# The Pattern Matching We Already Have

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# C++ pattern matching proposals

- Herb Sutter's P2392
- Michael Park's P2688 (follow-up to P1371)

# C++ pattern matching proposals

```
struct Shape { virtual                    default; };
struct Circle :
struct Rectan                                  ght; };
```

```
// With P2392
int get_area(
    return i
        [r] :
        [w, h
    };
}
```

```
// With P2688
int get_area(cons
    return shape
        Circle: le                     ;
        Rectangle: let [w, h] => w * h;
    };
}
```

# C++ pattern matching proposals

**There is no pattern matching in the language yet…**

**…right?**

# The pattern matching we already have

```cpp
bool foo(bool x) {
    return not x;
}
```

```cpp
template <class T>
requires std::floating_point<T>
void foo(T x) {
    std::cout << x;
}
```

```cpp
int foo(std::unique_ptr<int> x) {
    return x ? *x : 0;
}
```

```cpp
foo(+[]{});
```

```cpp
// foo(bool)
```

```cpp
foo(123);
```

```cpp
// foo(bool)
```

```cpp
foo("abc");
```

```cpp
// foo(bool)
```

# The pattern matching we already have

```
template <class T, class U>
struct is_same {
    static constexpr bool value = false;
};
```

```
template <class T>
struct is_same<T, T> {
    static constexpr bool value = true;
};
```

```
static_assert(is_same<int, int>::value);
```

```
static_assert(not is_same<int, int*>::value);
```

# The pattern matching we already have

- Function overload resolution
- Template specializations
- Template argument deduction
- Class template argument deduction

# Goal of this talk

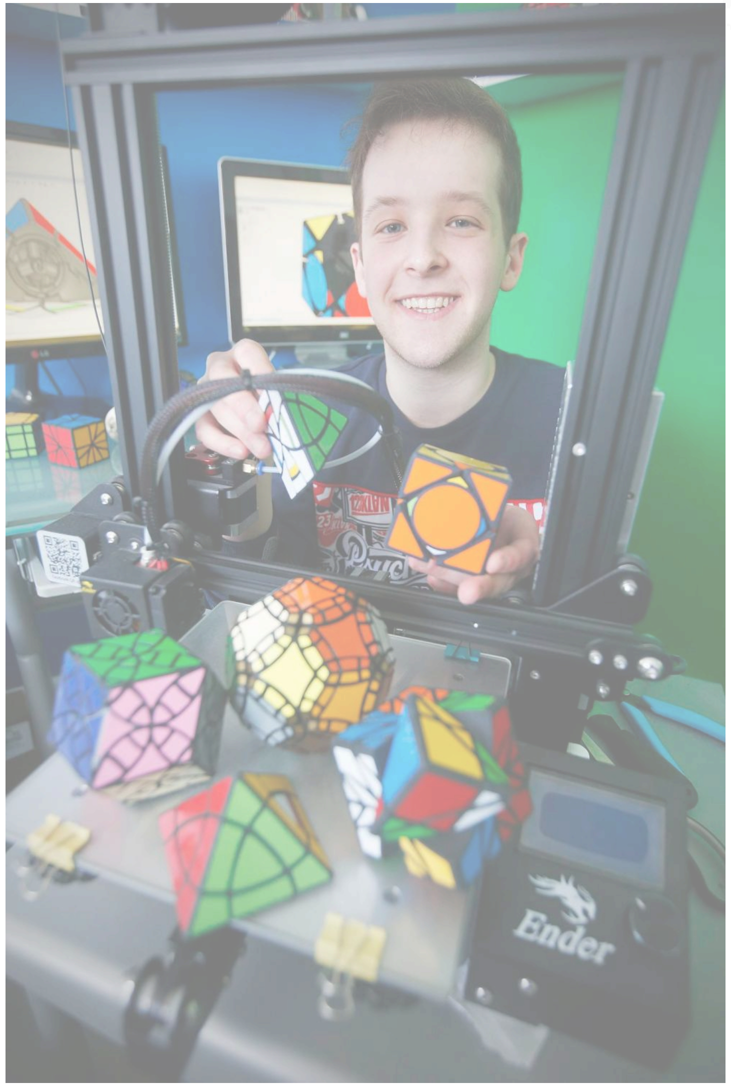
- Understand basic mechanism of these facilities
- Analogue reasoning about your code
- Give insight into the logical reasoning in C++

