



 <http://web.stanford.edu/class/cs106l/>



Functions and Lambdas

How can we make template functions even more general?

CS106L - Spring 23

Attendance!

<https://bit.ly/44knqp8>





Announcements!

- No class **next week** – midquarter break!
 - Office hours during class time (3-4:30pm)
 - Review material from the lectures so far!
- After this lecture, you will be able to complete Assignment 1!
 - Due **May 12th!**



 <http://web.stanford.edu/class/cs106l/>



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01. Recap: Template Functions



02. Functions and Lambdas

Passing input outside of parameters

03. Algorithms



CONTENTS



01. Recap: Template Functions



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03. Algorithms

Template functions are completely generic functions!

Just like classes, they work regardless of type!

Let's break it down:

Indicating this
function is a template

Specifies that
Type is generic

List of your
template
variables

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

Calling template functions

We can **explicitly** define what type we will pass, like this:

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

// int main() {} will be omitted from future examples
// we'll instead show the code that'd go inside it
cout << myMin<int>(3, 4) << endl; // 3
```



**Just like in
template classes!**

Calling template functions

We can also **implicitly** leave it for the compiler to deduce!

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

```
// int main() {} will be omitted from future examples  
// we'll instead show the code that'd go inside it  
cout << myMin(3.2, 4) << endl; // 3.2
```


Review: Template Functions

- Template functions allow you to parametrize the type of a function to be anything without changing functionality
- Generic programming can solve a complicated conceptual problem for any specifics – powerful and flexible!
- Template code is instantiated at compile time; template metaprogramming takes advantage of this to run code at compile time



CONTENTS



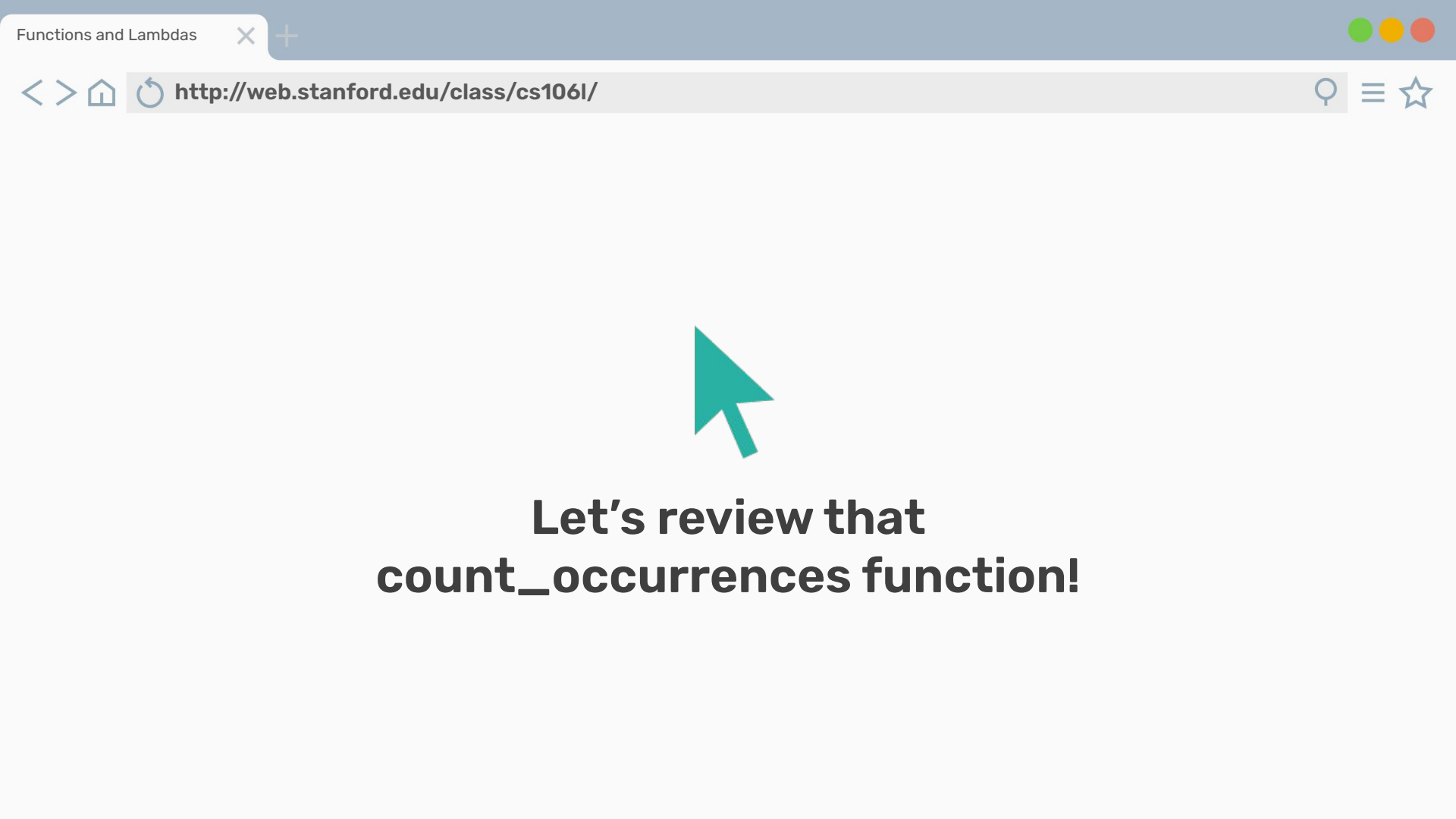
01. Recap: Template Functions



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**Let's review that
count_occurrences function!**

This is a successfully templated function!

This code will work for any containers with any types, for a single specific target.

