Welcome back! Link to Attendance Form ↓

Lecture 9: Template Classes

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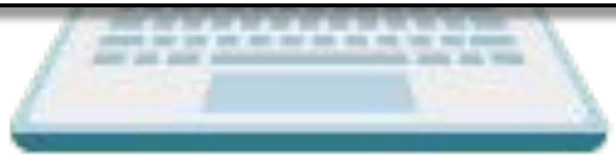
What are templates?

What are templates?

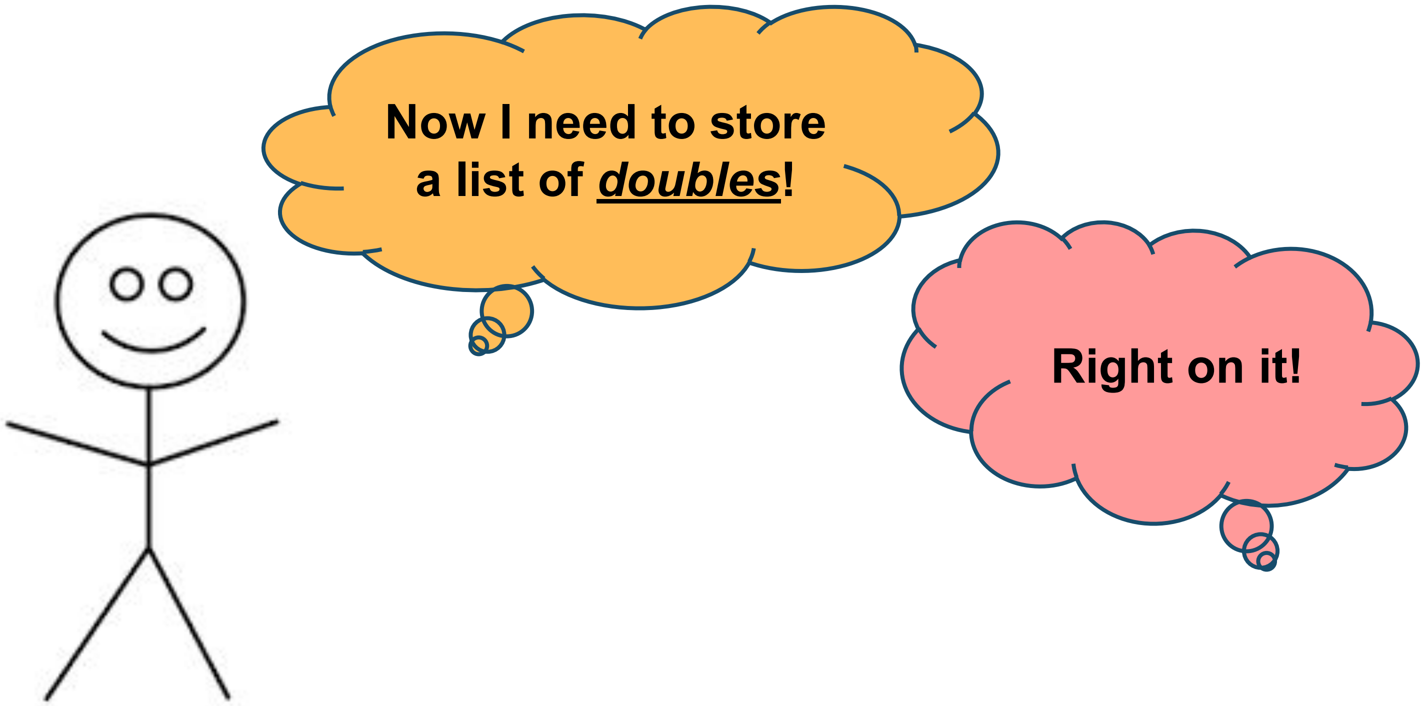

```
class IntVector {
    // Code to store
    // a list of
    // integers…
};
```



Recall: IntVector

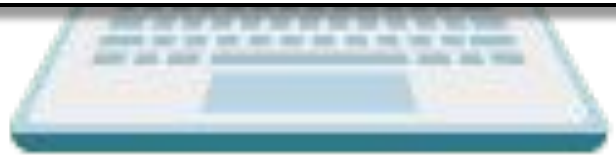
```
// Implements a sequence of strings
class IntVector {
public:
    IntVector();
    ~IntVector();

    size_t size();
    bool empty();

    void push_back(const int& elem);
    int& operator[](size_t index);
};
```

What are templates?