# In this talk

- Scratching the surface
- Minute details are glossed over
- Newly invented syntax for demonstration purposes
- Questions at any time!

# About me

- Canadian
- Licensed professional engineer
- I like twisty puzzles
- Working in C++ for 4 years
- On WG21 since 2023
- Run Winnipeg C++ Developers



# Function overload resolution

# Function overload resolution

- Since the beginning
- In the C++98 standard
- A defining feature of C++ compared to C
- Non-template pattern matching


#define init(p, ...) \
((void)0,init(p,__VA_ARGS__+0))
extern void (init)(Stack*, size_t);
C
C++
void init(Stack*);
void init(Stack*, size_t);
(code adapted from https://redd.it/r02cy4)
C++
Look what they need to
mimic a fraction of our power

# Function overloading

- Examples of function overloading
- How does overload resolution work?

# Examples of function overloading

```cpp
// From C++ standard [basic.scope.scope]
using Int = int;
void f(int);
void f(Int);
```

**redeclaration, overload, or ill-formed?**

# Examples of function overloading

```
// From C++ standard [basic.scope.scope]
enum E : int {};
void f(int);
void f(E);
```

**redeclaration, overload, or ill-formed?**

# Examples of function overloading

```cpp
// From C++98 standard [over.load]
void f(int);
void f(const int);
```

**redeclaration, overload, or ill-formed?**

# Examples of function overloading

```
void f(int*);
void f(const int*);
```

**redeclaration, overload, or ill-formed?**

# Examples of function overloading

```
// From C++98 standard [over.load]
int f(char*);
int f(char[]);
int f(char[7]);
```

**redeclaration, overload, or ill-formed?**

# Examples of function overloading

```cpp
// From C++98 standard [over.load]
void f(int i, int j);
void f(int i, int j = 99); // OK: redeclaration of f(int, int)
void f(int i = 88, int j); // OK: redeclaration of f(int, int)

void f(); // OK: overloaded declaration of f

void prog ()
{
    f(1, 2); // OK: call f(int, int)
    f(1); // OK: call f(int, int)
    f(); // Error: f(int, int) or f()?
}
```

# Examples of function overloading

```cpp
// From C++ standard [basic.scope.scope]
struct X {
    static void f();
    void f();
};
```

**redeclaration, overload, or ill-formed?**

# Examples of function overloading

```cpp
// From C++ standard [basic.scope.scope]
struct X {
    void g();
    void g() const;
};
```

**redeclaration, overload, or ill-formed?**

# Examples of function overloading

```
// From C++ standard [basic.scope.scope]
struct X {
    void g();
    void g() &;
};
```

**redeclaration, overload, or ill-formed?**

# Examples of function overloading

```cpp
struct X {
    void g() &;
    void g() &&;
    void g() const &;
    void g() const &&;
    void g() volatile &;
    void g() volatile &&;
    void g() const volatile &;
    void g() const volatile &&;
};
```

**redeclaration, overload, or ill-formed?**

# General mechanism

- Context of overload resolution, possible candidate functions
- List of viable candidate functions
- From the viable list, find the "best" one

# Distinct contexts of overload resolution

- Function calls
- Object `operator()`
- Operator overloading
- Constructors
- Conversion functions

# List of viable candidate functions

- Grab all candidate functions
- Grab the list of arguments
- Remove candidates with wrong number of parameters
- Remove candidates with unsatisfied constraints
- Remove candidates with incompatible arguments