```
template <typename InputIt, typename DataType>
int count_occurrences(InputIt begin, InputIt end, DataType val) {
    int count = 0;
    for (auto iter = begin; iter != end; ++iter) {
        if (*iter == val) count++;
    }
    return count;
}
```

Usage: `std::string str = "Xadia";`
`count_occurrences(str.begin(), str.end(), 'a');`

This is a successfully templated function!

This code will work for any containers with any types, for a single specific target.

Will this work for a more general category of targets than one specific value?

```
template <typename InputIt, typename DataType>
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        if (*iter == val) count++;
    }
    return count;
}
```

Usage: `std::string str = "Xadia";`
`count_occurrences(str.begin(), str.end(), 'a');`

What if we wanted to find all the vowels in "Xadia"?

This is a successfully templated function!

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Will this work for a more general category of targets than one specific value?

```
template <typename InputIt, typename DataType>
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    }
    return count;
}
```

isVowel(*iter) ?

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Predicate Functions

Any function that returns a boolean value is a predicate!



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```
bool isLowercaseA(char c) {  
    return c == 'a';  
}  
  
bool isVowel(char c) {  
    std::string vowels = "aeiou";  
    return vowels.find(c) != std::string::npos;  
}
```

```
bool isMoreThan(int num, int limit) {  
    return num > limit;  
}  
  
bool isDivisibleBy(int a, int b) {  
    return (a % b == 0);  
}
```

Predicate Functions

Any function that returns a boolean value is a predicate!

- `isVowel()` is an example of a predicate, but there are tons of others we might want!
- A predicate can have any amount of parameters...

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bool isLowercaseA(char c) {  
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Predicate Functions

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- `isVowel()` is an example of a predicate, but there are tons of others we might want!
- A predicate can have any amount of parameters...

Unary

```
bool isLowercaseA(char c) {  
    return c == 'a';  
}  
  
bool isVowel(char c) {  
    std::string vowels = "aeiou";  
    return vowels.find(c) != std::string::npos;  
}
```

Binary

```
bool isMoreThan(int num, int limit) {  
    return num > limit;  
}  
  
bool isDivisibleBy(int a, int b) {  
    return (a % b == 0);  
}
```

Let's use that!

```
template <typename InputIt, typename DataType, typename UniPred>
int count_occurrences(InputIt begin, InputIt end, UniPred pred) {
    int count = 0;
    for (auto iter = begin; iter != end; ++iter) {
        if (*iter == val pred(*iter)) count++;
    }
    return count;
}
```

```
bool isVowel(char c) {
    std::string vowels = "aeiou";
    return vowels.find(c) != std::string::npos;
}
```

```
Usage: std::string str = "Xadia";
       count_occurrences(str.begin(), str.end(), isVowel);
```

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```
template <typename InputIt, typename DataType, typename UniPred>
int count_occurrences(InputIt begin, InputIt end, UniPred pred) {
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bool isVowel(char c) {
    std::string vowels = "aeiou";
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bool isVowel(char c) {
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Usage: std::string str = "Xadia";
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bool isVowel(char c) {
    std::string vowels = "aeiou";
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```

