模板基础与移动语义

Template Basics and Move Semantics

现代C++基础
Modern C++ Basics

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- **Template Basics**
  - **Compile-time Evaluation**
  - **Compile-time Branch Selection**
    - **Specialization**
    - **Overload resolution**
  - **Tricky Details**
  - **Concepts**

- **Final part of Move Semantics**
  - **Universal Reference and Perfect Forwarding**

Supplementary

- Before starting, we'd supplement some basic knowledge.

1. Since C++14, it's allowed to define variable template.
   - E.g.

```
template<class T>
const T pi = T(3.1415926535897932385L);
```

   - Though it's `const`, it has external linkage (since it's a template).
   - Non-static variable template cannot be defined inside a class.
2. Member function template cannot be virtual.
   - Intuitive reason: compiler need to determine the size of vtable; so it needs to know number of virtual functions.
     - But function template can be instantiated freely.

Template Basics

Compile-time Evaluation

Motivation

- const has two functionalities in C++:
  - Not changeable;
  - Possibly can be determined in compile time.
- For example:

```cpp
void Test(int a)
{
    const int b = a;
    const int size = 10;
    int arr[size]{}; // legal
    // int arr[b]{}; // illegal, b isn't compile-time value.
}
```

- Sometimes we hope to force the variable to be determined in compile time.

constexpr variable

- So we need `constexpr`!

```
void Test(int a)
{
    // constexpr int b = a;  // compile error
    constexpr int size = 10;
    int arr[size]{}; // legal
}
```

- `constexpr` implies `const`, so it has internal linkage in global field.
  - Normally in header file/class it will also be decorated with `inline`.
- So what if we want the initial value determined in compile time, while make it changeable afterwards?
  - That is, `constexpr` without `const`!

constinit

- That’s `constinit` (since C++20).
  - You can only use `constinit` for global / static / thread-local variables.

```
static constinit int a = 10;

void Test(int a)
{
    // static constinit int b = a;  // compile error
    static constinit int size = 10;
    // int arr[size]{}; // illegal, since size isn't const.
}
```

- `constinit` can help to solve *static initialization order fiasco*.
  - That is, the initialization order of global variables in different TUs is not determined; so you cannot let one initialization rely on the other.

constinit

- Example:

```cpp
// a.h
extern int a;

// a.cpp
int a = 1;

// b.cpp, #include "a.h"
static int b = a; // a may have uninitialized value
```

- But constinit ensures by compilers that when it’s used, it’s definitely initialized.
  - For non-compile-time initialization, you still need singleton pattern.

```cpp
// a.h
extern constinit int a;

// a.cpp
constinit int a = 1;

// b.cpp, #include "a.h"
static int b = a; // a == 1
```

constexpr function

- We may want complex compile-time computation, so we need functions executed in compile time…
- And that's `constexpr` function.
- The history:
  - C++11 – only one line; `constexpr` function can only contain a return statement & type aliases & `static_assert`.
  - C++14 – allow multiple lines, e.g. branches like loop & condition;
  - C++20 – allow try – catch block, virtual function.
    - throwing an exception will lead to compile error.
  - C++23 – allow goto, use non-constexpr variables, static & thread-local variable.

Before C++23, `constexpr` ctor has less requirements than other `constexpr` functions; but C++23 makes them unified.

constexpr function

- So C++23 requirements are quite simple:

  A **constexpr function** must satisfy the following requirements:

  - it must not be a coroutine
  - for constructor and destructor, the class must have no virtual base classes

- For example, we want to know whether a number is prime at compile time.
  - In C++11, you have to use recursion to do it in a single return:

```
constexpr bool DoIsPrime(unsigned int a, unsigned int b)
{
    return b == 1 ? true : (a % b != 0 && DoIsPrime(a, b - 1));
}

constexpr bool IsPrime(unsigned int a)
{
    return a <= 1 ? false : DoIsPrime(a, a / 2);
}
```

constexpr function

- And in C++14, you can use loop to do it:

```
constexpr bool IsPrime(unsigned int a)
{
    if (a <= 1) return false;

    for (unsigned int i = 2; i <= a / 2; i++)
    {
        if (a % i == 0)
            return false;
    }
    return true;
}
```

constexpr & consteval function

- Unlike `constexpr` variables, `constexpr` functions are allowed to not get the value at the compile time.

```
constexpr bool p1 = IsPrime(2); // must be evaluated at compile time
bool p2 = IsPrime(3); // may or may not be evaluated at compile time
bool p3 = IsPrime(argc); // Okay, runtime
// constexpr bool p4 = IsPrime(argc); // compile error
```

But normally it is, due to compiler optimization.

- If you want to **force** the function to be evaluated at compile time, you need `consteval`.

```
consteval bool IsPrime(unsigned int a)
```

```
constexpr bool p1 = IsPrime(2); // must be evaluated at compile time
bool p2 = IsPrime(3); // must be evaluated at compile time
// bool p3 = IsPrime(argc); // compile error
// constexpr bool p4 = IsPrime(argc); // compile error
```

constexpr & consteval lambda

- These two specifiers can also be added in lambda.
  - `constexpr` since C++17, `consteval` since C++20.
  - E.g.

```cpp
auto isPrime = [](unsigned int a) consteval -> bool {
    return true;
};
```

  - Notice that if all operations in lambda is `constexpr`, `constexpr` is implied (so explicit specification can be omitted).
    - E.g.

```cpp
auto isPrime = [](unsigned int a) -> bool {
    return true;
};
constexpr bool b = isPrime(1);
```

Template Basics

Compile-time Branch Selection

Compile-time Branch Selection

- We’ve known branch since we’re novices…
  - However, code path selection only happens at runtime, depending on the value of the condition.
- But we’ve already learnt compile-time evaluation…
  - Correspondingly, we could choose to execute some code or not at compile time. Non-taken branch can be completely eliminated!
- There are several ways to do so:
  - By specialization, so when some conditions are met, only one of the specializations will be chosen.
    - And for functions, there is no partial specialization so overload may be needed.
  - By control statement in a code block, e.g. constexpr if.

Template Basics

- Compile-time branch selection
  - Function overload resolution and specialization
  - Class specialization
  - Selection in code block

Template specialization

- A simple template function:

```cpp
template<typename T>
void Func(T arg)
{
    std::println("Here {}.", arg);
}
```

- What if we want to output `“There!”` when `T` is `int`?
  - By specialization!

```cpp
template<>
void Func<int>(int arg)
{
    std::println("There {}!", arg);
}
```

```cpp
Func<char>('a');
Func<int>(1);
```

```
Here a.
There 1!
```

- From `int arg`, compilers can deduce the specialized type and we can just write:

```cpp
template<>
void Func(int arg)
{
    std::println("There {}!", arg);
}
```

Template specialization

- Note1: don't mistake it from explicit template instantiation.
  - Instantiation: no `<>` after `template`. `template void Func<int>(int arg);`
    - Instantiation can also eliminate `<int>` here since it could be deduced.
- Note2: a specialization must be declared before it's used, otherwise the behavior is implementation-defined.
  - For example, the compiler could generate according to the primary template since it doesn't see specialization here.
  - Or, it could search for specialization globally and use it directly.
- Note3: a full specialization isn't a template anymore; thus you cannot define it in header file (re-definition).
  - You can either use `inline`, or only write the specialization prototype.

```cpp
template<>
inline void Func(int arg)
{
    std::println("There {}!", arg);
}
```

```cpp
template<> void Func(int arg);
```

Template specialization

  - You can add new specifiers (e.g. `inline`, `constexpr`) since it can be viewed as a new function.
  - For class specialization, since class can be written directly in header file, it’s Okay.
- Note4: default template parameter can be omitted when writing specialization.

```cpp
template<typename T = int>
void Func();
// Equiv to Func<int>
template<> void Func()
{
    std::cout << "TestIt!";
}
```

Template specialization

- Note5: you can also specialize template member function, but it's not allowed to be defined inside class.
  - *But msvc and clang allow to do so.

```cpp
class A
{
    template<typename T>
    void Func() {}

    template<> void Func<int>(){ }
};
```

```cpp
class A
{
    template<typename T>
    void Func() {}
};

template<> void A::Func<int>() { }
```

- These notes also apply on class template specialization.