What are templates?

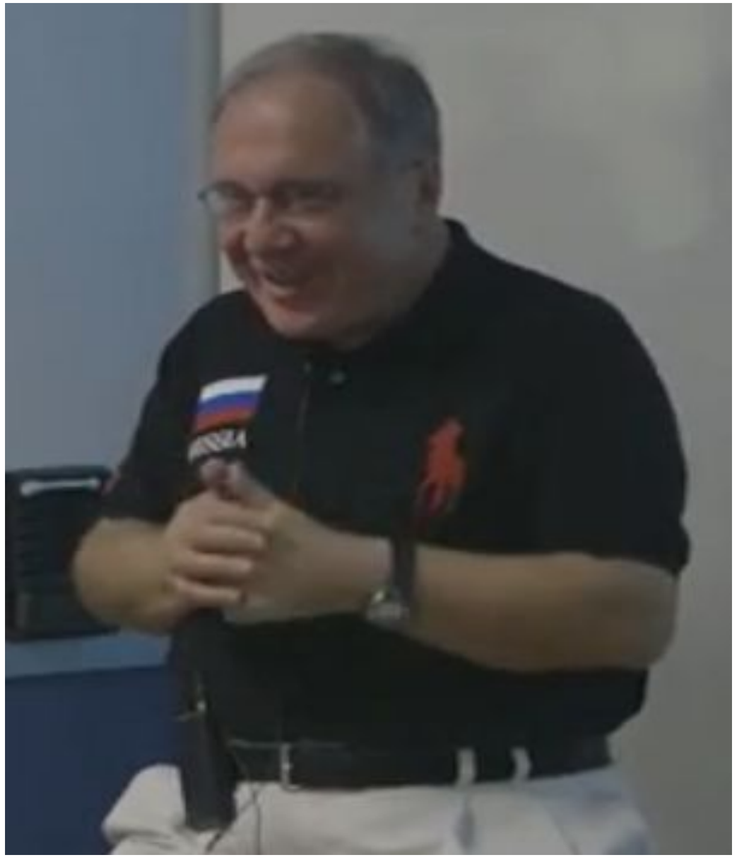

```
class DoubleVector {
    // Code to store
    // a list of
    // doubles…
};
```



What are templates?

Not so fast…

You realize you need to handle...



Alexander Stepanov
Creator of STL

Vector of doubles?

Vector of std::string?

Vector of vector of strings?

Vector of custom type I haven't even thought of yet?

What if we could keep the logic, but change the type?

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;
```

std::vector<T>

How does this <T> stuff work?

Today’s Agenda

- Template Classes
  - How can we generalize across different types?
- Const Correctness
  - Unlocking the power of `const`

What questions do you have?

bjarne_about_to_raise_hand

Template Classes

Templates: A bit of history

```
class IntVector {

};
```

```
class DoubleVector {

};
```

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

Templates: A bit of history

```
class IntVector {
public:
    int& at(size_t index);
    void push_back(const int& elem);
private:
    int* elems;
    size_t logical_size;
    size_t array_size;
};
```

Templates: A bit of history

```
class IntVector {
public:
    int& at(size_t index);
    void push_back(const int& elem);
private:
    int* elems;
    size_t logical_size;
    size_t array_size;
};
```

Templates: A bit of history

```
#define GENERATE_VECTOR(MY_TYPE)                 \
    class MY_TYPE##Vector {                      \
    public:                                      \
        MY_TYPE& at(size_t index);               \
        void push_back(const MY_TYPE& elem);     \
    private:                                     \
        MY_TYPE* elems;
        size_t logical_size;
        size_t array_size;
    };
```

Preprocessor Macro

Runs before compiler

Templates: A bit of history

