Welcome back! Link to Attendance Form ↓

Last Time: Classes

- What are classes?

Last Time: Classes

- What are classes?
  - Turn to the person next to you and think of one thing you remember from Tuesday's lecture!
- A class bundles data and methods for an object together

A `Point` on classes

```
class Point {
public:
    Point(int x, int y);
    ~Point();
    int getX();
    int getY();
    void setX();
    void setY();

private:
    int x;
    int y;
};
```

A Point on classes

```
class Point {
public:
    Point(int x, int y);
    ~Point();
    int getX();
    int getY();
    void setX();
    void setY();

private:
    int x;
    int y;
};
```

public:

Accessible by everyone!

private:

Only visible to us!
Implementation details

A Point on classes

```
class Point {
public:
    Point(int x, int y);
    ~Point();
    int getX();
    int getY();
    void setX();
    void setY();

private:
    int x;
    int y;
};
```

public:

Accessible by everyone!

constructor

Initializes this class

destructor

Cleans up this class

Usually don’t need this

private:

Only visible to us!
Implementation details

A Point on classes

```
class Point {
public:
    Point(int x, int y);
    ~Point();
    int getX();
    int getY();

private:
    int x;
    int y;
    std::string color;
}
```

Point.h (header file)

A Point on classes

```
class Point {
public:
    Point(int x, int y);
    ~Point();
    int getX();
    int getY();

private:
    int x;
    int y;
    std::string color;
}
```

```
#include “Point.h”

Point::Point(int x, int y)
    : x(x), y(y) {}

int Point::getX() {
    return x;
}

int Point::getY() {
    return y;
}
```

Point.h (header file)

Point.cpp

What is `this`?

The importance of this

```
int Point::getX() {
   return x;
}
```

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

The importance of this

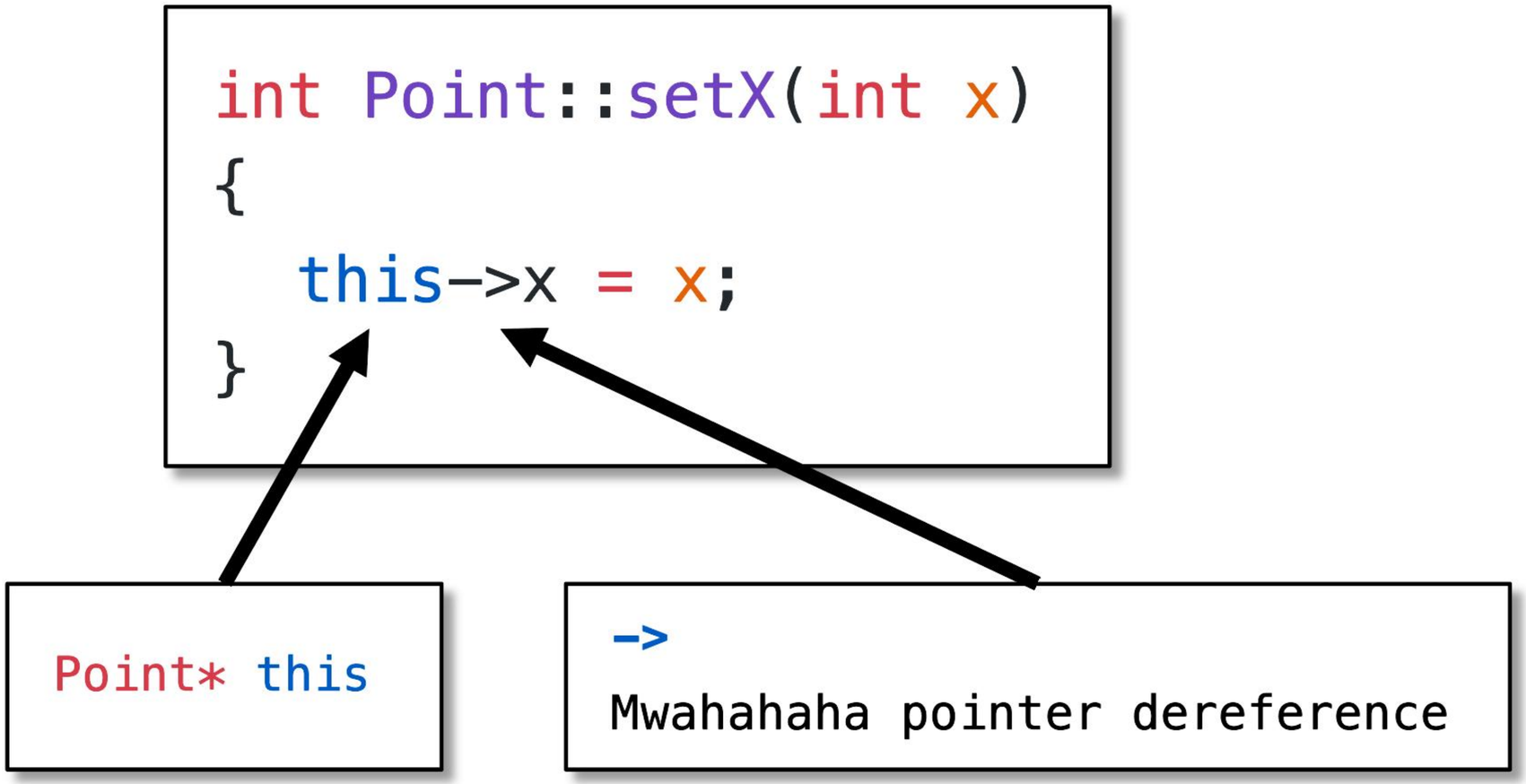
```
void Point::setX(int x)
{
   x = x;
}
```

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

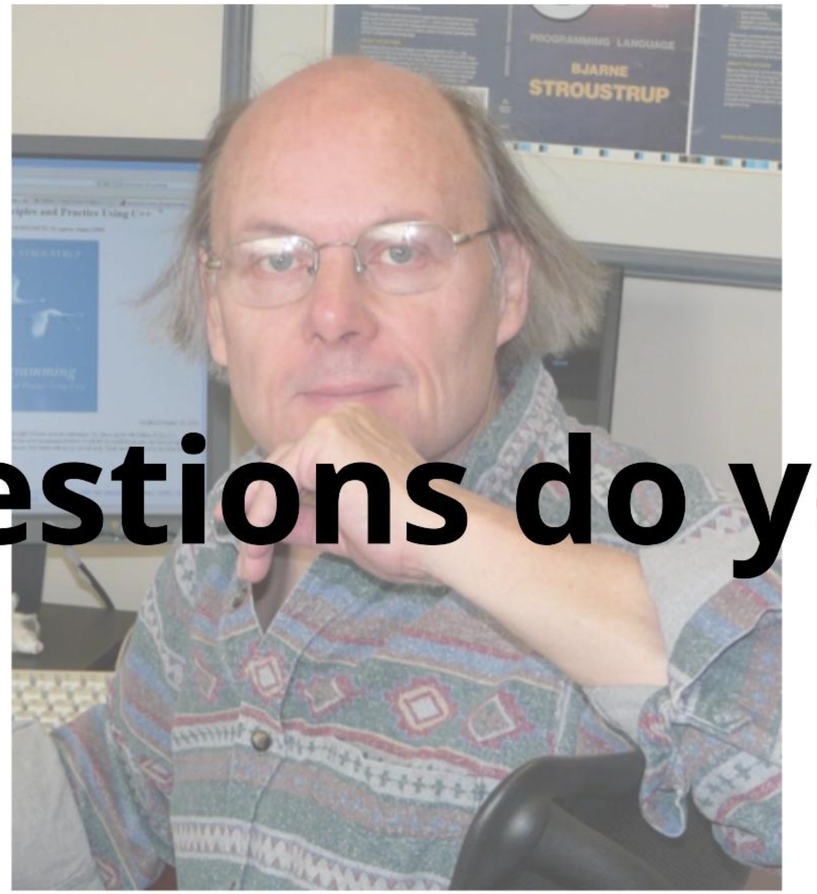
What is this?

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

What is this?


int Point::setX(int x)
{
this->x = x;
}
Point* this
->
Mwahahaha pointer dereference

What questions do you have?



