Welcome back! Link to Attendance Form ↓

Recall: What are templates?

- Turn to a partner and discuss:
  - What is a template class?
  - Why would you use a template class?
- Introduce yourself and take 60s to talk!

Recall: What are templates?

- What is a template class?
  - ✅ A blueprint for creating classes with generic types
- Why would you use a template class?
  - ✅ Template classes eliminate code redundancy!

Recall: What are templates?

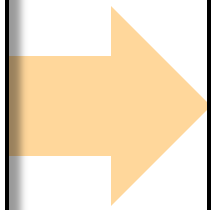
```
class IntVector {
```

```
class DoubleVector {
```

```
class StringVector {
  // Code to store
  // a list of
  // strings…
};
```

```
}
```

```
}
```



```
template <typename T>
class vector {
  // So satisfying.
};


vector<int> v1;
vector<double> v2;
vector<string> v3;
```

Recall: Template Instantiation

When you write code like this…

```
template <typename T>
class Vector {
  T& at(size_t index);
  // More methods...
};

Vector<int> v;
```

Compiler produces code like this…

```
class IntVector {
  int at(size_t index);
  // More methods...
};

IntVector v;
```

Is there more that templates can do?

Lecture 9: Template Functions

CS106L, Winter 2025

Today's Agenda

- Template Functions
  - How can we extend template classes to functions? Code demo!
- Concepts
  - How can we make C++ templates sane?
- Variadic Templates
  - How do we build functions that accept a variable number of arguments?
- Template Metaprogramming
  - How do we run code at compile time?

We may not get through everything today!

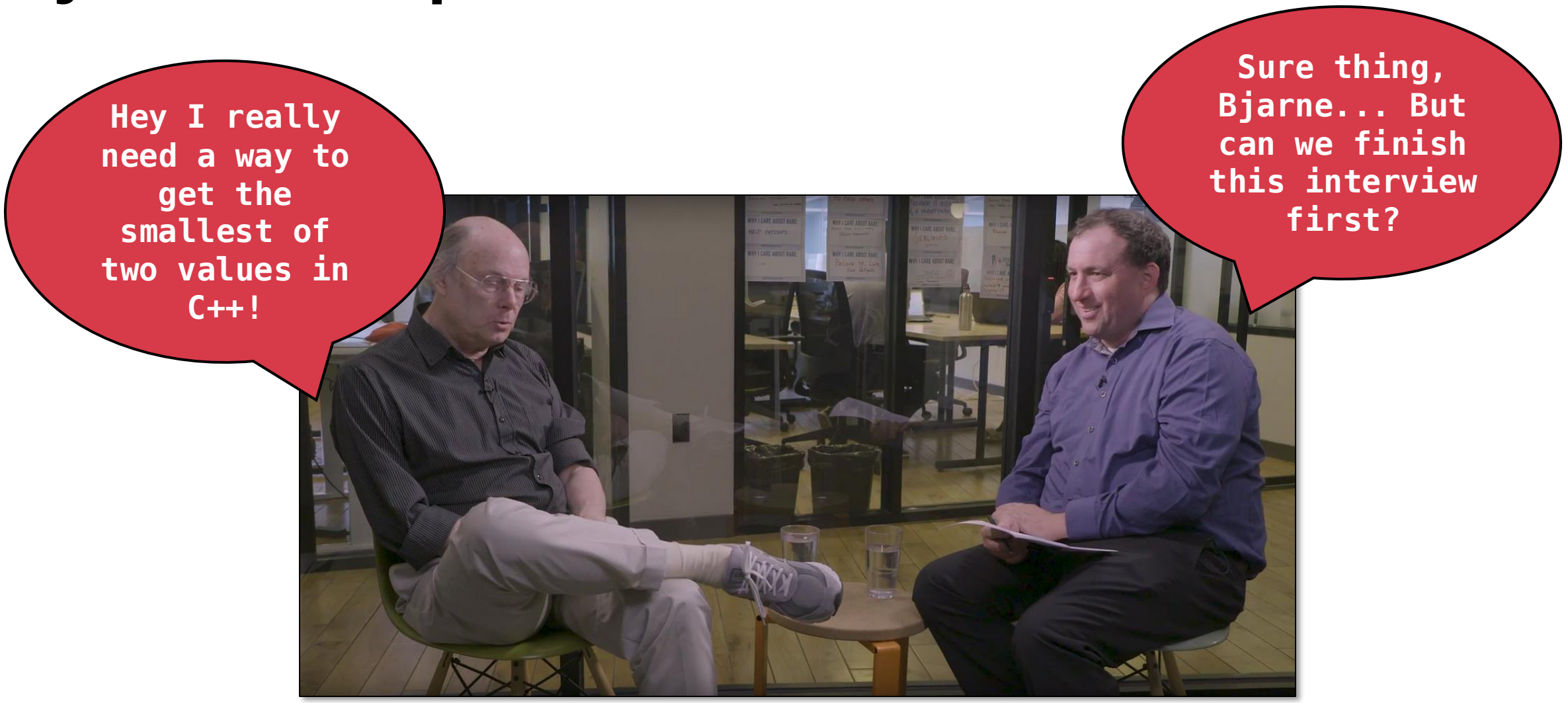
(Slides are posted if you want to review after)

What questions do you have?

bjarne_about_to_raise_hand

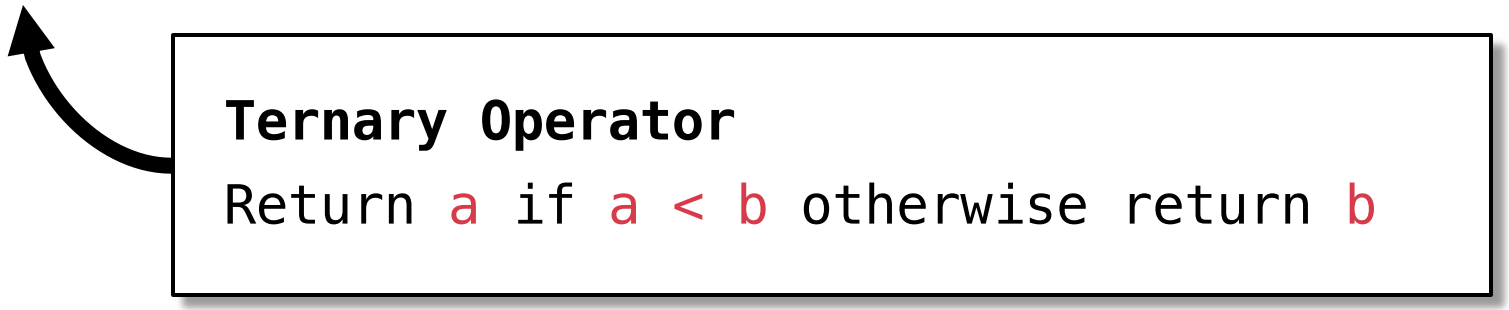
Template Functions

Bjarne has a problem...



Writing a `min` function

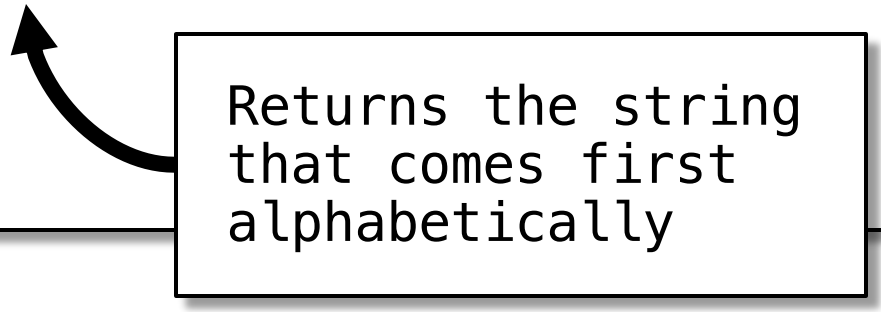
```
// Returns the smaller of a and b
int min(int a, int b) {
  return a < b ? a : b;
}
```



Writing a `min` function

`min` makes sense for more than just integers. How can we do this?

