TMP: template meta-programming (I)

Deep dive into C++

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杜浦數位安全
Persistent Cyber Threat Hunters

Outline

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Template 101 and type deduction

Perfect forwarding and reference collapsing

Variadic template and parameter pack

SFINAE

CTAD

Expression template

Concepts and constraints

CRTP and compile time polymorphism

Template 101 & type deduction

Generic type?

```
int square(int num) {
    return num * num;
}
```

```
template<typename T>
T square(T num) {
    return num * num;
}
```

_Generic (C11)

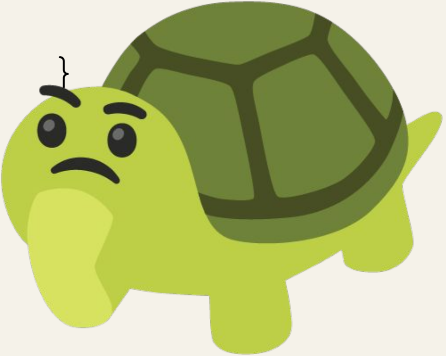
```c
// Specific square functions for different types
int square_int(int num) {
    return num * num;
}
double square_double(double num) {
    return num * num;
}
```

```c
#define square(X) _Generic((X), \
    int: square_int,           \
    double: square_double,     \
    default: square_int        \
)(X)
```

_Generic (C11)

```
// Spe                                    ifferent types
int s
    re
}
double sq      _double(double num) {
    return num * num;
}
```

```
#define square(X) _Generic((X), \
    int: square_int,            \
    double: square_double,      \
    default: square_int         \
)(X)
```



1. Hand-write name mangling
2. Lots of types
3. C89 you should write the specific version

Template 101

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

Template 101

```
template<parameter-list >
```

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template<typename T>
T max(T a, T b) {
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Template 101

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Type

Non-type

Template

Template 101

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template<parameter-list >
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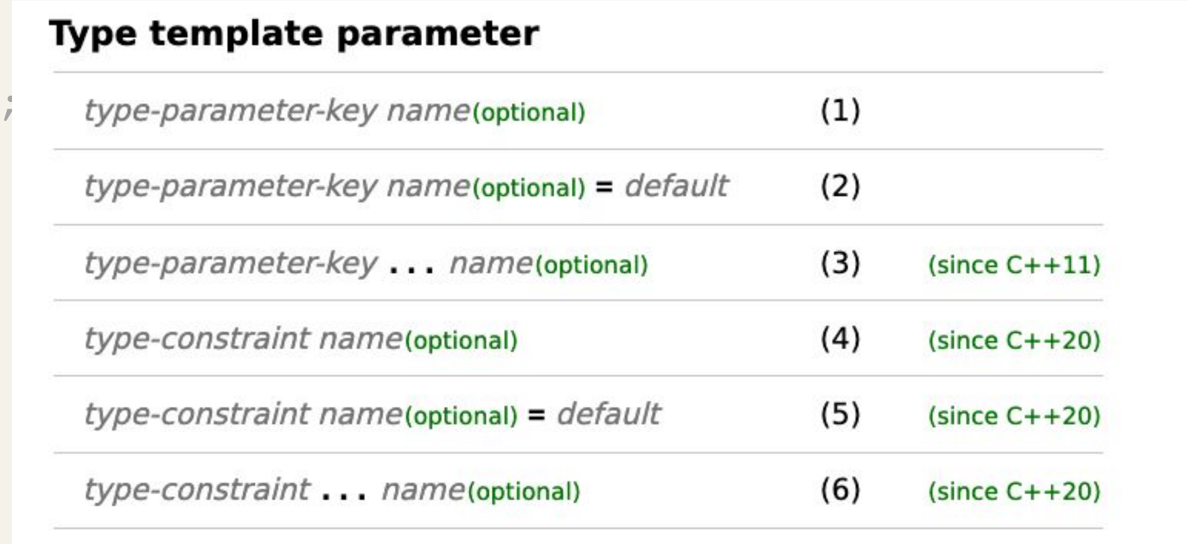

Type template parameter

type-parameter-key name(optional)	(1)	
type-parameter-key name(optional) = *default*	(2)	
type-parameter-key ... *name*(optional)	(3)	(since C++11)
type-constraint name(optional)	(4)	(since C++20)
type-constraint name(optional) = *default*	(5)	(since C++20)
type-constraint ... *name*(optional)	(6)	(since C++20)

Template 101

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template<parameter-list >
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Non-type

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    return a > b ? a : b;
}
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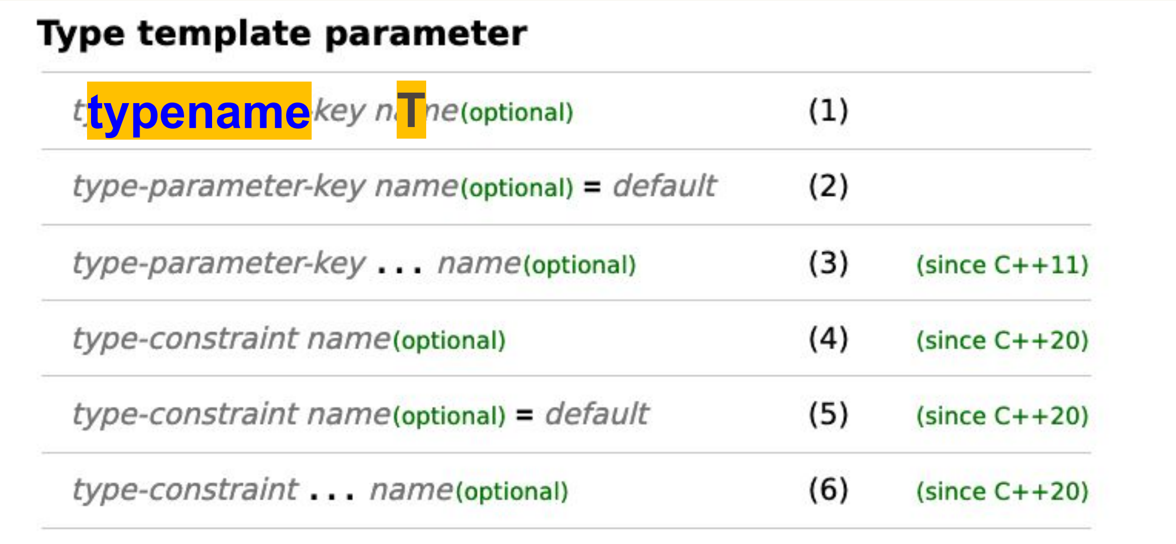

Type template parameter

t**typename**key n**T**ne(optional)	(1)	
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Template

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T max(T a, T b) {
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Non-type