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Last Time: IntVector

```
// Implements a sequence of strings
class IntVector {
public:





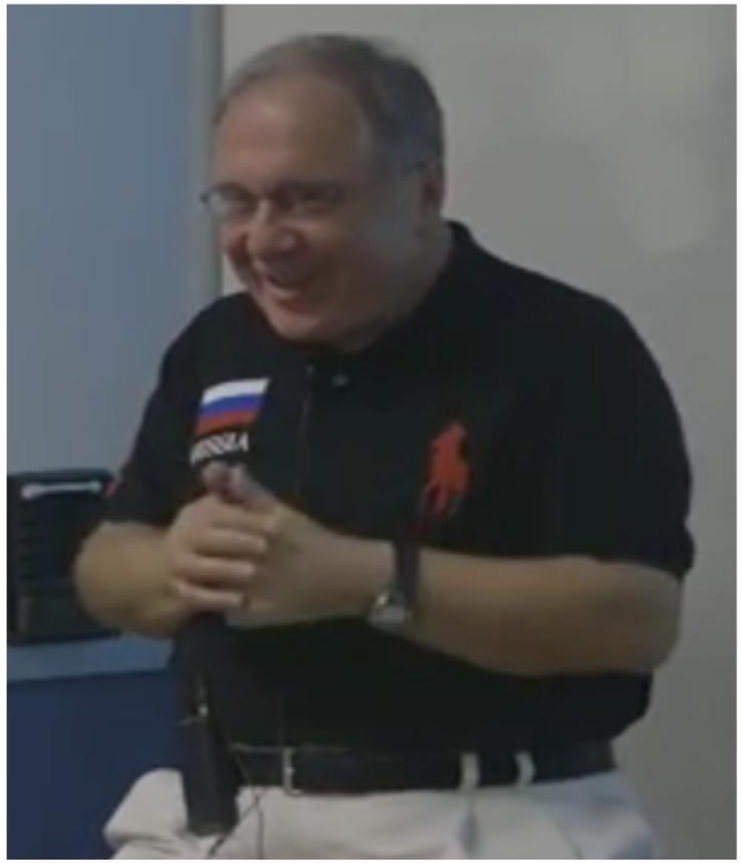




};
```

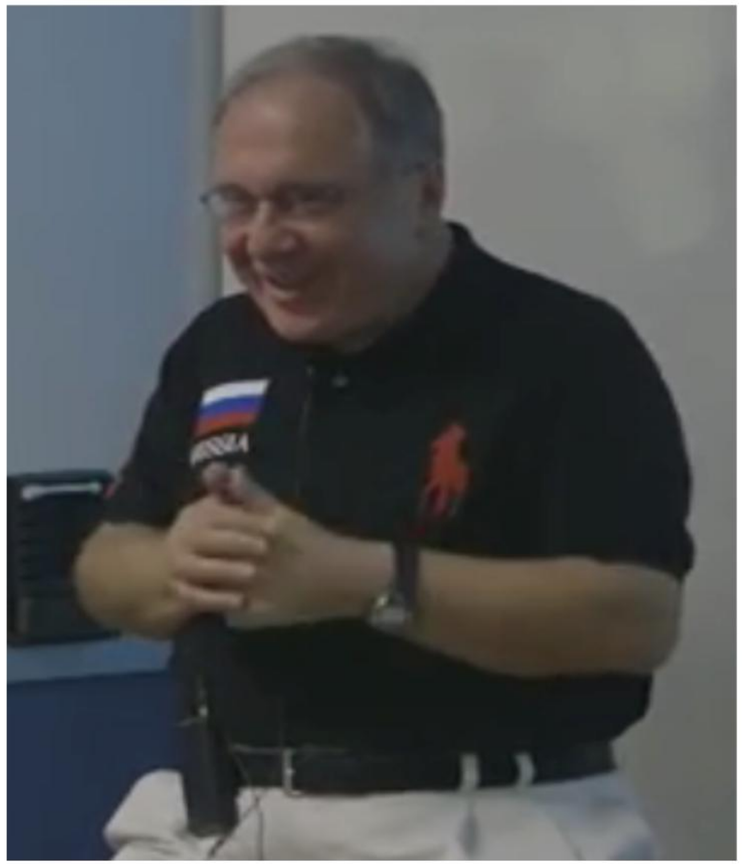
Not so fast...

You realize you need to handle...



Alexander Stepanov
Creator of STL

You realize you need to handle...

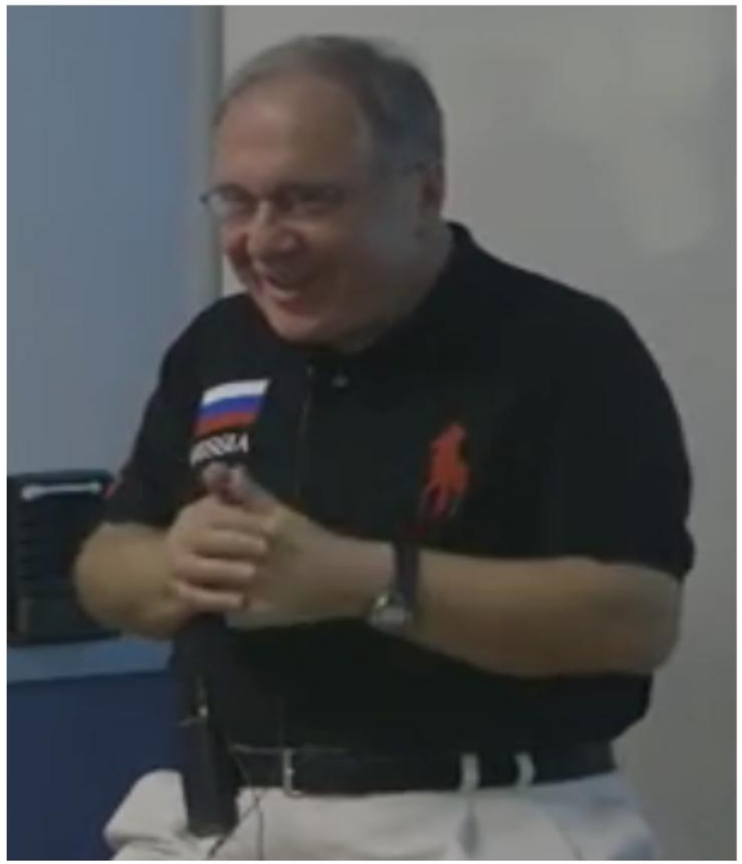


Alexander Stepanov
Creator of STL

```
Vector of doubles?
```

```
Vector of std::string?
```

You realize you need to handle…



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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?

`IntVector` is too specific

```
// 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);
};
```

`IntVector` is too specific

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

`IntVector` is too specific

```
class IntVector {

}
```

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

`IntVector` is too specific

```
class IntVector {
}
```

```
class DoubleVector {
}
```

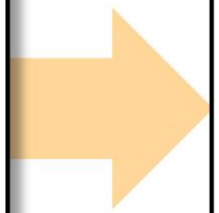
```
class StringVector {
   // Code to store
   // a list of
   // strings…
};
```

`IntVector` is too specific

```
class IntVector {
}
```

```
class DoubleVector {
}
```

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



```
template <typename T>
class vector {
  // So satisfying.
};
```