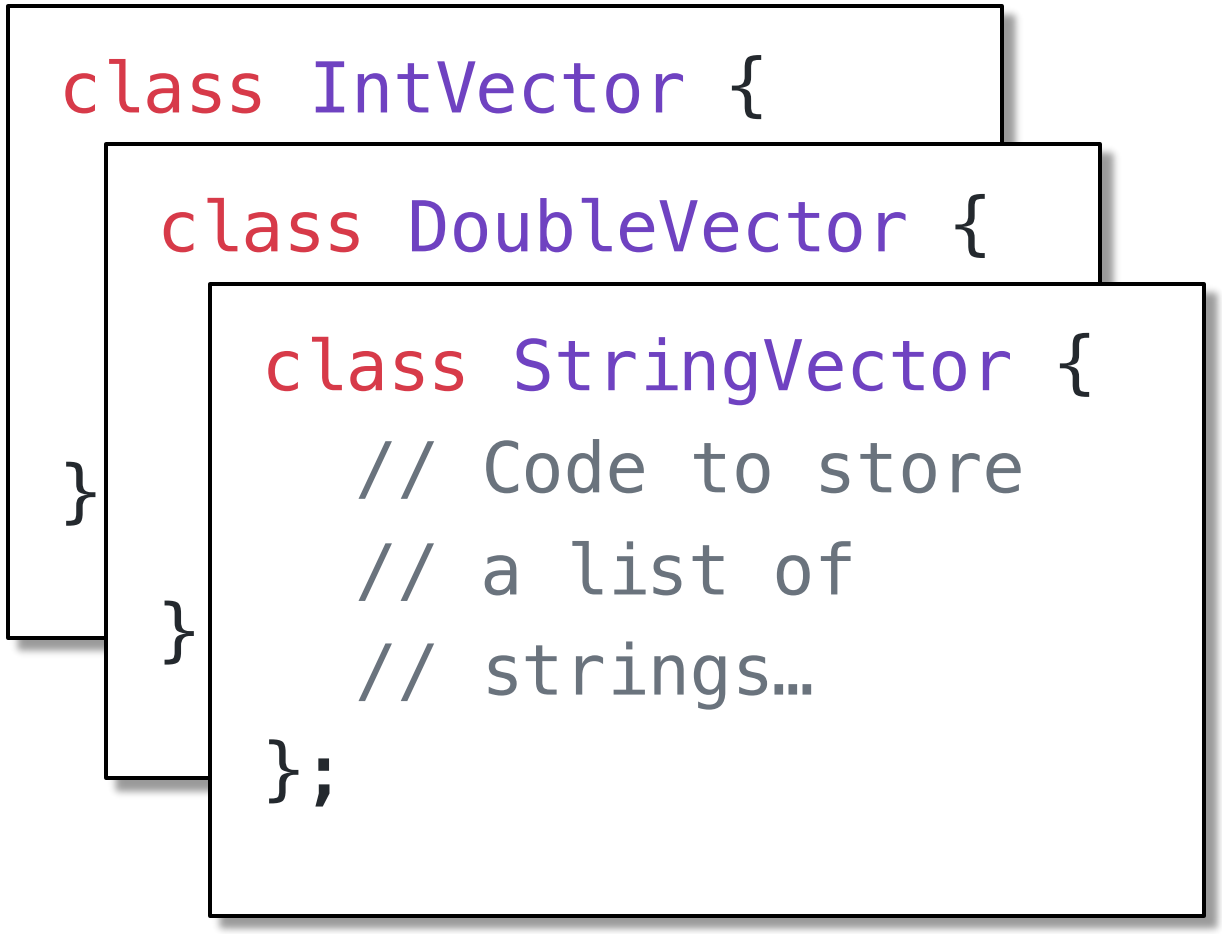
```
min(106, 107);              // int, returns 106
min(1.2, 3.4);              // double, returns 1.2
min("Jacob", "Fabio");      // string, returns "Fabio"
```



One solution: function overloading

```
int min(int a, int b) {
   return a < b ? a : b;
}

double min(double a, double b) {
   return a < b ? a : b;
}
std::string min(std::string a, std::string b) {
   return a < b ? a : b;
}
```

🤔 Hmm… this looks familiar!



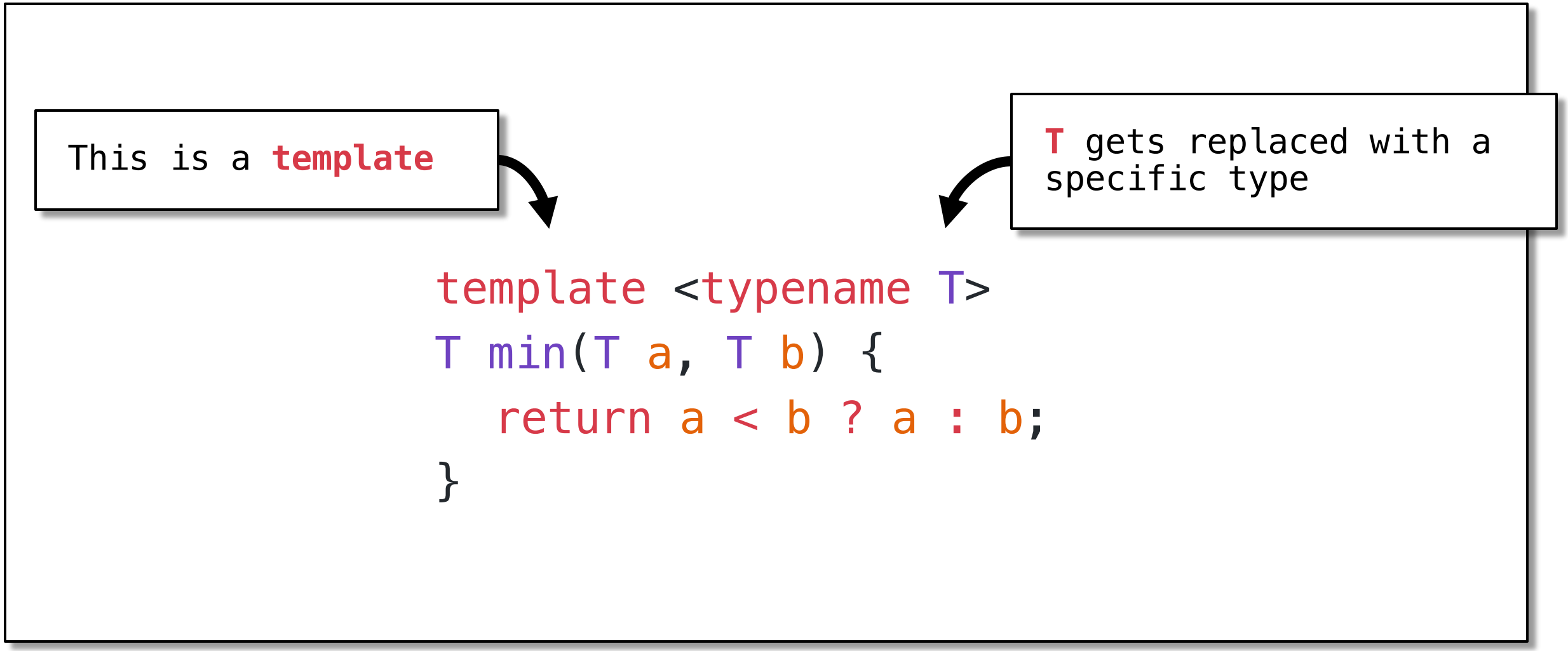
We can use templates!

Let’s take this…

```
int min(int a, int b) {
   return a < b ? a : b;
}

double min(double a, double b) {
   return a < b ? a : b;
}

std::string min(std::string a, std::string b) {
   return a < b ? a : b;
}
```

This works, but it’s missing the bigger idea!

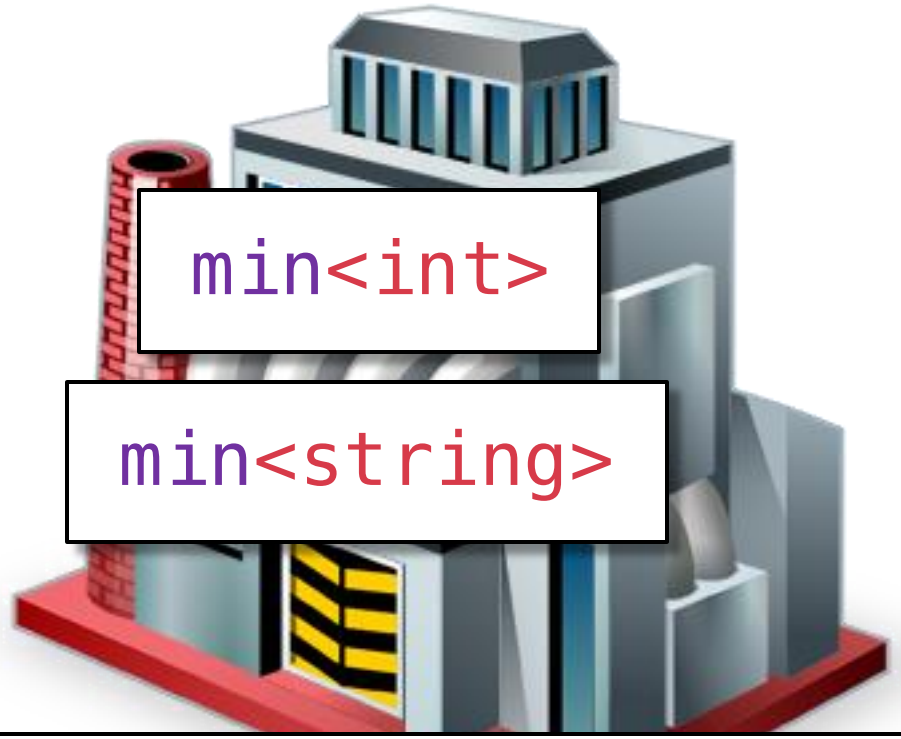
...and turn it into this!



A template is like a factory

```
int
```

```
string
```



```
min<int>
```

```
min<string>
```

```
template <typename T>
T min(T a, T b)
```

Remember: templates vs. functions

```
template <typename T>
T min(T a, T b)
```

```
min<std::string>
```

This is a template.

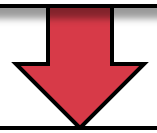
It's **not** a function

This is a function.

A.K.A a template instantiation

Template functions

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



We can also use references to avoid making a copy!

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

What questions do you have?

bjarne_about_to_raise_hand

How do we call template functions?

