

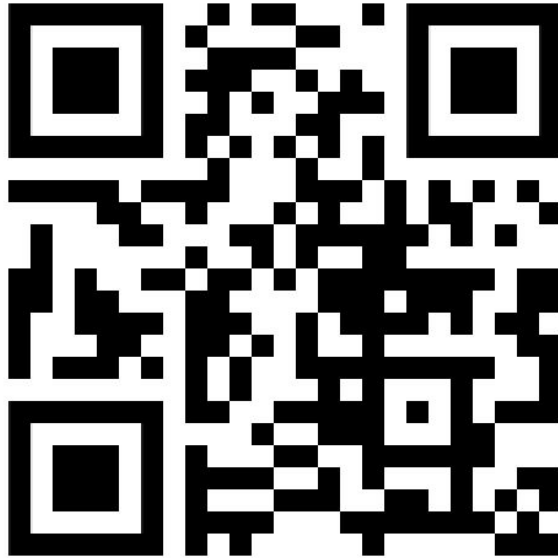
CS106L Lecture 14:

`std::optional` & type safety!

Winter 2024

Fabio Ibanez, Haven Whitney

Attendance



<https://tinyurl.com/safetyW24>

Important

We want you to pass :)

Important

To pass:

- 1. complete 5/7 assignments**
- 2. Come to class!**

Plan

1. Type safety
2. `std::optional`
 - Looking at real world applications of this stuff too!

Recapping some shtuff

Move semantics

- We have move semantics because sometimes the resource we're going to take is no longer needed by the original owner

Recapping some shtuff

Move semantics

- We have move semantics because sometimes the resource we're going to take is no longer needed by the original owner
- Use `std::move(x)` to turn `x`, an l-value, to an r-value so that you can immediately take its resources

Recapping some shtuff

Move semantics

- We have move semantics because sometimes the resource we're going to take is no longer needed by the original owner
- Use `std::move(x)` to turn `x`, an l-value, to an r-value so that you can immediately take its resources
- **Rule of zero:** if you have self-managing member variables, and don't need to define custom constructors, and operators, then don't!

Recapping some shtuff

Move semantics

- We have move semantics because sometimes the resource we're going to take is no longer needed by the original owner
- Use `std::move(x)` to turn `x`, an l-value, to an r-value so that you can immediately take its resources
- **Rule of zero:** if you have self-managing member variables, and don't need to define custom constructors, and operators, then don't!
- **Rule of three:** if you define a custom destructor then you need to also define a custom copy constructor and copy assignment operator.

Recapping some shtuff

Move semantics

- We have move semantics because sometimes the resource we're going to take is no longer needed by the original owner
- Use `std::move(x)` to turn `x`, an l-value, to an r-value so that you can immediately take its resources
- **Rule of Zero:** if you have self-managing member variables, and don't need to define custom constructors, and operators, then don't!
- **Rule of Three:** if you define a custom destructor then you need to also define a custom copy constructor and copy assignment operator.
- **Rule of Five:** If you have a custom copy constructor, and copy assignment operator, then you should also define a move constructor and a move assignment operator!

A definition!

Type Safety: The extent to which a language prevents typing errors.

Python (english) vs. C++

Python

```
def div_3(x):  
    return x / 3  
  
div_3("hello")
```

//CRASH during runtime,
can't divide a string

C++

```
int div_3(int x) {  
    return x / 3;  
}
```

```
div_3("hello")  
//Compile error: this code will  
never run
```

Python (english) vs. C++

Type Safety: The extent to which a language **guarantees the behavior of programs.**

What does this code do?

```
void removeOddsFromEnd (vector<int>& vec) {  
    while (vec.back() % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

vector::back() returns a reference to the last element in the vector

vector::pop_back() is like the opposite of **vector::push_back(elem)**. It removes the last element from the vector.

Anyone see a problem?

```
void removeOddsFromEnd (vector<int>& vec) {  
    while (vec.back() % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

vector::back() returns a reference to the last element in the vector

vector::pop_back() is like the opposite of **vector::push_back(elem)**. It removes the last element from the vector.

Anyone see a problem?

Hint!

```
void removeOddsFromEnd (vector<int>& vec)
    while (vec.back() % 2 == 1) {
        vec.pop_back();
    }
}
```

vector::back() returns a reference to the last element in the vector

vector::pop_back() is like the opposite of **vector::push_back(elem)**. It removes the last element from the vector.

Anyone see a problem?

```
void removeOddsFromEnd (vector<int>& vec) {  
    while (vec.back() % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

What if **vec** is {} / an empty vector!?

std::vector documentation

std::vector<T,Allocator>::back

reference back();	(until C++20)
constexpr reference back();	(since C++20)
const_reference back() const;	(until C++20)
constexpr const_reference back() const;	(since C++20)

Returns a reference to the last element in the container.

Calling back on an empty container causes **undefined behavior**.

Undefined behavior: Function could crash, could give us garbage, could accidentally give us some actual value

Taking another look at our code

```
void removeOddsFromEnd (vector<int>& vec) {  
    while (vec.back() % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

We can make no guarantees about what this function does!