std::vector<T>

Lecture 8: Template Classes

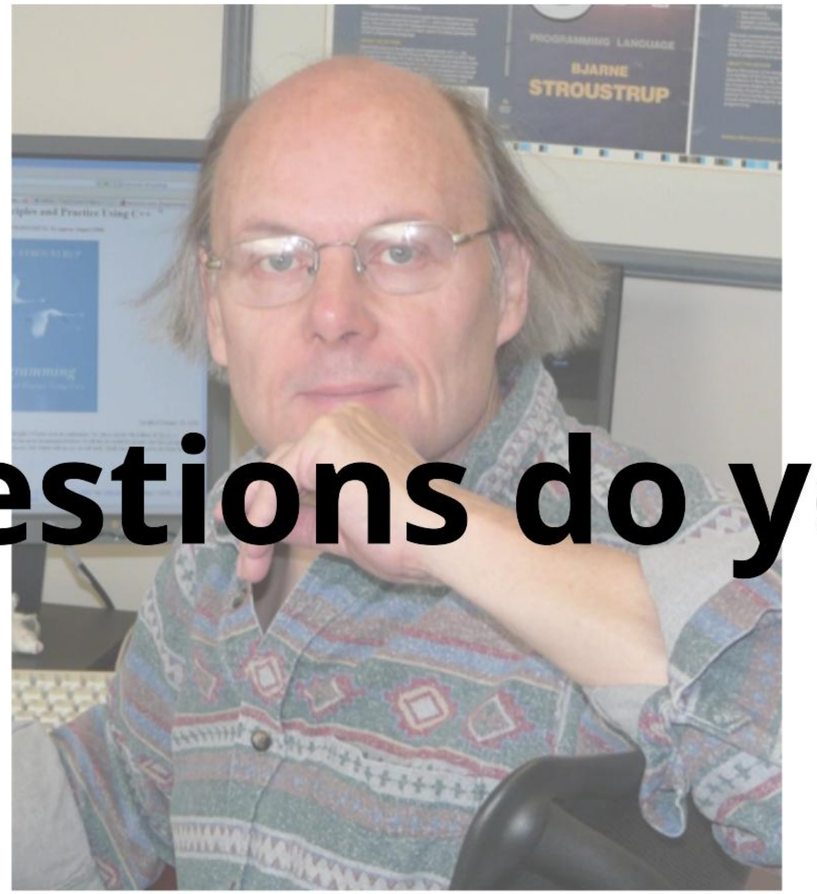
CS106L, Winter 2025

Today’s Agenda

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?



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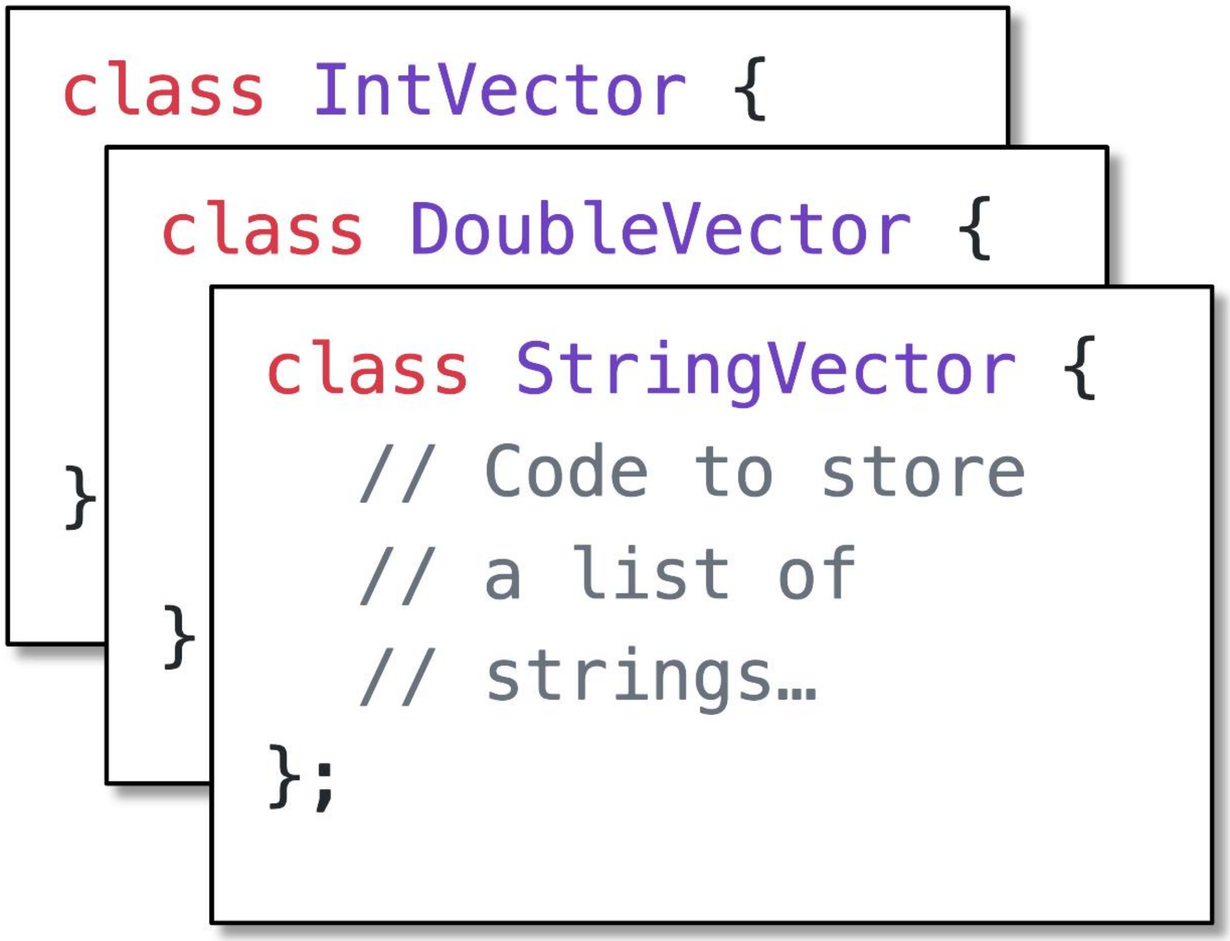
Template Classes

Templates: A bit of history



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

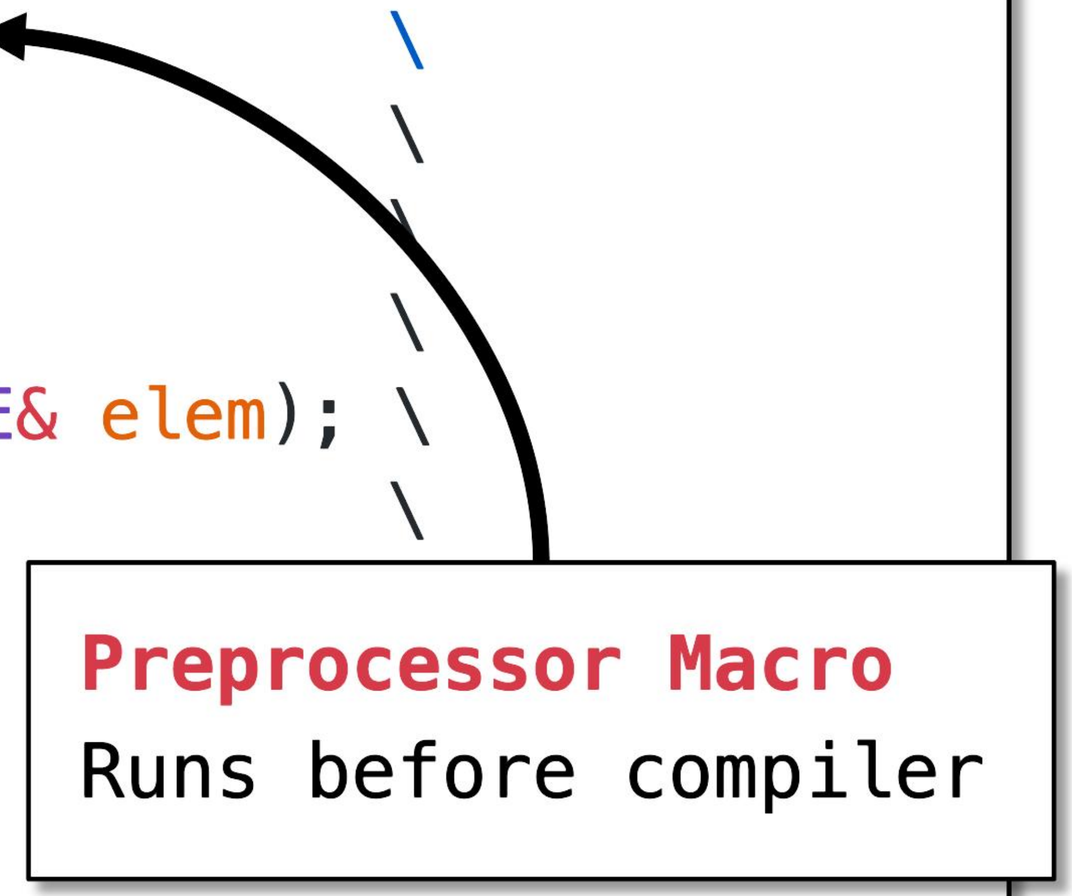
```
class IntVector {
public:
   int& at(size_t index);
   void push_back(const int& elem);
private:
   int* elems;
   size_t logical_size;
   size_t array_size;
};
```