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Usage: std::string str = "Xadia";
       count_occurrences(str.begin(), str.end(), isVowel);
```

What type is UniPred???

Let's use that!

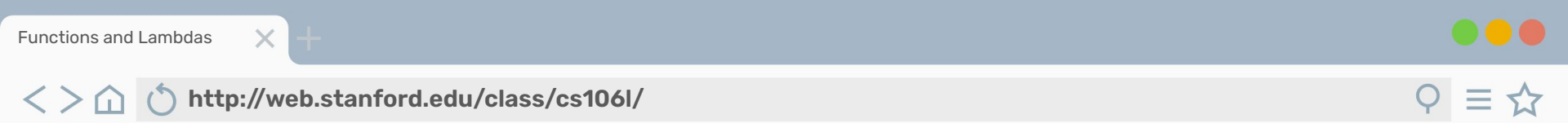
```
template <typename InputIt, typename DataType, typename UniPred>  
int count_occurrences(InputIt begin, InputIt end, UniPred pred) {  
    int count = 0;  
    for (auto iter = begin; iter != end; ++iter) {  
        if (pred(*iter)) ++count;  
    }  
    return count;  
}
```

```
bool isVowel(char c) {  
    std::string vowels = "aeiou";  
    return vowels.find(c) != std::string::npos;  
}
```

```
Usage: std::count_occurrences(begin, end, isVowel);
```



What type is UniPred???



Function Pointers

UniPred is what's called a **function pointer**!

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Function Pointers

UniPred is what's called a **function pointer**!

- Function pointers can be treated just like other pointers
- They can be passed around like variables as parameters or in template functions!
- They can be called like functions!

Is this good enough?

Are there any ways this could be an issue?

```
template <typename InputIt, typename DataType, typename UniPred>
int count_occurrences(InputIt begin, InputIt end, UniPred pred) {
    int count = 0;
    for (auto iter = begin; iter != end; ++iter) {
        if (*iter == val pred(*iter)) count++;
    }
    return count;
}
```

```
bool isVowel(char c) {
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}
```

```
Usage: std::string str = "Xadia";
       count_occurrences(str.begin(), str.end(), isVowel);
```

Poor Generalization

Unary predicates are pretty limited and don't generalize well.

```
bool isMoreThan3(int num) {  
    return num > 3;  
}  
  
bool isMoreThan4(int num) {  
    return num > 4;  
}  
  
bool isMoreThan5(int num) {  
    return num > 5;  
}
```


Poor Generalization

Unary predicates are pretty limited and don't generalize well.

Ideally, we'd like something like this!

```
bool isMoreThan3(int num) {  
    return num > 3;  
}  
  
bool isMoreThan4(int num) {  
    return num > 4;  
}  
  
bool isMoreThan5(int num) {  
    return num > 5;  
}  
  
// a generalized version of the above  
bool isMoreThan(int num, int limit) {  
    return num > limit;  
}
```

Can we use binary predicates?


If we could, it would be nice to use a binary predicate to handle this!

```
template <typename InputIt, typename BinPred>
int count_occurrences(InputIt begin, InputIt end, BinPred pred) {
    int count = 0;
    for (auto iter = begin; iter != end; ++iter) {
        if (pred(*iter, ???)) count++;
    }
    return count;
}
```

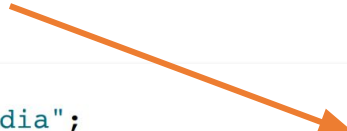
Can we use binary predicates?

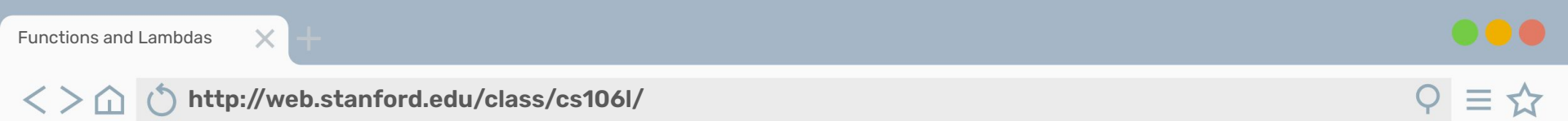
How do we know what value to use? What about unary (or any other number of arguments) predicates?

