CS106L Lecture 14:

`std::optional` & type safety!

Fall 2023

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Attendance

bit.ly/TypeSafetyF23

Quick announcements

You can start assignment 2 after next lecture!

9	NOVEMBER 28 15. RAII, Smart Pointers, and Building C++ Projects	NOVE Optional: No Class, Extra Office Hours
10	DECEMBER 5 Optional: No Class, Extra Office Hours	DECEMBER 7 No class, No office hours

Quick announcements

You are coming to this lecture

9	NOVEMBER 28 15. RAII, Smart Pointers, and Building C++ Projects	NOVEMBER 30 ~~Optional: No Class, Extra Office Hours~~
10	DECEMBER 5 Optional: No Class, Extra Office Hours	DECEMBER 7 No class, No office hours

Important

We want you to pass :)

Important

To pass:

1. complete both assignments (must build)
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

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- **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

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

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

C++

```cpp
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){
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Hint!

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

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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();
    }
}
```

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

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`

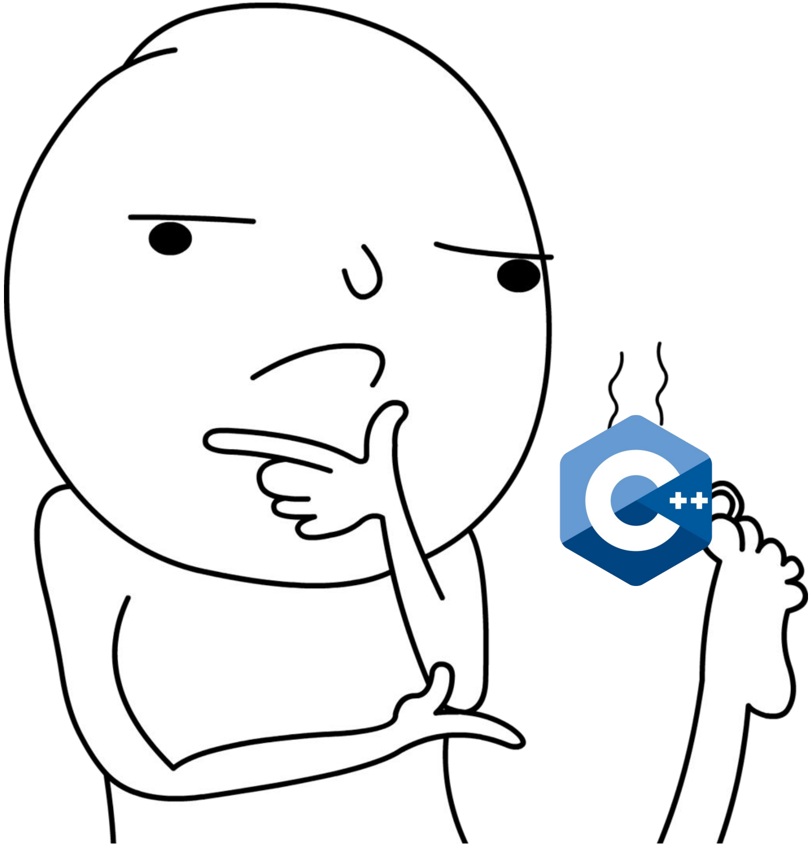
```
void removeOddsFromEnd(vector<int>& vec){
    while(vec.back().second % 2 == 1){
        vec.pop_back();
    }
}
```

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`)

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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

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

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- **`.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
  otherwise `r`

- `.transform(`

  returns the
  otherwise `r`

- `.or_else(fu`

  returns valu

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.

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- `.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!

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        if(num)
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        //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`

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- 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