# List of viable candidate functions

```cpp
int foo();
int foo(double);
int foo(int, double = 4.0);
int foo(int, bool);
int foo(...);
int foo(bool);
int foo(std::unique_ptr<int>);
template <class T>
    requires (sizeof(T) == 3)
int foo(T);
```

```cpp
void bar() {
    foo(nullptr);
}
```

- `int foo();`
- `int foo(double);`
- `int foo(int, double = 4.0);`
- `int foo(int, bool);`
- `int foo(...);`
- `int foo(bool);`
- `int foo(std::unique_ptr<int>);`
- `int foo<T>(T);`

# List of viable candidate functions

```cpp
int foo();
int foo(double);
int foo(int, double = 4.0);
int foo(int, bool);
int foo(...);
int foo(bool);
int foo(std::unique_ptr<int>);
template <class T>
    requires (sizeof(T) == 3)
int foo(T);
```

```cpp
void bar() {
    foo(nullptr);
}
```

- `int foo();`
- `int foo(double);`
- `int foo(int, double = 4.0);`
- `int foo(int, bool);`
- `int foo(...);`
- `int foo(bool);`
- `int foo(std::unique_ptr<int>);`
- `int foo<T>(T);`

# Find the best candidate function

- "Implicit conversion sequence" for each parameter-argument pair
- Rank the viable candidates based on conversions

# Find the best candidate function

```cpp
int foo(...);
int foo(bool);
int foo(std::unique_ptr<int>);
```

```cpp
void bar() {
    foo(nullptr);
}
```

`int foo(...);`

`nullptr_t` **to variadic**

**"ellipsis conversion sequence"**

`int foo(bool);`

`nullptr_t` **to** `bool`

**"standard conversion sequence"**

`int foo(std::unique_ptr<int>);`

`nullptr_t` **to** `std::unique_ptr<int>`

**"user-defined conversion sequence"**

# Find the best candidate function

```
int foo(...);
int foo(bool);
int foo(std::unique_ptr<int>);
```

```
void bar() {
    foo(nullptr);
}
```

1. "standard conversion sequence"
2. "user-defined conversion sequence"
3. "ellipsis conversion sequence"

**Calls `int foo(bool);`**

# Template specializations

# Template specializations

- Since the beginning
- In the C++98 standard
- Facilitate type traits in C++11
- "14.5.4.1 Matching of class template partial specializations"

# One could imagine...

```
// Syntax for demonstration purposes only
(T, U) match {
    (T, T) => true;
    _ => false;
};
```

```
// "Primary template"
template <class T, class U>
struct is_same {
    enum {
        value = (int)false
    };
};
```

```
// "Partial specialization"
template <class T>
struct is_same<T, T> {
    enum {
        value = (int)true
    };
};
```

# In C++11

```
// "Primary template"
template <class T, class U>
struct is_same {
    static constexpr bool value = false;
};
```

```
// "Partial specialization"
template <class T>
struct is_same<T, T> {
    static constexpr bool value = true;
};
```

# Backbone of the type traits

```cpp
template <class T>
struct remove_const {
    using type = T;
};
```

```cpp
template <class T>
struct remove_const<const T> {
    using type = T;
};
```

# Broad strokes

- Primary template
- Partial specializations
- Explicit specializations

# Primary template

```
template <class T>
struct my_trait {
    using type = T*;
};
```

# Partial specialization

```cpp
template <class T, class U>
struct my_trait<std::pair<T, U>> {
    using type = U*;
};
```

# Explicit specialization

```
template <>
struct my_trait<int> {
    using type = void;
};
```

# Specializations

```
template <class T>
struct my_other_trait {
    using type = T*;
};
```

```
template <>
struct my_other_trait<int*> {
    int foo() {
        return 123;
    }
};
```

```
template <class T>
struct my_other_trait<T*> {
    static constexpr bool value = true;
};
```

# [temp.expl.spec]/8

The placement of explicit specialization declarations for [...], and the placement of partial specialization declarations of [...] can affect whether a program is well-formed according to the relative positioning of the explicit specialization [...]. When writing a specialization, be careful about its location; or to make it compile will be such a trial as to kindle its self-immolation.

