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Lecture 10: Template Classes

CS106L, Spring 2025

What are templates?

What are templates?


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

Recall: IntVector

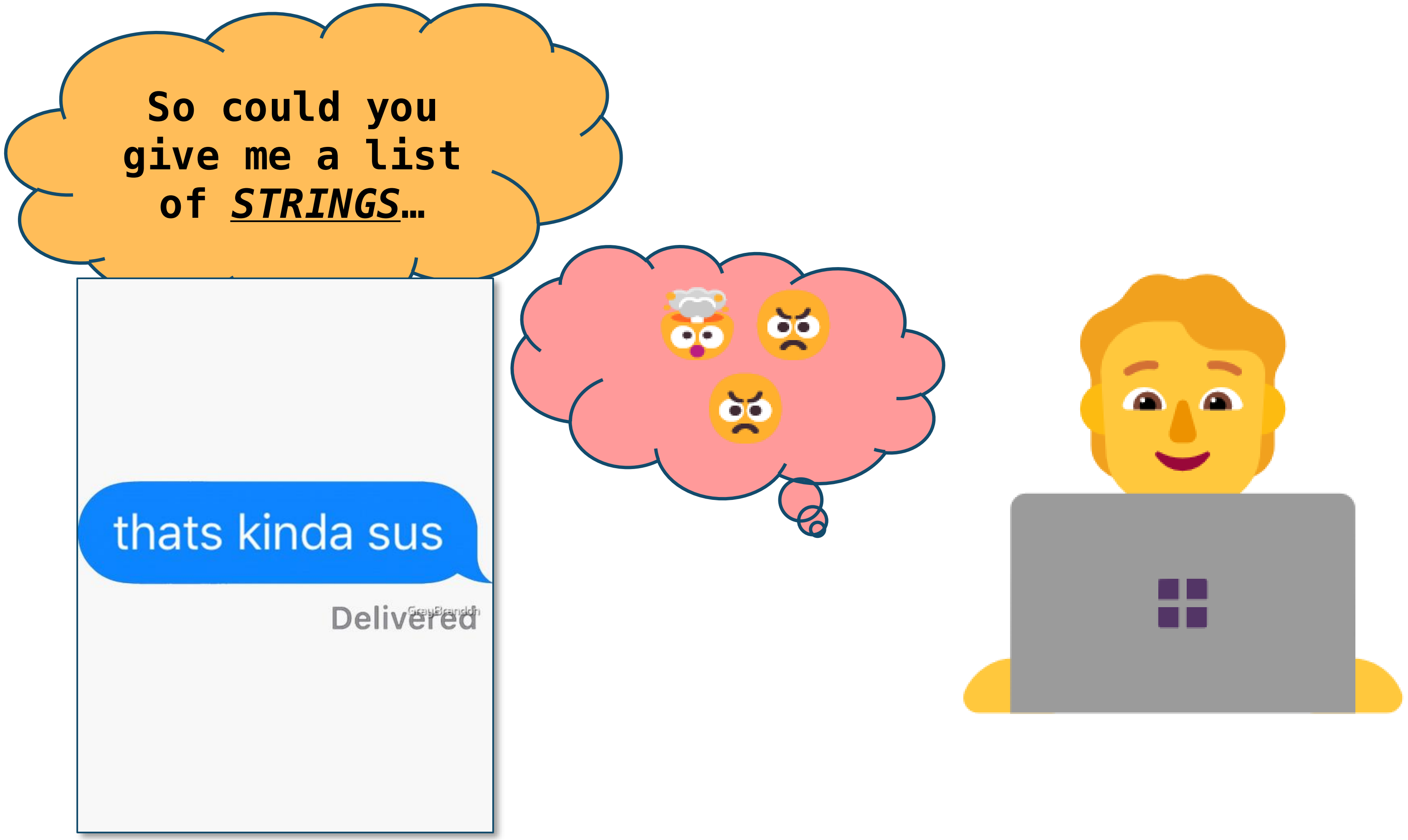
```
// Implements a sequence of strings
class IntVector {
public:
   IntVector();
   ~IntVector();

   size_t size();
   bool empty();

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

What are templates?

What are templates?

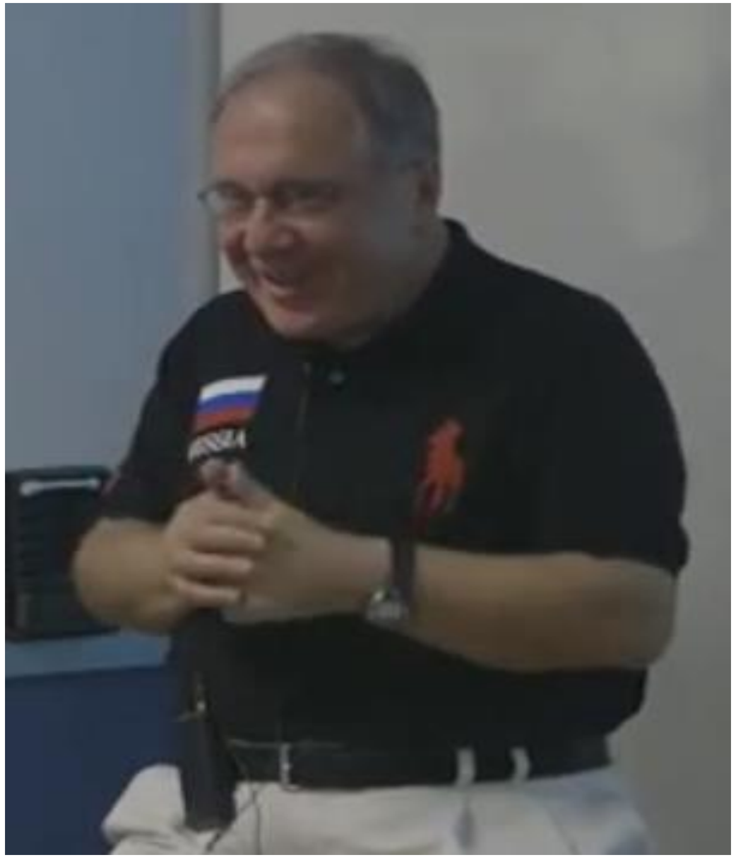