Template

```
T max(T a, T b) {
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}
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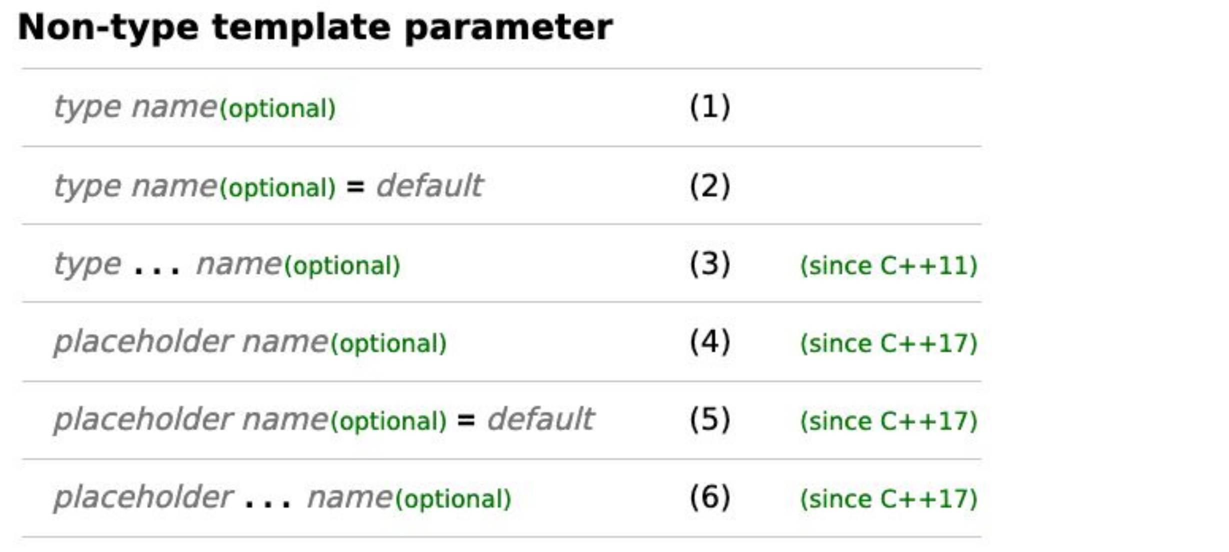


Non-type template parameter

type name(optional)	(1)	
type name(optional) = *default*	(2)	
type ... *name*(optional)	(3)	(since C++11)
placeholder name(optional)	(4)	(since C++17)
placeholder name(optional) = *default*	(5)	(since C++17)
placeholder ... *name*(optional)	(6)	(since C++17)

Template 101

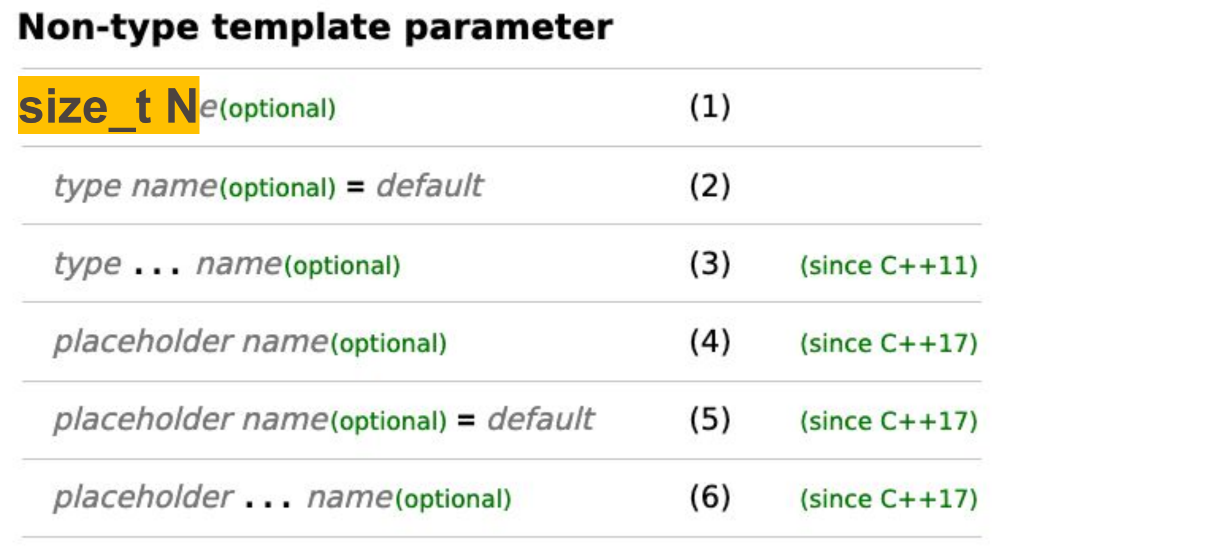
```
template<parameter-list >
```

Type

Non-type

Template

```
T max(T a, T b) {
    return a > b ? a :
}
```



Non-type template parameter

size_t Ne(optional)	(1)	
type name(optional) = *default*	(2)	
type ... *name*(optional)	(3)	(since C++11)
placeholder name(optional)	(4)	(since C++17)
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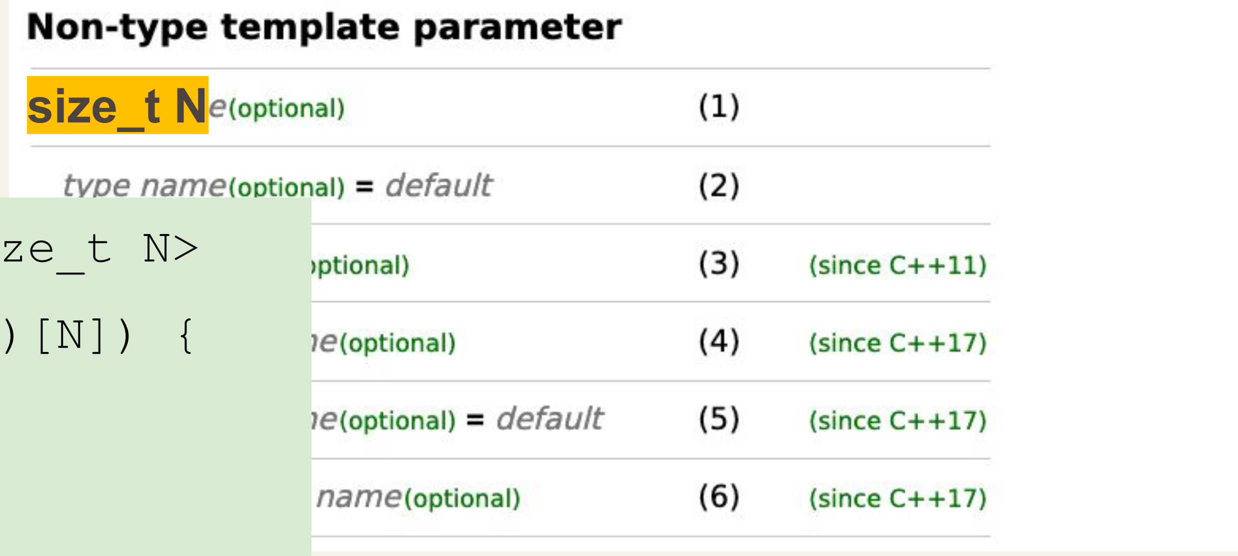
Template 101

```
template<parameter-list >
```

Type | Non-type | Template

```
T max(T a, T b) {
    return a > b ? a :
```



Non-type template parameter

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type name(optional) = default	(2)	
ptional)	(3)	(since C++11)
ne(optional)	(4)	(since C++17)
ne(optional) = default	(5)	(since C++17)
name(optional)	(6)	(since C++17)

```
template<typename T, size_t N>
size_t strlen(const T(&)[N]) {
    return N - 1;
}
```

Template 101

```
template<parameter-list >
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Type

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Template

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T max(T a, T b) {
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Template 101

template<parameter-list >

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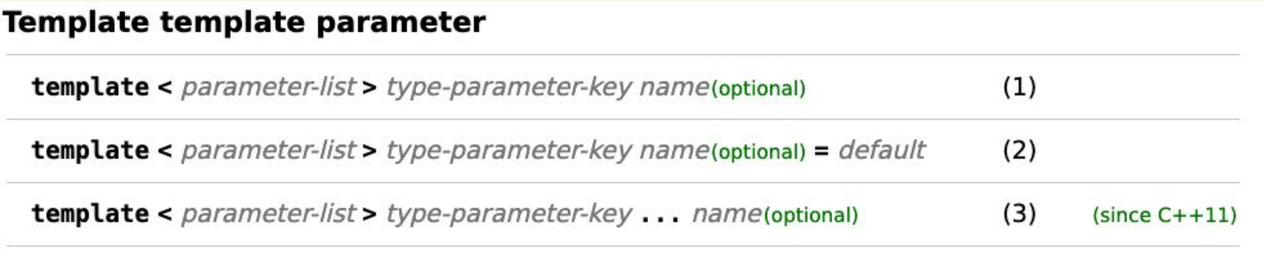