Option A: explicit instantiation

Explicit instantiation passes the types directly, just like template classes

```
min<int>(106, 107);        // Returns 106
min<double>(1.2, 3.4);     // Returns 1.2
```

Option A: explicit instantiation

Template functions cause the compiler to **generate code** for us

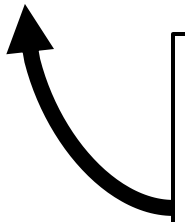
```
int min(int a, int b) {                 // Compiler generated
   return a < b ? a : b;                // Compiler generated
}                                       // Compiler generated

double min(double a, double b) {        // Compiler generated
   return a < b ? a : b;                // Compiler generated
}                                       // Compiler generated

min<int>(106, 107);             // Returns 106
min<double>(1.2, 3.4);          // Returns 1.2
```

Key Idea: Templates automate code generation

Option B: implicit instantiation

Implicit instantiation lets the compiler **infer** the types for us

```
min(106, 107);     // int, returns 106
min(1.2, 3.4);     // double, returns 1.2
```



I didn't specify any template types!

Implicit instantiation is kind of like `auto`

```
auto number = 106;
```

This still is an **int**,
we just let the
compiler figure it
out

Implicit instantiation is kind of like `auto`

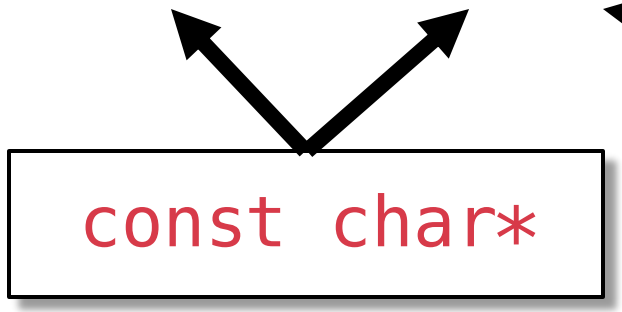
```
int m = min(106, 107);
```

It’s exactly as if we wrote

```
min<int>(106, 107)
```

Implicit instantiation can be finicky

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

min("Jacob", "Fabio");
```



What type is T? What are the types of the arguments?

Hint: you might know this if you've taken CS107!

Implicit instantiation can be finicky

```
const char* min(const char* a, const char* b) {
   return a < b ? a : b;
}

min<const char*>("Jacob", "Fabio");
```

Pointer comparison AHHHH!!! This is not what we wanted

← This is Bjarne judging you for using pointer comparison

Implicit instantiation can be finicky

We can always use explicit instantiation in ambiguous cases like this

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

min<std::string>("Jacob", "Fabio");
```

`const char*` gets converted to `std::string` here

↓ Here is Bjarne pleased with you for getting the compiler to understand you!

Implicit instantiation can be finicky

Another example: the types of the parameters don't strictly match

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

min(106, 3.14); // ❌ Doesn't compile
```

int

double

Explicit instantiation!

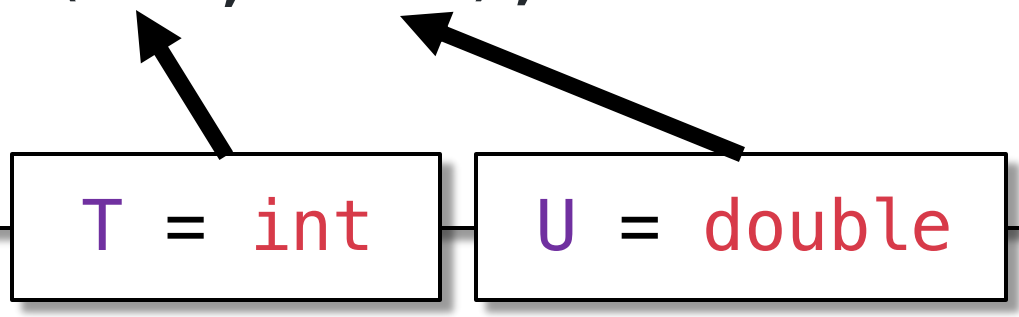
```
min<double>(106, 3.14)
```

Implicit instantiation can be finicky

Another solution: make our template a little bit more flexible.

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

min(106, 3.14);
```

What should the return type of this function be?



Implicit instantiation can be finicky

Another solution: make our template a little bit more flexible.

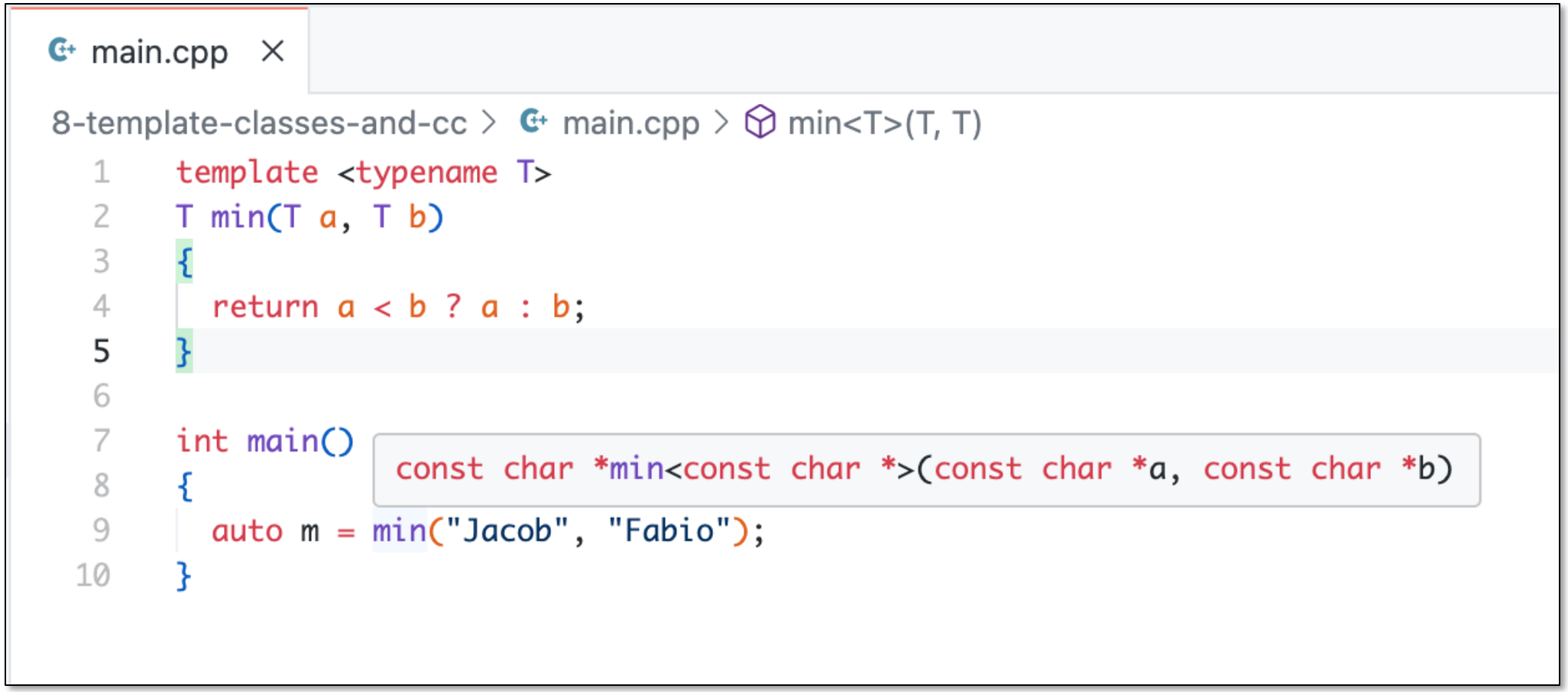
```
template <typename T, typename U>
auto min(const T& a, const U& b) {
   return a < b ? a : b;
}

min(106, 3.14);
```

What should the return type of this function be?

It's complicated, let the compiler figure it out with auto

Pro tip: Use IDE to see instantiation types

IDEs (e.g. VSCode, QtCreator) can show what types were actually used



What questions do you have?

bjarne_about_to_raise_hand

Code Demo

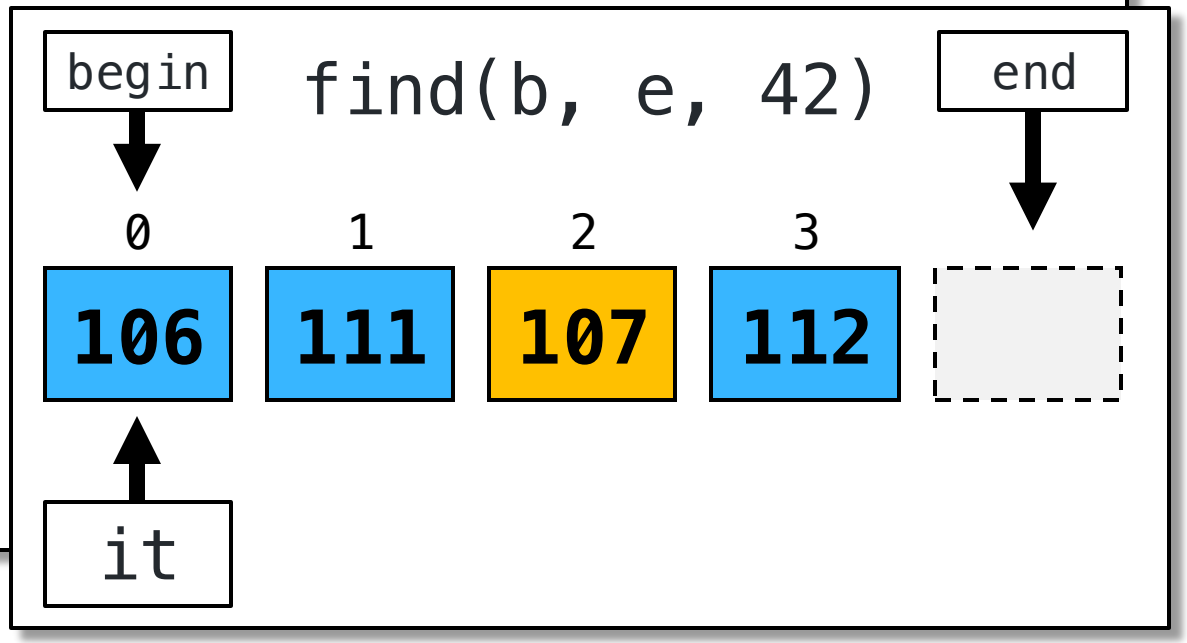
Q: Where do we use template functions in practice?