Credit to Jonathan Müller of foonathan.net for the example!

One solution

```
void removeOddsFromEnd(vector<int>& vec) {  
    while(!vec.empty() && vec.back() % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

One solution

```
void removeOddsFromEnd(vector<int>& vec) {  
    while (!vec.empty() && vec.back() % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

Key idea: it is the **programmers job** to enforce the **precondition** that **vec** be non-empty, otherwise we get undefined behavior!

There may or may not be a “last element” in
`vec`

How can `vec.back()` have deterministic
behavior in either case?

The problem

```
valueType& vector<valueType>::back() {  
    return *(begin() + size() - 1);  
}
```

Dereferencing a pointer without verifying it points to real memory is undefined behavior!

The problem

```
valueType& vector<valueType>::back() {  
    if(empty()) throw std::out_of_range;  
    return *(begin() + size() - 1);  
}
```

Now, we will at least reliably error and stop the program **or** return the last element whenever back() is called

The problem

Deterministic behavior is great, but can we do better?

There may or may not be a “last element” in `vec`
How can `vec.back()` warn us of that when we
call it?

Revisiting our definition

Type Safety: The extent to which a **function signature** guarantees the behavior of a **function**.

Back to the problem

```
valueType& vector<valueType>::back() {  
    return *(begin() + size() - 1);  
}
```

back() is promising to return something of type **valueType** when its possible no such value exists!


A look at a first solution

```
std::pair<bool, valueType&> vector<valueType>::back() {  
    if(empty()) {  
        return {false, valueType()};  
    }  
    return {true, *(begin() + size() - 1)};  
}
```

back() now advertises that there may or may not be a last element

A look at a first solution

```
std::pair<bool, valueType&> vector<valueType>::back() {  
    if(empty()) {  
        return {false, valueType()};  
    }  
    return {true, *(begin() + size() - 1)};  
}
```



Default constructor
of **valueType()**

back() now advertises that there may or may not be a last element

Problems with `std::pair`

```
std::pair<bool, valueType&> vector<valueType>::back() {  
    if(empty()) {  
        return {false, valueType()};  
    }  
    return {true, *(begin() + size() - 1)};  
}
```

- **valueType** may not have a default constructor

Problems with `std::pair`

```
std::pair<bool, valueType&> vector<valueType>::back() {  
    if(empty()) {  
        return {false, valueType()};  
    }  
    return {true, *(begin() + size() - 1)};  
}
```

- **valueType** may not have a default constructor
- Even if it does, calling constructors is **expensive**

Problems with `std::pair`

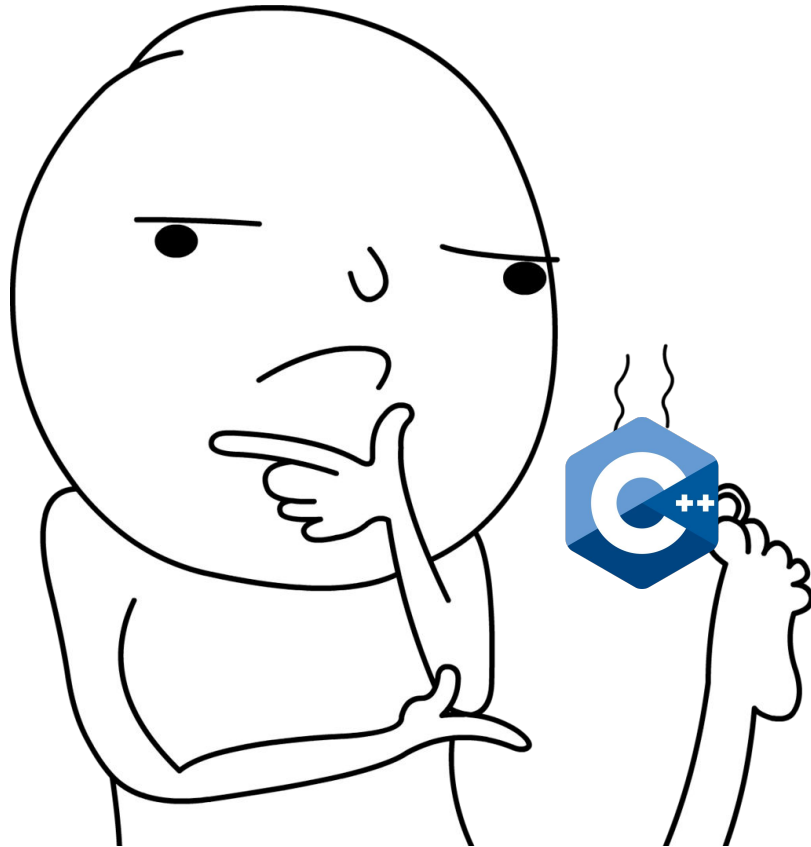
```
void removeOddsFromEnd(vector<int>& vec) {  
    while (vec.back().second % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

This is still pretty unpredictable behavior! What if the default constructor for an `int` produced an odd number?

What should back return in this case?