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;                            \
   };
```

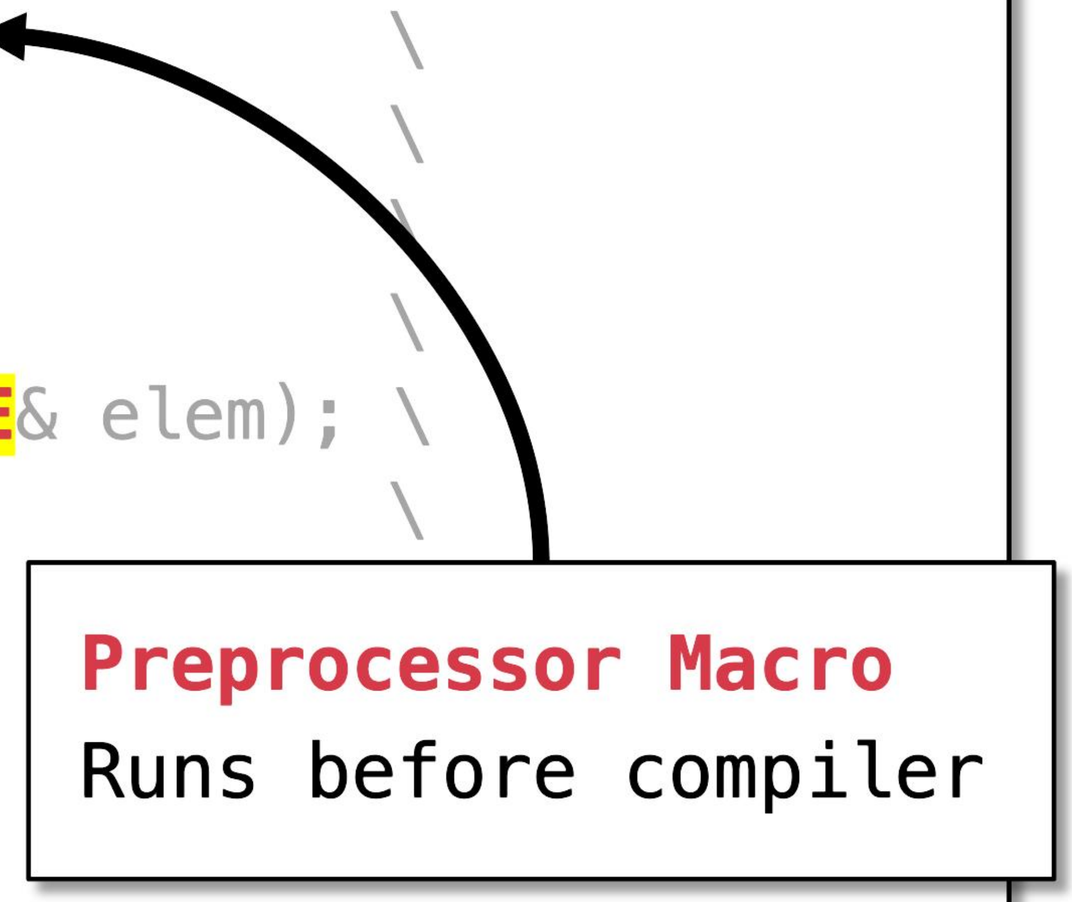
Templates: A bit of history

```
#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;                            \
   };
```



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;                            \
   };
```



Templates: A bit of history

```
#include "grandmas_template.h"

GENERATE_VECTOR(int)

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

Templates: A bit of history

```
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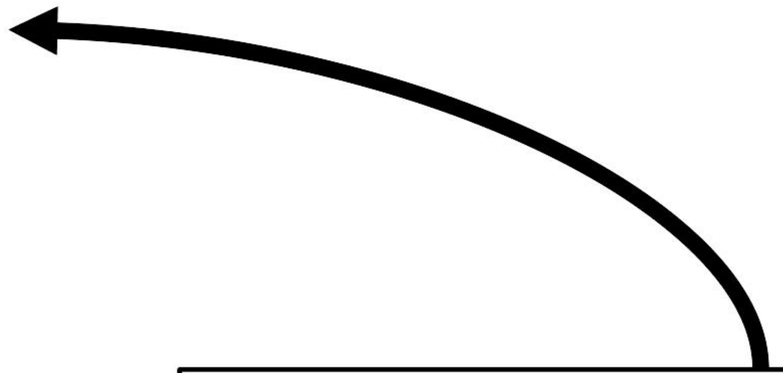


Code generation!!!

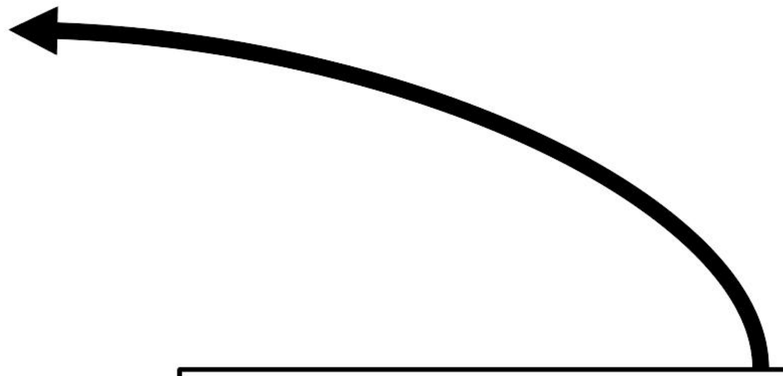
Depending on what type we pass in, we get a different vector!

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

Problems with macros

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

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- 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;
};
```

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`

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

```
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 Instantiation

When you write code like this...

```
template <typename T>
class Vector {
   T& at(size_t index);
   // More methods...
};

Vector<int> v;
```

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...

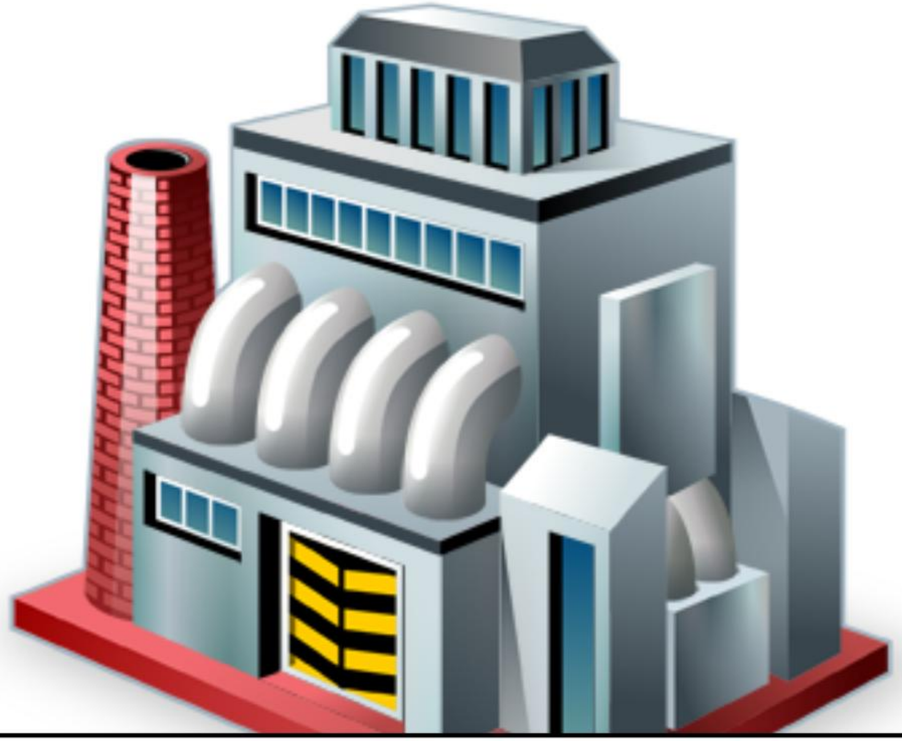
```
class IntVector {
  int at(size_t index);
  // More methods...
};

IntVector v;
```