# Specialization matching

- Use explicit specialization if available
- Otherwise, use template argument deduction* to match partial specializations
- If 0 matching partial specializations, use the primary
- If 1 matching partial specialization, use it
- If multiple matching partial specializations, choose the "best"

# Examples of specialization matching

```
template <class T1, class T2> struct A          {};
template <class T1, class T2> struct A<T1*, T2> {};
template <class T1, class T2> struct A<T1, T2*> {};
```

# Examples of specialization matching

```
1 template <class T1, class T2> struct A          {};
2 template <class T1, class T2> struct A<T1*, T2> {};
3 template <class T1, class T2> struct A<T1, T2*> {};
```

```
A<int, int>
```

**1, 2, or 3?**

# Examples of specialization matching

```cpp
template <class T1, class T2> struct A          {};
template <class T1, class T2> struct A<T1*, T2> {};
template <class T1, class T2> struct A<T1, T2*> {};
```

```cpp
A<int*, int>
```

**1, 2, or 3?**

# Examples of specialization matching

```cpp
1 template <class T1, class T2> struct A           {};
2 template <class T1, class T2> struct A<T1*, T2> {};
3 template <class T1, class T2> struct A<T1, T2*> {};
```

```cpp
A<int***, int>
```

**1, 2, or 3?**

# Examples of specialization matching

```
1 template <class T1, class T2> struct A             {};
2 template <class T1, class T2> struct A<T1*, T2> {};
3 template <class T1, class T2> struct A<T1, T2*> {};
```

```
A<int, int*>
```

**1, 2, or 3?**

# Examples of specialization matching

```cpp
1 template <class T1, class T2> struct A          {};
2 template <class T1, class T2> struct A<T1*, T2> {};
3 template <class T1, class T2> struct A<T1, T2*> {};
```

```cpp
A<int*, int*>
```

**1, 2, or 3?**

# Matching against partial specialization

- Rewrite class templates as function templates
- Use template argument deduction*, and overload resolution
- Ultimately use the specialization corresponding to the resolved function

# Rewrite class templates as function templates

```
1 template <class T1, class T2> struct A          {};
2 template <class T1, class T2> struct A<T1*, T2> {};
3 template <class T1, class T2> struct A<T1, T2*> {};
```

```
// 2
template <class T1, class T2>
void __imaginary_function(A<T1*, T2>) { };
// 3
template <class T1, class T2>
void __imaginary_function(A<T1, T2*>) { };
```

# Rewrite class templates as function templates

```cpp
// 2
template <class T1, class T2>
void __imaginary_function(A<T1*, T2>) { };
// 3
template <class T1, class T2>
void __imaginary_function(A<T1, T2*>) { };
```

```cpp
__imaginary_function(A<int*, int>{});
// Calls 2 - __imaginary_function<int, int>(A<int*, int>)
```

```cpp
__imaginary_function(A<int, int*>{});
// Calls 3 - __imaginary_function<int, int>(A<int, int*>)
```

```cpp
__imaginary_function(A<int*, int*>{}); // error: ambiguous
// Could be 2 - __imaginary_function<int, int*>(A<int*, int*>)
// Could be 3 - __imaginary_function<int*, int>(A<int*, int*>)
```