Type Deduction

- Similarly, you don't need to write `<…>` when calling it if they could be deduced from the parameters.

```
Func('a');
Func(1);
```

  - Non-deducible template type parameters may be written first to minimize explicit ones.

```
template<typename U, typename V, typename T>
V Func2(T a)
{
    std::vector<U> vec;
    return V{};
}
```

```
Func2<int, double>(0); // T isn' needed explicitly
```

Notice that the returned type **cannot be deduced from the caller**, e.g. `double b = Func2<…>(…)` cannot deduce `V` as `double`.

  - By contrast: here `T` must be specified explicitly.

```
template<typename T, typename U, typename V>
V Func2(T a)
{
    std::vector<U> vec;
    return V{};
}
```

```
Func2<int, int, double>(0);
```

Overload and specialization

- But there are some special conditions…
  - For example, we want to use some code when "T is pointer".
- For class, you can use *partial specialization*; but functions don't provide it.
- Reason & Solution: functions can use overloads!

```cpp
template<typename T>
void Func(T* arg)
{
    std::println("Nobody.");
}
```

```cpp
int a = 1;
Func(&a);
```

```
Here.
There 1!
Nobody.
```

- What if we use `nullptr` as parameter?
  - Oops!

```cpp
Func(nullptr);
```

```
Here.
There 1!
Here.
```

Overload resolution

- So in fact we have two candidates:
  - `template<typename T> void Func(T);` (named as F1)
  - `template<typename T> void Func(T*);` (named as F2)
- When we use `int*`, F2 is preferred over F1; when we use `nullptr`, F1 is preferred over F2.
- So there is an inner matching order; that's **overload resolution**.

Overload resolution

- So which function is called is determined in these procedures:
  1. Names are looked up to find all possible functions to form an *overload set*.
     - ADL helps in this step but we don't cover it.
  2. Discard illegal functions by judging from their prototypes to form *viable function candidates*.
     - E.g. non-deducible templates;
     - E.g. `Func(int, double)` cannot be called by `Func(1)` due to wrong parameter number.
  3. Perform *overload resolution* to find the best candidate. If there isn't the best one, compile error.
  4. Check whether the candidate compiles.
     - E.g. if it's `=delete`, then compile error (yes, it's not excluded in step2);
     - E.g. there is `static_assert` in function body that's not satisfied.

Overload resolution

- To put it simply, overload resolution just tries to find “the most precise one” determined by parameters. The order is:
  1. Perfect match or match with minimal adjustments (i.e. decay, add cv-qualifier).
  2. Match with promotion, e.g. `short->int`, `float->double`.
  3. Match with standard conversions (pre-defined ones), e.g. `int->short`.
     - For a conversion sequence (at most s-u-s), match the shorter.
  4. Match with user-defined conversions.

Overload resolution

- If there are still more than one candidates, more rules will apply:
  1. More specialized ones are preferred, including considering value category;
  2. Non-template ones are preferred than template ones;
  3. For pointers, conversion order is: `Derived-to-base > void* > bool`.
  4. For `initializer_list`, when using universal initialization, it's preferred over other ones.
     - And that's why `std::vector<int>(5, 1) ≠ std::vector<int>{5, 1}`.
  5. Functors are preferred over surrogate functions (i.e. need conversion to become callable functor).
  - …
- It's very complicated and we don't cover it more; it you're interested, see [over.match].

Overload resolution

- So now we know why:

  So in fact we have two candidates:
  - `template<typename T> void Func(T);` (named as F1)
  - `template<typename T> void Func(T*);` (named as F2)

  When we use `int*`, F2 is preferred over F1; when we use `nullptr`, there is a conversion to match `T*`, thus F1 is preferred over F2.

  - `int*`: both exact match, but F2 is more specialized than F1.
  - `nullptr`: F1 exact match (`T` is `nullptr_t`), while F2 doesn't.
- Exercise: what if we add `void Func(int*);` as F3?
  - `int*`: F3 > F2 > F1, since non-template is preferred when all exact match.
  - `nullptr`: F1 exact match, F3 needs conversion, so F1 > F3.

To use only template, you need to explicitly write `Func<…>()` (so non-template won't be a candidate due to syntax error).

“More specialized”

- One more concern: what is “more specialized”?
- Formally, we say template A is more specialized than B if:
  - Hypothesize that there exist concrete types U1, U2, … to substitute all template parameters in A, if it couldn’t be deduced by B, then we say A isn’t more specialized by B.
- “More specialized” is a partial ordering, so maybe neither template is more specialized than the other, which causes **ambiguous call**.
  - Notice that this will only be judged when calling, not when functions are defined.

“More specialized”

- Example:

```
template<class T>
void f(T, T*);    // #1
template<class T>
void f(T, int*); // #2
```

- It seems that #2 is more specialized than #1, but:
- #1 from hypothetic #2: for `f(U1, int*)`, #1 will:
    - For first parameter, deduce `T` as `U1`;
    - For second parameter, deduce `T` as `int`.
    - `U1 ≠ int`, thus deduction fails -> #2 is not more specialized than #1.
- #2 from hypothetic #1: for `f(U1, U1*)`, #2 will:
    - For first parameter, deduce `T` as `U1`;
    - For second parameter, fail to call -> #1 is not more specialized than #2.
- Thus, ambiguous call:

```
void m(int* p)
{
    f(0, p); //
```

Notice that `f(0.0, double*)` isn't ambiguous since #1 is exact match while #2 isn't.

Template Basics

- Compile-time branch selection
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Class template specialization

- Similarly, you can define full specialization for class:

```cpp
template<typename T>
class A
{
    int m;
public:
    int GetM() const { return m; }
};
```

```cpp
template<>
class A<int>
{
    double c;
public:
    int GetC() const { return c; }
};
```

  - Typical example in standard library: `std::vector` and `std::vector<bool>`.
  - Specialized class is a separate class, which can have completely different data member and member functions.
    - You may just see it as a normal class.

```cpp
template<typename T> class B {};
template<> class B<int> { public: void f(); };
```

No `template<>` when split member function definition, just like a normal class.

```cpp
void B<int>::f() { }
```

Class template specialization

- And, you can also define partial specialization!

```
template<typename T>
class A<T*>
{
    int k;
};
```

  - Unlike functions, you cannot "overload" a class, like define non-template `class A`; `template<typename T, typename U> class A`; etc.
- Matching order is just choosing the most specialized one among all candidates.
  - E.g. `A<int*>` can match both `A<T*>` and `A<T>`, but the former is more specialized (formally, you can use a hypothetic type to deduce it).
  - `A<int>` can only match `A<T>`, so it's `A<T>`.

Partial specialization

- Note1: partial specialization is not allowed to have default template parameter.
  - Reason: specialization only determines “whether a type matches it”; it doesn’t determine “what a type is”.
  - Example:

```cpp
template<typename T, typename U = int>
class A { };

template<typename T = int>
class A<T, T> { };
```

❌

  - `A<int>` is determined to be `A<int, int>` by the primary template; then `A<int, int>` is judged to match the specialized one.