Template template parameter

template < *parameter-list* > *type-parameter-key name*(optional)	(1)	
template < *parameter-list* > *type-parameter-key name*(optional) = *default*	(2)	
template < *parameter-list* > *type-parameter-key* **...** *name*(optional)	(3)	(since C++11)

Template 101

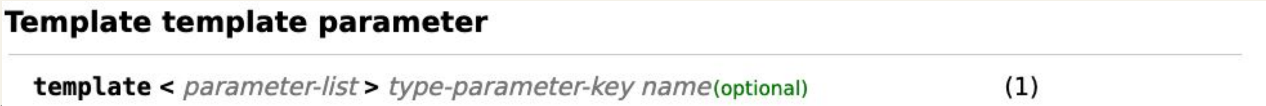
template<parameter-list >

Type

Non-type

Template

```
T max(T a, T b) {
    return a > b ? a
```



Template template parameter

template < *parameter-list* **>** *type-parameter-key name*(optional) (1)

```
template<typename T, template<typename> typename Container>
void print(Container<T> v) {
    for (const auto& item : v)
        std::cout << item << " ";
}
```

Template specialization

```
std::vector<bool>
```

```
template<typename T>
class Vector {
    std::vector<T> data;

public:
    void push_back(const T& v) { data.push_back(v); }
    void push_back(T&& v) { data.push_back(std::forward<T>(v)); }
    const T& at(size_t pos) const { return data[pos]; }
    T& at(size_t pos) { return data[pos]; }
    size_t size() const { return data.size(); }
};
```

https://godbolt.org/z/649aYfTvz

```
template<>
class Vector<bool> {
    using T = bool;
    std::vector<char> data;

public:
    void push_back(const T& v) { data.push_back(v); }
    void push_back(T&& v) { data.push_back(std::forward<T>(v)); }
    bool at(size_t pos) const { return data[pos]; }
    size_t size() const { return data.size(); }
};
```

https://godbolt.org/z/649aYfTvz

Type deductions

Fundamental types

graphiz

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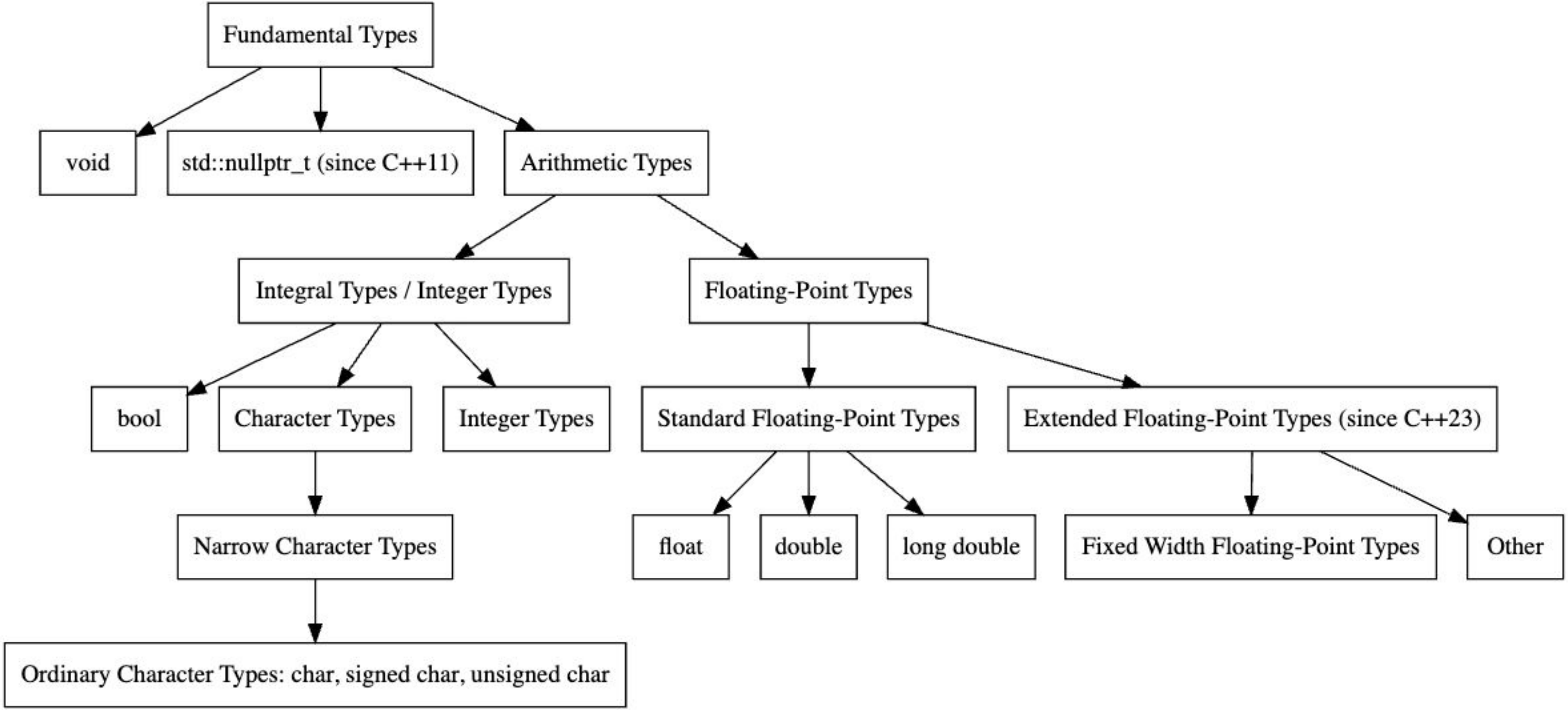
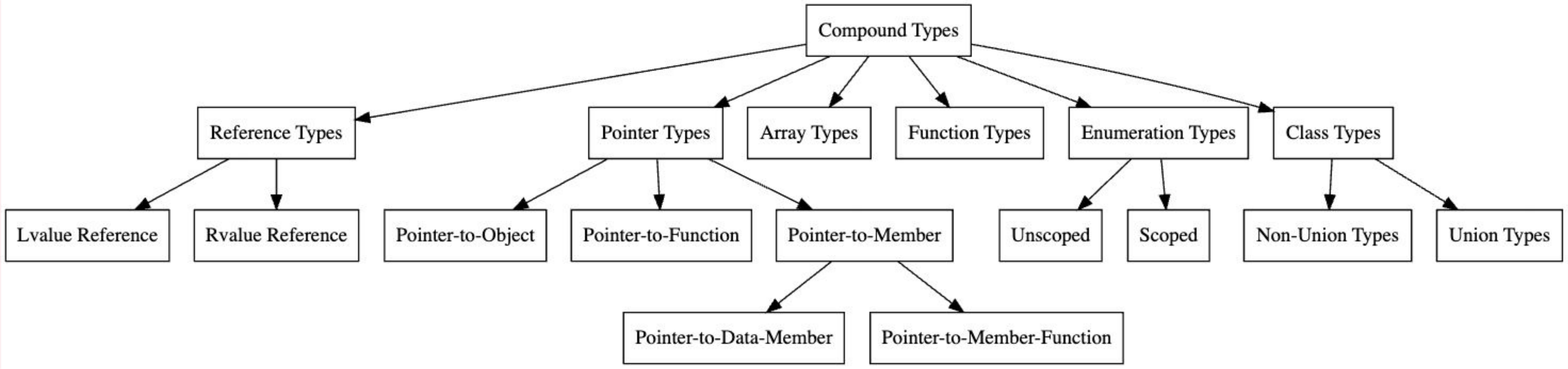