```
#define GENERATE_VECTOR(MY_TYPE)          \
    class MY_TYPE##Vector {             \
    public:                               \
        MY_TYPE& at(size_t index);      \
        void push_back(const MY_TYPE& elem); \
    private:                              \
        MY_TYPE* elems;
        size_t logical_size;
        size_t array_size;
    };
```

Preprocessor Macro

Runs before compiler

Templates: A bit of history

```
#include "grandmas_template.h"

GENERATE_VECTOR(int)

intVector v1;
v1.push_back(5);
```

Code generation!!!

Depending on what type we pass in, we get a different vector!

Templates: A bit of history

```
#include "grandmas_template.h"

class intVector {
public:
	int& at(size_t index);
	void push_back(const int& elem);
private:
	int* elems;
	size_t logical_size;
	size_t array_size;
};

intVector v1;
v1.push_back(5);
```

Code generation!!!

Depending on what type we pass in, we get a different vector!

Templates: A bit of history

```
#include "grandmas_template.h"

class intVector {
public:
    int& at(size_t index);
    void push_back(const int& elem);
private:
    int* elems;
    size_t logical_size;
    size_t array_size;
};

intVector v1;
v1.push_back(5);
```

Problems with macros

- Clunky syntax
- Hard to type check
- What if you forget to call macro?
  - Or call it more than once?

Key Idea: **Templates automate code generation**

Templates have come a long way

```
template <typename T>
class Vector {
public:
    T& at(size_t index);
    void push_back(const T& elem);
private:
    T* elems;
};
```

Template Declaration

Vector is a template that takes in *the name of a type* T

T gets replaced when Vector is **instantiated**

Template Instantiation

```
Vector<int> intVec;
Vector<double> doubleVec;
Vector<std::string> strVec;

Vector<Vector<int>> vecVec;

struct MyCustomType {};
Vector<MyCustomType> structVec;
```

Template Instantiation

Code for a specific type is generated on-demand, when you use it

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;
```

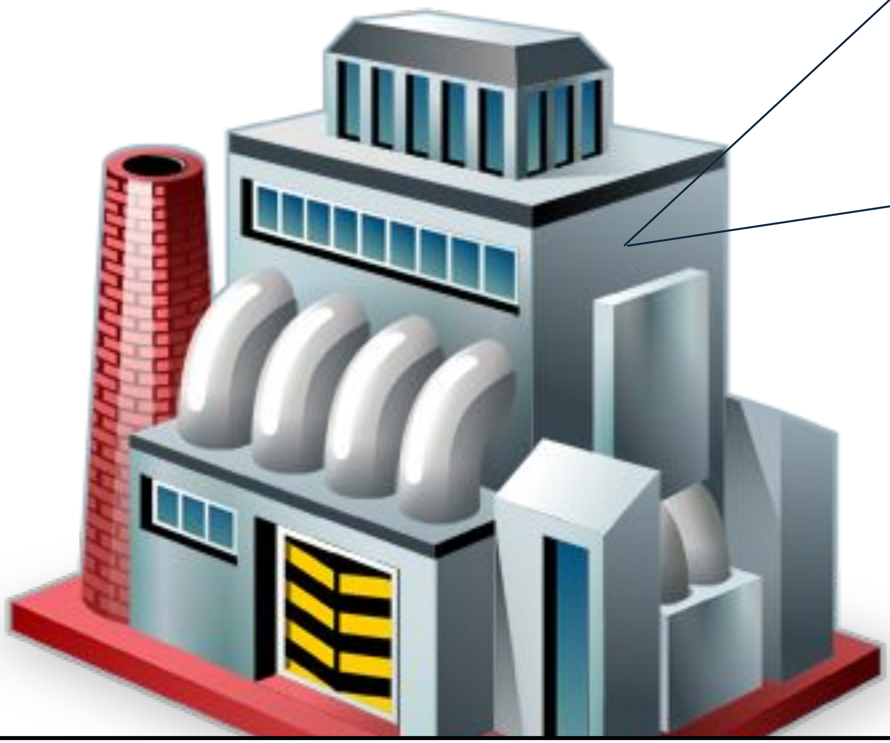
What questions do you have?