Partial specialization

- Note2: NTTP partial specialization cannot depend on other template parameters.
  - Forbidden cases:

```
template<int N, int M>
class A {};

template<typename T>
class A<T::a, T::b> { };
```

```
template<class T, T t> struct C {}; // primary template
template<class T> struct C<T, 1>;   // error: type of the argument 1 is T,
                                    // which depends on the parameter T

template<int X, int (*array_ptr)[X]> class B {}; // primary template
int array[5];
template<int X> class B<X, &array> {}; // error: type of the argument &array is
                                       // int(*)[X], which depends on the parameter X
```

Partial specialization

- Note3: variable template can also be specialized.
  - Partial specialization of variable template isn't regulated in the standard but all compilers implement it.
  - Particularly, the type of specialized variable can be different from the primary template.
- Note4: partial specialization is allowed to be defined inside the class.
  - Example:

```
class A
{
    template<typename T> class B {};
    template<typename T> class B<T*> { int a; };
    // template<> class B<int> {}; // wrong
};

template<> class A::B<int> {}; // right
```

Template Basics

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constexpr if

- Sometimes it's too troublesome to define all special cases by specialization…
  - For example:

```cpp
template<int N> struct M
{ static inline constexpr int value2 = N + 1; };
template<> struct M<0>
{ static inline constexpr int value = 100; };

template<int N>
int Func() { return M<N>::value2; }

template<> int Func<0>() { return M<0>::value; }
```

- It can't be better if we can code them together:

```cpp
template<int N>
int Func() {
    if (N == 0)
        return M<0>::value;
    else
        return M<N>::value2;
}
```

constexpr if

- However, it won't compile when instantiation.
  - E.g. `N == 0`, then `M<0>::value2` is invalid.
  - Though this branch is always not taken, but that's runtime thing!
- What we want: when some compile-time condition isn't met, the code segment isn't checked and generated at all.
  - That's constexpr if!
    - Since C++17.

```
if constexpr (N == 0)
    return M<0>::value;
else
    return M<N>::value2;
```

  - Notice that `else if` should use `constexpr` too; only `else` can omit it.

constexpr if

- Example: previous homework on variant
  - For `std::variant<int, double, std::string>`, convert to a string.

```
std::visit(
    [](const auto &value) {
        using InnerType = std::decay_t<decltype(value)>;
        if constexpr (std::is_same_v<InnerType, std::string>)
            return value;
        else
            return std::to_string(value);
    }, currVar);
```

consteval if

- There exists a special condition – when it's evaluated at compile time, do something.
  - For example, we want to write a constexpr $\sin x$.
    - At runtime, it's better to use std::sin directly, which may utilize hardware utility to accelerate.
    - At compile time, we may use Taylor expansion $\sin x = \sum_{i=0}^{+\infty} (-1)^i x^i / (2i+1)!$ to evaluate; it is slow but can at least be evaluated at compile time.
  - That's consteval if since C++23.
    - No parentheses!
  - Negate: if !consteval {…}.

```cpp
template<std::size_t N = 1024>
constexpr float Sin(float x)
{
    if consteval
    {
        float sin = 0.0, temp = x;
        for (std::size_t i = 0; i < N; ++i)
        {
            sin += temp;
            temp *= -x * x / ((2 * i + 2) * (2 * i + 3));
        }
        return sin;
    }
    else {
        return std::sin(x);
    }
}
```

```cpp
float x = Sin(1); // Just same as std::sin(1);
constexpr float y = Sin(1); // Just same as Taylor expansion with 1024 terms.
```

For more compile-time math function implementations, see [C++：constexpr的数学库 - 知乎]; C++23 will also make e.g. std::sin to be constexpr directly.

is_constant_evaluated

- C++20 introduces `std::is_constant_evaluated`, which is same as:

```
constexpr bool is_constant_evaluated() {
    if consteval {
        return true;
    } else {
        return false;
    }
}
```

```
template<std::size_t N = 1024>
constexpr float Sin(float x)
{
    if (std::is_constant_evaluated())
    {
        float sin = 0.0, temp = x;
```

  - Notice that you cannot use `if constexpr (std::is_constant_evaluated())`, since the condition of `if constexpr` is always evaluated at compile time, which means **it's always true** here.
- Since it can only be used in runtime branch, it's less powerful than if consteval.

```
consteval int f(int i) { return i; }

constexpr int g(int i) {
    if consteval {
        return f(i) + 1; // ok: immediate function context
    } else {
        return 42;
    }
}
```

Cannot be substituted with `if (std::is_constant_evaluated());`

Template Basics

Tricky Details

Most tricky details in templates
are caused by ambiguity!

Name lookup

- Names could be divided into two parts:
  - Dependent / Non-dependent name: if a name depends on template parameter, then it’s dependent name.
  - Qualified / Non-qualified name: if a name is specified by `::`, `.`, `->`, then it’s qualified. A fully qualified name is like `::a.b`.
    - Compilers need to automatically determine the identity of non-qualified name. ADL helps here (but we don’t cover it).
    - Since C++ allows name reuse (in different blocks), so it will be looked up upwards.
- In templates, two-phase lookup is performed.
  - Non-dependent names are looked up when template is defined.
  - Dependent names are looked up when template is instantiated.

this->

1. When the base class is dependent name, then `this->` is needed to access members of base class.
   - E.g.

```cpp
int a = 0;
template<typename T>
class A
{
public:
    int a;
};
```

```cpp
template<typename T>
class B : public A<T>
{
public:
    int func() { return this->a; }
};
```

   - Reason: `a` is non-dependent name, so it's looked up when the template is defined, not when instantiated. Thus `return a;` will then be returning the global one.
     - If the global `a` is not defined, `return a;` will cause compilation error.

Two-phase lookup

- Why don’t we lookup all names when templates are defined?
  - Reason: template may be specialized afterwards, which needs lookup in the second phase to know whether the identity exists.
  - For example:

```cpp
template<typename T>
class A {};

template<typename T>
class B : public A<T>
{
public:
    int func() { return a; }
};
```

Then define

```cpp
template<>
class A<int>
{
public:
    int a;
};
```

You cannot know whether a exists when B is defined!

  - Thus C++ requires to access data member by `this->` in this case; `this` is dependent so its name lookup is performed in the second stage.

Two-phase lookup

- Why don't we lookup all names when templates are instantiated?
  - We can, but C++ hopes to expose syntax error as early as possible. Thus statements with only non-dependent names can be checked directly without instantiation.

