Type Safety and `std::optional`

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How can we use c++'s type system to prevent errors at compile time?

Attendance

bit.ly/3EOZ8Zl

Today

- Recap: Const-correctness
- Type Safety
- The need for "sometimes-a-thing"
  - std::optional

Today

But first! A quick story about move semantics

- Type Safety
- The need for "sometimes-a-thing"
  - std::optional

Today

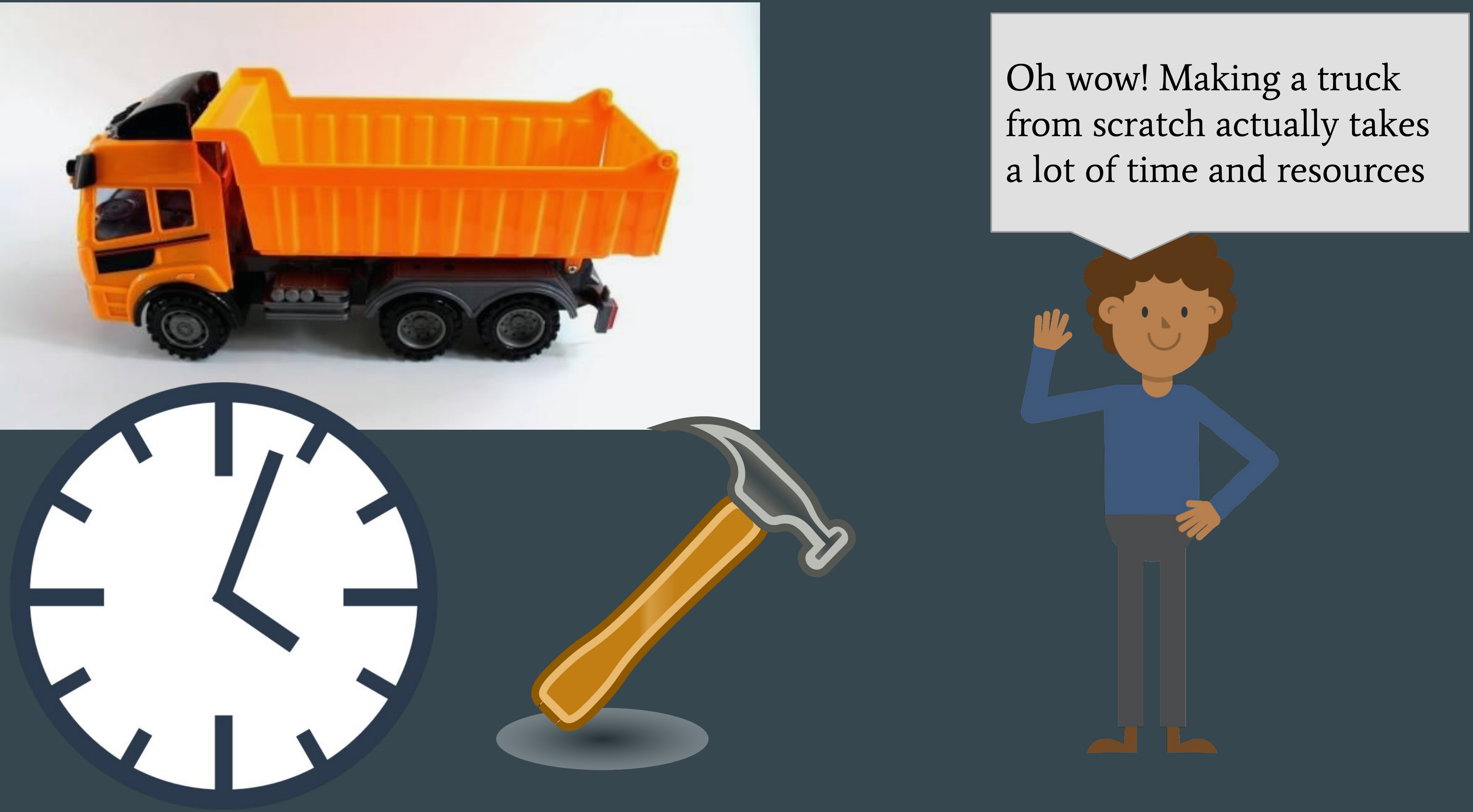
If you're looking at the slides outside of lecture. The wordy version of the story is at the [end of the slide deck]

"sometimes-a-thing"