# Examples of specialization matching

```
1 template <class T1, class T2> struct A          {};
2 template <class T1, class T2> struct A<T1*, T2> {};
3 template <class T1, class T2> struct A<T1, T2*> {};
```

```
4 template <class T1, class T2> struct A<T1*, T2*> {};
```

```
// 2
template <class T1, class T2>
void __imaginary_function(A<T1*, T2>) { };
// 3
template <class T1, class T2>
void __imaginary_function(A<T1, T2*>) { };
// 4
template <class T1, class T2>
void __imaginary_function(A<T1*, T2*>) { };
```

# Examples of specialization matching

```cpp
// 2
template <class T1, class T2>
void __imaginary_function(A<T1*, T2>) { };
// 3
template <class T1, class T2>
void __imaginary_function(A<T1, T2*>) { };
// 4
template <class T1, class T2>
void __imaginary_function(A<T1*, T2*>) { };
```

```cpp
__imaginary_function(A<int*, int*>{});
// Could be 2  - __imaginary_function<int, int*>(A<int*, int*>)
// Could be 3  - __imaginary_function<int*, int>(A<int*, int*>)
// Tie breaker - __imaginary_function<int, int>(A<int*, int*>)
```

# Template argument deduction

# Template argument deduction

```
template <class T>
void foo(std::vector<T>);
```

```
int main() {
    std::vector<int> vec;
    foo(vec);
    foo<int>(vec);
}
```

# Template argument deduction

- Since the beginning
- In the C++98 standard
- Deduce template arguments of function templates
- Can specify some template arguments explicitly
- New semantics in C++11 with forwarding

# Template argument deduction

- General mechanism
- Non-deduced context
- Forwarding

# General mechanism

- For each function parameter-argument pair:
- Ignore top-level cv qualifiers
- Process the parameter's and argument's "special forms"
- Match the template parameters to the corresponding template arguments

# "Special forms"

- $cv_{opt}$ T
- T*
- T&
- T&&
- T [$i_{opt}$]
- T (U...) noexcept($i_{opt}$)
- T U::*
- TT<...>
- TT<>

# General mechanism examples

```
template <class T>
void foo(T*);
```

```
std::vector<int> vec;
foo(&vec);
```

- Parameter `T*`, argument `std::vector<int>*`
- Match the form `T*`
- Therefore `T` is `std::vector<int>`

# General mechanism examples

```
template <class T>
void foo(std::vector<T>*);
```

```
std::vector<int> vec;
foo(&vec);
```

- **Parameter `std::vector<T>*`, argument `std::vector<int>*`**
- **Match the form `T*`**
- **Therefore `std::vector<T>` is `std::vector<int>`**
- **Match the form `TT<T>`, where `TT` is known to be `std::vector`**
- **Therefore `T` is `int`**

# General mechanism examples

```
template <template <class...> class Vec, class T>
void foo(Vec<T>*);
```

```
std::vector<int> vec;
foo(&vec);
```

- Parameter `Vec<T>*`, argument `std::vector<int>*`
- Match the form `T*`
- Therefore `Vec<T>` is `std::vector<int>`
- Match the form `TT<T>`
- Therefore `Vec` is `std::vector` and `T` is `int`

# General mechanism examples

```
template <class T, class U>
void foo(std::vector<T>, std::pair<T, U>);
```

```
std::vector<int> vec;
std::pair<int, float> pair;
foo(vec, pair);
```

- **Parameter `std::vector<T>`, argument `std::vector<int>`**
- **Match the form `TT<T>`, where `TT` is known to be `std::vector`**
- **Therefore `T` is `int`**

- **Parameter `std::pair<T,U>`, argument `std::pair<int,float>`**
- **Match the form `TT<T1,T2>`, where `TT` is known to be `std::pair`**
- **Therefore `T` is `int` and `U` is `float`**

# General mechanism examples

```
template <class T, class U>
void foo(std::vector<T>,      pair<T, U>);
```

```
std::vector<int> vec;
std::pair<double, float>
foo(vec, pair);
```

- Parameter `std::vector` … `std::vector<int>`
- Match the form `TT<T` … to be `std::vector`
- Therefore `T` is `in` …