```
??? vector<valueType>::back() {  
    if(empty()) {  
        return ??;  
    }  
    return *(begin() + size() - 1);  
}
```

What questions do we have?




Introducing `std::optional`

What is `std::optional<T>`

- `std::optional` is a template class which will either contain a value of type `T` or contain nothing (expressed as `nullopt`)

What is `std::optional<T>`

- `std::optional` is a template class which will either contain a value of type `T` or contain nothing (expressed as `nullopt`)



Note: that's `nullopt` NOT `nullptr`. It's a new thing!

Nullptr: an object that can be converted to a value of any **pointer** type

Nullopt: an object that can be converted to a value of any **optional** type

What is `std::optional<T>`

- `std::optional` is a template class which will either contain a value of type `T` or contain nothing (expressed as `nullopt`)

```
void main() {  
    std::optional<int> num1 = {}; //num1 does not have a value  
    num1 = 1; //now it does!  
    num1 = std::nullopt; //now it doesn't anymore  
}
```



Can be used interchangeably!

What is `std::optional<T>`

```
std::optional<valueType> vector<valueType>::back() {  
    if (empty()) {  
        return {};  
    }  
    return *(begin() + size() - 1);  
}
```

What using `back ()` look like:

```
void removeOddsFromEnd (vector<int>& vec) {  
    while (vec.back () % 2 == 1) {  
        vec.pop_back ();  
    }  
}
```

We can't do arithmetic with an optional, we have to get the value inside the optional (if it exists) first!

What's the interface of `std::optional`?

`std::optional` types have a

- `.value()` method:
returns the contained value or throws `bad_optional_access` error

What's the interface of `std::optional`?

`std::optional` types have a

- `.value()` method:

returns the contained value or throws `bad_optional_access` error

- `.value_or(valueType val)`

returns the contained value or default value, parameter **val**

What's the interface of `std::optional`?

`std::optional` types have a

- `.value()` method:

returns the contained value or throws `bad_optional_access` error

- `.value_or(valueType val)`

returns the contained value or default value, parameter **val**

- `.has_value()`

returns true if contained value exists, false otherwise

Revisiting back ()

```
void removeOddsFromEnd(vector<int>& vec) {  
    while (vec.back().value() % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

Now, if we access the back of an empty vector, we will at least reliably get the **bad_optional_access** error

Revisiting back ()

```
void removeOddsFromEnd(vector<int>& vec) {  
    while (vec.back().has_value() && vec.back().value() % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

This will no longer error, but it is pretty unwieldy :/

Revisiting back ()

```
void removeOddsFromEnd(vector<int>& vec) {  
    while (vec.back() && vec.back().value() % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

Better?

Revisiting back ()

```
void removeOddsFromEnd(vector<int>& vec) {  
    while (vec.back().value_or(2) % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

Totally hacky, but totally works ;)

Revisiting back ()

```
void removeOddsFromEnd (vector<int>& vec) {  
    while (vec.back().value_or(2) % 2 == 1) {  
        vec.pop_back();  
    }  
}
```

Totally hacky, but totally works ;) Please don't do this!

Recap: The problem with `std::vector::back()`

- Why is it so easy to accidentally call `back()` on empty vectors if the outcome is so dangerous?
- The function signature gives us a false promise!

```
valueType& vector<valueType>::back()
```

- Promises to return an something of type `valueType`
- But in reality, there either may or may not be a “last element” in a vector

An optional take on `realVector`

More bad code!

```
int thisFunctionSucks (vector<int>& vec) {  
    return vec[0];  
}
```

What happens if `vec` is empty? More undefined behavior!

`std::optional<T&>` is not available!