`bjarne_about_to_raise_hand`

A template is like a factory

int

string



Vector<int>

Vector<string>

template <typename T>
class Vector

Templates vs. Types

template <typename T>
class Vector

Vector<std::string>

This is a template.
It's **not** a type

This is a type.
A.K.A a template instantiation

Templates vs. Types

The template

The type

Vector<string>

template <typename T>
class Vector

What’s the problem with this code?

```
void foo(std::vector<int> v);

int main() {
    std::vector<double> v;
    foo(v);
}
```

❌ No suitable user-defined conversion from "std::vector<double>" to "std::vector<int>" exists

Note: These are two distinct types

Vector<double>

Vector<int>

These two instantiations (of the same template) are completely different (runtime and compile-time) types

Food for thought: compare this to a language like Java where an ArrayList<int> and ArrayList<double> share the same runtime type.

Fun Fact: non-typename template parameters

```
template <typename T>
class Vector{};
```

```
template <size_t N>
class SizeTemplate {};

SizeTemplate<5> s;
```

```
template <bool B>
class BoolTemplate {};

BoolTemplate<true> b;
```

Fun Fact: non-typename template parameters

```
template<typename T, std::size_t N>
struct std::array { /* ... */ };

// An array of exactly 5 strings
std::array<std::string, 5> arr;
```

Why use an array over vector? It avoids heap allocations.

The compiler will know exactly how much space an array<string, 5> takes (the size is baked into the type!), allowing it to be stack allocated

What questions do you have?

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👻 A few template quirks 👻

(1) Must copy template <...> syntax in .cpp

Template class implementation

When implementing a template, you might try something like this

```cpp
// Vector.h

template <typename T>
class Vector {
public:
    T& at(size_t i);
};
```

```cpp
// Vector.cpp

T& Vector::at(size_t i) {
    // Implementation...
}
```

Compiler: "I don't know what T is!"

Template class implementation

When implementing a template, must copy over template declaration

```
// Vector.cpp

template <typename T>
T& Vector::at(size_t i) {
    // Implementation...
}
```

Does anyone still see a problem with this?

Template class implementation

Vector is not a type, but Vector<T> is

```cpp
// Vector.cpp

template <typename T>
T& Vector<T>::at(size_t i) {
    // Implementation...
}
```

Compiler: "Ahh.. I'm happy now 😌😌"

(2) .h must include .cpp at bottom of file

Normal class implementation

For non-template classes, the .cpp file includes the .h file

```cpp
// StrVector.h

class StrVector {
public:
    string& at(size_t i);
};
```

```cpp
// StrVector.cpp

#include "StrVector.h"

string& StrVector::at(size_t i)
{
    // Implementation...
}
```

Template class implementation

For template classes, the .h file includes the .cpp file

```cpp
// Vector.h

template <typename T>
class Vector {
public:
	T& at(size_t i);
};

#include "Vector.cpp"
```

```cpp
// Vector.cpp

template <typename T>
T& Vector<T>::at(size_t i) {
	// Implementation...
}
```

That’s pretty weird 🤨 Why?

- Template .h must include .cpp due to the way template code generation is implemented in the compiler (and linker)
- Don’t worry too much about the *why* (unless you’re curious!)
- There are ways to get around this (ask us after!)

(3) typename is the same as class

(3) typename is the same as class

```
template <typename T>
class Vector{};
```

```
template <class T>
class Vector{};
```

(3) typename is the same as class

All of the following are identical:

```
template <typename K, typename V>
struct pair;
```

```
template <class K, class V>
struct pair;
```

```
template <class K, typename V>
struct pair;
```

```
template <class K, typename V>
struct pair;
```

What questions do you have?

bjarne_about_to_raise_hand

Code Demo

Let’s implement Vector<T>

Let’s code this together 👫

106l.vercel.app/vector

What questions do you have?

bjarne_about_to_raise_hand

Const Correctness

Let’s use our Vector class!

```
void printVec(const Vector<int>& v) {
    for (size_t i = 0; i < v.size(); i++) {
        std::cout << v.at(i) << " ";
    }
    std::cout << std::endl;
}
```

Compiler: “No such method size!”