- Parameter `std::pair<T,U>`, argument `std::pair<double,float>`
- Match the form `TT<T1,T2>`, where `TT` is known to be `std::pair`
- Therefore `T` is `double` and `U` is `float`

# General mechanism examples

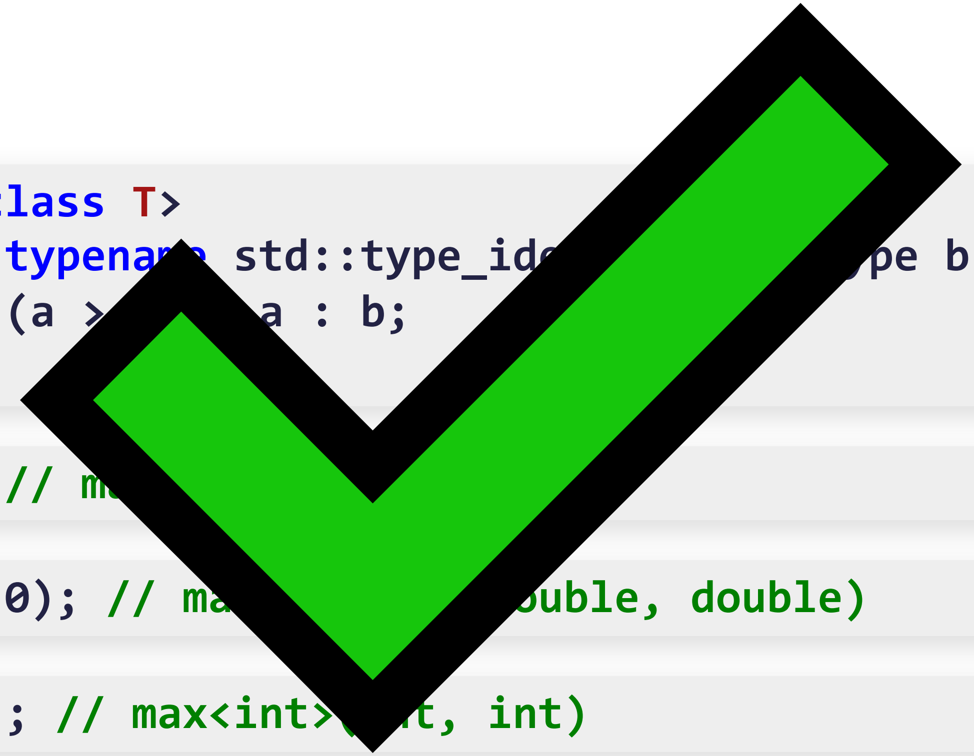
```
// From [temp.ove
template <class T>
T max(T a, T b) {
    return (a > b) ? a :
}
```

```
max(1, 2); // max<int
```

```
max(1.0, 2.0); //          (doubl
```

```
max(1, 2.0); // er       annot generate m        int, double)
```

# Non-deduced context



```
template <class T>
T max(T a, typena  std::type_id            pe b) {
    return (a >     a : b;
}
```

```
max(1, 2); // m
```

```
max(1.0, 2.0); // ma          ouble, double)
```

```
max(1, 2.0); // max<int>(  t, int)
```

# Non-deduced context (most common cases)

- The "nested-name-specifier" of a qualified type name
- `decltype` expression
- Parameter is not `std::initializer_list` but the argument is a braced init list

# Non-deduced context

```
template <class T>
struct S {
    using type = int;
};
template <class T>
void foo(typename S<T>::type);
```

```
foo(123); // error, cannot deduce T
```

- Parameter `typename S<T>::type`, a qualified name
- "nested-name-specifier" `S<T>`, which is a non-deduced context
- Therefore cannot deduce `T`

# Non-deduced context

```
template <class T>
struct S {
    using type = int;
};
template <class T>
void foo(typename S<T>::type, T);
```

```
foo(123, 456);
```