- std::optional

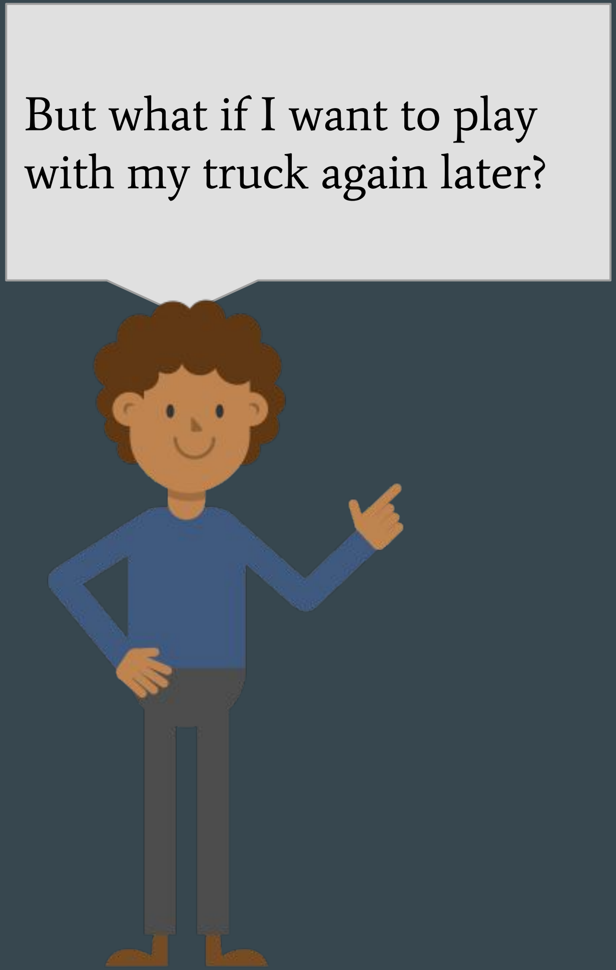

Haven’s birthday is coming up! I know! I’ll make a copy of my favorite truck to give to her!


To: Haven
Better get started on making the copy!


Oh wow! Making a truck from scratch actually takes a lot of time and resources

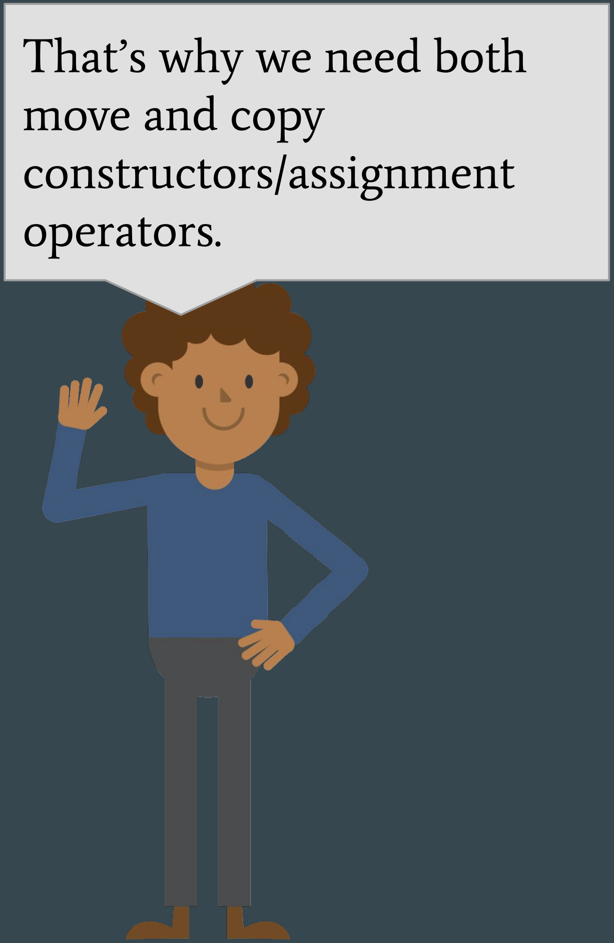
Wait! I don’t need to build a copy. I can just give Haven the original


To: Haven


But what if I want to play with my truck again later?

You can't! There's no take backs with move semantics! Once you've said you don't need it anymore, you can't get it back.


To: Haven


That’s why we need both move and copy constructors/assignment operators.

Sometimes we want to play with our truck after gifting it, so we need to make a copy

Other times, we’re done playing with our truck, so we can gift the original! (yay for saving time and resources!)

TLDR: Move Semantics

- Move semantics is a way to make copying things faster and more efficient
- Using move semantics tells the program “you can use this now, I don’t need it anymore”

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- Define these by overloading your copy constructor and assignment to be defined for `Type&& other` as well as `Type& other`

TLDR: Move Semantics

- Move semantics is a way to make copying things faster and more efficient
- Using move semantics tells the program "you can use this now, I don't need it anymore"
- If your class has copy constructor and copy assignment defined, you should also define a move constructor and move assignment
- Define these by overloading your copy constructor and assignment to be defined for `Type&& other` as well as `Type& other`

- Use `std::move` to force the use of other types' move assignments and constructors
- All `std::move(x)` does is cast `x` as an rvalue
- Be wary of `std::move(x)` in main function code!

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- Type Safety
- The need for "sometimes-a-thing"
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Recap: Const-Correctness

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Recap: Const-Correctness

- We pass big pieces of data **by reference** into helper functions by to avoid making copies of that data
- If this function accidentally or sneakily changes that piece of data, it can lead to hard to find bugs!
- **Solution**: mark those reference parameters `const` to guarantee they won't be changed in the function!

How does the compiler know when it’s safe to call member functions of `const` variables?