```
template <typename InputIt, typename BinPred>
int count_occurrences(InputIt begin, InputIt end, BinPred pred) {
    int count = 0;
    for (auto iter = begin; iter != end; ++iter) {
        if (pred(*iter, ???)) count++;
    }
    return count;
}
```

 **We can't pass this in from the predicate!**

Usage: `std::string str = "Xadia";`
`count_occurrences(str.begin(), str.end(), isVowel);`





The Catch-22

We want our function to know more information about our predicate.



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However, we can't pass in more than one parameter.

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We want our function to know more information about our predicate.

However, we can't pass in more than one parameter.

How can we pass along information without needing another parameter?

Let's use lambdas!

Lambdas are inline, anonymous functions that can know about functions declared in their same scope!

```
auto var = [capture-clause] (auto param) -> bool
{
    ...
}
```

Let's use lambdas!

Lambdas are **inline**, anonymous functions that can know about variables declared in their same scope!

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auto var = [capture-clause] (auto param) -> bool
{
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}
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{
    ...
}
```

Let's use lambdas!

Lambdas are inline, **anonymous** functions that can know about variables declared in their same scope!

Outside parameters
go here

Specifies that
Type is generic

```
auto var = [capture-clause] (auto param) -> bool
{
    ...
}
```

Function body
goes here!

Let's use lambdas!

It might look something like this!

```
int limit = 5;  
auto isMoreThan = [limit] (int n) { return n > limit; };  
isMoreThan(6); // true
```

Let's use lambdas!

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int limit = 5;  
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isMoreThan(6); // true
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Capture Clauses

You can capture any outside variable, both by reference and by value.

```
[ ]           // captures nothing
[limit]       // captures limit by value
[&limit]      // captures limit by reference
[&limit, upper] // captures limit by reference, upper by value
[&, limit]    // captures everything except limit by reference
[&]          // captures everything by reference
[=]          // captures everything by value
```

Capture Clauses

You can capture any outside variable, both by reference and by value.

- Use just the = symbol to capture everything by value, and just the & symbol to capture everything by reference

```
[ ]           // captures nothing
[limit]       // captures limit by value
[&limit]      // captures limit by reference
[&limit, upper] // captures limit by reference, upper by value
[&, limit]    // captures everything except limit by reference
[&]           // captures everything by reference
[=]           // captures everything by value
```

We've solved our problem!

```
template <typename InputIt, typename UniPred>
int count_occurrences(InputIt begin, InputIt end, UniPred pred) {
    int count = 0;
    for (auto iter = begin; iter != end; ++iter) {
        if (pred(*iter)) count++;
    }
    return count;
}
```

Usage:

```
int limit = 5;
auto isMoreThan = [limit] (int n) { return n > limit; };
std::vector<int> nums = {3, 5, 6, 7, 9, 13};

count_occurrences(nums.begin(), nums.end(), isMoreThan);
```