  - Notice that some compilers may check all things only at instantiation, e.g. msvc.
    - Since VS2017 (msvc 15.3), msvc adds `/permissive-` to enable two-phase lookup.

typename

2. `A::B` could be either a type or a variable.
   - For non-dependent names, it could be easily determined; but for dependent names, it's still ambiguous…

```
template <typename T> struct X {
    using MemberType = int;
};

template<> struct X<float> {
    static inline const int MemberType = 1;
};
```

```
template<typename T> void Test()
{
    int b = 1;
    {
        T::MemberType * b;
    }
    return;
}

int main()
{
    Test<X<int>>(); int* b in Test.
    Test<X<float>>(); 1 * b in Test.
    return 0;
}
```

typename

- C++ chooses to always regard it as variable!
  - When it's actually type, you need to add a `typename`.
- For example:

```cpp
template<typename T>
class A
{
public:
    void func(std::vector<T> &vec)
    {
        typename std::vector<T>::iterator it = vec.begin();
    }
};
```

Dependent name

```cpp
template<typename T>
void func()
{
    typename T::type a{}
}
```

- Note: You cannot have an identity that's possibly data or types; it **must** be determined before instantiation.

typename

- To be specific, you **can** use `typename` when:
  - The type is a qualified name;
  - It's not after keywords `class/struct/union/enum`;
  - It's not Base class appears at inheritance specification and ctor.
    - i.e. `class A: typename B<T>` is wrong;
    - `A(int a) : typename B<T>{a} {}` is wrong.
- And you **must** use `typename` when:
  - Rules above;
  - The type is a dependent name;
  - It's not the current instantiation.
    - i.e. just the current type itself.

```
template<typename T>
class A
{
public:
    using Type = int;

    template<typename U>
    void func()
    {
        A<T>::Type p; // current instantiation, can neglect typename
        typename A<U>::Type p2; // unknown specialization
    }
};
```

typename

- Exercise: which `typename` is wrong / correct but unnecessary / correct & must?

```
template<typename₁ T>
struct S : typename₂ X<T>::Base {
    S() : typename₃ X<T>::Base(typename₄ X<T>::Base(0)) {
    }
    typename₅ X<T> f() {
        typename₆ X<T>::C * p;    // declaration of pointer p
        X<T>::D * q;              // multiplication!
    }
    typename₇ X<int>::C * s;

    using Type = T;
    using OtherType = typename₈ S<T>::Type;
};
```

typename

- Since C++20, many rules are relaxed.
  - To be short, when a dependent name appears where only type is possible, `typename` can be omitted.
- To be specific:
  - Return type of functions and lambda;
  - Aliasing declarations, e.g. `using Type = A<U>::Type`;
  - Target type of C++-style cast (e.g. `static_cast<A<U>::Type>(…)`);
  - Type of new expression (e.g. `new A<U>::Type{1}`);
  - Parameter type in *requires expression*, covered later.
  - Data member type, NTTP type;
  - Parameter types of member function & lambda;
  - Default value of template type parameter (e.g. `template <typename T, typename U = A<T>::Type>`)

typename

- Notice that member function parameter and global function parameter differ here.

```
template<typename T>
TYPENAME T::value_type                              // typename optional
foo(const T& cont, typename T::value_type arg)      // typename required
```

```
template<typename T,
         auto ValT = typename T::value_type{}>      // typename required
class MyClass {
  void print(TYPENAME T::iterator) const;           // typename optional
};
```

```
template<typename T>
class MyClass {
public:
    template<typename U>
    void print(T arg, U::v arg2);
};
```

Okay too.

typename

- A full example adopted from *C++20 – the Complete Guide*.

Rarely used.

```
template<typename T,
         auto ValT = typename T::value_type{}>    // typename required
class MyClass {
  TYPENAME T::value_type val;                     // typename optional
 public:
  using iterator = TYPENAME T::iterator;          // typename optional

  TYPENAME T::iterator begin() const;             // typename optional
  TYPENAME T::iterator end() const;               // typename optional
  void print(TYPENAME T::iterator) const;         // typename optional
  template<typename T2 = TYPENAME T::value_type>  // second typename optional
    void assign(T2);
};

template<typename T>
TYPENAME T::value_type                            // typename optional
foo(const T& cont, typename T::value_type arg)    // typename required
{
  typedef typename T::value_type ValT2;           // typename required
  using ValT1 = TYPENAME T::value_type;           // typename optional
  typename T::value_type val;                     // typename required

  typename T::value_type other1(void);            // typename required
  auto other2(void) -> TYPENAME T::value_type;    // typename optional

  auto l1 = [] (TYPENAME T::value_type) {         // typename optional
          };

  auto p = new TYPENAME T::value_type;            // typename optional
  val = static_cast<TYPENAME T::value_type>(0);   // typename optional
  ...
}
```

template

3. Template parameter specification is also ambiguous…
   - E.g. `std::function<int()> f;`
     - It could be parsed as `(std::function < int()) > f`, where `std::function` and `f` are interpreted as variables.

```
namespace std {
    int function = 1;
}

int f = 0;

int main()
{
    std::function<int()> f;
}
```

   - So how to parse is determined by the identity again (whether it's a template or not).
   - C++ regulates that if the name is a template, `<` is always interpreted as the beginning of parameter specification; otherwise less-than operator.

template

- Again, dependent name cannot determine its identity…
  - So it will always be interpreted as less-than operator; when it’s actually a template, you need to use `template` keyword explicitly.

```
template<std::size_t N>
void Test(std::bitset<N>& n)
{
    n.template to_string<char>();
}
```

  - Here `n` is dependent and thus `to_string` cannot know whether it’s a template. When `<` follows, it would be interpreted as less-than.

template

- Another horrible example:

```
template<typename T>
class Shell {
  public:
    template<int N>
    class In {
      public:
        template<int M>
        class Deep {
            public:
            virtual void f();
        };
    };
};
```

```
template<typename T, int N>
class Weird {
  public:
    void case1 (
            typename Shell<T>::template In<N>::template Deep<N>* p) {
        p->template Deep<N>::f();  // inhibit virtual call
    }
```

This typename can be omitted since C++20, as it’s parameter of member function.

Credit: C++ Templates – The Complete Guide 2nd ed. by *David Vandevoorde, Nicolai M. Josuttis, Douglas Gregor*

template

- Note1: in template parameter specification, the first closing `>` will always be interpreted as the ending.
  - It's parsed as `M<a> b > m`.
  - You need additional parentheses to make it right: `M<(a > b)> m;`

```
template<bool S>
struct M {};

int main()
{
    constexpr int a = 1, b = 0;
    M<a > b> m;
}
```

- Note2: nested template (e.g. `vector<vector<int>>`) needs additional space (i.e. `int> >`) before C++11, to prevent ambiguity with operator `>>`.
  - Since C++11, it's also specially regulated.

template

- Note3: C++ exists digraph and trigraph (e.g. `<:` equiv. to `[`), which makes e.g. `S<::i>` ambiguous.
  - Since C++11, it's specially regulated that `<::` is never treated as `<:` + `:` (which makes it `[:`), but as a whole.
  - And since C++17, trigraph is removed.

Nested Specialization*

- Sometimes we may specialize a template in a template class…
  - It has many restrictions and is not always possible.
  - Very complicated and not commonly used, so we make it **optional**.

1. A fully specialized template cannot be defined in a not-fully specialized enclosing template.

```cpp
template<typename T> class A {
public:
    template<typename U> class B {};
};

template<> template<> class A<int>::B<int> { void func(); };
// template<typename T> template<> class A<T>::B<int> {};
// template<typename T> template<> class A<T*>::B<int> {};
```

Primary template & partially specialized template aren't allowed.