A: All over the place!

One prominent example: iterators

Writing a `find` function

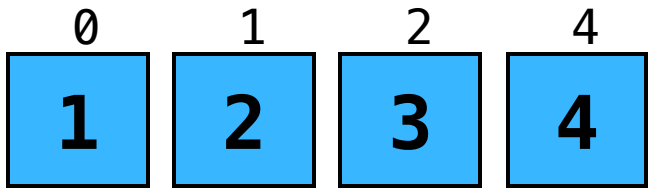
```
std::vector<int> v { 106, 111, 42, 112 };
auto it = find(v.begin(), v.end(), 42);
*it = 107;
// v = { 106, 111, 107, 112 }
```



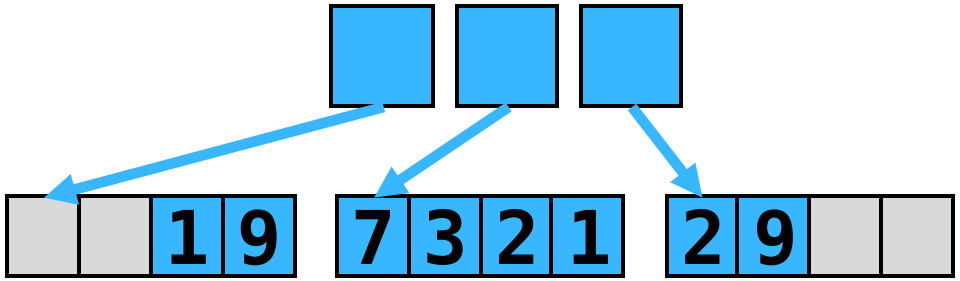
Writing a `find` function

```
std::vector<int>::iterator find(
   std::vector<int>::iterator begin,
   std::vector<int>::iterator end,
   int value
) {
   // Logic to find the iterator in this container
   // Should return end if no such element is found
}
```

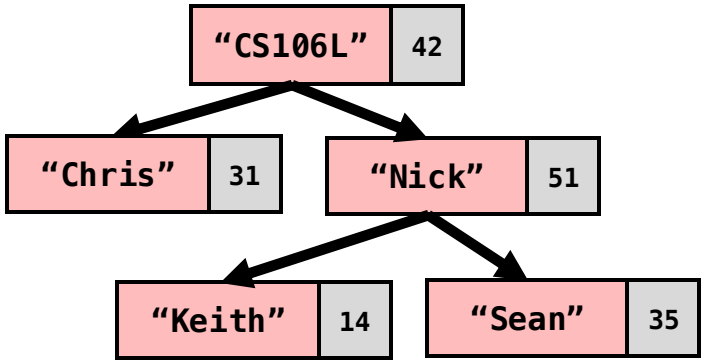
Recall: we have many iterator types!



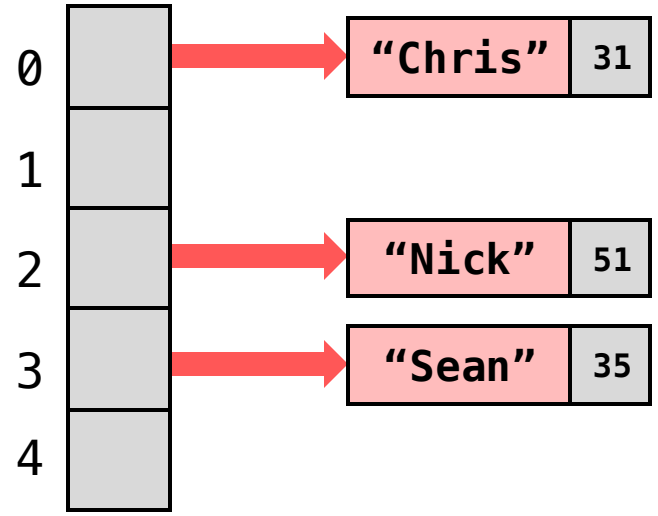
vector<T>::iterator



deque<T>::iterator



map<K, V>::iterator



unordered_map<K, V>::iterator

But they all share the same interface!

```
// Copy construction
auto it = c.begin();
```

```
// Increment iterator forward
++it;
```

```
// Dereference iterator -- undefined if it == end()
auto elem = *it;
```

```
// Equality: are we in the same spot?
if (it == c.end()) ...
```

This definition is too specific!

```
std::vector<int>::iterator find(
   std::vector<int>::iterator begin,
   std::vector<int>::iterator end,
   int value
) {
   // Logic to find the iterator in this container
   // Should return end if no such element is found
}
```

Writing a `find` function

Our `find` function won't work for other vectors, or other containers

```
std::vector<std::string> v { "seven", "kingdoms" };
auto it = find(v.begin(), v.end(), "kingdoms");
// Won't compile

std::set<std::string> s { "house", "targaryen" };
auto it = find(s.begin(), s.end(), "targaryen");
// Gods help us
```

What questions do you have?

bjarne_about_to_raise_hand

Let’s write a template function!

Writing a `find` function... but templated

Form a small group and let's implement this function! Link on next slide.

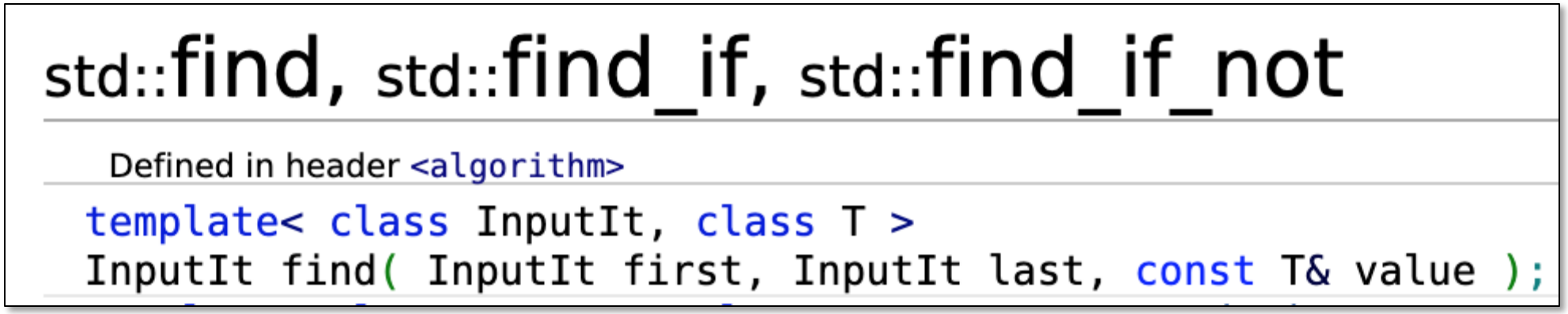
```
template <typename Iterator, typename TElem>
???? find(???? begin, ???? end, ???? value) {
  // Logic to find and return the iterator
  // in this container whose element is value
  // Should return end if no such element is found
}

find<std::vector<int>::iterator, int>(b, e, 42);
```

Let’s code this together 👬

`106l.vercel.app/find`

`find` function in the STL

- Part of `<algorithm>` header (we'll talk more about this on Thursday)!
- You guys have all the tools now to read the C++ standard!




BUT WAIT
THERES MORE
makeameme.org

Concepts

Back to our `min` function

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

// For which T will the following compile successfully?
T a = /* an instance of T */;
T b = /* an instance of T */;
min<T>(a, b);
```

What **must be true** of a type `T` for us to be able to use `min`?

Back to our `min` function

T must have an `operator<` to make sense in this context

```
struct StanfordID; // How do we compare two IDs?

StanfordID jacob { "Jacob", "jtrb" };
StanfordID fabio { "Fabio", "fabioi" };
min<StanfordID>(jacob, fabio); // ❌ Compiler error
```

What happened?

```
$ g++ main.cpp --std=c++20
main.cpp:9:12: error: invalid operands to binary expression
('const StanfordID' and 'const StanfordID')
return a < b ? a : b;
       ~ ^ ~
main.cpp:20:3: note: in instantiation of function template
specialization 'min<StanfordID>' requested here
min<StanfordID>(jacob, fabio);
^
1 error generated.
```

What happened?