Fundamental Types
void
std::nullptr_t (since C++11)
Arithmetic Types
Integral Types / Integer Types
Floating-Point Types
bool
Character Types
Integer Types
Standard Floating-Point Types
Extended Floating-Point Types (since C++23)
Narrow Character Types
float
double
long double
Fixed Width Floating-Point Types
Other
Ordinary Character Types: char, signed char, unsigned char

Compound types



graphiz

頭腦體操

```
print_type<decltype(1 + 1ull)>();       // unsigned long long
print_type<decltype(1. + 1)>();         // double
print_type<decltype(+ -+-+-+ +true)>(); // int
print_type<decltype([]{})>();           // lambda type
print_type<decltype("dummy")>();        // const char (&) [6]
print_type<decltype(struct {})>();      // (anonymous struct)
print_type<void (*)()>();               // void (*)()
print_type<decltype(nullptr)>();        // std::nullptr_t
print_type<decltype(3.14f * 'a')>();    // float
print_type<decltype(0b1010 + 0xFF)>();  // int
print_type<decltype(~~~0u)>();          // unsigned int
print_type<decltype("C++Expert"[3])>(); // const char &
```

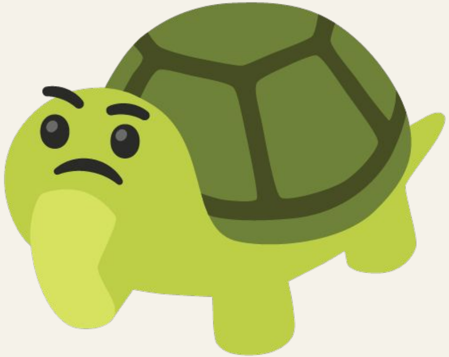
https://godbolt.org/z/Tazrnfzd7

So, it’s easy

```
template<typename T>
void print_type(){
    auto me = std::string(__PRETTY_FUNCTION__);
    // ...
}
```

So, it’s easy

```
void print_type(auto v){
    auto me = std::string(__PRETTY_FUNCTION__);
    // ...
}
```

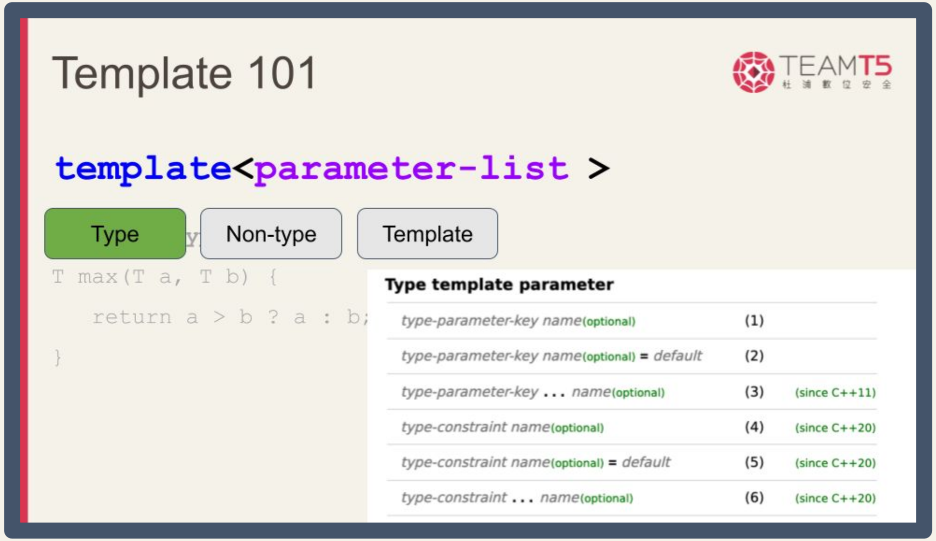


C++20
syntactic sugar

Deducting type from Args

```
template<typename Para>
void f(Para param);


f(expr);
```



Template 101

```
template<parameter-list >
```

```
T max(T a, T b) {
   return a > b ? a : b;
}
```

Type template parameter

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void f(Para param);


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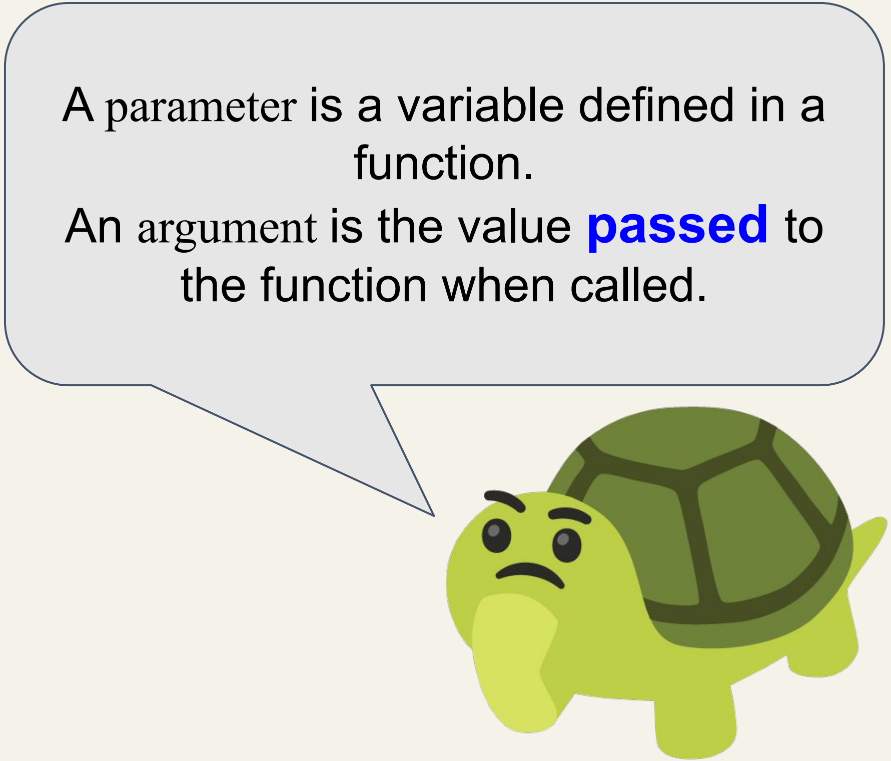


A parameter is a variable defined in a function.

An argument is the value **passed** to the function when called.

Deducting type from Args

```
template<typename Para>
void f(Para param);


f(expr);
```

A parameter is a variable defined in a function.

An argument is the value **passed** to the function when called.

Deducing Args type and making Para being defined.

Deducting type from Args

```
template<typename Para>
void f(Para param);


f(expr);
```

A parameter is a variable defined in a function.

An argument is the value **passed** to the function when called.

Deducing Args type and making Para being defined.