A template is like a factory

```
int
```

```
string
```

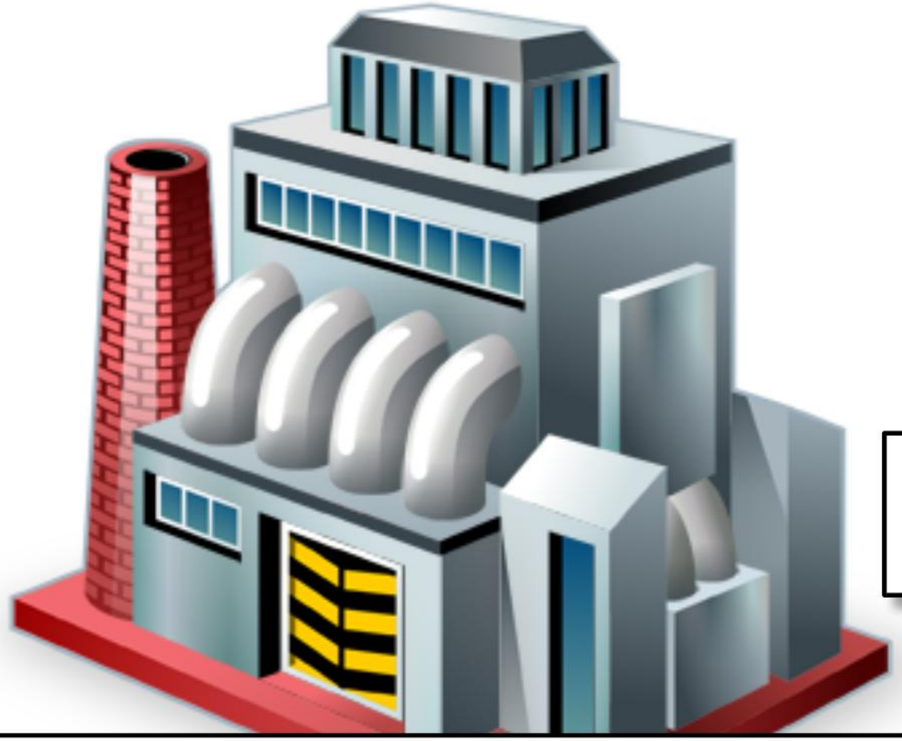


```
template <typename T>
class Vector
```

A template is like a factory

```
int
```

```
string
```

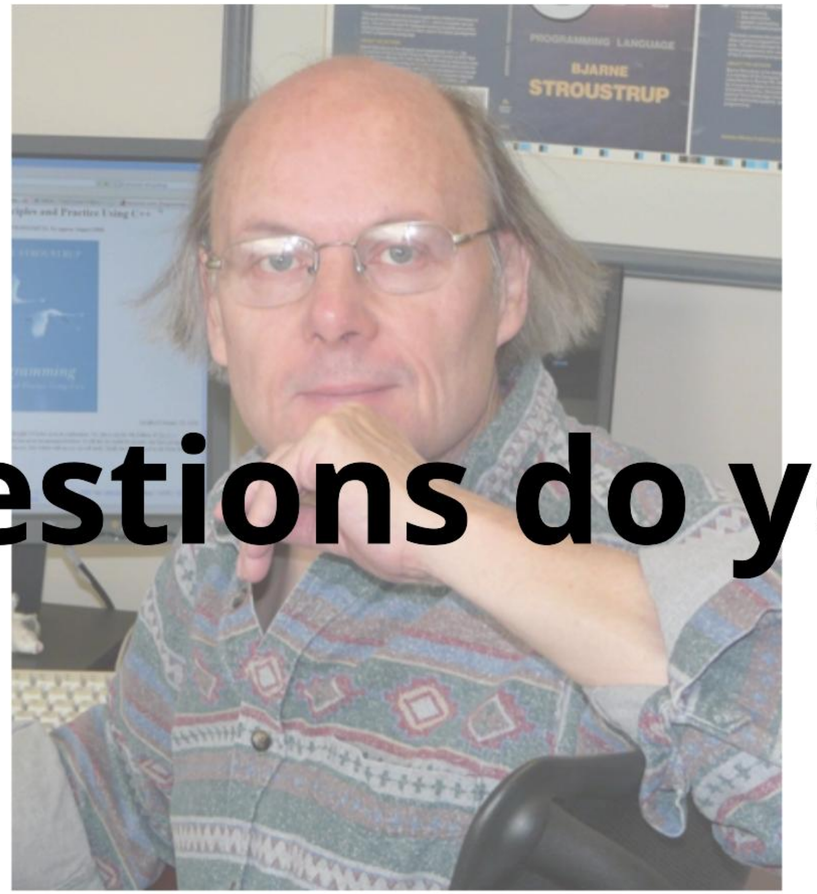


```
Vector<int>
```

```
Vector<string>
```

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

What questions do you have?



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Templates vs. Types

Templates vs. Types

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

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

Templates vs. Types

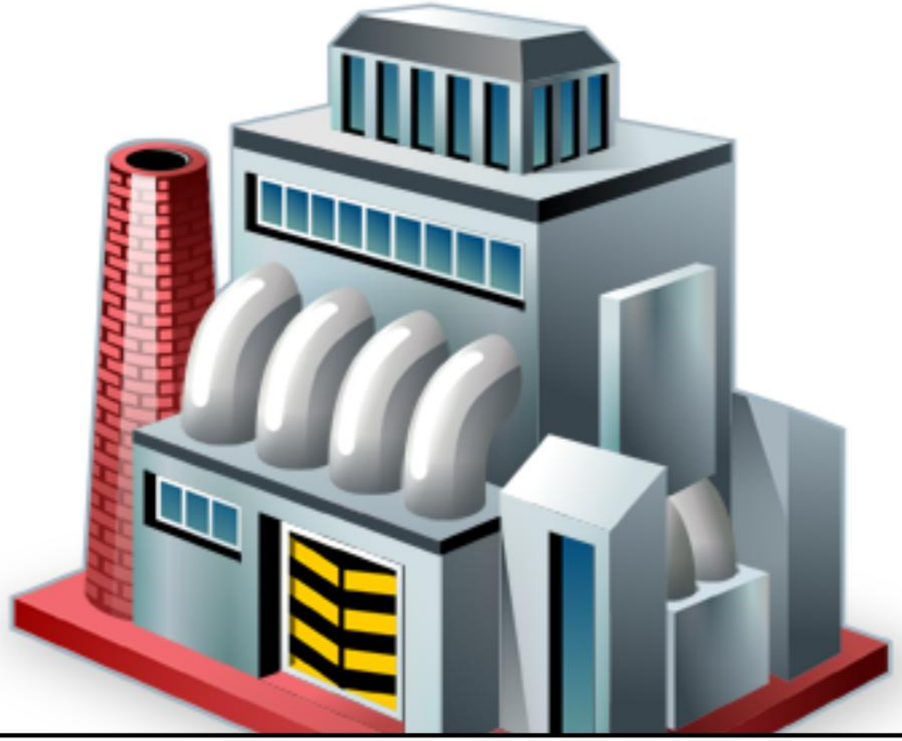
```
template <typename T>
class Vector
```

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

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

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

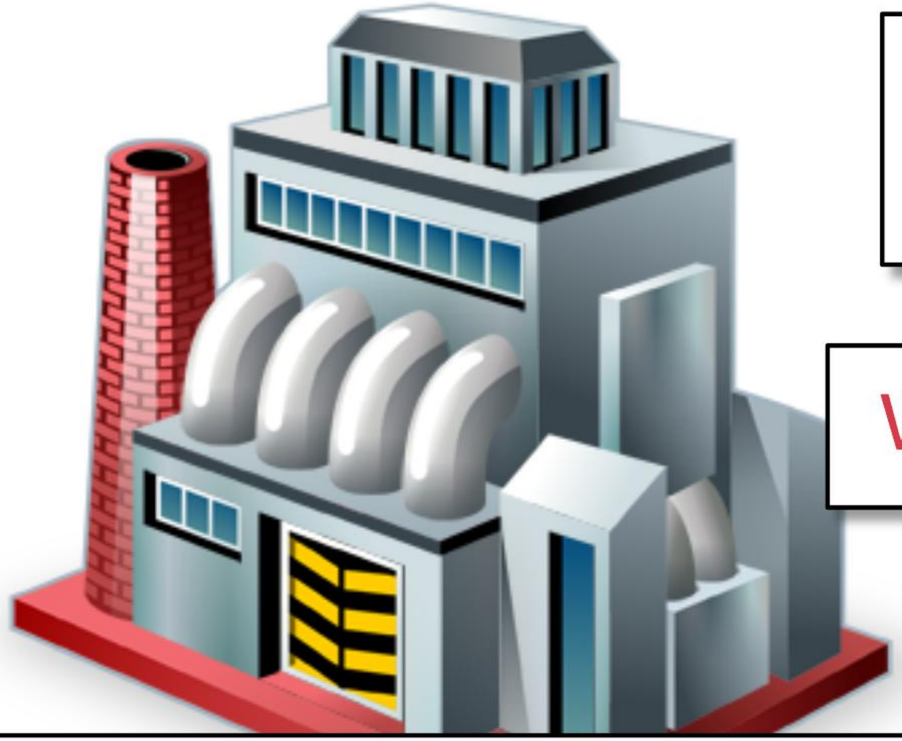
Templates vs. Types



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

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);