- Parameter `typename S<T>::type`, a qualified name
- "nested-name-specifier" `S<T>`, which is a non-deduced context
- Therefore cannot deduce `T`

- Parameter `T`, argument `int`
- Therefore `T` is `int`

# Non-deduced context

```
template <class T>
struct S {
    using type = int;
};
template <class T>
void foo(decltype(S<T>{}));
```

```
S<double> s;
foo(s); // error, cannot deduce T
```

- Parameter `decltype(S<T>{})`
- A `decltype` expression, which is a non-deduced context
- Therefore cannot deduce `T`

# Non-deduced context

```cpp
template <class T>
void foo(std::vector<T>);
```

```cpp
foo({1, 2, 3}); // error, cannot deduce T
```

- Parameter `std::vector<T>`, argument is a braced init list
- Parameter is not a `std::initializer_list`
- Braced init list argument causes a non-deduced context
- Therefore cannot deduce `T`

# Forwarding

- A special mention in the deduction rules
- "An rvalue reference to a cv-unqualified template parameter"
- i.e. `T&&`
- Must be a template parameter of the function itself

# Forwarding

```
// [temp.deduct.call]/3
template <class T>
int f(T&& heisenreference);
```

```
int i = 0;
f(i); // calls f<int&>(int&)
```

```
f(0); // calls f<int>(int&&)
```

# Reference collapsing

- `T&` `&` is `T&`
- `T&` `&&` is `T&`
- `T&&` `&` is `T&`
- `T&&` `&&` is `T&&`

# Reference collapsing

```cpp
using R1 = int&;
using R2 = R1&;
static_assert(std::same_as<R2, int&>);
```

```cpp
using R1 = int&;
using R2 = R1&&;
static_assert(std::same_as<R2, int&>);
```

# Reference collapsing

```cpp
using R1 = int&&;
using R2 = R1&;
static_assert(std::same_as<R2, int&>);
```

```cpp
using R1 = int&&;
using R2 = R1&&;
static_assert(std::same_as<R2, int&&>);
```

# Forwarding

```
template <class T>
void foo(T&&);
```

```
int i = 0;
foo(i);
```

- Parameter `T&&`, argument `int&`
- Match the form `T&&`
- Remember, `int&` is `int& &&`
- Therefore `T&&` is `int& &&`
- Therefore `T` is `int&`
- `foo<int&>(int&)`

# Forwarding

```
template <class T>
void foo(T&&);
```

```
foo(0);
```

- Parameter `T&&`, argument `int&&`
- Match the form `T&&`
- Therefore `T` is `int`
- `foo<int>(int&&)`

# Class template argument deduction

# Class template argument deduction

- Since C++17
- "CTAD" ("see-tad")
- Same as template argument deduction
- ...but for classes (shocking)
- "resolving a placeholder for a deduced class type"

# Class template argument deduction

```
std::pair p{ 1, 2.0 };
```

```
// Deduced as std::pair<int, double>
```

```
std::vector<int> foo() {
    // ...
}
```

```
std::vector v = foo();
```

```
// Deduced as std::vector<int>
```

# Class template argument deduction

- General mechanism
- Deduction guides

# General mechanism

- Create a theoretical set of function templates, the "guides"
- One for each constructor
- One for each deduction guide*
- Then do overload resolution and template argument deduction
- The winning function's return type is chosen

# General mechanism

```
template <class T, class U>
struct MyStruct {
    MyStruct(std::vector<T>, U);
    template <class V>
    MyStruct(T, std::pair<U, V>);
};
```

```
template <class T, class U>
MyStruct<T, U> __imaginary_function(std::vector<T>, U);
```

```
template <class T, class U, class V>
MyStruct<T, U> __imaginary_function(T, std::pair<U, V>);
```

```
std::vector<int> vec;
MyStruct s1{ vec, 1.0 };
// Deduced as MyStruct<int, double>
```

```
std::pair<char, double> p;
MyStruct s2{ 123, p };
// Deduced as MyStruct<int, char>
```