Template
Argument
Deduction

template type

```
template<typename Para>
void f(Para param);


f(expr);
```

Regular

Reference

Universal/Forwarding reference

template type

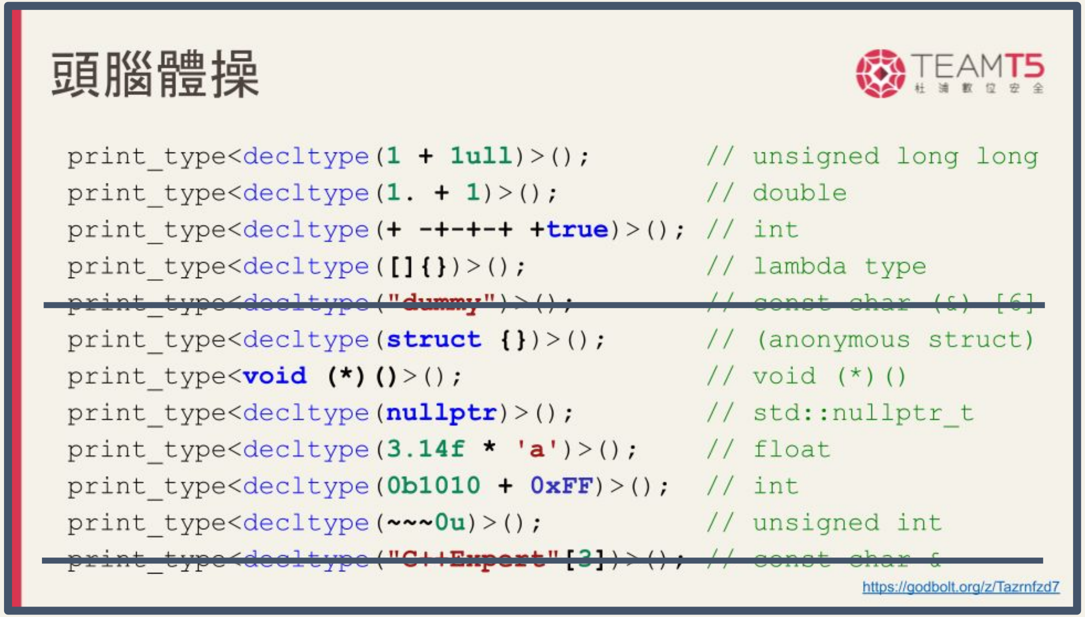
- Regular
- Reference
- Universal/Forwarding reference

template type

Regular

Reference

Universal/Forwarding reference



頭腦體操

```
print_type<decltype(1 + 1ull)>();         // unsigned long long
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print_type<decltype([]{})>();             // lambda type
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print_type<decltype(struct {})>();        // (anonymous struct)
print_type<void (*)()>();                 // void (*)()
print_type<decltype(nullptr)>();          // std::nullptr_t
print_type<decltype(3.14f * 'a')>();      // float
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print_type<decltype(~~~0u)>();            // unsigned int
~~print_type<decltype("C++Expert"[3])>(); // const char &~~
```

https://godbolt.org/z/Tazrnfzd7

Regular

Ignore the cv-qualifier and any references. Copy it anyway.

```
template<typename T>

void f(T param);



int x = 27;
const int cx = x;
const int& rx = x;

f(x);  // T's and param's types are both int
f(cx); // T's and param's types are again both int
f(rx); // T's and param's types are still both int
```

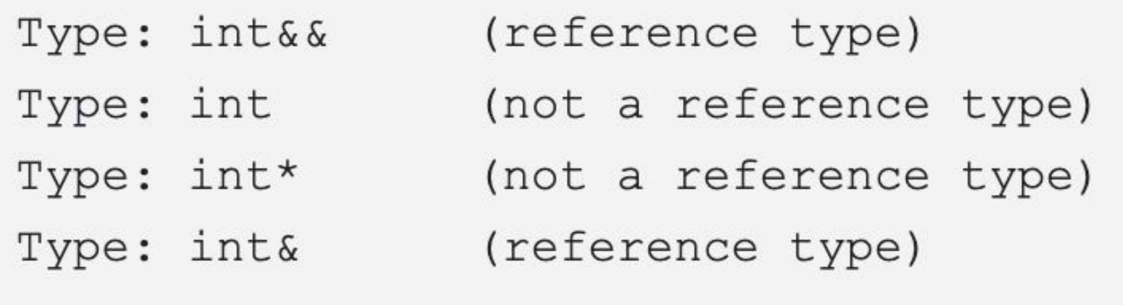
template type

Regular

Reference

Universal/Forwarding reference

```
int main() {
  print_type<decltype(std::move(1))>();
  print_type<decltype(1)>();

  int a = 42;
  print_type<decltype(&a)>();
  print_type<int&>();
//print_type<std::unwrap_reference_t<
              decltype(std::ref(a))>>();
}
```



```
Type: int&&        (reference type)
Type: int          (not a reference type)
Type: int*         (not a reference type)
Type: int&         (reference type)
```

https://godbolt.org/z/vYE7YKWxK

Reference

ParamType is a Reference or Pointer, but not a Universal Reference

1. If ***expr***'s type is a reference, **ignore** the reference part.
2. Then pattern-match ***expr***'s type against ***ParamType*** to determine T.

```
template<typename T>
void f(T& param);


int x = 27;
const int cx = x;
const int& rx = x;
```

Reference

ParamType is a Reference or Pointer, but not a Universal Reference

1. If ***expr***'s type is a reference, **ignore** the reference part.
2. Then pattern-match ***expr***'s type against ***ParamType*** to determine T.

```
template<typename T>

void f(T& param);

int x = 27;

const int cx = x;

const int& rx = x;
```

```
f(x);   // T is int, param's type is int&
f(cx); // T is const int, param's type is const int&
f(rx); // T is const int, param's type is const int&
```

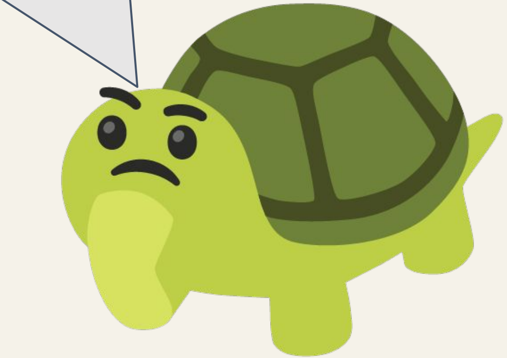
template type

Regular

Reference

Universal/Forwarding reference

We discuss it later. It’s a key point that C++ can be faster than C.



頭腦體操

```
template<typename T>
void F(T param) {}
```

```
int x = 27;
const int cx = x;
const int& rx = x;

F(x);  // T and param's type is int
F(cx); // T and param's type is int (const is ignored)
F(rx); // T and param's type is int (const and ref are ignored)
F(27); // T and param's type is int (rvalue)
```

https://godbolt.org/z/xevoc4ch4

頭腦體操

```
template<typename T>
void F(T param) {}
```

```
const char* const ptr = "Fun with templates";
// T and param's type are const char* (const from pointer itself is ignored)
F(ptr);
// Both T and param's type are const char* (array decays to pointer)
F("temporary string");
```

https://godbolt.org/z/xevoc4ch4

auto type deduction

- Almost the same as template-type deduction
- auto keyword, no longer be a storage specifier, type specifier instead
- auto&& is a universal reference (forwarding reference)

https://www.stroustrup.com/C++11FAQ.html#auto

auto type deduction

```
template<class T>
void printall(const vector<T>& v) {
    for (typename vector<T>::const_iterator p = v.begin(); p!=v.end(); ++p )
        cout << *p << "\n";
}


template<class T>
void printall(const vector<T>& v) {
    for (auto p = v.begin(); p!=v.end(); ++p)
        cout << *p << "\n";
}
```

auto type deduction

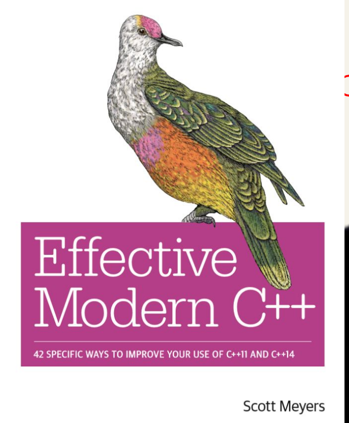
```
#include <initializer_list>
template<typename T>
void foo(T v) {}

int main() {
    auto v = {1, 2, 4}; // OK.
    foo({1, 2, 4});      // template could not deduce the T
}
```

https://godbolt.org/z/h8W5Weha7

auto type deduction

I wonder this myself. Alas, I have not been able to find a convincing explanation. But the rule is the rule…

```
#include <initializer_list>
template<typename T>
void foo(T v) {}

int main() {
    auto v = {1, 2, 4}; // OK.
    foo({1, 2, 4});     // template cou            ce
}
```



