltype((f))   d4 = f; // bool (&)(int)

decltype(a.x)    d5;      // int
decltype((a.x)) d6 = x; // const int&
```

C++11

```
template<typename T, typename R>
decltype(T{} + R{}) add(T x, R y) {
    return x + y;
}

unsigned v1 = add(1, 2u);
double   v2 = add(1.5, 2u);
```

C++14

```
template<typename T, typename R>
auto add(T x, R y) {
    return x + y;
}
```

# Type Traits

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## Introspection

**Introspection** is the ability to inspect a type and query its properties

## Reflection

**Reflection** is the ability of a computer program to examine, introspect, and modify its own structure and behavior

C++ provides compile-time reflection and introspection capabilities through type traits

## Type traits (C++11)

Type traits define a compile-time interface to *query* or *modify* the properties of types

The problem:

```
template<typename T>
T integral_div(T a, T b) {
    return a / b;
}

integral_div(7, 2);      // returns 3 (int)
integral_div(71, 21);   // returns 3 (long int)
integral_div(7.0, 3.0); // !!! a floating-point value is not an integral type
```

Two alternatives: (1) Specialize (2) Type Traits + `static_assert`

If we want to prevent floating-point/other objects division at compile-time, a first solution consists in specialize for all integral types

```
template<typename T>
T integral_div(T a, T b) = delete; // declaration, error for other types

template<>
char integral_div<char>(char a, char b) {    // specialization
    return a / b;
}
template<>
int integral_div<int>(int a, int b) {        // specialization
    return a / b;
}
...unsigned char
...short
...
```

Very redundant!!

The best solution is to use **type traits**

```
#include <type_traits>      // <-- std type traits library
template<typename T>
T integral_div(T a, T b) {
    static_assert(std::is_integral<T>::value,
                  "integral_div accepts only integral types");
    return a / b;
}
```

`std::is_integral<T>` is a `struct` with a `static constexpr` boolean field `value`  
`value` is true if `T` is `bool`, `char`, `short`, `int`, `long`, `long long`, false otherwise

---

C++17 provides utilities to improve the readability of type traits

```
std::is_integral_v<T>; // std::is_integral<T>::value
```

- `is_integral` checks for an integral type (`bool`, `char`, `unsigned char`,  
`short`, `int`, `long`, etc.)
- `is_floating_point` checks for a floating-point type (`float`, `double`)
- `is_arithmetic` checks for a integral or floating-point type
- `is_signed` checks for a signed type (`float`, `int`, etc.)
- `is_unsigned` checks for an unsigned type (`unsigned`, `bool`, etc.)
- `is_enum` checks for an enumerator type (`enum`, `enum class`)
- `is_void` checks for (`void`)
- `is_pointer` checks for a pointer (`T*`)
- `is_null_pointer` checks for a (`nullptr`) C++14

### Entity type queries:

- `is_reference` checks for a reference ( `T&` )
- `is_array` checks for an array ( `T (&) [N]` )
- `is_function` checks for a function type

### Class queries:

- `is_class` checks for a class type ( `struct` , `class` )
- `is_abstract` checks for a class with at least one pure virtual function
- `is_polymorphic` checks for a class with at least one virtual function

### Type property queries:

- `is_const` checks if a type is `const`

### Type relation:

- `is_same<T, R>` checks if `T` and `R` are the same type
- `is_base_of<T, R>` checks if `T` is base of `R`
- `is_convertible<T, R>` checks if `T` can be converted to `R`

## Example - const Deduction

```
#include <type_traits>
template<typename T>
void f(T x) { cout << std::is_const_v<T>; }

template<typename T>
void g(T& x) { cout << std::is_const_v<T>; }

const int a = 3;
f(a); // print false, "const" drop in pass by-value
g(a); // print true

const int* b = nullptr;
g(b); // print false!! T: (const int)*, 'b' can be modified by 'g()'

int* const c = nullptr;
g(c); // print true!! T: const (int*), 'c' cannot be modified by 'g()'
```

## Example - Type Relation

```
#include <type_traits>
template<typename T, typename R>
T add(T a, R b) {
    static_assert(std::is_same_v<T, R>, "T and R must have the same type");
    return a + b;
}
add(1, 2);      // ok
// add(1, 2.0); // compile error, "T and R must have the same type"
```

```
#include <type_traits>
struct A {};
struct B : A {};

std::is_base_of_v<A, B>;           // true
std::is_convertible_v<int, float>; // true
```

# Type Manipulation

Type traits allow also to manipulate types by using the `type` field

Example: produce `unsigned` from `int`

```
#include <type_traits>

using U = typename std::make_unsigned<int>::type; // see next lecture to understand
                                                    // why 'typename' is needed here
U y = 5; // unsigned
```

C++14 provides utilities to improve the readability of type traits

```
std::make_unsigned_t<T>; // instead of 'typename std::make_unsigned<T>::type'
```

## Signed and Unsigned types:

- `make_signed` makes a signed type
- `make_unsigned` makes an unsigned type

## Pointers and References:

- `remove_pointer` remove pointer (`T*` → `T`)
- `remove_reference` remove reference (`T&` → `T`)
- `add_pointer` add pointer (`T` → `T*`)
- `add_lvalue_reference` add reference (`T` → `T&`)

## const specifiers:

- `remove_const` remove `const` (`const T → T`)
- `add_const` add `const`

## Other type transformation:

- `common_type<T, R>` returns the common type between `T` and `R`
- `conditional<pred, T, R>` returns `T` if `pred` is `true`, `R` otherwise
- `decay<T>` returns the same type as a function parameter passed by-value

## Type Manipulation Example

```
#include <type_traits>
template<typename T>
void f(T ptr) {
    using R = std::remove_pointer_t<T>;
    R x = ptr[0]; // char
}

template<typename T>
void g(T x) {
    using R = std::add_const_t<T>;
    R y = 3;
//    y = 4;    // compile error
}

char a[] = "abc";
f(a); // T: char*
g(3); // T: int
```

## std::common\_type Example

```
#include <type_traits>

template<typename T, typename R>
std::common_type_t<R, T> // <-- return type
add(T a, R b) {
    return a + b;
}

auto x = add(3, 4.0f); // 'x' has type float
// we can also use decltype to derive the result type
using result_t = decltype(add(3, 4.0f)); // 'result_t' is float
result_t x = add(3, 4.0f);

// NOTE
// decltype(T{} + R{}) is not the same of std::common_type_t<R, T>, e.g.
//     decltype(short{} + short{})      -> int
//     std::common_type_t<short, short> -> short
```

## std::conditional Example

```
#include <type_traits>

template<typename T, typename R>
auto f(T a, R b) {
    constexpr bool pred = sizeof(T) > sizeof(R);
    using S = std::conditional_t<pred, T, R>;
    return static_cast<S>(a) + static_cast<S>(b);
}

f( 2, 'a'); // return 'int'
f( 2, 2ull); // return 'unsigned long long'
f(2.0f, 2ull); // return 'unsigned long long'
```