Huh? But there is a method called size

```
template<class T>
class Vector {
public:
    size_t size();
    bool empty();

    T& operator[] (size_t index);
    T& at(size_t index);
    void push_back(const T& elem);
};
```

What is the problem?

```
void printVec(const Vector<int>& v) {
    for (size_t i = 0; i < v.size(); i++) {
        std::cout << v.at(i) << " ";
    }
    std::cout << std::endl;
}
```

- By passing v as const, we promise not to modify v
- Compiler cannot be sure if methods like size and at will modify v
- Remember, member functions *can* access member variables

How do we fix it?

```
template<class T>
class Vector {
public:
    size_t size() const;
    bool empty() const;

    T& operator[] (size_t index);
    T& at(size_t index) const;
    void push_back(const T& elem);
};
```

const method:

”Dear compiler,

I promise not to modify this object inside of this method. Please hold me accountable.

Love, Rachel <3”

How do we fix it (.cpp file)?

```
template <class T>
size_t Vector<T>::size() const {
    return logical_size;
}

// Other methods...
```

Make sure to also add **const** to the implementation, or the compiler will scream

How do we fix it (.cpp file)?

```
template <class T>
size_t Vector<T>::size() const {
    this->logical_size = 106; // 😈😈😈
    return logical_size;
}

// error: cannot assign to non-static d
// within const member function 'size'
```

Inside a **const** method, **this** has type **const Vector<T>***

What is this?

```
void Point::setX(int x)
{
    this->x = x;
}
```

```
Point* this
```

```
void Point::getX(int x)
const
{
    return this->x;
}
```

```
const Point* this
```

The const interface

- Objects marked as const can only make use of the **const interface**
- The const interface are the functions that are const in an object

The const interface

```
template<class T>
class Vector {
public:
	size_t size() const;
	bool empty() const;
	void push_back(const T& elem);
private:
	size_t logical_size;
	T* elems;
};
```

Vector<T>

```
template<class T>
class Vector {
public:
	size_t size() const;
	bool empty() const;
	void push_back(const T& elem);
private:
	const size_t logical_size;
	const T* elems;
};
```

const Vector<T>

What questions do you have?

bjarne_about_to_raise_hand

Back to our Vector class!

```
void printVec(const Vector<int>& v) {
    for (size_t i = 0; i < v.size(); i++) {
        std::cout << v.at(i) << " ";
    }
    std::cout << std::endl;
}
```

Compiler: “🦁 **const Vector<int>** has no **size**, **at**!!!”

Back to our Vector class!

```
template<class T>
class Vector {
public:
    size_t size();
    bool empty();

    T& operator[] (size_t index);
    T& at(size_t index);
    void push_back(const T& elem);
};
```

Let’s add **const** to the methods which don’t modify **Vector**

Back to our Vector class!

```
template<class T>
class Vector {
public:
    size_t size() const;
    bool empty() const;

    T& operator[] (size_t index);
    T& at(size_t index) const;
    void push_back(const T& elem);
};
```

Let’s add **const** to the methods which don’t modify **Vector**

Back to our Vector class!

```
void printVec(const Vector<int>& v) {
    for (size_t i = 0; i < v.size(); i++) {
        std::cout << v.at(i) << " ";
    }
    std::cout << std::endl;
}
```

Compiler: "✅ Everything looks good to me!"

Back to our Vector class!

```
template<class T>
class Vector {
public:
    size_t size() const;
    bool empty() const;

    T& operator[] (size_t index);
    T& at(size_t index) const;
    void push_back(const T& elem);
};
```

There's at least **one (or maybe two)** problems with how this method is declared.

Turn to a partner and take 60s to talk about why!

Problem #1: const consumers can modify!

Since we return a **non-const reference**, we can assign to it!

```
T& at(size_t index) const;


void oops(const Vector<int>& v) {
    v.at(0) = 42;
}
```

Remember, since v is const, we shouldn't be able to modify it

Solution: return a const reference

```
template<class T>
class Vector {
public:
    size_t size() const;
    bool empty() const;

    T& operator[] (size_t index);
    const T& at(size_t index) const;
    void push_back(const T& elem);
};
```

Hmm... There's still a problem here

Problem #2: non-const consumers can't modify!