We've solved our problem!

```
template <typename InputIt, typename UniPred>
int count_occurrences(InputIt begin, InputIt end, UniPred pred) {
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    }
    return count;
}
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Usage:

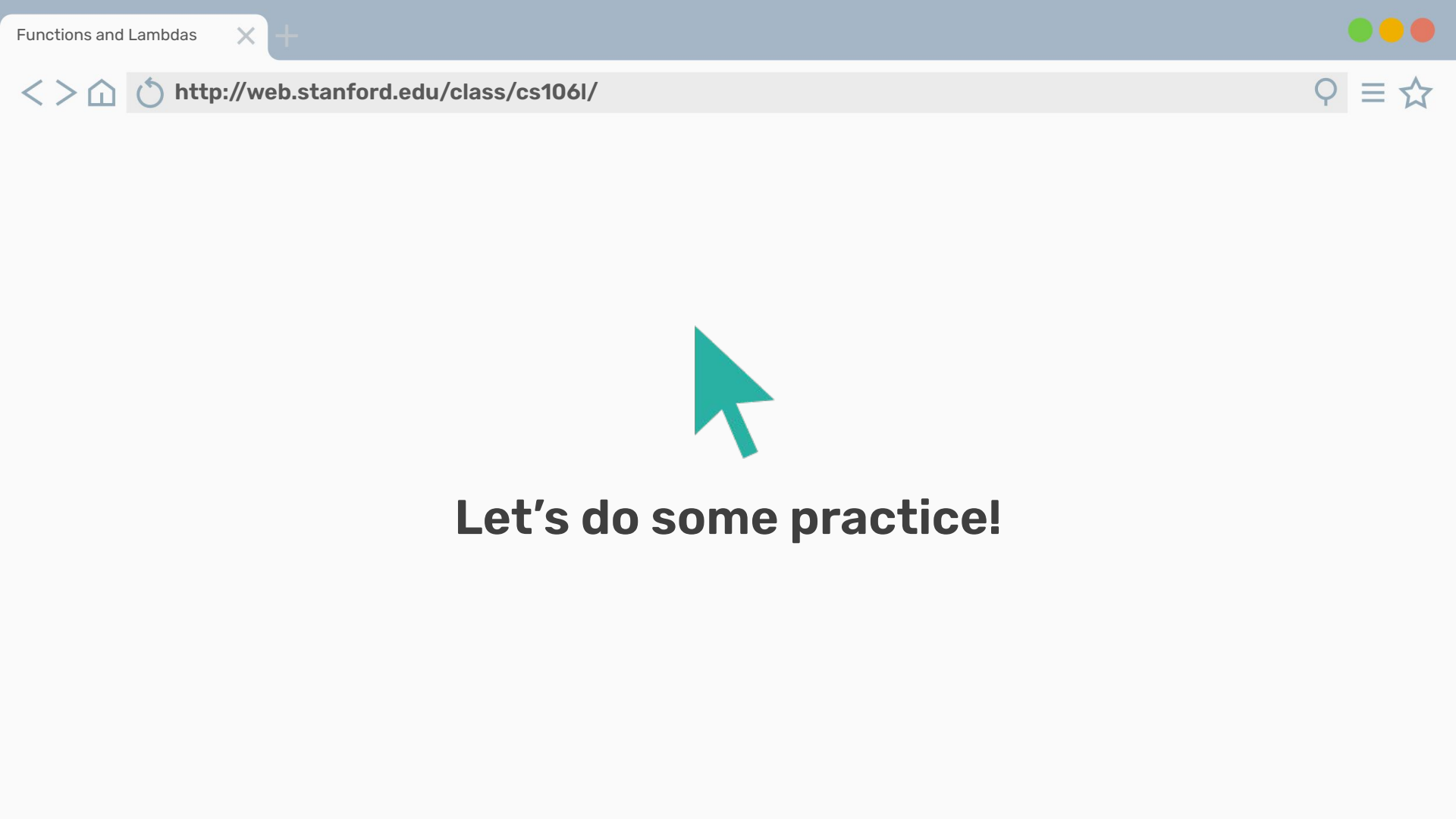
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std::vector<int> nums = {3, 5, 6, 7, 9, 13};

count_occurrences(nums.begin(), nums.end(), isMoreThan);
```


Using Lambdas

Lambdas are pretty computationally cheap and a great tool!

- Use a lambda when you need a short function or to access local variables in your function.
- If you need more logic or overloading, use function pointers.



Let's do some practice!

Aside: What the Functor?

A **functor** is any class that provides an implementation of `operator()`.

```
class functor {  
public:  
    int operator() (int arg) const { // parameters and function body  
        return num + arg;  
    }  
private:  
    int num; // capture clause  
};  
  
int num = 0;  
auto lambda = [&num] (int arg) { num += arg; };  
lambda(5);
```

Aside: What the Functor?

A **functor** is any class that provides an implementation of `operator()`.

- They can create **closures** of “customized” functions!

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Closure: a single instantiation of a functor object

Aside: What the Functor?

A **functor** is any class that provides an implementation of `operator()`.

- They can create **closures** of “customized” functions!
- Lambdas are just a reskin of functors!

```
class functor {  
public:  
    int operator() (int arg) const { // parameters and function body  
        return num + arg;  
    }  
private:  
    int num; // capture clause  
};  
  
int num = 0;  
auto lambda = [&num] (int arg) { num += arg; };  
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Closure: a single instantiation of a functor object



Tying it all together

So far, we've talked about lambdas, functors, and function pointers.



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std::function<return_type (param_types)> func;
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The STL has an overarching, standard function object!

```
std::function<return_type (param_types)> func;
```

Everything (lambdas, functors, function pointers) can be cast to a standard function!



Much bigger and more expensive than a function pointer or lambda!

Aside: Virtual Functions

Be careful using function pointers with classes, especially if you have a subclass of another class!