Nested Specialization*

- But when a fully specialized enclosing class is explicitly defined, this `template<>` isn’t needed anymore…
  - As we’ve said, fully specialized class is just a normal class.

```cpp
template<> class A<int> {
public:
    template<typename U> class C {};
};

template<> class A<int>::C<int> { public: int a; };
```

  - `template<>` is only needed when explicit specialization isn’t specified.
  - Similarly, to define `func` here:
    - Since `B<int>` is already a normal class.

```cpp
template<> template<> class A<int>::B<int> { void func(); };
void A<int>::B<int>::func() { }
```

Nested Specialization*

2. Partial specialization can be normally defined regardless of the specialization status of the enclosing class.

```
template<typename T>
class C {
    template<typename U> class D {};

    template<typename U> class D<U**> {}; // Okay
};

template<typename T>
    template<typename U>
class C<T>::D<U*> { }; // Okay
```

- So sometimes to bypass the full-specialization restriction, you could add a dummy type parameter.

```
template<typename T>
class C {
    // The second param is never used.
    template<typename U, typename=void> class D {};
};

template<typename T>
    template<typename Dummy>
class C<T>::D<int, Dummy> { }; // Okay
```

Template Basics

Concept

Template Basics

- Concept
  - require clause and concept
  - Subsumption
  - Some exercises on concept

Motivation

- Templates are good at reducing code replication.
  - What if we instantiate it by some unintended types?
- For example:

```
template<typename T>
T Max(const T& a, const T& b)
{
    return a < b ? b : a;
}
```

```
Max<const char*>("12", "34");
```

  - E.g. We don’t want users to compare pointers.
  - It will also report error when T isn’t comparable, and users have to read the full source code / the error message to know all illegal operations…
- So why not add explicit constraints on types? Then users just need to read these constraints directly!

Concept

- That’s what concept for.
  - Before C++20, users can add constraint in an obscure way called “SFINAE”, which is miserable for both users to read and programmers to write.
- Let’s show an example for concept directly:

The parentheses are necessary when it’s an expression instead of a pure value.

```cpp
template<typename T>
requires (!std::is_pointer_v<T>)
T Max(const T& a, const T& b)
{
    return a < b ? b : a;
}
```

requires clause

```
1>main.cpp
1>D:\Work\CS\C++\Test\Project2\main.cpp(16,5): error C2672: “Max”: 未找到匹配的重载函数
1>    D:\Work\CS\C++\Test\Project2\main.cpp(9,3):
1>    可能是“T Max(const T &,const T &)”
1>        D:\Work\CS\C++\Test\Project2\main.cpp(16,5):
1>        未满足关联约束
1>            D:\Work\CS\C++\Test\Project2\main.cpp(8,11):
1>            未满足约束
```

Concept

- Any template parameter can be constrained by requires clause:

```cpp
template<typename T>
requires (!std::is_pointer_v<T>)
class A
```

```cpp
template<typename T>
requires (!std::is_pointer_v<T>)
static T var{};
```

```cpp
template<typename T>
requires (!std::is_pointer_v<T>)
using Type = T::value_type;
```

- You can also connect multiple constraints by && and ||.

```cpp
template<typename T>
requires (!std::is_pointer_v<T>) && (sizeof(T) >= 8)
T Max(const T& a, const T& b)
```

- But we may hope to reuse these constraints, instead of writing it over and over again…

Concept

- So we can declare a concept!

```
template<typename T>
concept MyNotPointer = !std::is_pointer_v<T> && sizeof(T) >= 8;

template<typename T>
requires MyNotPointer<T>
T Max(const T& a, const T& b)
{
    return a < b ? b : a;
}
```

- That’s still naïve; we need more constraints…
  - For example, what kind of expressions should be legal?
- Then you need *requires expression*.

Concept

- For example:

```
template<typename T>
concept MyLessThan = requires(T x) { x < x; };
```

```
template<typename T>
requires MyNotPointer<T> && MyLessThan<T>
T Max(const T& a, const T& b)
```

  - It checks whether `x < x` is legal, i.e. whether `T` can be compared by `<`. It never uses its runtime result.
  - `T x` is just a hypothetic parameter; it doesn't matter whether it has an accessible ctor. If parameters aren't needed, `requires { … }` is enough.
- You can also combine a requires expression with logical operators.

```
template<typename T>
concept MyMaxConstraint = !std::is_pointer_v<T> && sizeof(T) >= 8
    && requires(T x) { x < x; };
```

Concept

- Sometimes we just use a concept once, so we can insert it into the requires clause anonymously.

```cpp
template<typename T>
requires requires(T x) { x < x; }
T Max(const T& a, const T& b)
```

requires expression

requires clause

  - Such constraint is same as `requires MyLessThan<T>`.
- Small exercise: can we combine two concepts like

```cpp
template<typename T>
concept MyMaxConstraint = requires(T x) {
    !std::is_pointer_v<T>;
    sizeof(T) >= 8;
    x < x;
};
```

Concept

- Nope.
  - As we've said, it just checks whether the expression is legal, instead of whether it's true.
    - E.g. `sizeof(char) >= 8` results in `false`, but it's legal to write this expression. So it doesn't check anything.
- Similarly, this doesn't check anything either:

```
template<typename T>
concept MyMaxConstraint = requires(T x) {
    MyNotPointer<T>;
    x < x;
};
```

- Remember: it doesn't check something **valid but not true**!

Requires expression

- So what we write before in requires expression is called *simple requirement*.
  - Beyond that, there exist other three types of requirements.
  - Type requirement: `typename xxx;`
    - E.g.

```cpp
template<typename T>
concept MyMaxConstraint = requires(T x) {
    x < x;
    typename T::value_type;
};
```

satisfy

```cpp
class A
{
public:
    using value_type = int;
    auto operator<(const A&) const { return true; }
};
```

    - Notice that if `typename` isn't added, then it's simple requirement that checks whether there exists a static data member.

```cpp
template<typename T>
concept MyMaxConstraint = requires(T x) {
    x < x;
    T::value;
};
```

satisfy

```cpp
class A
{
public:
    static int value;
    auto operator<(const A&) const { return true; }
};
```

Requires expression

- Compound requirement: check whether the expression is legal **and** whether the type of result satisfies some constraints.

{ *expression* } **noexcept**(optional) *return-type-requirement*(optional) **;**

---

return-type-requirement - **->** *type-constraint*

```
template<typename T>
concept MyLessThan = requires(T x)
{
    { x < x } noexcept -> std::same_as<bool>;
};
```

  - The `noexcept` requires the operation to be `noexcept`.
  - And `std::same_as<bool>` is equivalent to `std::same_as<decltype(x < x), bool>`; the result type will be fed as the first type parameter directly.

Requires expression

- Nested requirement: `requires BooleanExpression;`
  - This checks both whether the expression is legal and whether it’s true.

```
template<typename T>
concept MyMaxConstraint = requires(T x) {
    x < x;
    requires !std::is_pointer_v<T> && sizeof(T) >= 8;
};
```

Concept

- Note1: for any type deduction & template parameter, you can add a single constraint by abbr.:

```cpp
template<MyMaxConstraint T>
T Max(const T& a, const T& b)
{
    return a < b ? b : a;
}
```

```cpp
MyMaxConstraint auto a = A{};
```

```cpp
MyMaxConstraint decltype(auto) Test()
{
    return 1.0;
}
```

When the deduced type doesn't match the constraint, compile error.

```cpp
auto Max(const MyMaxConstraint auto& a, const MyMaxConstraint auto& b)
{
    return a < b ? b : a;
}
```

The deduced parameter will be the first parameter of the concept, same as compound requirements.