```
$ g++ main.cpp --std=c++20
main.cpp:9:12: error: invalid operands to binary expression
('const StanfordID' and 'const StanfordID')
return a < b ? a : b;
       ~ ^ ~
main.cpp:20:3: note: in instantiation of function template
specialization 'min<StanfordID>' requested here
min<StanfordID>(jacob, fabio);
^
1 error generated.
```

What happened?

Compiler instantiated our template, and only then did it spot the error

```
StanfordID jacob { "Jacob", "jtrb" };
StanfordID fabio { "Fabio", "fabioi" };
min<StanfordID>(jacob, fabio);

StanfordID min(const StanfordID& a, const StanfordID& b)
{
   return a < b ? a : b;
}
```

Compiler: ”min for StanfordIDs, coming right up!”

Compiler: ”AHHH what do I do here! I don’t know how to compare two StanfordIDs”

Compiler only finds the error *after* instantiation

Recall: `std::set` also requires an `operator<`

Bad templates can produce really confusing compiler errors…

```
std::set<StanfordID> s { jacob, fabio };
```

Recall: `std::set` requires `operator<`

```
jacobrobertsbaca@Jacobs-MacBook-Pro-3 8-template-classes-and-cc % clang++ main.cpp --std=c++20
In file included from main.cpp:1:
In file included from /Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/Mac
OSX.sdk/usr/include/c++/v1/string:520:
In file included from /Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/Mac
OSX.sdk/usr/include/c++/v1/__functional_base:16:
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.sdk/usr/include/c+
+/v1/__functional/operations.h:487:21: error: invalid operands to binary expression ('const StanfordID' and '
const StanfordID')
        {return __x < __y;}
                ~~~ ^ ~~~
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.s
+/v1/__tree:2023:28: note: in instantiation of member function 'std::less<StanfordID>::opera
here
    if (__hint == end() || value_comp()(__v, *__hint))  // check before
                           ^
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.s
+/v1/__tree:2114:36: note: in instantiation of function template specialization 'std::__tree
:less<StanfordID>, std::allocator<StanfordID>>::__find_equal<StanfordID>' requested here
    __node_base_pointer& __child = __find_equal(__p, __parent, __dummy, __k);
                                   ^
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.sdk/usr/include/c+
+/v1/__tree:1257:16: note: in instantiation of function template specialization 'std::__tree<StanfordID, std:
:less<StanfordID>, std::allocator<StanfordID>>::__emplace_hint_unique_key_args<StanfordID, const StanfordID &
>' requested here
        return __emplace_hint_unique_key_args(__p, _NodeTypes::__get_key(__v), __v).first;
               ^
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.sdk/usr/include/c+
```

The error message continues to go on 😭

Also a problem for our `find` function

```
int main() {
   int idx = find(1, 5, 3); // eh... 3 I guess? haelp
🥶
}
```

```
main.cpp:16:9: error: indirection requires pointer operand ('int' invalid)
    if (*it == value) {
        ^~~
main.cpp:29:3: note: in instantiation of function template specialization 'find<int, int>'
  find(1, 5, 3); // eh... 3 I guess? haelp <U+1F972>
  ^
1 error generated.
```

C++ beginner: “Uhh.. Compiler, what the @!#* do you mean?”

Idea: How do we put constraints on templates?

Idea: How do we put constraints on templates?

- Templates are great, but the errors they produce when used incorrectly are unintuitive
- How can we be up-front about what we require of a template type?

C#

```
class EmployeeList<T>
where T : notnull,
Employee,
IComparable<T>, new()
```

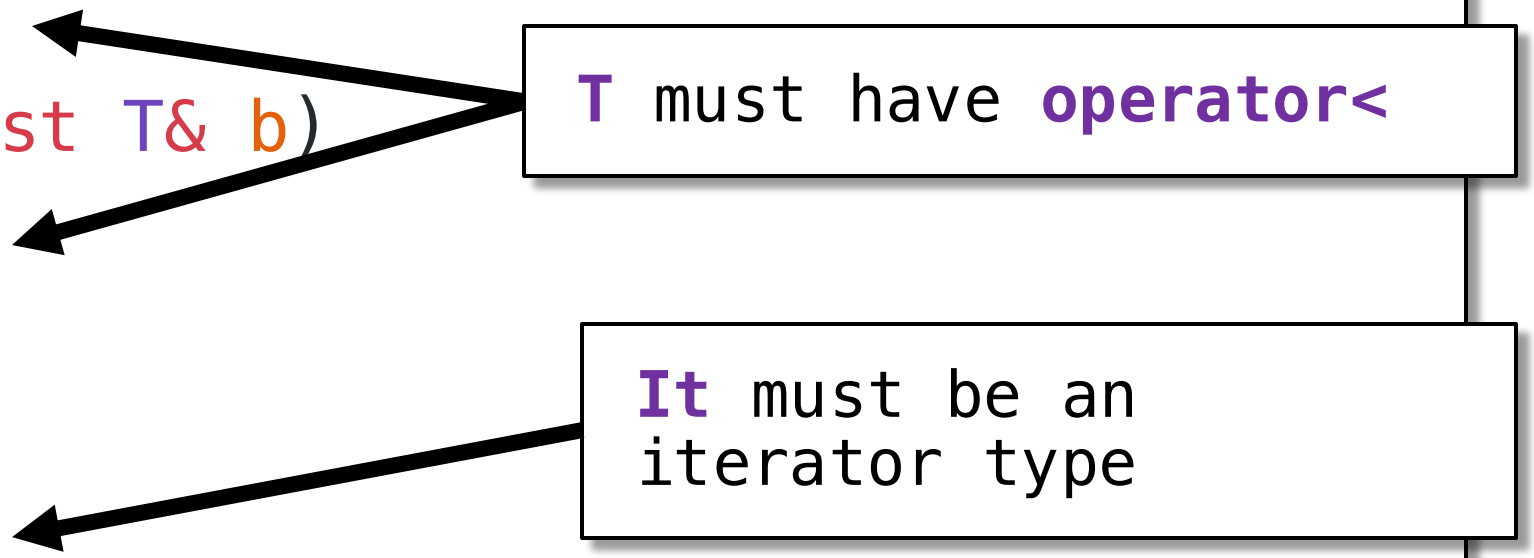
Java

```
class ListObject<T
extends Comparable<T>>
```

Idea: How do we put constraints on templates?

Compiler shouldn't instantiate a template unless all constraints are met

```
template <typename T>
T min(const T& a, const T& b)

template <typename T>
struct set;

template <typename It, typename T>
It find(It begin, It end, const T& value)
```



What questions do you have?

bjarne_about_to_raise_hand

Introducing C++ concepts!

Creating a `Comparable` concept

```
template <typename T>
concept Comparable = requires(T a, T b) {
   { a < b } -> std::convertible_to<bool>;
};
```

Creating a Comparable concept

concept: a named set of ***constraints***

```
template <typename T>
concept Comparable = requires(const T a, const T b) {
   { a < b } -> std::convertible_to<bool>;
};
```

Creating a Comparable concept

concept: a named set of ***constraints***

requires:

Given two T's, I expect the following to hold

```
template <typename T>
concept Comparable = requires(const T a, const T b) {
  { a < b } -> std::convertible_to<bool>;
};
```

Creating a Comparable concept

concept: a named set of ***constraints***

requires:

Given two T's, I expect the following to hold

```
template <typename T>
concept Comparable = requires(const T a, const T b) {
   { a < b } -> std::convertible_to<bool>;
};
```

constraint: Anything inside the { } must compile without error

Creating a Comparable concept

concept: a named set of ***constraints***

requires:

Given two T's, I expect the following to hold

```
template <typename T>
concept Comparable = requires(const T a, const T b) {
  { a < b } -> std::convertible_to<bool>;
};
```

constraint: Anything inside the { } must compile without error

constraint: ...and the result must be bool-like

convertible_to is also a concept!

Creating a Comparable concept

concept: a named set of ***constraints***

requires:

Given two T's, I expect the following to hold

```
template <typename T>
concept Comparable = requires(const T a, const T b) {
   { a < b } -> std::convertible_to<bool>;
};
```

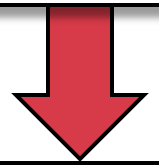
constraint: Anything inside the { } must compile without error

constraint: ...and the result must be bool-like

convertible_to is also a concept!

Using our Comparable concept

```
template <typename T> requires Comparable<T>
T min(const T& a, const T& b);
```



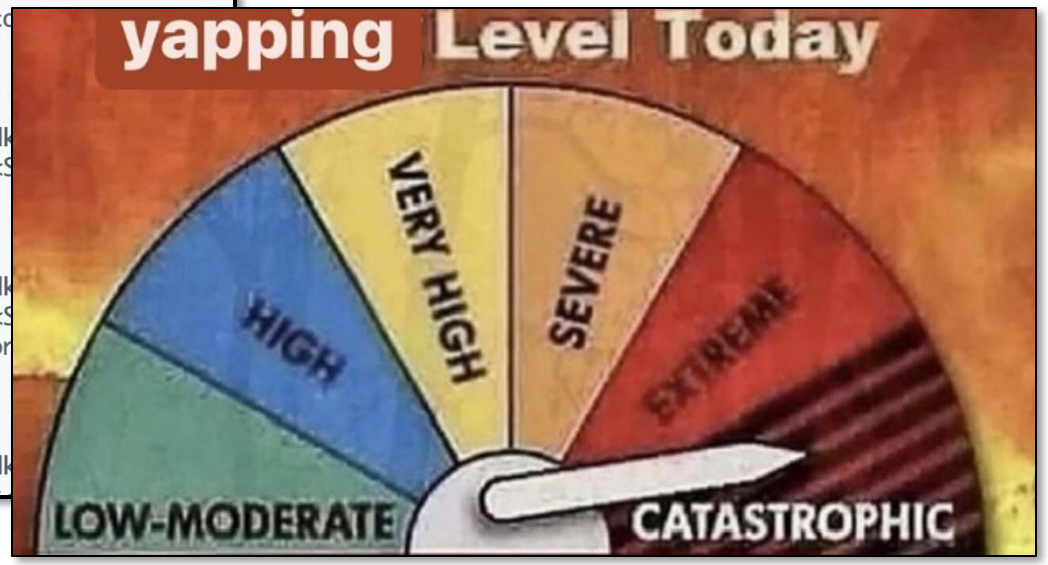
```
// Super slick shorthand for the above
template <Comparable T>
T min(const T& a, const T& b);
```

Concepts greatly improve compiler errors

Here's the error from before when instantiating a set **without** a concept