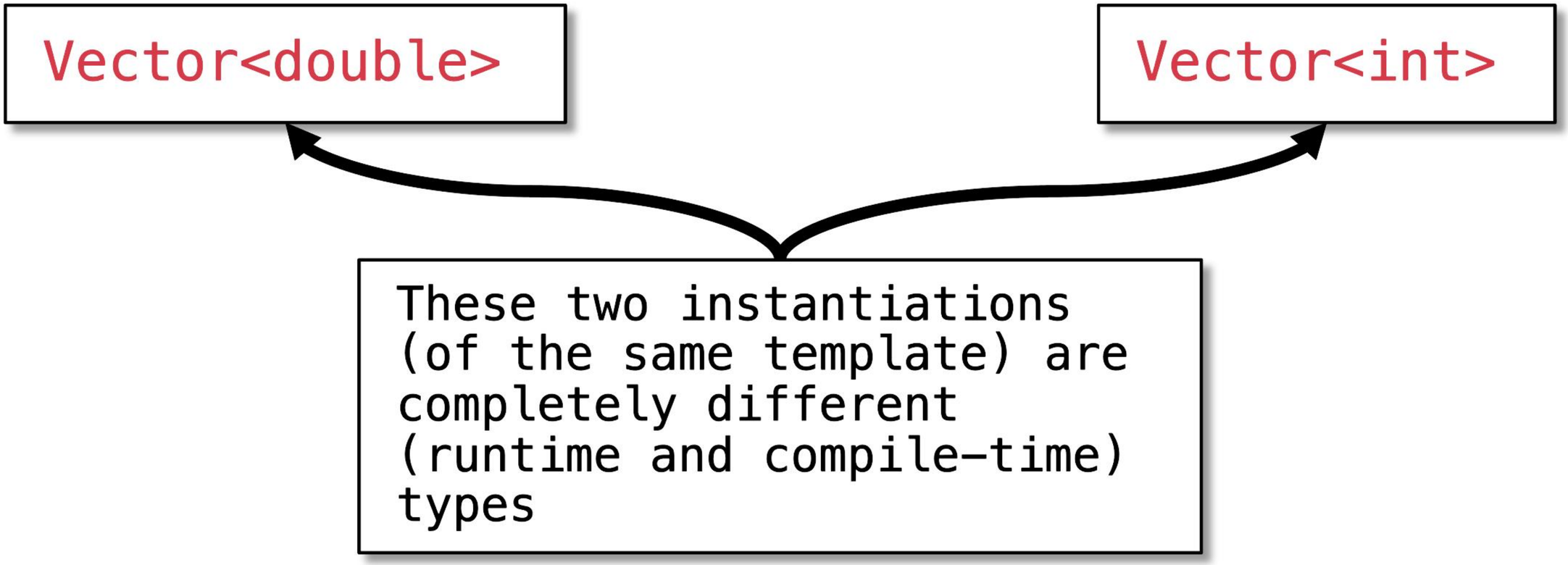
int main() {
   std::vector<double> v;
   foo(v);
}
```

Note: These are two distinct types

```
Vector<double>
```

```
Vector<int>
```

Note: These are two distinct types



Fun Fact: typename is interchangeable

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

Fun Fact: typename is interchangeable

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

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

SizeTemplate<5> s;
```

Fun Fact: typename is interchangeable

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

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

SizeTemplate<5> s;
```

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

BoolTemplate<true> b;
```

Fun Fact: typename is interchangeable

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

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

Fun Fact: typename is interchangeable

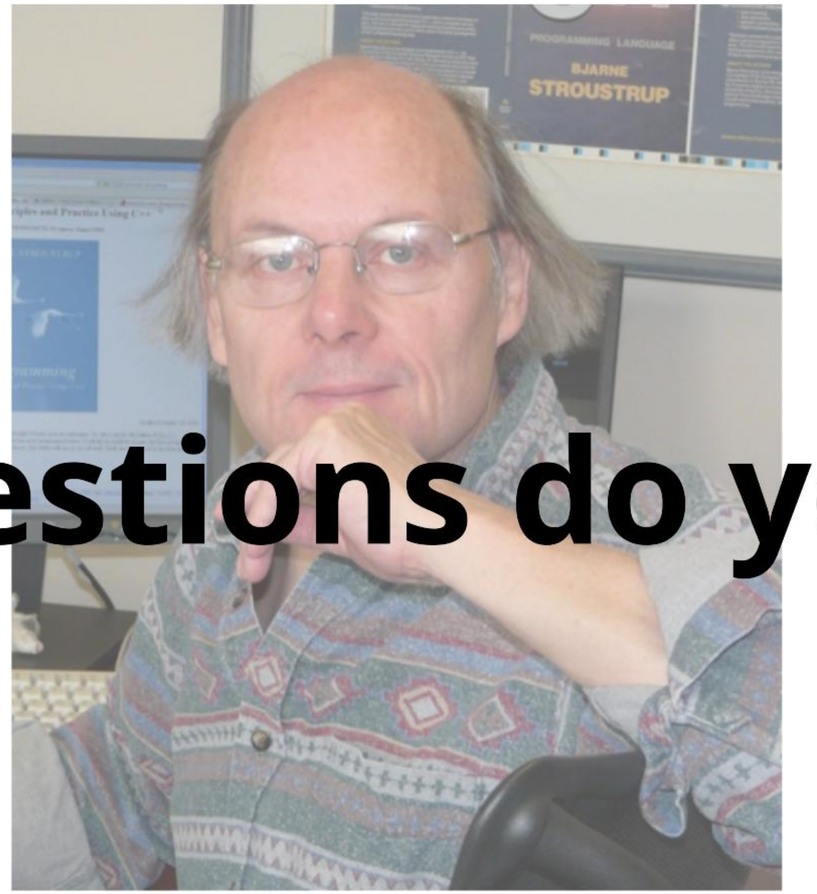
```
template<typename T, std::size_t N>
struct std::array { /* ... */ };

// 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

Template class implementation

When implementing a template, you might try something like this

```
// Vector.h

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

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When implementing a template, you might try something like this

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```
// Vector.cpp

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

Template class implementation

When implementing a template, you might try something like this

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template <typename T>
class Vector {
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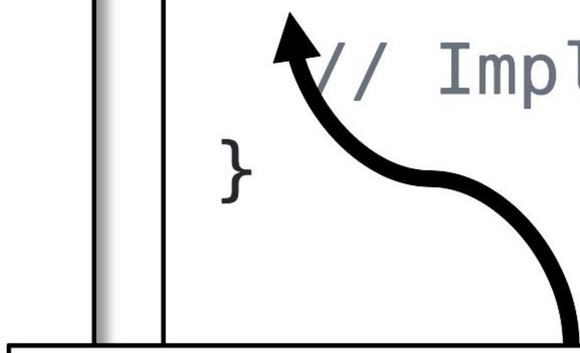


Compiler: “I don’t know what T is!”