# General mechanism

```
template <class T, class U>
struct MyStruct {
    MyStruct(std::vector<T>, U);
    template <class V>
    MyStruct(T, std::pair<U, V>);
};
```

```
template <class T, class U>
MyStruct<T, U> __imaginary_function(std::vector<T>, U);
```

```
template <class T, class U, class V>
MyStruct<T, U> __imaginary_function(T, std::pair<U, V>);
```

```
std::vector<int> vec;
std::pair<char, double> p;
MyStruct s{ vec, p };
// Deduced as MyStruct<int, std::pair<char, double>>
```

# General mechanism

```
template <class T, class U>
struct MyStruct {
    template <class A>
    MyStruct(std::vector<T, A>, U);
    template <class V>
    MyStruct(T, std::pair<U, V>);
};
```

```
template <class T, class U, class A>
MyStruct<T, U> __imaginary_function(std::vector<T, A>, U);
```

```
template <class T, class U, class V>
MyStruct<T, U> __imaginary_function(T, std::pair<U, V>);
```

```
std::vector<int> vec;
std::pair<char, double> p;
MyStruct s{ vec, p };
// Ambiguous!
```

# Deduction guides

- More specificity with how CTAD behaves
- Defined after the class template
- Must align with the available constructors

# Deduction guides

```
template <class T, class U> struct MyStruct {
    template <class A> MyStruct(std::vector<T, A>, U);
    template <class V> MyStruct(T, std::pair<U, V>);
};
template <class T, class U, class A, class V>
MyStruct(std::vector<T, A>, std::pair<U, V>) -> MyStruct<T, std::pair<U, V>>;
```

```
template <class T, class U, class A>
MyStruct<T, U> __imaginary_function(std::vector<T, A>, U);
```

```
template <class T, class U, class V>
MyStruct<T, U> __imaginary_function(T, std::pair<U, V>);
```

```
template <class T, class U, class A, class V>
MyStruct<T, std::pair<U, V>> __imaginary_function(std::vector<T, A>, std::pair<U, V>);
```

```
std::vector<int> vec;
std::pair<char, double> p;
MyStruct s{ vec, p };
// Deduced as MyStruct<int, std::pair<char, double>>
```

# Deduction guides

```
template <class T, class U> struct MyStruct {
    template <class A> MyStruct(std::vector<T, A>, U);
    template <class V> MyStruct(T, std::pair<U, V>);
};
template <class T, class U, class A, class V>
MyStruct(std::vector<T, A>, std::pair<U, V>) -> MyStruct<T, U>;
```

```
template <class T, class U, class A>
MyStruct<T, U> __imaginary_function(std::vector<T, A>, U);
```

```
template <class T, class U, class V>
MyStruct<T, U> __imaginary_function(T, std::pair<U, V>);
```

```
template <class T, class U, class A, class V>
MyStruct<T, U> __imaginary_function(std::vector<T, A>, std::pair<U, V>);
```

```
std::vector<int> vec;
std::pair<char, double> p;
MyStruct s{ vec, p };
// No matches
```

# Conclusion

# C++ has pattern matching!

- Function overload resolution
- Template specializations
- Template argument deduction
- Class template argument deduction

# I read the standard so you don't have to

- [over.match]
- [temp.names], [temp.spec.partial], [temp.spec]
- [temp.deduct]
- [over.match.class.deduct], [dcl.type.class.deduct], [temp.deduct.guide]
- Cppreference is also an amazing resource

# Takeaways

- We already have pattern matching!
- The general rules can be quite elegant
- ...but the edge cases can get gnarly
- Analogue reasoning about your code is a muscle
- Get curious, exercise that muscle
- Appreciate how far C++ has come

# Thank you!

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