```
jacobrobertsbaca@Jacobs-MacBook-Pro-3 8-template-classes-and-cc % clang++ main.cpp --std=c++20
In file included from main.cpp:1:
In file included from /Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Dev
OSX.sdk/usr/include/c++/v1/string:520:
In file included from /Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Dev
OSX.sdk/usr/include/c++/v1/__functional_base:16:
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.sdk
+/v1/__functional/operations.h:487:21: error: invalid operands to binary expression ('const St
const StanfordID')
        {return __x < __y;}
                ~~~ ^ ~~~
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.sdk/usr/include/c+
+/v1/__tree:2023:28: note: in instantiation of member function 'std::less<StanfordID>::operato
here
    if (__hint == end() || value_comp()(__v, *__hint))  // check before
                           ^
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.sdk
+/v1/__tree:2114:36: note: in instantiation of function template specialization 'std::__tree<S
:less<StanfordID>, std::allocator<StanfordID>>::__find_equal<StanfordID>' requested here
    __node_base_pointer& __child = __find_equal(__p, __parent, __dummy, __k);
                                   ^
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.sdk
+/v1/__tree:1257:16: note: in instantiation of function template specialization 'std::__tree<S
:less<StanfordID>, std::allocator<StanfordID>>::__emplace_hint_unique_key_args<StanfordID, cor
>' requested here
        return __emplace_hint_unique_key_args(__p, _NodeTypes::__get_key(__v), __v).first;
               ^
/Applications/Xcode.app/Contents/Developer/Platforms/MacOSX.platform/Developer/SDKs/MacOSX.sdk
```

```
template <typename T>
struct std::set;
```



Concepts greatly improve compiler errors

Here's the error when instantiating a set **with** a concept

```
main.cpp:32:3: error: constraints not satisfied for class template 'set' [with T = StanfordID]
  set<StanfordID> ids { jacob, fabio };
  ^~~~~~~~~~~~~~~~
main.cpp:13:11: note: because 'StanfordID' does not satisfy 'Comparable'
template <Comparable T>
          ^
main.cpp:10:7: note: because 'a < b' would be invalid: invalid operands to binary expression ('
const StanfordID' and 'const StanfordID')
  { a < b } -> std::convertible_to<bool>;
      ^
4 errors generated.
```

```
template <Comparable T>
struct std::set;
```

C++ comes with many built-in concepts

Core language concepts

Defined in header <concepts>

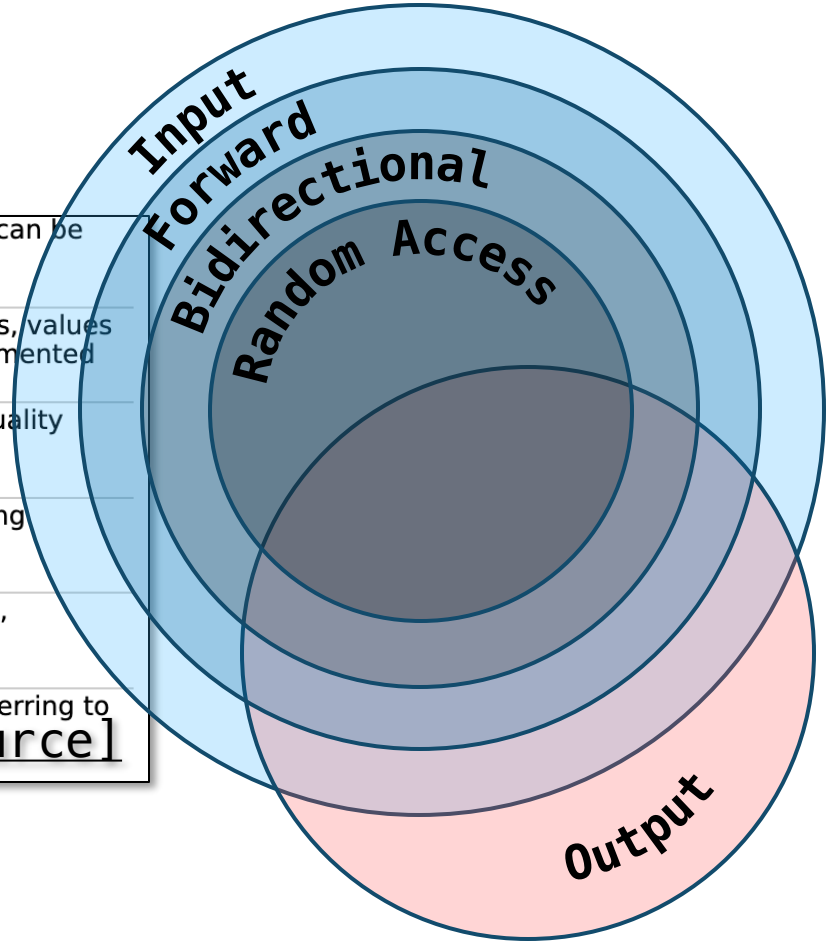
same_as (C++20)	specifies that a type is the same as another type (concept)
derived_from (C++20)	specifies that a type is derived from another type (concept)
convertible_to (C++20)	specifies that a type is implicitly convertible to another type (concept)
common_reference_with (C++20)	specifies that two types share a common reference type (concept)
common_with (C++20)	specifies that two types share a common type (concept)
integral (C++20)	specifies that a type is an integral type (concept)
signed_integral (C++20)	specifies that a type is an integral type that is signed (concept)
unsigned_integral (C++20)	specifies that a type is an integral type that is unsigned (concept)
floating_point (C++20)	specifies that a type is a floating-point type (concept)
assignable_from (C++20)	specifies that a type is assignable from another type (concept)
swappable **swappable_with** (C++20)	specifies that a type can be swapped or that two types can be swapped with each other (concept)

[source]

...including iterator concepts!

input_iterator (C++20)	specifies that a type is an input iterator, that is, its referenced values can be read and it can be both pre- and post-incremented (concept)
output_iterator (C++20)	specifies that a type is an output iterator for a given value type, that is, values of that type can be written to it and it can be both pre- and post-incremented (concept)
forward_iterator (C++20)	specifies that an `input_iterator` is a forward iterator, supporting equality comparison and multi-pass (concept)
bidirectional_iterator (C++20)	specifies that a `forward_iterator` is a bidirectional iterator, supporting movement backwards (concept)
random_access_iterator (C++20)	specifies that a `bidirectional_iterator` is a random-access iterator, supporting advancement in constant time and subscripting (concept)
contiguous_iterator (C++20)	specifies that a `random_access_iterator` is a contiguous iterator, referring to elements that are contiguous in memory (concept)

[source]



Remember our iterator types?

Fixing up our `find` function

```
template <std::input_iterator It, typename T>
It find(It begin, It end, const T& value);

int idx = find(1, 5, 3); // WHY DOES THIS NOT WORK?
```

```
main.cpp:10:11: note: because 'int' does not satisfy 'input_iterator'
template <std::input_iterator It, typename T>
          ^
```

Concepts recap

- Two reasons to use concepts
  - Better compiler error messages
  - Better IDE support (Intellisense/autocomplete, etc.)
- Concepts are still a new feature
  - STL does not yet support them fully
  - We'll talk more about this on Thursday!

What questions do you have?

bjarne_about_to_raise_hand

Variadic Templates

How do we create a function that accepts a variable number of parameters?

Back to our `min` function

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

min(2.4, 7.5);              // This works
min(2.4, 7.5, 5.3);         // What about this?
min(2.4, 7.5, 5.3, 1.2); // or this?
```

One solution: function overloading

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

template <Comparable T>
T min(const T& a, const T& b, const T& c) {
   auto m = min(b, c);
   return a < m ? a : m;
}

template <Comparable T>
T min(const T& a, const T& b, const T& c, const T& d) {
   auto m = min(b, c, d);
   return a < m ? a : m;
}
```

3 element overload calls 2 element

4 element overload calls 3 element

Seems almost recursive!

One solution: function overloading

```
min(2.4, 7.5);                  // This works
min(2.4, 7.5, 5.3);             // This works now
min(2.4, 7.5, 5.3, 1.2); // and this works too!


min(2.4, 7.5, 5.3, 1.2, 3.4, 6.7, 8.9, 9.1);


// Time to write 7 overloads I guess...
```

Wait… Templates are all about code generation

Can the compiler write the overloads for us?

Yes! Templates + recursion 🎉🤯

But first… a (slightly) different solution

Can't we solve this recursively using `std::vector`!?

```
template <Comparable T>
T min(const std::vector<T>& values);

// Passing a vector<double> here!
// Note the { } braces (uniform initialized vector)
min({ 2.4, 7.5 });
min({ 2.4, 7.5, 5.3 });
min({ 2.4, 7.5, 5.3, 1.2 });
```

But first… a (slightly) different solution

Can't we solve this recursively using `std::vector`!?

```
template <Comparable T>
T min(const std::vector<T>& values) {
   if (values.size() == 1) return values[0];
   const auto& first = values[0];
   std::vector<T> rest(++values.begin(), values.end());
   auto m = min(rest);
   return first < m ? first : m;
}
```

Talk to a partner for 60s. What should the last two lines be?

But first… a (slightly) different solution

Can’t we solve this recursively using `std::vector`!?