If we return a const reference, now we cannot update elements!

```
const T& at(size_t index) const;

void ooh(Vector<int>& v) {
    v.at(0) = 42;
}
```

❌ Can't assign to const int&

Solution: const overloading!

- Let's define two versions of our at method
- One version gets called for const instances
- …And another that gets called for non-const instances

```
template<class T>
class Vector {
public:
    const T& at(size_t index) const;
    T& at(size_t index);
};
```

Solution: const overloading (.cpp file)!

```
template <class T>
const T& Vector<T>::at(size_t index) const {
    return elems[index];
}

template <class T>
T& Vector<T>::at(size_t index) {
    return elems[index];
}
```

What questions do you have?

bjarne_about_to_raise_hand

Solution: const overloading (.cpp file)!

```
template <class T>
const T& Vector<T>::at(size_t index) const {
    return elems[index];
}

template <class T>
T& Vector<T>::at(size_t index) {
    return elems[index];
}
```

Two methods with the same implementation.

It's a bit redundant, but it's only one line

What if we added a findElement?

```
template<class T>
class Vector {
public:
    T& at(size_t index);
    const T& at(size_t index) const;
    T& findElement(const T& value);
    const T& findElement(const T& value) const;
};
```

Implementing findElement

```
template <typename T>
T& Vector<T>::findElement(const T& value) {
    for (size_t i = 0; i < logical_size; i++) {
        if (elems[i] == elem) return elems[i];
    }
    throw std::out_of_range("Element not found");
}

// What about the const version of findElement?
```

Implementing findElement

```
template <typename T>
T& Vector<T>::findElement(const T& value) {
	for (size_t i = 0; i < logical_size; i++) {
		if (elems[i] == elem) return elems[i];
	}
	throw std::out_of_range("Element not found");
}

template <typename T>
const T& Vector<T>::findElement(const T& value) con
	for (size_t i = 0; i < logical_size; i++) {
		if (elems[i] == elem) return elems[i];
	}
	throw std::out_of_range("Element not found");
}
```

This works, but it's super redundant. There must be a better way!

A slight (but useful) aside

- Casting: the process of converting one type to another
  - There are *many* ways to cast in C++
- const_cast allows us to "cast away" the const-ness of a variable
  - Usage: const_cast<target_type>(expression)
  - So why is this useful?

Implementing findElement

```
template <typename T>
T& Vector<T>::findElement(const T& value) {
    for (size_t i = 0; i < logical_size; i++) {
        if (elems[i] == elem) return elems[
    }
    throw std::out_of_range("Element not
}

template <typename T>
const T& Vector<T>::findElement(const T& value) const {
    return const_cast<Vector<T>&>(*this).findElement(value);
}
```

Ahh no more redundancy…
But what in the Bjarne is going on here?

```
const_cast<Vector<T>&>(*this).findElement(value);
```

const_cast casts away the const

```
const_cast<Vector<T>&>(*this).findElement(value);
```

const_cast casts away the const

this dereferences a const Vector<T>, giving us a const-ref

```
const_cast<Vector<T>&>(*this).findElement(value);
```

```
const Vector<T>&
```

const_cast casts away the const

this dereferences a const Vector<T>, giving us a const-ref

```
const_cast<Vector<T>&>(*this).findElement(value);
```

Vector<T>& is a **non-const** reference, the type we would like

const_cast casts away the const

this dereferences a const Vector<T>, giving us a const-ref

```
const_cast<Vector<T>&>(*this).findElement(value);
```

Vector<T>& is a **non-const** reference, the type we would like

Phew... This is the non-const version of findElement

const_cast casts away the const

this dereferences a const Vector<T>, giving us a const-ref

```
const_cast<Vector<T>&>(*this).findElement(value);
```