Notice that this is equivalent to
`template<MyMaxConstraint T, MyMaxConstraint U> auto Max(const T& a, const U& b)`

Concept

- You can also combine it with requires clause:
  - Equivalent to combine with &&.

```cpp
template<MyMaxConstraint T>
requires AnotherConcept<T>
T Max(const T& a, const T& b)
```

- Note2: concept can be used as boolean expression.
  - The result is whether the concept is fulfilled.

```cpp
constexpr bool m = MyMaxConstraint<A>;
```

- Note3: NTTP can also use concept:
  - It cannot use abbr.

```cpp
template<std::size_t N>
concept LessThan8 = N <= 8;

template<std::size_t N>
requires LessThan8<N>
struct MyArray { int a[N]; };
```

Concept

- Note4: concept only adds syntactic constraints, not semantic constraints.
  - E.g. "`.size()` should be $O(1)$"; this cannot be checked by compilers (halting problem).
  - Semantic constraints should be documented explicitly.
  - E.g. in the standard library, `std::invocable<F, Args…>` and `std::regular_invocable<F, Args…>`.
    - They have the same syntactic constraints, i.e. check whether `F` is callable with `Args`.
    - However, the latter has semantic constraints equality preserving; that is, it shouldn't change the status of function objects and parameters.
    - Concept cannot check whether a callable satisfies it, so they're equivalent from the compiler's view; the semantic difference is only documented.

Concept

- Sometimes, the semantic constraint is added by manual tags.
  - The most typical one is iterator categories; you cannot distinguish contiguous iterators with random iterators syntactically.
  - That is, you cannot know whether continuous memory is occupied by iterators.
- So, standard library just adds a type alias `iterator_concept` since C++20.
  - For example, for iterator of vector, `using iterator_concept = std::contiguous_iterator_tag`.
  - Before C++20, it's `iterator_category = std::random_iterator_tag`; that's not accurate so it's recommended to:
    - Use `std::iter_value_t` instead of `iterator_traits<>::value_type`.
    - Use `std::iter_reference_t` instead of `iterator_traits<>::reference`.
    - Use `std::iter_difference_t` instead of `iterator_traits<>::difference_type`.

Notice that requirements of iterators are also slightly changed in C++20, e.g. input iterators is allowed to not provide copying.

Concept

- Note5: There exist lots of concepts in the standard library.
  - As we've seen before, `std::same_as<T, U>`.
  - We're not going to talk about them in details; basically the functionality can be deduced from the name.

Credit: C++20 – The Complete Guide by *Nicolai M. Josuttis*. For more details, see Chapter 5.

You can borrow it from PKU library.

Concept	Constraint
`integral`	Integral type
`signed_integral`	Signed integral type
`unsigned_integral`	Unsigned integral type
`floating_point`	Floating-point type
`movable`	Supports move initialization/assignment and swaps
`copyable`	Supports move and copy initialization/assignment and swaps
`semiregular`	Supports default initialization, copies, moves, and swaps
`regular`	Supports default initialization, copies, moves, swaps, and equality comparisons
`same_as`	Same types
`convertible_to`	Type convertible to another type
`derived_from`	Type derived from another type
`constructible_from`	Type constructible from others types
`assignable_from`	Type assignable from another type
`swappable_with`	Type swappable with another type
`common_with`	Two types have a common type
`common_reference_with`	Two types have a common reference type
`equality_comparable`	Type supports checks for equality
`equality_comparable_with`	Can check two types for equality
`totally_ordered`	Types support a strict weak ordering
`totally_ordered_with`	Can check two types for strict weak ordering
`three_way_comparable`	Can apply all comparison operators (including the `operator <=>`)
`three_way_comparable_with`	Can compare two types with all comparison operators (including `<=>`)
`invocable`	Type is a callable for specified arguments
`regular_invocable`	Type is a callable for specified arguments (no modifications)
`predicate`	Type is a predicate (callable that returns a Boolean value)
`relation`	A callable type defines a relationship between two types
`equivalence_relation`	A callable type defines an equality relationship between two types
`strict_weak_order`	A callable type defines an ordering relationship between two types
`uniform_random_bit_generator`	A callable type can be used as a random number generator

Table 5.1. Basic concepts for types and objects

Concept	Constraint
`default_initializable`	Type is default initializable
`move_constructible`	Type supports move initializations
`copy_constructible`	Type supports copy initializations
`destructible`	Type is destructible
`swappable`	Type is swappable
`weakly_incrementable`	Type supports the increment operators
`incrementable`	Type supports equality-preserving increment operators

Table 5.2. Auxiliary concepts

Concept	Constraint
range	Type is a range
output_range	Type is a range to write to
input_range	Type is a range to read from
forward_range	Type is a range to read from multiple times
bidirectional_range	Type is a range to read forward and backward from
random_access_range	Type is a range that supports jumping around over elements
contiguous_range	Type is a range with elements in contiguous memory
sized_range	Type is a range with cheap size support
common_range	Type is a range with iterators and sentinels that have the same type
borrowed_range	Type is an lvalue or a borrowed range
view	Type is a view
viewable_range	Type is or can be converted to a view
indirectly_writable	Type can be used to write to where it refers
indirectly_readable	Type can be used to read from where it refers
indirectly_movable	Type refers to movable objects
indirectly_movable_storable	Type refers to movable objects with support for temporaries
indirectly_copyable	Type refers to copyable objects
indirectly_copyable_storable	Type refers to copyable objects with support for temporaries
indirectly_swappable	Type refers to swappable objects
indirectly_comparable	Type refers to comparable objects
input_output_iterator	Type is an iterator
output_iterator	Type is an output iterator
input_iterator	Type is (at least) an input iterator
forward_iterator	Type is (at least) a forward iterator
bidirectional_iterator	Type is (at least) a bidirectional iterator
random_access_iterator	Type is (at least) a random-access iterator
contiguous_iterator	Type is an iterator to elements in contiguous memory
sentinel_for	Type can be used as a sentinel for an iterator type
sized_sentinel_for	Type can be used as a sentinel for an iterator type with cheap computation of distances
permutable	Type is (at least) a forward iterator that can reorder elements
mergeable	Two types can be used to merge sorted elements into a third type
sortable	A type is sortable (according to a comparison and projection)
indirectly_unary_invocable	Operation can be called with the value type of an iterator
indirectly_regular_unary_invocable	Stateless operation can be called with the value type of an iterator
indirect_unary_predicate	Unary predicate can be called with the value type of an iterator
indirect_binary_predicate	Binary predicate can be called with the value types of two iterators
indirect_equivalence_relation	Predicate can be used to check two values of the passed iterator(s) for equality
indirect_strict_weak_order	Predicate can be used to order two values of the passed iterator(s)

Table 5.3. Concepts for ranges, iterators, and algorithms

Template Basics

- Concept
  - require clause and concept
  - Subsumption
  - Some exercises on concept

Concept subsumption

- We know that specialization just means “implement a different version for special cases”.
  - While concepts just describe “some special cases”.
  - So of course we can use concept to do specialization!
- For example:

```cpp
template<typename T>
class SomeClass {};
```

Is specialization of

```cpp
template<IsPointer T>
class SomeClass<T> {};
```

- But specialization has matching order; the “most specialized” one will be the selected one among all templates.
  - So if we add multiple specializations by concept, we need to know their order.
  - For example:

```cpp
template<IsPointer T>
class SomeClass<T> {};
```

More specialized than

```cpp
template<typename T>
requires IsPointer<T> && (sizeof(T) >= 8)
class SomeClass<T> {};
```