```
template <Comparable T>
T min(const std::vector<T>& values) {
  if (values.size() == 1) return values[0];
  const auto& first = values[0];
  std::vector<T> rest(++values.begin(), values.end());
  auto m = min(rest);
  return first < m ? first : m;
}
```

Base Case: if we only have one element, return that element!

But first… a (slightly) different solution

Can’t we solve this recursively using `std::vector`!?

```
template <Comparable T>
T min(const std::vector<T>& values) {
  if (values.size() == 1) return values[0];
  const auto& first = values[0];
  std::vector<T> rest(++values.begin(), values.end());
  auto m = min(rest);
  return first < m ? first : m;
}
```

Recursive Case: compare first element to min of remaining elements!

What questions do you have?

bjarne_about_to_raise_hand

But first… a (slightly) different solution

Can't we solve this recursively using `std::vector`!?

```
template <Comparable T>
T min(const std::vector<T>& values) {
   if (values.size() == 1) return values[0];
   const auto& first = values[0];
   std::vector<T> rest(++values.begin(), values.end());
   auto m = min(rest);
   return first < m ? first : m;
}
```

This solution is correct. But does anyone see any **inefficiencies**?

Some problems with this approach…

- It recursively copies the vector (can avoid with wrapper function!)
- Must allocate a vector for every call (unavoidable overhead)

```
template <Comparable T>
T min(const std::vector<T>& values);

// Passing a vector<double> here!
// Note the { } braces (list initialized vector)
min({ 2.4, 7.5 });
min({ 2.4, 7.5, 5.3 });
min({ 2.4, 7.5, 5.3, 1.2 });
```

What we would like to have

```
min(2.4, 7.5);                  // This works
min(2.4, 7.5, 5.3);             // This works now
min(2.4, 7.5, 5.3, 1.2); // and this works too!

// This just works!
min(2.4, 7.5, 5.3, 1.2, 3.4, 6.7, 8.9, 9.1);
```

Recall: function overloading

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

template <Comparable T>
T min(const T& a, const T& b, const T& c) {
   auto m = min(b, c);
   return a < m ? a : m;
}

template <Comparable T>
T min(const T& a, const T& b, const T& c, const T& d) {
   auto m = min(b, c, d);
   return a < m ? a : m;
}
```

3 element overload calls 2 element

4 element overload calls 3 element

Seems almost recursive!

Introducing… variadic templates

Variadic Templates

```
template <Comparable T>
T min(const T& v) { return v; }

template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args) {
   auto m = min(args...);
   return v < m ? v : m;
}
```

Variadic Templates

Base case function:

Needed to stop recursion

```
template <Comparable T>
T min(const T& v) { return v; }


template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args) {
   auto m = min(args...);
   return v < m ? v : m;
}
```

Variadic Templates

Base case function:
Needed to stop recursion

```
template <Comparable T>
T min(const T& v) { return v; }


template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args) {
   auto m = min(args...);
   return v < m ? v : m;
}
```

Variadic Templates

Base case function:
Needed to stop recursion

Variadic template:
matches 0 or more *types*

```
template <Comparable T>
T min(const T& v) { return v; }

template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args) {
   auto m = min(args...);
   return v < m ? v : m;
}
```

Variadic Templates

Base case function:
Needed to stop recursion

```
template <Comparable T>
T min(const T& v) { return v; }

template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args) {
   auto m = min(args...);
   return v < m ? v : m;
}
```

Variadic template:
matches 0 or more *types*

Parameter pack: 0 or more *parameters*

Variadic Templates

Base case function:
Needed to stop recursion

```
template <Comparable T>
T min(const T& v) { return v; }

template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args) {
   auto m = min(args...);
   return v < m ? v : m;
}
```

Variadic template:
matches 0 or more *types*

Parameter pack: 0 or more *parameters*

Pack expansion:
replaces ...args with actual parameters

Variadic Templates

Base case function:
Needed to stop recursion

```
template <Comparable T>
T min(const T& v) { return v; }

template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args) {
   auto m = min(args...);
   return v < m ? v : m;
}
```

Variadic template:
matches 0 or more *types*

Parameter pack: 0 or more *parameters*

Pack expansion:
replaces ...args with actual parameters

Phew… this is a lot to unpack

(no pun intended)

What's going on?

Recursive Case:

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

Base Case:

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
min(2, 7, 5, 1)
```

Implicit instantiation!

What happens when the compiler sees a function call like this?

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
Args = [int, int, int]
```

```
min<int, int, int, int>(2, 7, 5, 1)
```

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args) {
   auto m = min(args...);
   return v < m ? v : m;
}
```

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
Args = [int, int, int]
```

```
min<int, int, int, int>(2, 7, 5, 1)
```

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args) {
    auto m = min(args...);
    return v < m ? v : m;
}
```

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
Args = [int, int, int]
```

```
min<int, int, int, int>(2, 7, 5, 1)
```

```
template <Comparable... Args>
int min(const int& v, const Args&... args) {
    auto m = min(args...);
    return v < m ? v : m;
}
```

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

T = int
Args = [int, int, int]

```
min<int, int, int, int>(2, 7, 5, 1)
```

```
template <Comparable... Args>
int min(const int& v, const Args&... args) {
    auto m = min(args...);
    return v < m ? v : m;
}
```

Pack expansion: Args is expanded

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
Args = [int, int, int]
```

```
min<int, int, int, int>(2, 7, 5, 1)
```

```
template <Comparable... Args>
int min(const int& v, const int& a0, const int& a1, const int& a2) {
    auto m = min(args...);
    return v < m ? v : m;
}
```

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

T = int
Args = [int, int, int]

```
min<int, int, int, int>(2, 7, 5, 1)
```

```
template <Comparable... Args>
int min(const int& v, const int& a0, const int& a1, const int& a2) {
    auto m = min(args...);
    return v < m ? v : m;
}
```

Pack expansion: args is expanded

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
Args = [int, int, int]
```

```
min<int, int, int, int>(2, 7, 5, 1)
```

```
int min(const int& v, const int& a0, const int& a1, const int& a2) {
    auto m = min(a0, a1, a2);
    return v < m ? v : m;
}
```

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
Args = [int, int, int]
```

```
min<int, int, int, int>(2, 7, 5, 1)
```

```
int min(const int& v, const int& a0, const int& a1, const int& a2) {
    auto m = min(a0, a1, a2);
    return v < m ? v : m;
}
```

What did we just generate?

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
Args = [int, int, int]
```

```
min<int, int, int, int>(2, 7, 5, 1)
```

```
int min(const int& v, const int& a0, const int& a1, const int& a2) {
    auto m = min(a0, a1, a2);
    return v < m ? v : m;
}
```

Voila! The compiler **generated an overload** for us!!!

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
min<int, int, int, int>(2, 7, 5, 1)
```

T = int

Args = [int, int, int]

```
int min(const int& v, const int& a0, const int& a1, const int& a2) {
    auto m = min(a0, a1, a2);
    return v < m ? v : m;
}
```

Wait... what is this?

It's another template instantiation!

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
Args = [int, int]
```

```
min<int, int, int>(a0, a1, a2);
```

```
int min(const int& v, const int& a0, const int& a1) {
    auto m = min(a0, a1);
    return v < m ? v : m;
}
```

Hey look! Another template instantiation

What's going on?

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
Args = [int]
```

```
min<int, int>(a0, a1);
```

```
int min(const int& v, const int& a0) {
    auto m = min(a0);
    return v < m ? v : m;
}
```

Hey look! Another template instantiation

What's going on?

✅ Compiler always tries to choose most specific template

```
template <Comparable T, Comparable... Args>
T min(const T& v, const Args&... args)
```

```
T = int
Args = []
```

```
template <Comparable T>
T min(const T& v) { return v; }
```

```
T = int
```

```
min<int>(a0);
```

```
int min(const int& v) {
    return v;
}
```

What just happened?

A single call to `min(2, 7, 5, 1)` generated the following functions

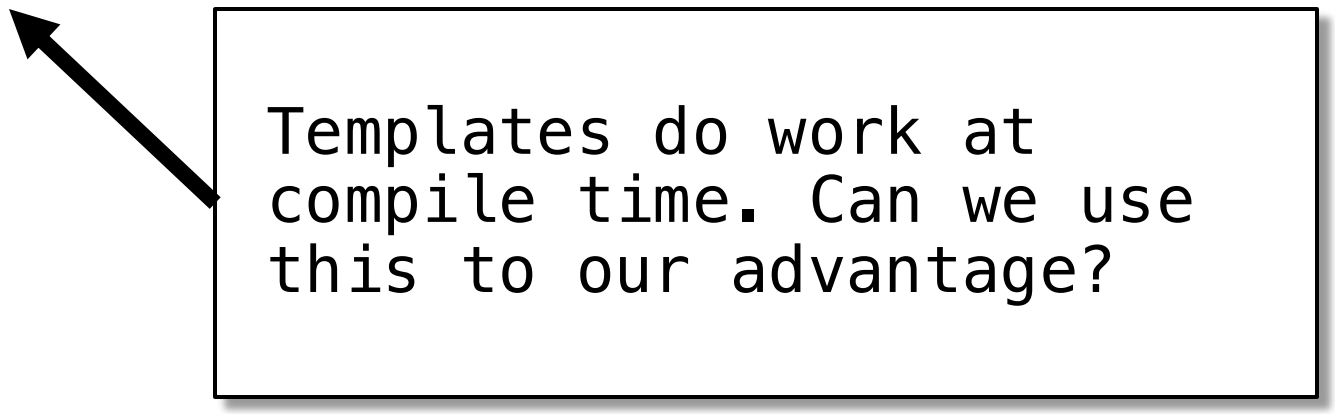
```
min(2, 7, 5, 1);

min<int, int, int, int>  // T = int, Args = [int, int, int]
min<int, int, int>       // T = int, Args = [int, int]
min<int, int>            // T = int, Args = [int]
min<int>                 // T = int
```

What questions do you have?

bjarne_about_to_raise_hand

Variadic templates recap

- Compiler generates any number of overloads using recursion
  - This allows us to support any number of function parameters
- For more advanced variadic templates, check the hidden slides!
  - If you're curious, this technique is how `std::tuple<T1,T2,…>` works!
- Instantiation happens at compile time



Template Metaprogramming

How can we do work at compile time?

TMP Basics: Factorial