Template class implementation

When implementing a template, must copy over template declaration

```
// Vector.cpp

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

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...
}
```

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

Normal class implementation

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

```
// StrVector.h

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

```
// 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

```
// Vector.h

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

#include "Vector.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)

(3) `typename` is the same as `class`

(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:

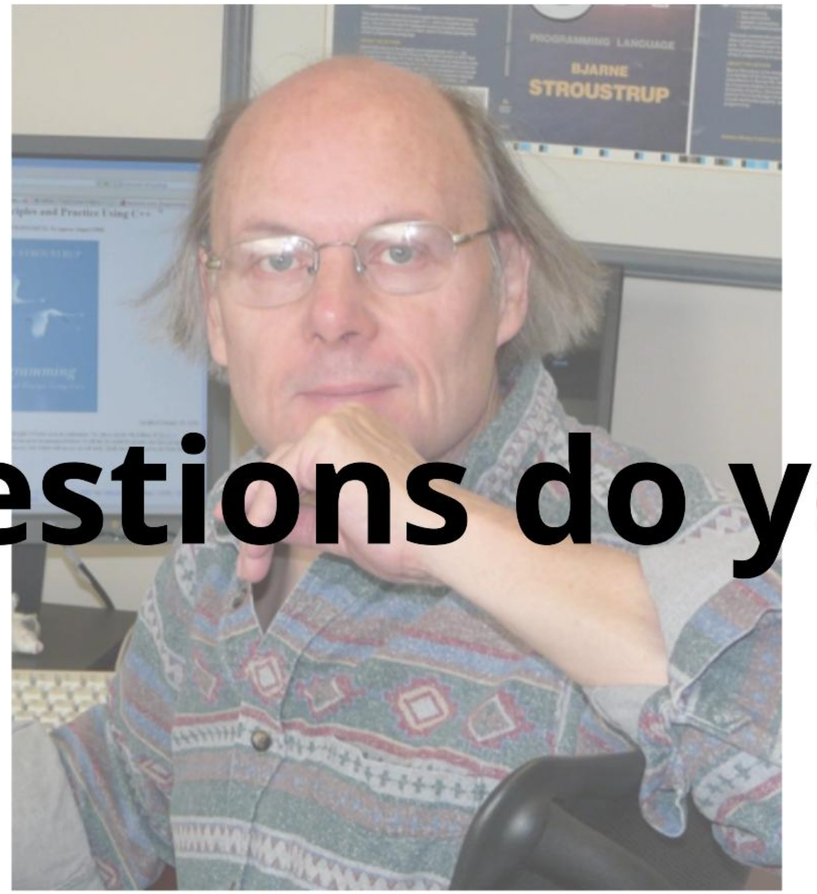
```
template <typename K, typename V>
struct pair;
```

```
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?



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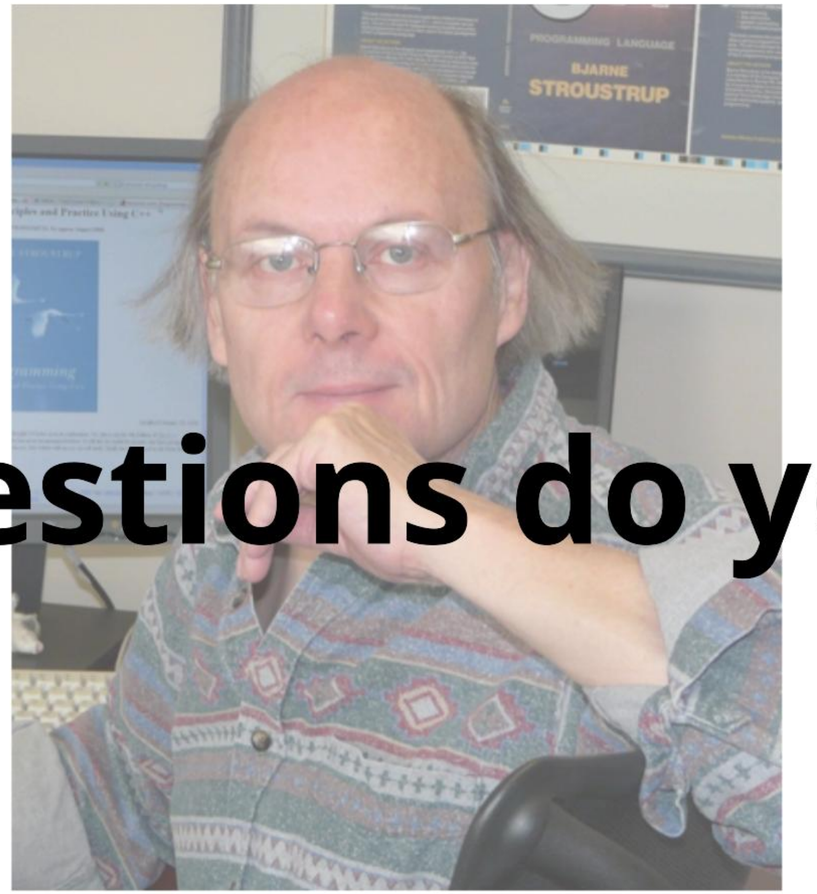
Code Demo

Let’s code this together 👫

106l.vercel.app/vector

What questions do you have?



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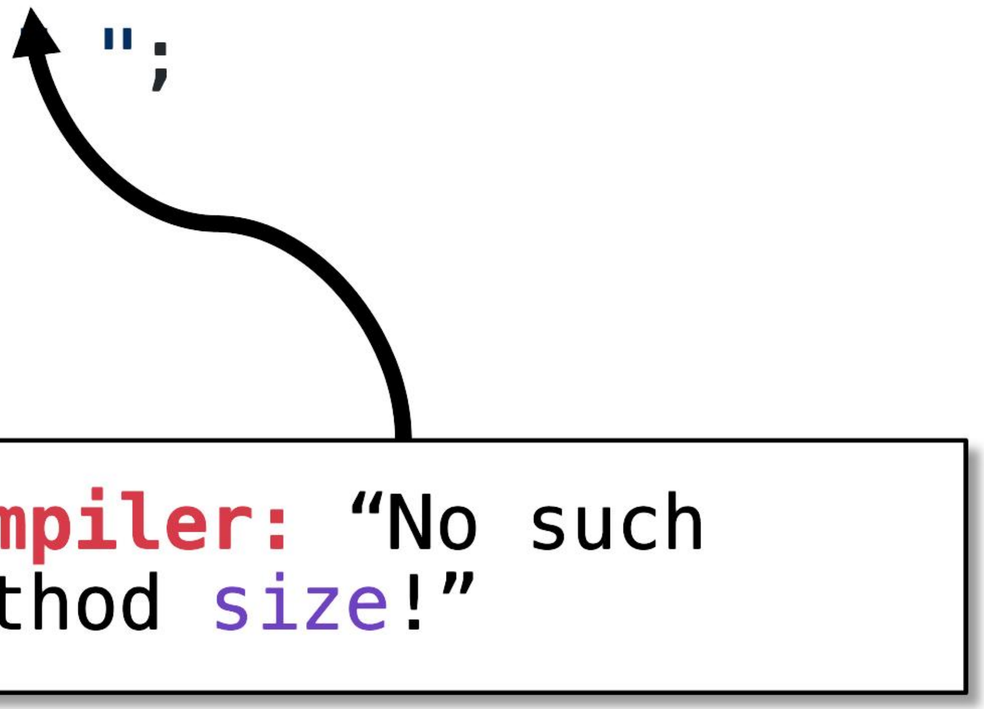
Const Correctness

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;
}
```

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;
}
```



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);
};
```

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;
}
```

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);
};
```

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...
```

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 {

   return logical_size;
}
```

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 data member
// within const member function 'size'
```