```
class Animal {  
    // constructors and other methods go here!  
    void speak() {  
        std::cout << "I'm an animal!" << std::endl;  
    } // private information and the rest of the class goes here!  
}  
  
class Dog : Animal { // this syntax tells us we're a subclass of Animal!  
    // constructors and private information here!  
    void speak() {  
        std::cout << "I'm an animal!" << std::endl;  
    } // private information and the rest of the class goes here!  
}
```

Aside: Virtual Functions

What happens if we try to pass a Dog object to a function that expects an Animal?

```
void func(Animal* animal) { // can take in any animal and make it speak!
    animal->speak();
}

int main() {
    Animal* myAnimal = new Animal;
    Dog* myDog = new Dog;
    func(myAnimal);
    func(myDog);
}
```

Aside: Virtual Functions

What happens if we try to pass a Dog object to a function that expects an Animal?

```
void func(Animal* animal) { // can take in any animal and make it speak!
    animal->speak();
}

int main() {
    Animal* myAnimal = new Animal;
    Dog* myDog = new Dog;
    func(myAnimal); \\ I'm an animal!
    func(myDog);    \\ I'm an animal!
}
```

The function expects an Animal, so it will try to use the Animal speak function! It doesn't know it's been overridden!



Aside: Virtual Functions

If you have a function that can take in a pointer to the superclass, it won't know to use the subclass's function!



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To fix this, we can mark the overridden function as **virtual** in the header!

Aside: Virtual Functions

If you have a function that can take in a pointer to the superclass, it won't know to use the subclass's function!

The same issue happens if we create a superclass pointer to an existing subclass object.

To fix this, we can mark the overridden function as **virtual** in the header!

Virtual functions are functions in the superclass we expect to be overridden later on.

Aside: Virtual Functions

Let's change Animal to have a virtual implementation of speak()!

```
class Animal {  
    // constructors and other methods go here!  
    virtual void speak() {  
        std::cout << "I'm an animal!" << std::endl;  
    } // private information and the rest of the class goes here!  
}  
  
class Dog : Animal { // this syntax tells us we're a subclass of Animal!  
    // constructors and private information here!  
    void speak() {  
        std::cout << "I'm an animal!" << std::endl;  
    } // private information and the rest of the class goes here!  
}
```

Aside: Virtual Functions

Let's change Animal to have a virtual implementation of speak()!

```
void func(Animal* animal) { // can take in any animal and make it speak!
    animal->speak();
}

int main() {
    Animal* myAnimal = new Animal;
    Dog* myDog = new Dog;
    func(myAnimal); \\ I'm an animal!
    func(myDog);    \\ I'm a dog!
}
```

**Now calling speak() will use
the correct subclass version!**



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Coding Philosophy 101

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1. Look both ways before crossing the street.



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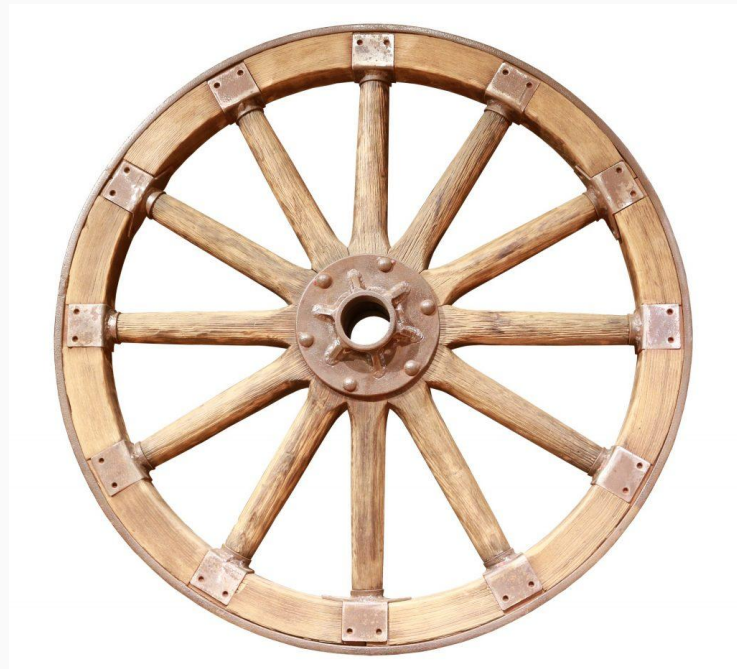
1. Look both ways before crossing the street.
2. Never tell a pre-med you're stressed.



Coding Philosophy 101

There are few universal, scientifically proven pieces of wisdom that will lead to a happier life:

1. Look both ways before crossing the street.
2. Never tell a pre-med you're stressed.
3. When coding, never reinvent the wheel.



New toys!

The STL implements an entire library of algorithms written by C++ developers!

- To utilize, `#include <algorithm>` in your file!
- All algorithms are **fully generic, templated** functions!