Definition

const-interface: All member functions marked `const` in a class definition. Objects of type `const ClassName` may only use the const-interface.

RealVector's const-interface

```
template<class ValueType> class RealVector {
public:
    using iterator = ValueType*;
    using const_ iterator = const ValueType*;
    /*...*/
    size_t size() const;
    bool empty() const;
    /*...*/
    void push_back(const ValueType& elem);
    iterator begin();
    iterator end();
    const_iterator cbegin()const;
    const_iterator cend()const;
    /*...*/
```

Key Idea: Sometimes **less** functionality is **better** functionality

- Technically, adding a const-interface only **limits** what `RealVector` objects marked `const` can do
- Using types to enforce assumptions we make about function calls help us prevent programmer errors!

Questions?

Definition

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

Recall: Python 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

Definition

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.

What does this code do?

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

What happens when input is {} ?

`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

What does this code do?

```
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 (also the status quo)

```
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

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?

Definition

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

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 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

Problems with using `std::pair<bool, valueType&>`

```
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 using `std::pair<bool, valueType&>`

```
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 using `std::pair<bool, valueType&>`

```
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?

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

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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- `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. 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 = std::optional<int>{1}; //now it does!
    num1 = std::nullopt; //now it doesn't anymore
}
```

What if `back()` returned an optional?

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

How would it look to use `back()`?

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

This would not compile!

How would it look to use `back()`?

```
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!

`std::optional` interface

- `.value()`

  returns the contained value or throws `bad_optional_access` error

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- `.value_or(valueType val)`

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

`std::optional` interface

- `.value()`

  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

Checking if an optional has value...

```
std::optional<Student> lookupStudent(string name){//something}

std::optional<Student> output = lookupStudent("Keith");

if(output.has_value()){
    cout << output.value().name << " is from " <<
                                  output.value().state << endl;
} else {
    cout << "No student found" << endl;
}
```

Evaluate optionals for a value like bools!

```
std::optional<Student> lookupStudent(string name){//something}

std::optional<Student> output = lookupStudent("Keith");

if(output){
    cout << output.value().name << " is from " <<
                                output.value().state << endl;
} else {
    cout << "No student found" << endl;
}
```

How would it look to use `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

How would it look to use `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 :/

How would it look to use `back()`?

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

Better?

How would it look to use `back()`?

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

Totally hacky, but totally works ;)

How would it look to use `back()`?

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

Totally hacky, but totally works ;) 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!

Implementation of vector [] operator

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

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?

`std::optional` "monadic" interface (C++23 sneak peek!)

- `.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

`std::optional` "monadic" interface (C++23 sneak peek!)

- `.and_then(f`
  returns the
  otherwise n
- `.transform(`
  returns the
  otherwise n
- `.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.

`std::optional` "monadic" interface (C++23 sneak peek!)

- `.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

Code might look like this…

```
std::optional<Student> lookupStudent(string name){//something}

std::optional<Student> output = lookupStudent(“Keith”);

auto func = (std::optional<Student> stu)[] {

    return stu ? stu.value().name + “is from “ +

                                to_string(stu.value().state) : {};

}

cout << output.and_then(func).value_or(“No student found”);
```

How would it look to use `back()`?

```
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();
    }
}
```

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

Recall: Design Philosophy 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 ~~optionals~~ monads

- Rust 🥰😍

  Systems language that guarantees memory and thread safety (take 110L!)

- Swift

  Apple's language, made especially for app development

- JavaScript

  Everyone's favorite

Type safety still matters in C++!

A sneaky example of type safety...

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

More bad code

```
void removeFirstA(string& str){
    int index = str.find('a');
    //do something with index
}
```

- What if there is no 'a' in str?
- No reason str.find shouldn't return an optional (IMO)

Classes with an emphasis on safety

- CS110L - Safety in Systems Programming
  - Companion course to ~~110~~ 111, whenever you take it!
  - Systems...but in Rust
- CS242 - Programming Languages
  - Take at least 107 first!
  - Learn a lot of languages
  - Emphasis on Rust

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!
- The ball is in your court!
- Besides using them in classes, you can use them in application code where it makes sense! This is highly encouraged :)

“Well typed programs cannot go wrong.”

- Robert Milner (very important and good CS dude)

Move semantics is a way to make copying things faster!

Imagine you have a toy truck and want to give it to your friend...

You could make a copy of the truck and give it to your friend, but that takes time and resources.

With move semantics, you can just give your friend the original truck and you won't need to make a copy. This is faster and save resources. Huzzah!

In the same way, move semantics in C++ lets you move things around in your program without having to make extra copies, which can make your program faster and more efficient.

But, you may wonder, what if I still want my truck?

Then, you can't use move semantics. "Moving" an object in this context means telling the program "you can use this now, I don't need it anymore".

So, if you still want to use your toy truck after giving it to your friend, you wouldn't use move semantics, instead you would make a copy of the truck and give it to your friend.

Similarly, in programming, if you still need to use an object after “giving” it to another part of the program, you would make a copy so that you can keep using the original