Vector<T>& is a **non-const** reference, the type we would like

Phew... This is the non-const version of findElement

const_cast forces compiler to pick right overload

```
template<class T>
class Vector {
public:
    T& at(size_t index);
    const T& at(size_t index) const;
    T& findElement(const T& value);
    const T& findElement(const T& value) const;
};
```

Implementing findElement

```
template <typename T>
T& Vector<T>::findElement(const T& value) {
    for (size_t i = 0; i < logical_size; i++) {
        if (elems[i] == elem) return elems[i];
    }
    throw std::out_of_range("Element not found");
}

template <typename T>
const T& Vector<T>::findElement(const T& value) const {
    return const_cast<Vector<T>&>(*this).findElement(value);
}
```

When to use const_cast?

- Short answer: just about never
- const_cast tells the compiler: “don’t worry I’ve got this”
- If you need a mutable value, just don’t add const in the first place
- Valid uses of const_cast are few and far between

What questions do you have?

bjarne_about_to_raise_hand

const_cast makes an *entire* object mutable

Is there anything more fine-grained?

A C++ party trick: mutable keyword

Like const_cast, mutable circumvents const protections. Use it carefully!

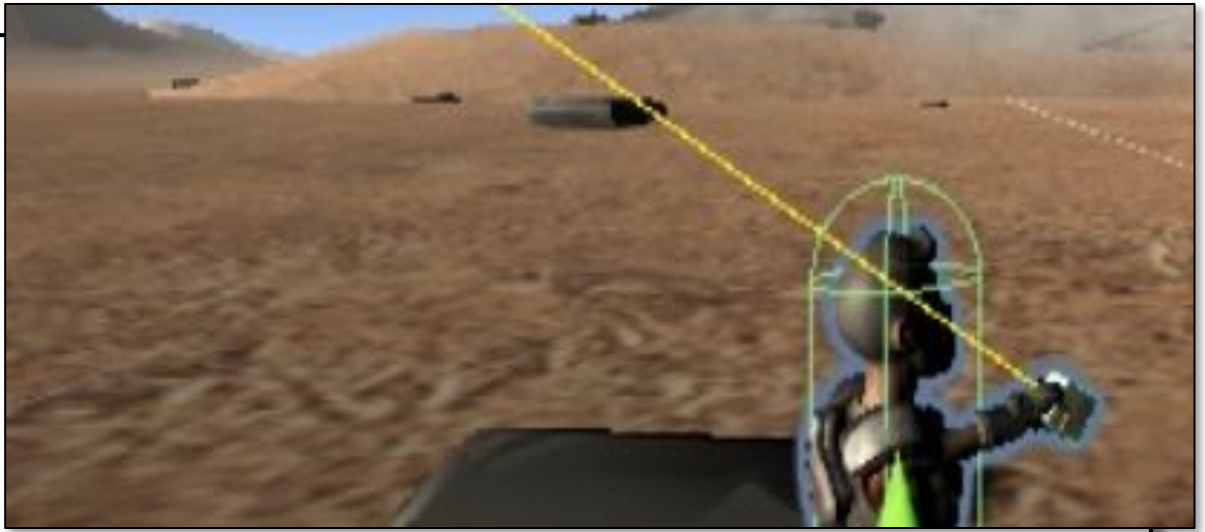
```
struct MutableStruct {
    int dontTouchThis;
    mutable double iCanChange;
};

const MutableStruct cm;
// cm.dontTouchThis = 42;  // ❌ Not allowed, cm is const
cm.iCanChange = 3.14;            // ✅ Ok, iCanChange is mutable
```

mutable example: storing debug info

```
struct CameraRay {
    Point origin;
    Direction direction;
    mutable Color debugColor;
}

void renderRay(const CameraRay& ray) {
    ray.debugColor = Color.Yellow; // Show debug ray
    /* Rendering logic goes here ... */
}
```



Recap

Meme of the Day

What We Covered

- Template Classes
  - Template classes generalize logic across types!
- Const Correctness
  - const makes an entire object read-only
  - Mark methods const when they don't modify the object
  - const_cast and mutable can circumvent compiler in *rare* cases!

Next Time: Template Functions

Unlocking the power of templates