Concept subsumption

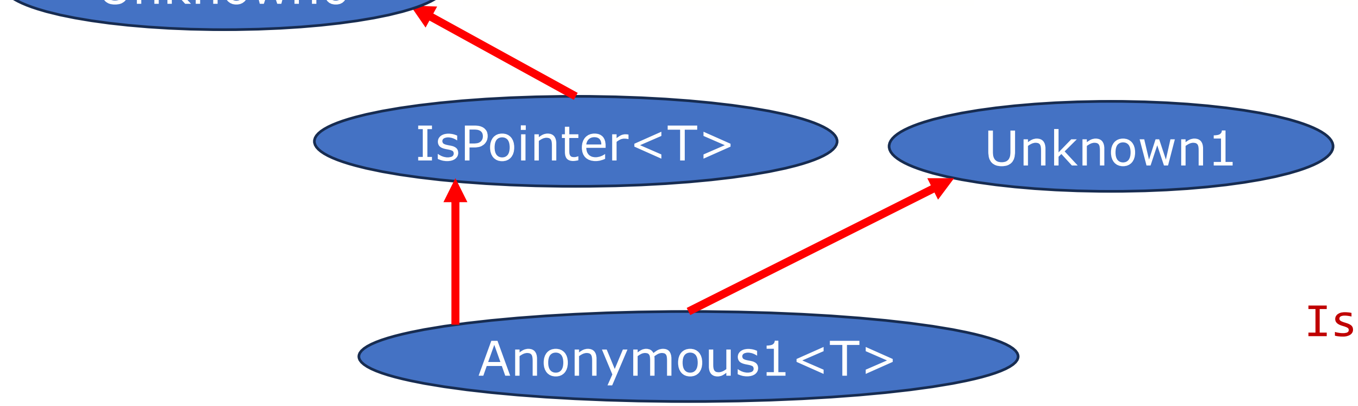
- So how is the concept order determined?
  - We can notice that concept is just logical expressions.
    - Some atomic constraints, with &&, ||, !.
  - And logical expressions can imply（蕴含）!
    - E.g. a && b → a.
  - So generally, concept A is more specialized than / subsumes concept B ⬄ logical expressions A imply expressions B.
- But, implication is not easy to deduce.
  - From mathematical logic, we know $a \rightarrow b$ can be transformed as a ^ $\neg b$.
  - Assuming that for any type T, $a_i(T), b_j(T)$ may be true or false freely, then it will be SAT problem to judge whether it could be satisfied. That's NP-complete!

Concept subsumption

- So to solve that, compilers don’t do full logical judgement; instead, it only considers equivalence by concept name.
  - Non-concepts (including `!Concept`) will be always considered not related.
  - So we could build a concept subsumption graph;
  - And A subsumes B ⇔ graph B is subgraph of graph A.
- For example:

```cpp
template<IsPointer T>
class SomeClass<T> {};
```

```cpp
template<typename T>
requires IsPointer<T> && (sizeof(T) >= 8)
class SomeClass<T> {};
```



Not a concept, so always unrelated.

`IsPointer` is subgraph of the latter.

Concept subsumption

- What if:

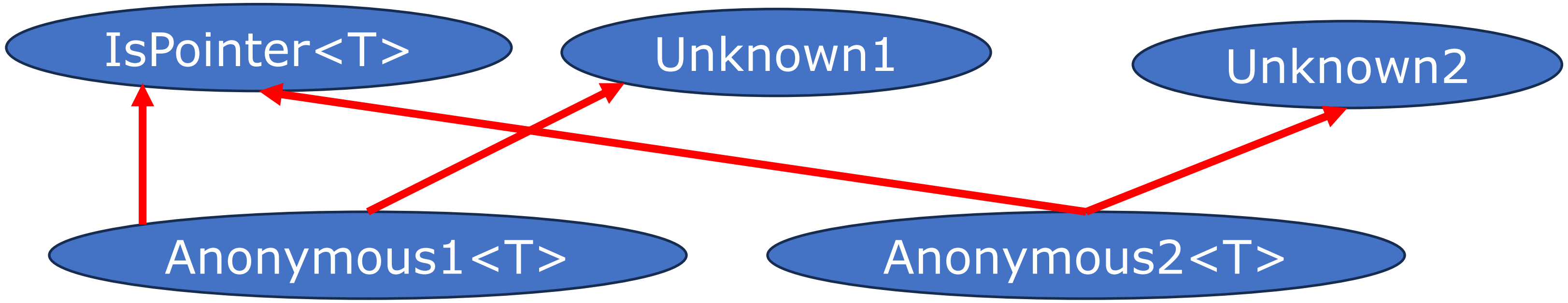
```
template<typename T>
requires IsPointer<T> && (sizeof(T) >= 8)
class SomeClass<T> {};

template<typename T>
requires IsPointer<T> && (sizeof(T) >= 4)
class SomeClass<T> {};
```

```
error: ambiguous template instantiation for 'class
SomeClass<int*>' x86-64 gcc 14.2 #1
```

- We can deduce the first one is more specialized than the second one, but compilers don't know.
- Graph:

Unknown1 and Unknown2 are always seen as unrelated, so they don't subsume.



Concept subsumption

- Part of subsumption graph of concepts in the standard library:

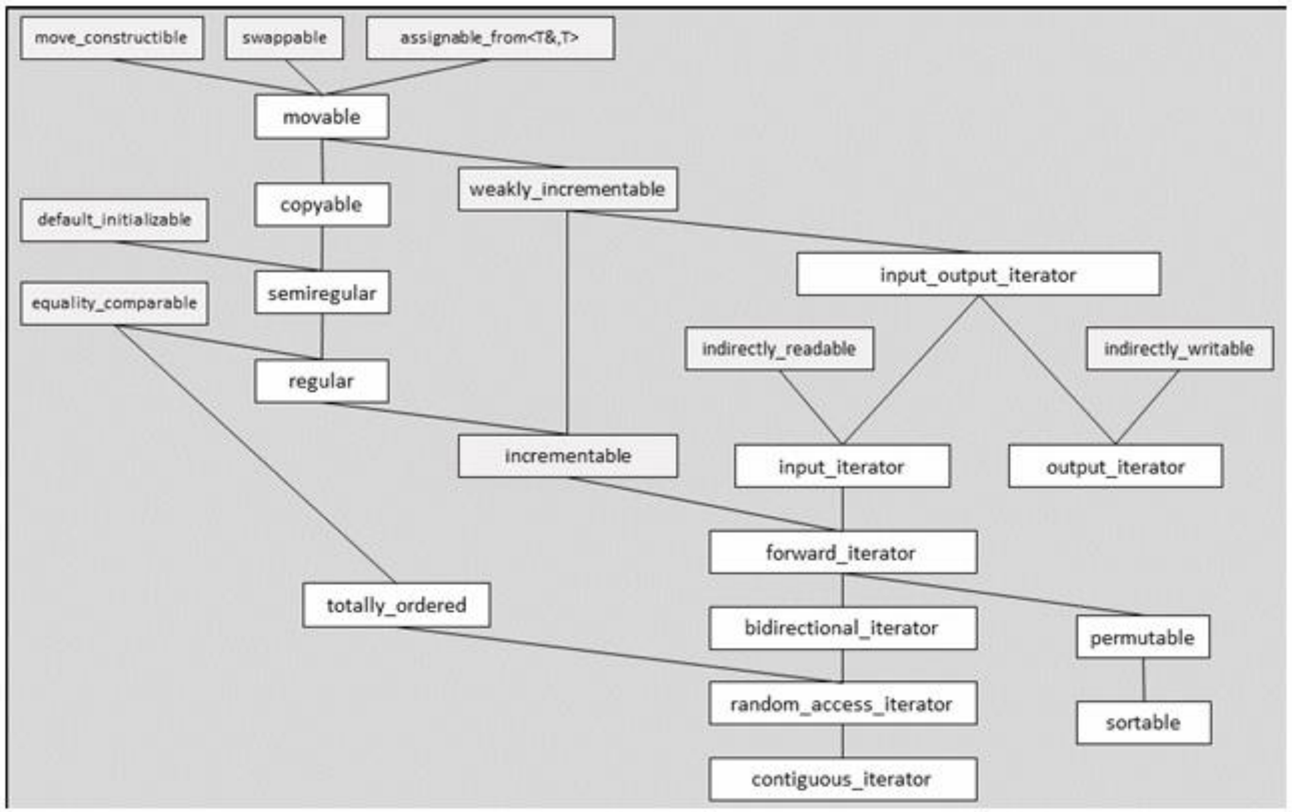


Figure 5.1. Subsumption graph of C++ standard concepts (extract)

Credit: C++20 – The Complete Guide by *Nicolai M. Josuttis*.