```

Constrained algorithms and algorithms on ranges (C++20)
Constrained algorithms, e.g. ranges::copy, ranges::sort, ...
Execution policies (C++17)
execution::seq          (C++17) execution::sequenced_policy
execution::par          (C++17) execution::parallel_policy
execution::par_unseq    (C++17) execution::parallel_unsequenc
execution::unseq        (C++20) execution::parallel_unsequenc
is_execution_policy (C++17)

Non-modifying sequence operations
all_of (C++11)          count          search
any_of (C++11)          count_if       search_n
none_of (C++11)         mismatch      lexicographical_compare
for_each                equal          lexicographical_compare_three
for_each_n (C++17)      adjacent_find

Modifying sequence operations
copy                    fill          remove
copy_if (C++11)         fill_n       remove_if
copy_n (C++11)          generate     replace
copy_backward           generate_n   replace_if
move (C++11)            swap        reverse
move_backward (C++11)  iter_swap   rotate
shift_left (C++20)      swap_ranges unique
shift_right (C++20)     sample (C++17) random_shuffle (until C++17)
transform

Partitioning operations
is_partitioned (C++11)  partition    stable_partition
partition_point (C++11) partition_copy (C++11)

Sorting operations
is_sorted (C++11)      sort        partial_sort
is_sorted_until (C++11) stable_sort    partial_sort_copy

Binary search operations
lower_bound            upper_bound    binary_search

Set operations (on sorted ranges)
merge                  set_difference set_symmetric_difference
inplace_merge          set_intersection set_union

Heap operations

```

What kind of algorithms?

With the algorithm library, we can...

```
#include <algorithm>:
```

What kind of algorithms?

With the algorithm library, we can...

- check if a condition is true across any elements

```
#include <algorithm>:
```

```
any_of  all_of  none_of
```

What kind of algorithms?

With the algorithm library, we can...

- check if a condition is true across any elements
- apply a function to all elements in a container

```
#include <algorithm>:  
  
any_of    all_of    none_of  
  
for_each
```

What kind of algorithms?

With the algorithm library, we can...

- check if a condition is true across any elements
- apply a function to all elements in a container
- search for specific elements or a range

```
#include <algorithm>:  
  
any_of  all_of  none_of  
  
        for_each  
  
        find      search
```

What kind of algorithms?

With the algorithm library, we can...

- check if a condition is true across any elements
- apply a function to all elements in a container
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```
#include <algorithm>:
```

```
any_of  all_of  none_of
```

```
for_each
```

```
find
```

```
search
```

What kind of algorithms?

With the algorithm library, we can...

- check if a condition is true across any elements
- apply a function to all elements in a container
- search for specific elements or a range
- copy, remove, add elements from one container to another

```
#include <algorithm>:
```

```
any_of  all_of  none_of
```

```
for_each
```

```
find      search
```

```
copy
```

What kind of algorithms?

With the algorithm library, we can...

- check if a condition is true across any elements
- apply a function to all elements in a container
- search for specific elements or a range
- copy, remove, add elements from one container to another
- and much, much more!

```
#include <algorithm>:  
  
any_of  all_of  none_of  
  
        for_each  
  
        find      search  
  
        copy
```


Look familiar?

count_occurrences

```
template <typename InputIt, typename UniPred>  
int count_occurrences(InputIt begin, InputIt end, UniPred pred);
```

Look familiar?

count_occurrences

```
template <typename InputIt, typename UniPred>
int count_occurrences(InputIt begin, InputIt end, UniPred pred);
```

std::count_if

```
template< class InputIt, class T >
typename iterator_traits<InputIt>::difference_type
count( InputIt first, InputIt last, const T& value );
```