```
std::optional<valueType&>  
vector<valueType>::operator[] (size_t index) {  
    return *(begin() + index);  
}
```

The underlying memory implications actually get very complicated...

Best we can do is error..which is what .at () does

```
valueType& vector<valueType>::operator[] (size_t index) {  
    return *(begin() + index);  
}  
  
valueType& vector<valueType>::at (size_t index) {  
    if (index >= size()) throw std::out_of_range;  
    return *(begin() + index);  
}
```

🤔 Why have both?

Is this.....good?

Pros of using `std::optional` returns:

- Function signatures create more informative contracts
- Class function calls have guaranteed and usable behavior

Cons:

- You will need to use `.value()` EVERYWHERE
- (In cpp) It's still possible to do a `bad_optional_access`
- (In cpp) optionals can have undefined behavior too (*optional does same thing as `.value()` with no error checking)
- In a lot of cases we want `std::optional<T&>...` which we don't have

Why even bother with optionals?

Is this.....good?

- `.and_then(function f)`
returns the result of calling `f(value)` if contained value exists,
otherwise `null_opt` (f must return `optional`)
- `.transform(function f)`
returns the result of calling `f(value)` if contained value exists,
otherwise `null_opt` (f must return `optional<valueType>`)
- `.or_else(function f)`
returns value if it exists, otherwise returns result of calling f

Is this.....good?

- `.and_then(f)` returns the result of `f` if it succeeds, otherwise returns `None`
- `.transform(f)` returns the result of `f` if it succeeds, otherwise returns `None`
- `.or_else(f)` returns the result of `f` if it fails, otherwise returns the result of the computation

Monadic: a software design pattern with a structure that combines program fragments (functions) and wraps their return values in a type with additional computation

These all let you try a function and will either return the result of the computation or some default value.

Is this.....good?

- `.and_then(function f)`
returns the result of calling `f(value)` if contained value exists,
otherwise `null_opt` (`f` must return `optional`)
- `.transform(function f)`
returns the result of calling `f(value)` if contained value exists,
otherwise `null_opt` (`f` must return `optional<valueType>`)
- `.or_else(function f)`
returns value if it exists, otherwise returns result of calling `f`

Revisiting our back () code...again!

```
void removeOddsFromEnd(vector<int>& vec) {  
    auto isOdd = [] (optional<int> num) {  
        if (num)  
            return num % 2 == 1;  
        else  
            return std::nullopt;  
        //return num ? (num % 2 == 1) : {};  
    };  
    while (vec.back().and_then(isOdd)) {  
        vec.pop_back();  
    }  
}
```

Revisiting our back () code...again!

```
void removeOddsFromEnd(vector<int>& vec) {  
    auto isOdd = [] (optional<int> num) {  
        if (num)  
            return num % 2 == 1;  
        else  
            return std::nullopt;  
        //return num ? (num % 2 == 1) : {};  
    };  
    while (vec.back().and_then(isOdd)) {  
        vec.pop_back();  
    }  
}
```

Recall lambda
functions!

**Disclaimer: `std::vector::back()` doesn't
actually return an optional
(and probably never will)**

Recall: Design philosophies of C++

- Only add features if they solve an actual problem
- Programmers should be free to choose their own style
- Compartmentalization is key
- Allow the programmer full control if they want it
- Don't sacrifice performance except as a last resort
- **Enforce safety at compile time whenever possible**

Languages that *really* use ~~optional~~ monads

- Rust 🥰🥰

Systems language that guarantees memory and thread safety

- Swift

Apple's language, made especially for app development

- JavaScript

Everyone's favorite

Recap: Type safety and `std::optional`

- You can guarantee the behavior of your programs by using a strict type system!

Recap: Type safety and `std::optional`

- You can guarantee the behavior of your programs by using a strict type system!
- `std::optional` is a tool that could make this happen: you can return either a value or nothing: `.has_value()` , `.value_or()` , `.value()`

Recap: Type safety and `std::optional`

- You can guarantee the behavior of your programs by using a strict type system!
- `std::optional` is a tool that could make this happen: you can return either a value or nothing: `.has_value()` , `.value_or()` , `.value()`
- This can be unwieldy and slow, so cpp doesn't use optionals in most stl data structures

Recap: Type safety and `std::optional`

- You can guarantee the behavior of your programs by using a strict type system!
- `std::optional` is a tool that could make this happen: you can return either a value or nothing: `.has_value()` , `.value_or()` , `.value()`
- This can be unwieldy and slow, so cpp doesn't use optionals in most stl data structures
- Many languages, however, do!

Recap: Type safety and `std::optional`

- You can guarantee the behavior of your programs by using a strict type system!
- `std::optional` is a tool that could make this happen: you can return either a value or nothing: `.has_value()` , `.value_or()` , `.value()`
- This can be unwieldy and slow, so cpp doesn't use optionals in most stl data structures
- Many languages, however, do!

Recap: Type safety and `std::optional`

- You can guarantee the behavior of your programs by using a strict type system!
- `std::optional` is a tool that could make this happen: you can return either a value or nothing: `.has_value()` , `.value_or()` , `.value()`
- This can be unwieldy and slow, so cpp doesn't use optionals in most stl data structures
- Many languages, however, do!
- Besides using them in classes, you can use them in application code where it makes sense! This is highly encouraged :)

All in all

**“Well typed programs
cannot go wrong.”**

- Robert Milner (very
important and good CS
dude)

Let's look at some
code