https://godbolt.org/z/h8W5Weha7

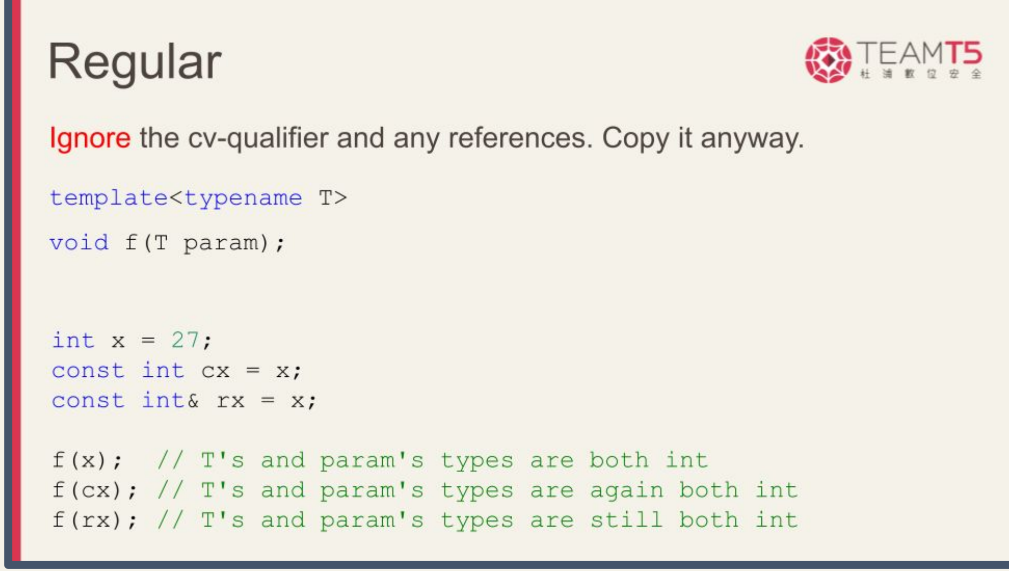
auto type deduction C++14

```
auto foo() { // 14
   return 42;
}

auto foo() -> int { // 11
   return 42;
}
```

decltype(auto)

```
int arr[10];

auto foo() {
    return arr[3]; // return int type
}
```

decltype(auto)



Regular

Ignore the cv-qualifier and any references. Copy it anyway.

```
template<typename T>
void f(T param);


int x = 27;
const int cx = x;
const int& rx = x;

f(x);  // T's and param's types are both int
f(cx); // T's and param's types are again both int
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```

```
int arr[10];

auto foo() {
   return arr[3]; // return int type
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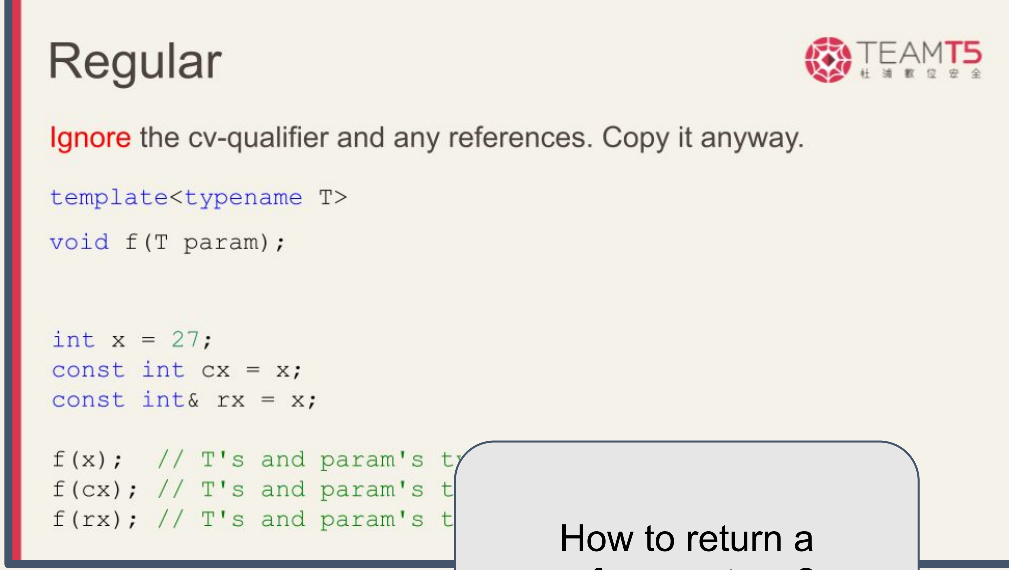
decltype(auto)



Regular

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const int cx = x;
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f(x);  // T's and param's ty
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f(rx); // T's and param's t
```

```
int arr[10];

auto foo() {
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}
```
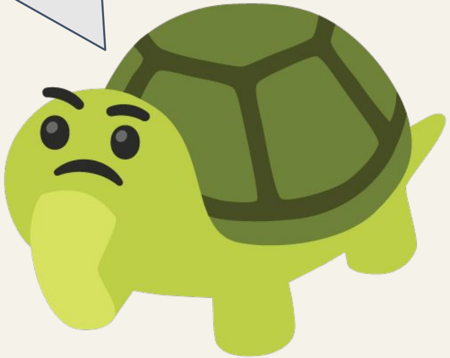

How to return a reference type?



decltype(auto)

```
int arr[10];

auto foo() -> decltype(auto) {
    return arr[3]; // return int type
}
```

decltype(auto)

```
int arr[10];

auto foo() -> decltype(arr[3]) {
    return arr[3]; // return int type
}
```

decltype(auto)

int &

```
int arr[10];

auto foo() -> decltype(arr[3]) {
    return arr[3]; // return int type
}
```

Take away

Template Argument Deduction

- Deducing parameter type from argument
- CV-qualifiers are in the type system

Auto type deduction is similar to TAD, but not initialized_list

- Be careful on curly braces {} initialization

decltype(auto)

- Deduce type from the return expression

Thank you!

scc@teamt5.org

TEAMT5

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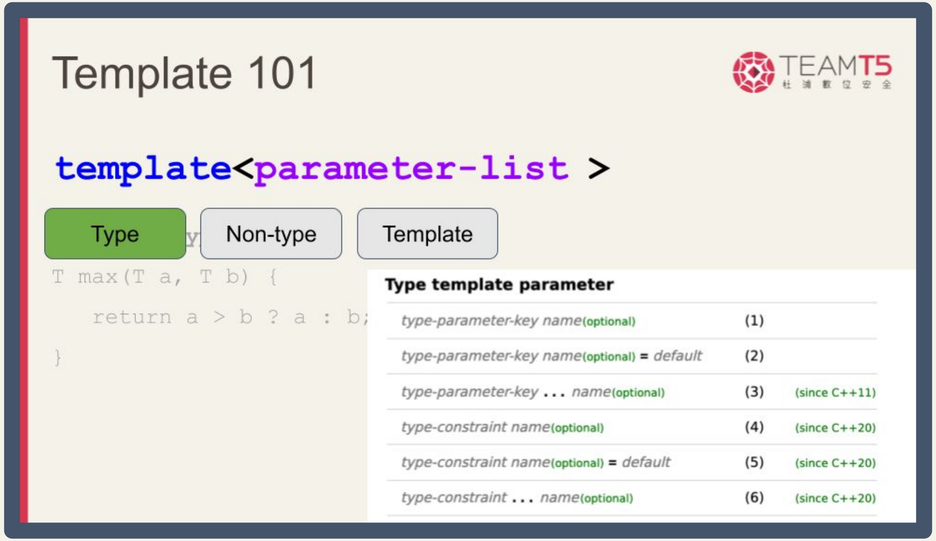
Deducting type from Params