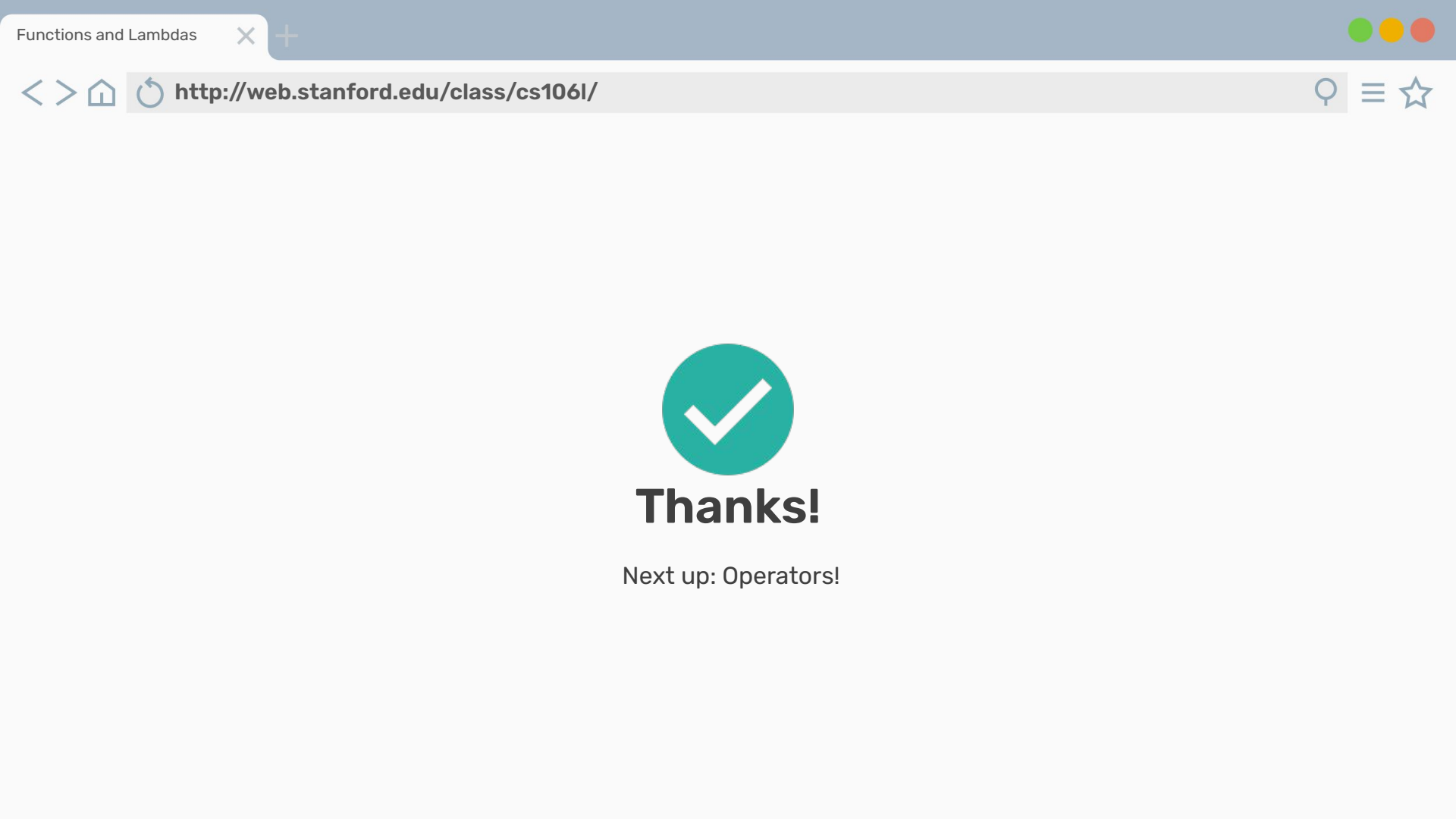
Algorithms

All standard algorithms work on iterators.

- Efficient searching, sorting, complex data structure operations, smart pointers, and more are all there for you to use!
- Check out the documentation to get more information!

Summary

- Lambda functions are inline functions that let you pass outside variables in using capture clauses!
- Lambdas can be used to pass predicate function pointers to template functions for more generalizability.
- The STL implements tons of cool algorithms that we can use without rewriting them!



Thanks!

Next up: Operators!