```
class DoubleVector {
  // Code to store
  // a list of
  // doubles…
};
```

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?
- Code Demo
  - Implementing a template class
- 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

```cpp
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

```cpp
#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;
```

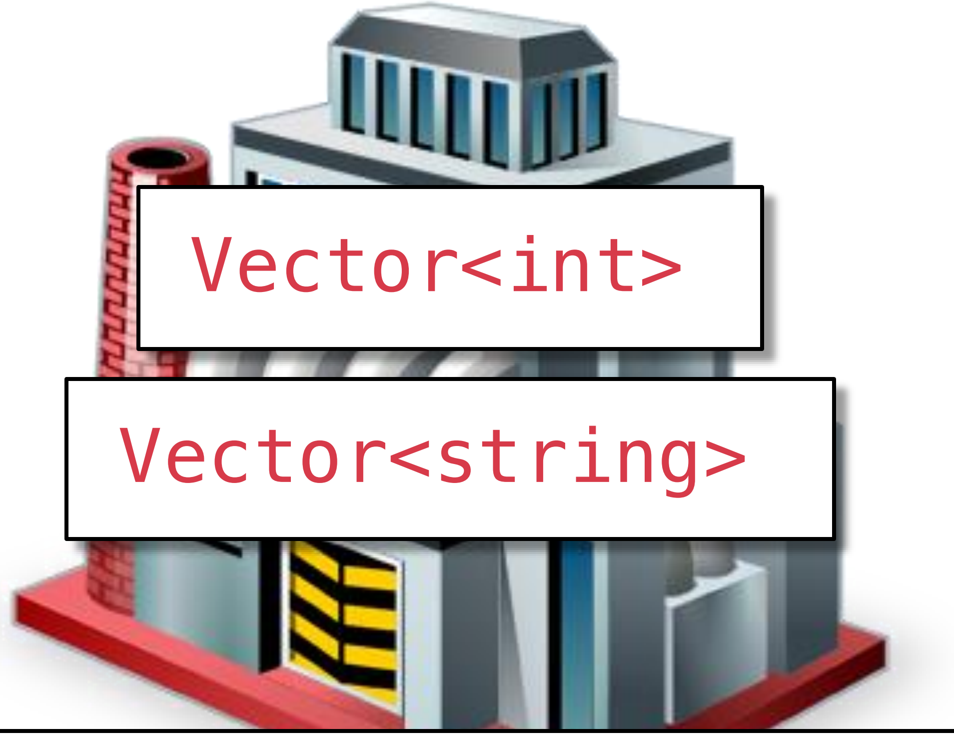
What questions do you have?