```
template<typename ParamType>

void f(ParamType param);


f(expr);
```



Template 101

```
template<parameter-list >
```

```
T max(T a, T b) {
   return a > b ? a : b;
}
```

Type template parameter

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type-parameter-key name(optional) = *default*	(2)	
type-parameter-key ... *name*(optional)	(3)	(since C++11)
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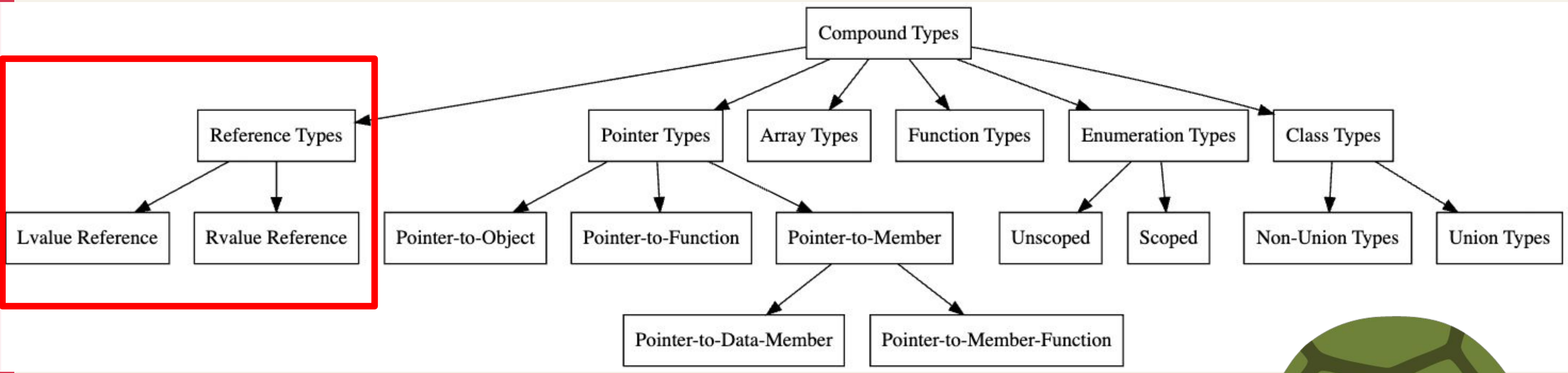
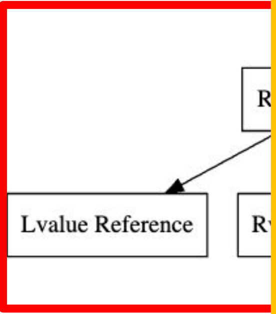
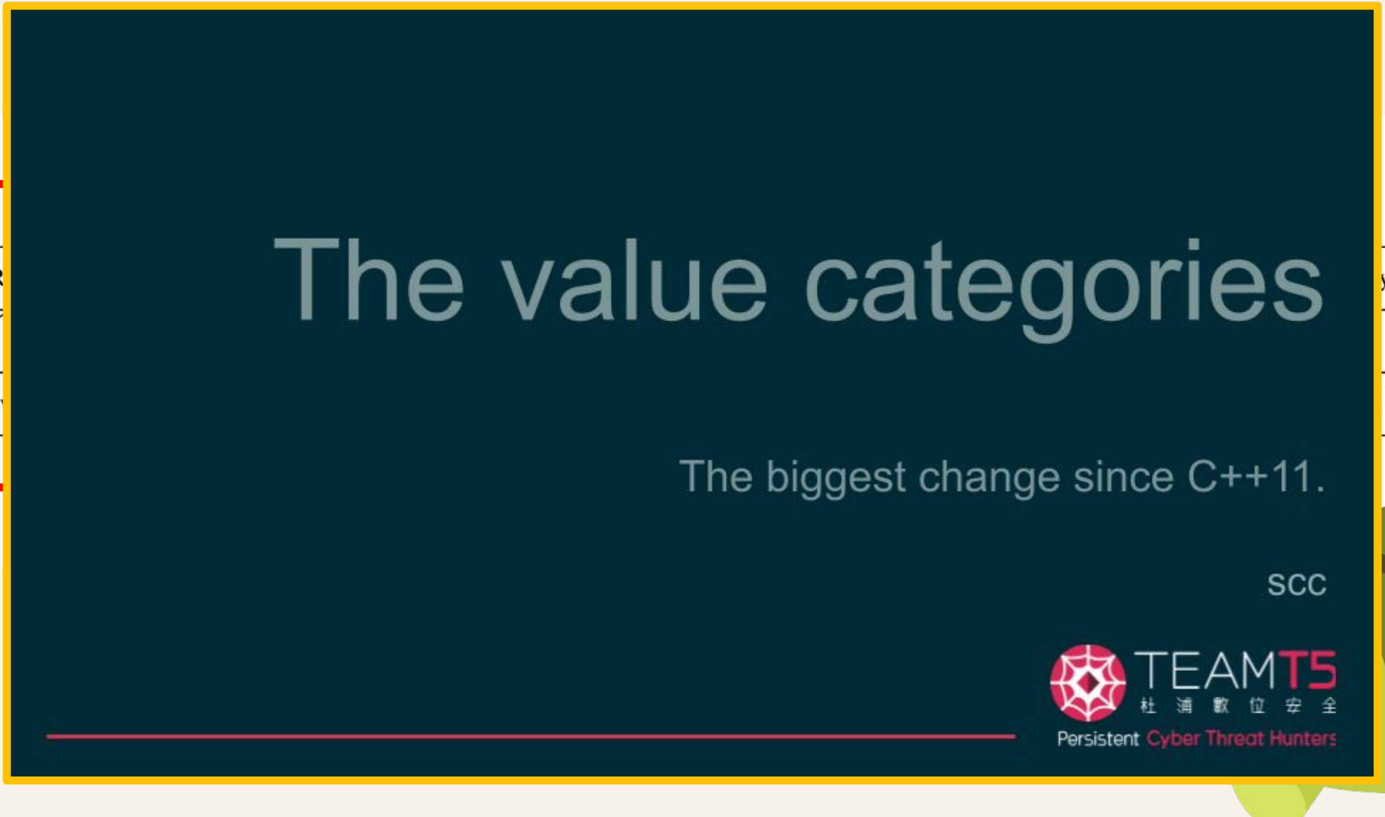
type-constraint ... *name*(optional)	(6)	(since C++20)

Reference type



Reference type





The value categories

The biggest change since C++11.

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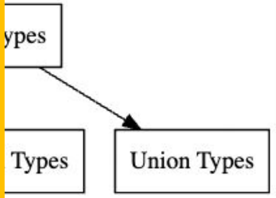
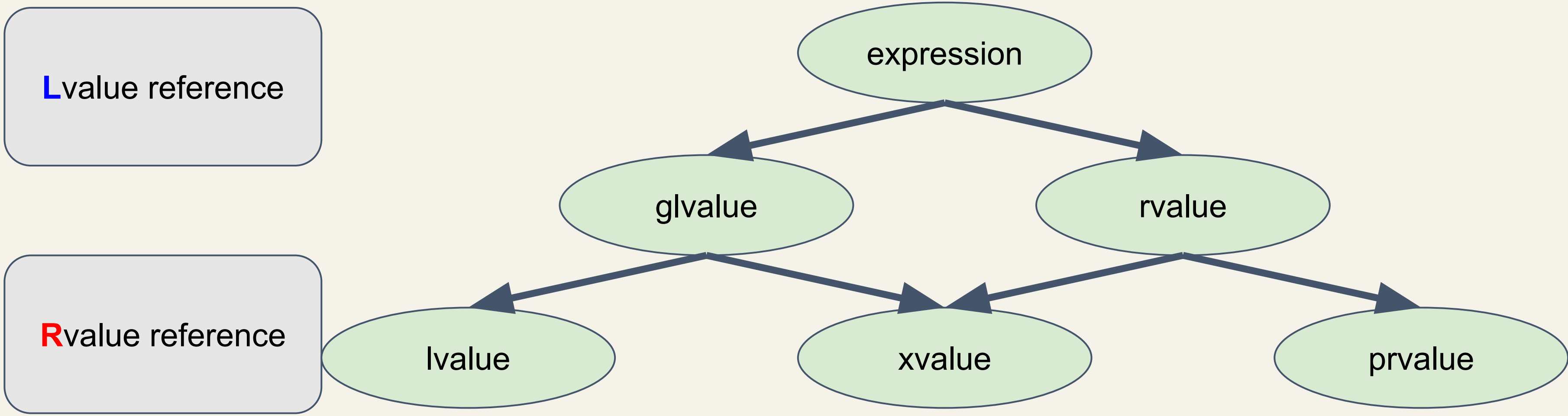


Reference

Declares a named variable as a reference, that is, an alias to an already-existing object or function.

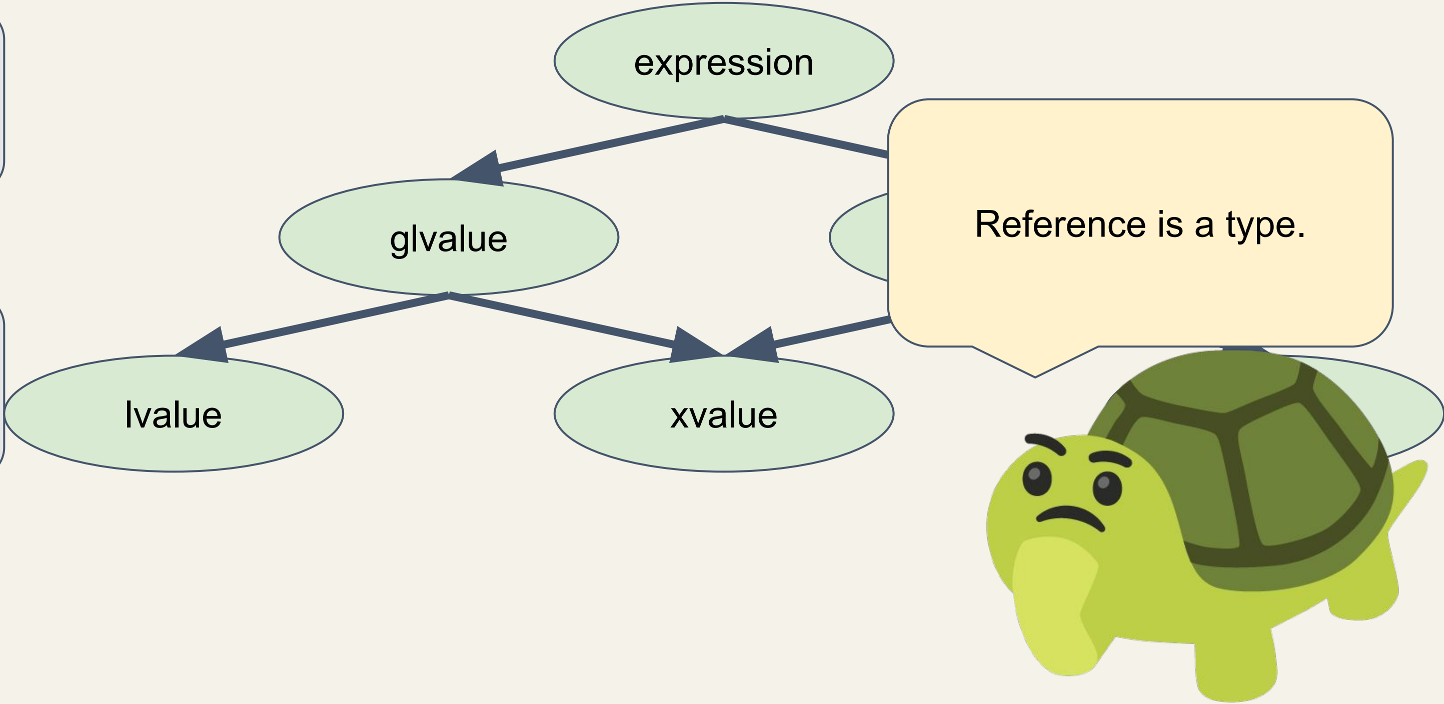


Reference

Declares a named variable as a reference, that is, an alias to an already-existing object or function.

Lvalue reference

Rvalue reference



Rules in templates

An *id-expression* naming a non-type *template-parameter* of class type T denotes a static storage duration object of type const T, known as a *template parameter object*, which is template-argument-equivalent ([temp.type]) to the corresponding template argument after it has been converted to the type of the *template-parameter* ([temp.arg.nontype]). No two template parameter objects are template-argument-equivalent.

[*Note 3*: If an *id-expression* names a non-type non-reference *template-parameter*, then it is a prvalue if it has non-class type. Otherwise, if it is of class type T, it is an lvalue and has type const T ([expr.prim.id.unqual]). — *end note*]

頭腦體操！