```
template <>
struct Factorial<0> {
   enum { value = 1 };
};

template <size_t N>
struct Factorial {
   enum { value = N * Factorial<N - 1>::value };
};

std::cout << Factorial<7>::value << std::endl;
```

Base Case:

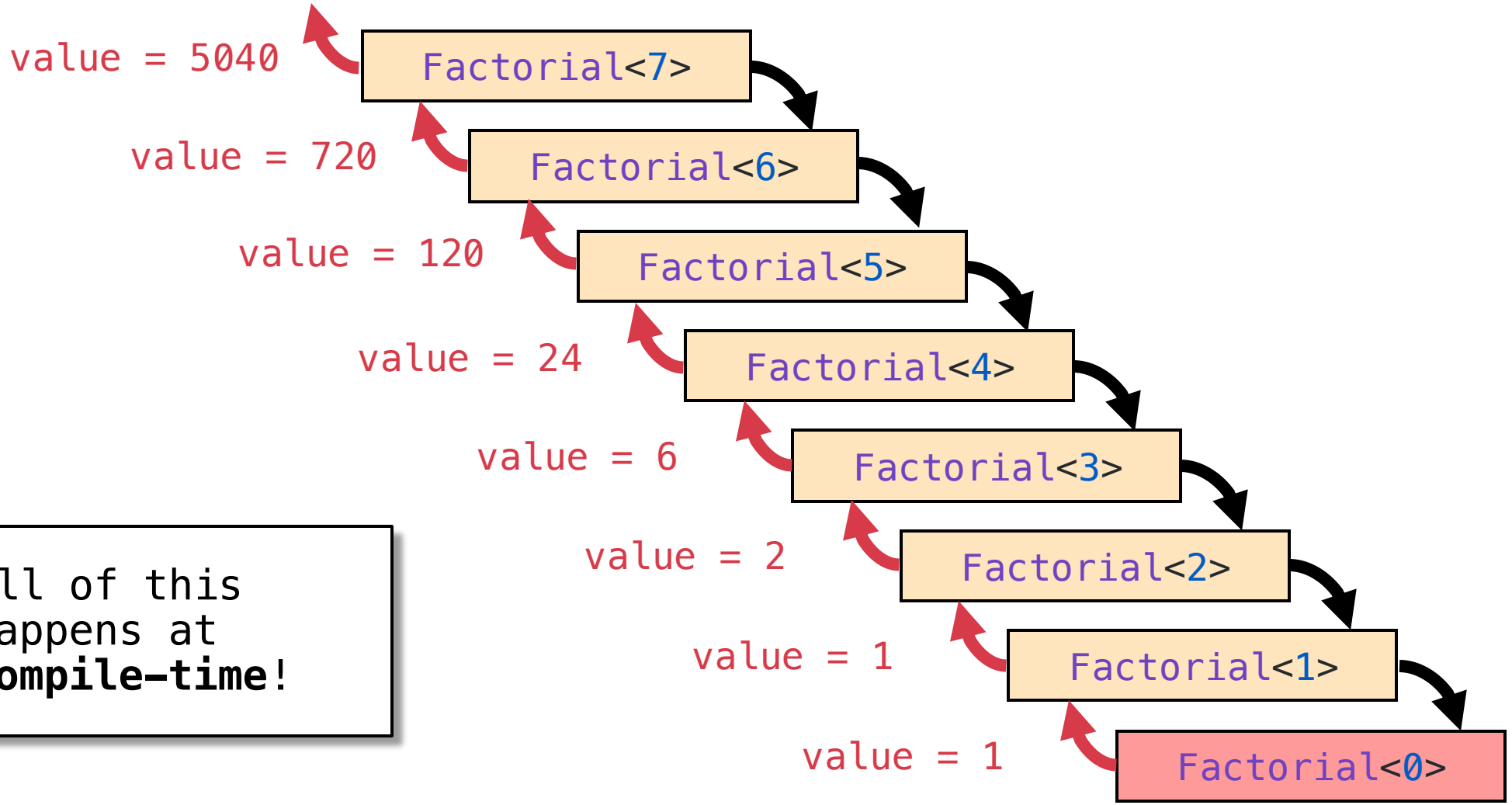
This is a *template specialization* for N=0

enum: a way to store a compile-time constant

Oooh compile-time recursion

Prints **5040**, but computes at compile time

Template instantiations for `Factorial<7>`



All of this happens at **compile-time**!

Output assembly of `Factorial<7>`

```
int main() {
    std::cout << Factorial<7>::value;
    return 0;
}
```

```
main:
    push rax
    mov edi, offset cout
    mov esi, 5040
    call ostream::operator<<(int)
    xor eax, eax
    pop rcx
    ret
```

Result is **baked in** to the executable

What questions do you have?

bjarne_about_to_raise_hand

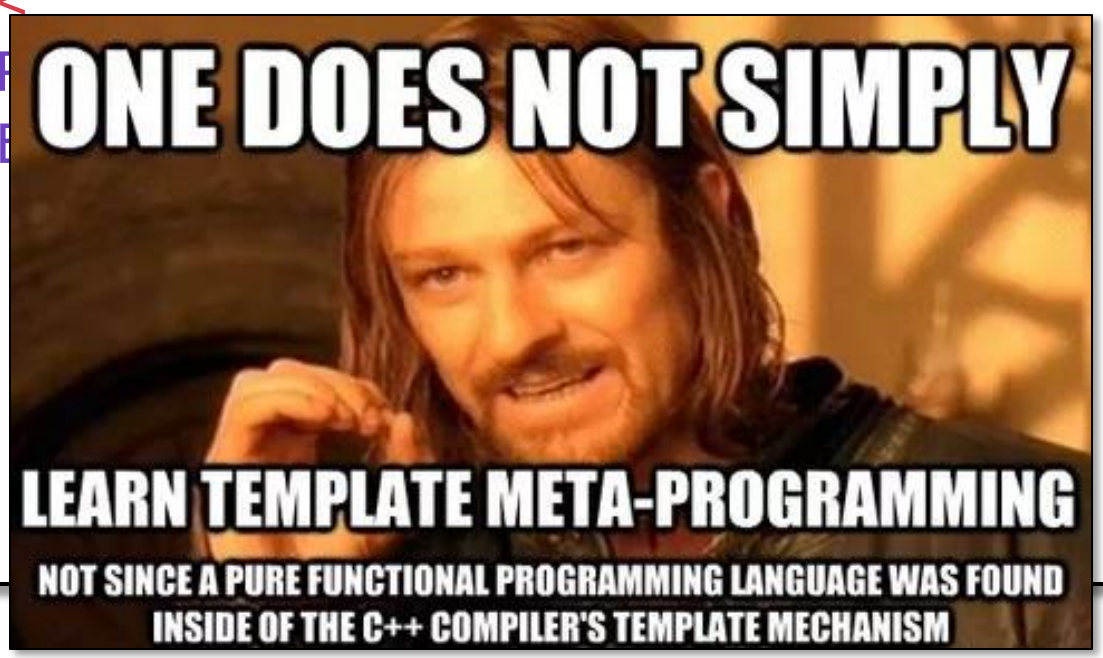
What is TMP?

TMP is Turing complete

We can execute arbitrary code at compile time

But the syntax is not always pretty...

```
template<>
struct push_back_impl< aux::vector_tag<BOOST_PP_DEC(i_)> >
{
   template< typename Vector, typename T > struct apply
   {
      typedef BOOST_PP_CAT(vector,i_)<
         BOOST_PP_ENUM_PARAMS(BOOST_PP
         BOOST_PP_COMMA_IF(BOOST_PP_DE
         T
         > type;
   };
};
```



How can we have

1) Compile-time execution

2) Readable code

Instead of this...

```
template <>
struct Factorial<0> {
   enum { value = 1 };
};

template <size_t N>
struct Factorial {
   enum { value = N * Factorial<N - 1>::value };
};

std::cout << Factorial<7>::value << std::endl;
```

Use constexpr/consteval

An institutionalization of template metaprogramming (new in C++20)

```
constexpr size_t factorial(size_t n) {
   if (n == 0) return 1;
   return n * factorial(n - 1);
}

consteval size_t factorial(size_t n) {
   if (n == 0) return 1;
   return n * factorial(n - 1);
}
```

constexpr

"Dear compiler, please *try* to run me at compile time 😘"

consteval

"Dear compiler, YOU MUST RUN ME AT COMPILE TIME 😡😡"

What questions do you have?

bjarne_about_to_raise_hand

Recap

When should I use templates?

- I want the compiler to automate a repetitive coding task
  - Template functions, variadic templates
- I want better error messages
  - Concepts
- I don’t want to wait until runtime
  - Template metaprogramming, constexpr/consteval

Next Time: Functions and Algorithms

Writing smarter, more flexible algorithms