bjarne_about_to_raise_hand

A template is like a factory

`int`

`string`




```
template <typename T>
class Vector
```

Templates vs. Types

```
template <typename T>
class Vector
```

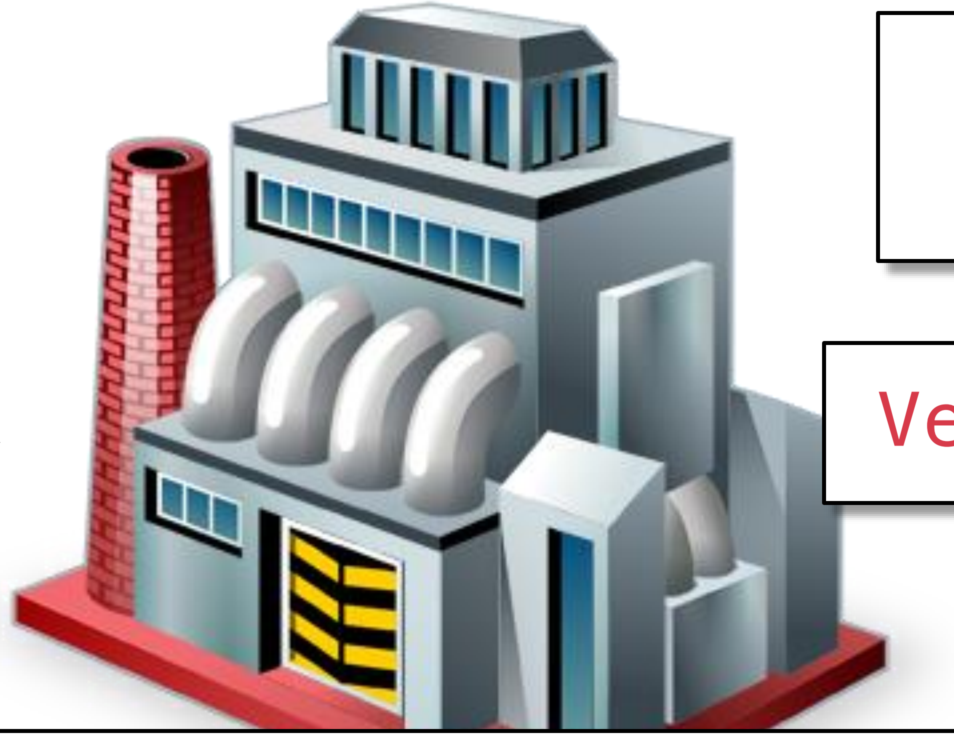
```
Vector<std::string>
```

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

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

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

SizeTemplate<5> s;
```

```cpp
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?

`bjarne_about_to_raise_hand`

👻 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

```
// 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, Jacob 😘”

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 r
// within const member funct
```

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
}

template <typename T>
const T& Vector<T>::findElement(const T&
    for (size_t i = 0; i < logical_size;
        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 < logi
      if (elems[i] == elem) ret
   }
   throw std::out_of_range("El
}

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

```cpp
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?

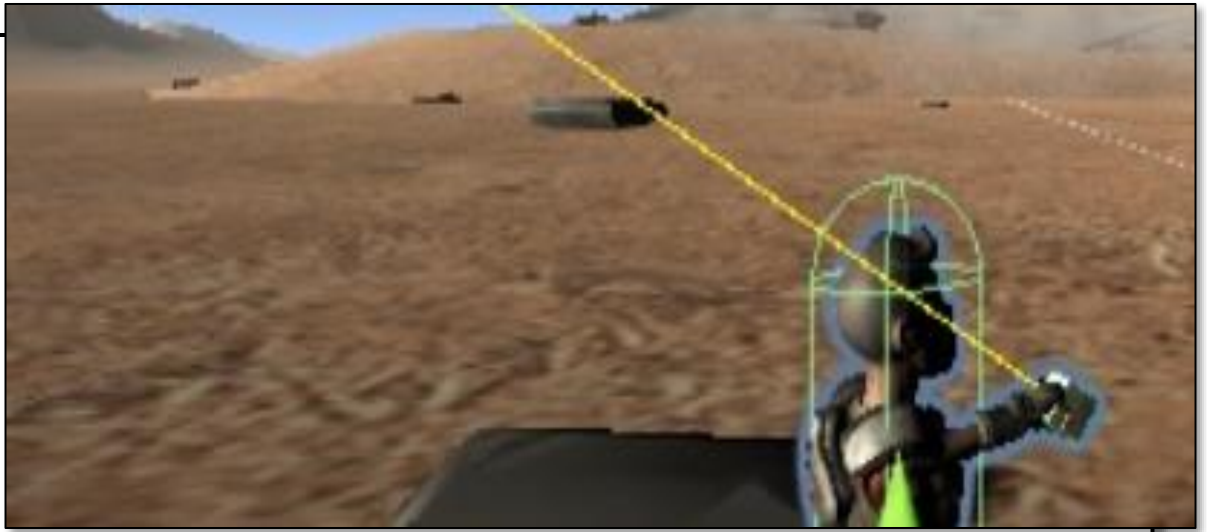
A C++ party trick: mutable keyword

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!
- Code Demo
    - We implemented a templated `Vector`!
- 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