```
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;
    &x;

    &i;
    &a;
    int& ri = i;
    const int& cri = i;
    const A& ra = a;
}
```

頭腦體操！

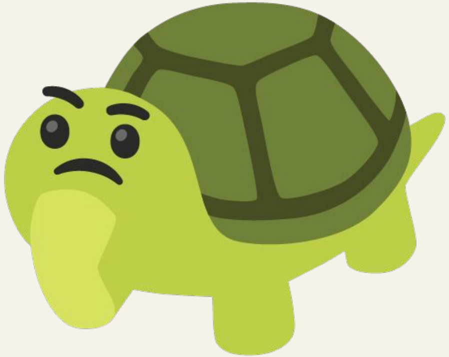
```
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;
    &x;

    &i;
    &a;
    int& ri = i;
    const int& cri = i;
    const A& ra = a;
}
```

頭腦體操！

```
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++; // error: change of template-parameter value
    &x;

    &i;
    &a;
    int& ri = i;
    const int& cri = i;
    const A& ra = a;
}
```

頭腦體操！

```
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;

    &x;

    &i;
    &a;
    int& ri = i;
    const int& cri = i;
    const A& ra = a;
}
```



頭腦體操！

```
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;

    &x; // OK


    &i;
    &a;
    int& ri = i;
    const int& cri = i;
    const A& ra = a;
}
```

頭腦體操！

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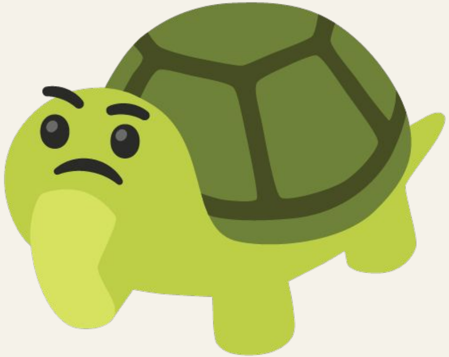
```
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;
    &x;

    &i;
    &a;
    int& ri = i;
    const int& cri = i;
    const A& ra = a;
}
```



頭腦體操！

```
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;
    &x;

    &i; // error: address of non-reference template-parameter
    &a;
    int& ri = i;
    const int& cri = i;
    const A& ra = a;
}
```

頭腦體操！

```
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;
    &x;

    &i;
    &a;
    int& ri = i;
    const int& cri = i;
    const A& ra = a;
}
```

頭腦體操！

```
using X = int;
struct A {};
template<const X& x, int i, A a> void f() {
    i++;
    &x;

    &i;
    &a;
    int& ri = i;
    const int& cri = i;
    const A& ra = a;
}
```