Concept subsumption

- Exercise: implement communicative concept `SameAs` by type traits `std::is_same_v`.
  - Is it correct to use:

```
template<typename T, typename U>
concept SameAs = std::is_same_v<T, U>;
```

  - No, since it's not communicative, `SameAs<T, U>` isn't considered equivalent as `SameAs<U, T>`.
  - Now is it correct?

```
template<typename T, typename U>
concept SameAs = std::is_same_v<T, U> && std::is_same_v<U, T>;
```

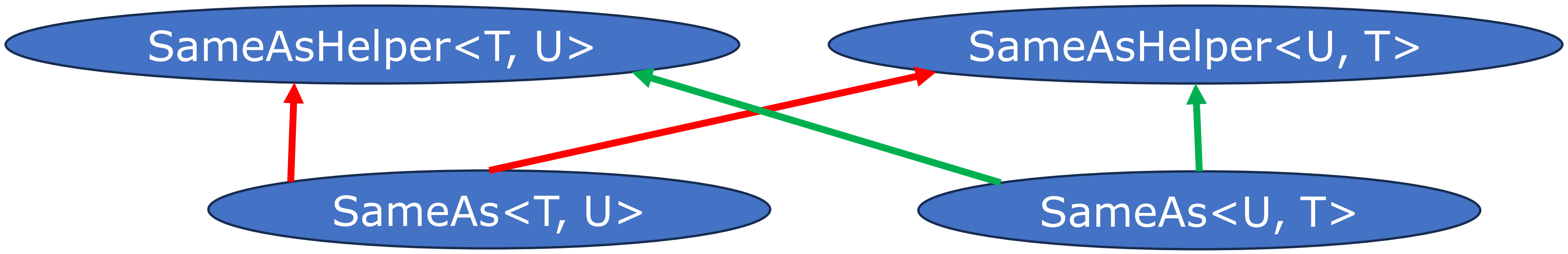
  - No, since non-concepts will always be considered unrelated; the atomic constraint is just `SameAs<T, U>` and `SameAs<U, T>`, which is considered not equivalent.
  - Solution:

```
template<typename T, typename U>
concept SameAsHelper = std::is_same_v<T, U>;

template<typename T, typename U>
concept SameAs = SameAsHelper<T, U> && SameAsHelper<U, T>;
```

Concept subsumption

- Now, the atomic constraint is `SameAsHelper`, so the graph is like:



- So `SameAs<T, U>` and `Same<U, T>` have the same graph, and they're considered equivalent!

Concept subsumption

- Concept also matters in overloading resolution ("more specialized").
  - When a concept subsumes another, then it's preferred in resolution.
- For example:

```cpp
template<typename T>
T Max(const T& a, const T& b) { return a < b ? b : a; }

template<IsPointer T>
auto Max(const T& a, const T& b) { return *a < *b ? *b : *a; }

int main()
{
    int a = 1;
    Max(&a, &a);
}
```

“More specialized”

- Notice that the second one cannot be changed as `Max(T a, T b)` since it breaks “more specialized”. If you want it, you need:

```
template<typename T>
requires (!IsPointer<T>)
T Max(const T& a, const T& b) { return a < b ? b : a; }
```

```
template<typename T>
requires IsPointer<T>
T Max(T a, T b) { }
```

- Reason: when both of two candidates are not more specialized than the other with rules before, more rules kick in:
  - If their template parameters or function parameters differ in length, ambiguous;
  - Otherwise, if template parameters are not equivalent or function parameters are not of same type, ambiguous;
  - Otherwise, if one template is more constrained (determined by concept subsumption) than the other, it’s regarded as more specialized.

Notice that the actual rules are slightly more complex since some function call can be reordered (e.g. `a == b` can be rewritten as `b == a` to make it compile since C++20), don’t cover it here.

"More specialized"

- Now you can explain why we need additional constraint before!
- We know that
```cpp
template<typename T>
T Max(const T& a, const T& b)
```
and
```cpp
template<typename T>
T Max(T a, T b);
```
are not more specialized than the other when calling…
  - So they're first checked by parameter length, which is same.
  - Then their parameter forms are checked; though template parameters are equivalent, but functions parameter are not, so ambiguous.
  - Concepts aren't checked yet, so `IsPointer<T>` doesn't help to make the function "more specialized".

Template Basics

- Concept
  - require clause and concept
  - Subsumption
  - Some exercises on concept

Concept

- By concepts, we could do more interesting things.
  - E.g. more special compile-time computation; more type traits.
- Exercise1: implement `std::is_nothrow_move_constructible` and `std::is_nothrow_move_assignable` by concept.

```cpp
template<typename T>
concept NoexceptMoveConstructible = requires(T x) {
    { T{ std::move(x) } } noexcept;
};

template<typename T>
concept NoexceptMoveAssignible = requires(T x) {
    { x = std::move(x) } noexcept;
};
```

Concept

- Exercise2: utilize concept & class specialization to write `IsPrime`.
  - Consider: Isn't it enough to implement it like this? Where is concept and specialization?

```
template<unsigned int N, unsigned int M>
struct DoIsPrime
{
    static constexpr inline bool value = M == 1 ? true : (N % M != 0 && DoIsPrime<N, M-1>::value);
};

template<unsigned int N>
struct IsPrime
{
    static constexpr inline bool value = N <= 1 ? false : DoIsPrime<N, N / 2>::value;
};
```

Concept

- Let's try it: `bool p = IsPrime<4>::value;`

```
<source>:4:92: fatal error: template instantiation depth exceeds maximum of 900 (use '-ftemplate-depth=' to increase the maximum)
    4 |     static constexpr inline bool value = M == 1 ? true : (N % M != 0 && DoIsPrime<N, M-1>::value);
      |                                                                                              ^~~~~
```

- Reason: expressions need to be checked whether it's valid.
    - `IsPrime<4>` → `DoIsPrime<4,2>` → `DoIsPrime<4,1>`
    - It should stop now, but there is no short circuit for expression validity check, so it will continue to instantiate…
        - `DoIsPrime<4,1>` → `DoIsPrime<4,0>` → `DoIsPrime<4,(unsigned)-1>` → …
- So the recursion never stops.

- To make it stop early, we need specialization; only the most specialized one will be instantiated.

Concept

- Solution:

IsPrime<4> → DoIsPrime<4,2> → DoIsPrime<4,1>

And then only the most specialized one is instantiated, so only the second one is used. No infinite recursion!

```
template<unsigned int N, unsigned int M>
struct DoIsPrime
{
    static constexpr inline bool value = N % M != 0 && DoIsPrime<N, M-1>::value;
};

template<unsigned int N, unsigned int M>
requires (M == 1)
struct DoIsPrime<N, M>
{
    static constexpr inline bool value = true;
};

template<unsigned int N>
struct IsPrime
{
    static constexpr inline bool value = DoIsPrime<N, N / 2>::value;
};

template<unsigned int N>
requires (N <= 1)
struct IsPrime<N>
{
    static constexpr inline bool value = false;
};
```