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
```

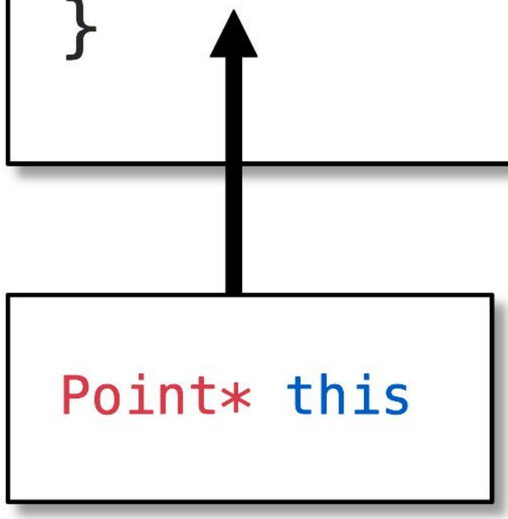
Inside a **const** method, **this** has type **const Vector<T>***

What is this?

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

What is this?

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




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

The const interface

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

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>

The const interface

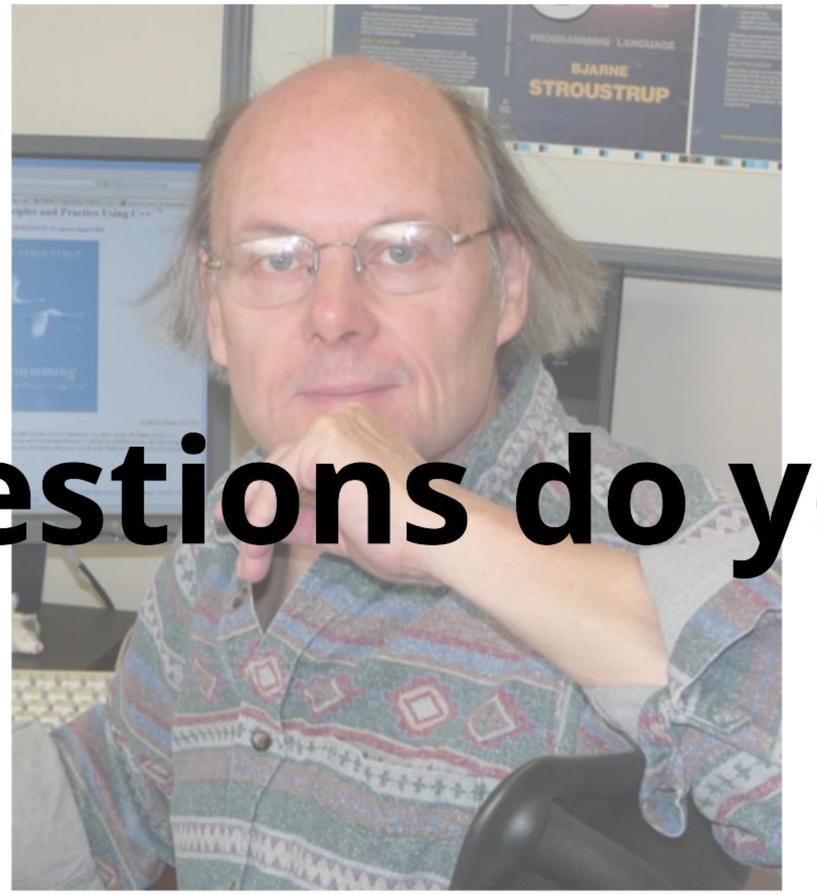
```
template<class T>
class Vector {
public:
   size_t size() const;
   bool empty() const;
   void push_back(const T& elem);
private:
   size_t logical_size;
   T* elems;
};
```

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;
}
```

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);
};
```

Back to our `Vector` class!

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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!

```
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);
};
```

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;
}
```

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);
};
```

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;
}
```

Solution: `const` overloading!

Solution: `const` overloading!

- Let's define two versions of our `at` method

```
template<class T>
class Vector {
public:



};
```

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);
};
```

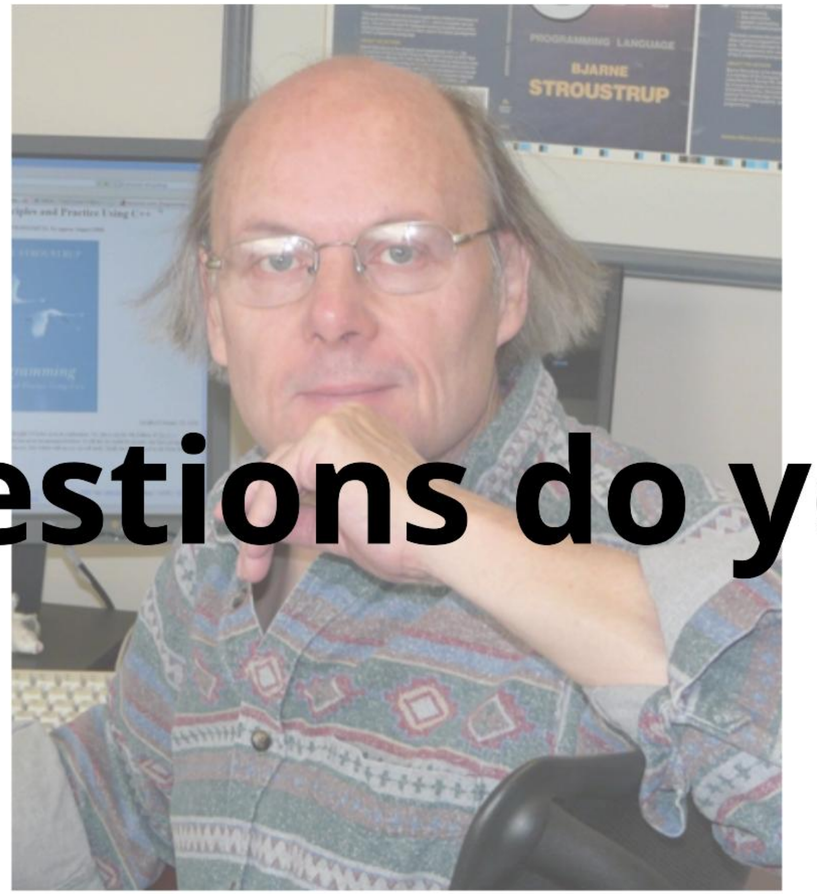
Solution: `const` overloading (`.cpp` file)!

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?



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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];
}
```

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;



};
```

Implementing findElement

```
template <typename T>
T& Vector<T>::findElement(const T& value) {




}
```

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");
}
```

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 {
    for (size_t i = 0; i < logical_size; i++) {
        if (elems[i] == elem) return elems[i];
    }
    throw std::out_of_range("Element not found");
}
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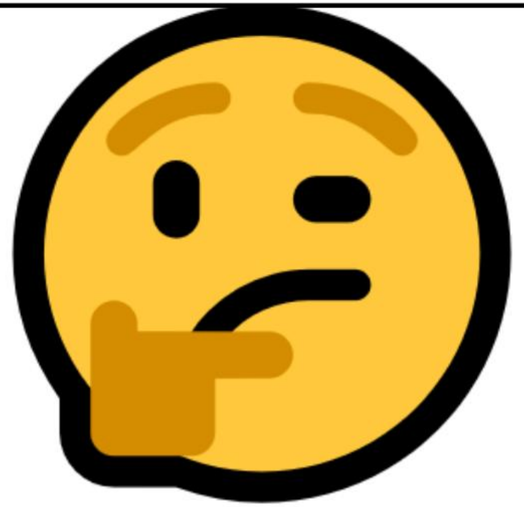
Implementing findElement

```
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");
}

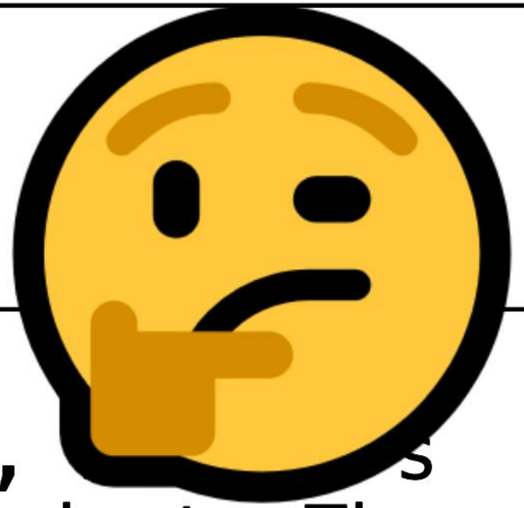
template <typename T>
const T& Vector<T>::findElement(const T& value) const {
    for (size_t i = 0; i < logical_size; i++) {
        if (elems[i] == elem) return elems[i];
    }
    throw std::out_of_range("Element not found");
}
```



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, [illegible] super redundant. There must be a better way!

A slight (but useful) aside

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

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);
}
```

Implementing findElement

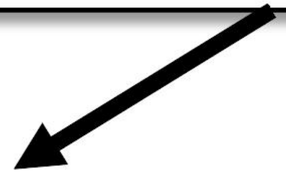
```
template <typename T>
T& Vector<T>::findElement(const T& value) {
   for (size_t i = 0; i < logi
      if (elems[i] == elem) ret
   }
   throw std::out_of_range("El
}

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);
```

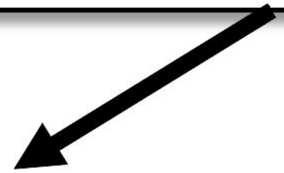
`const_cast` casts away the const



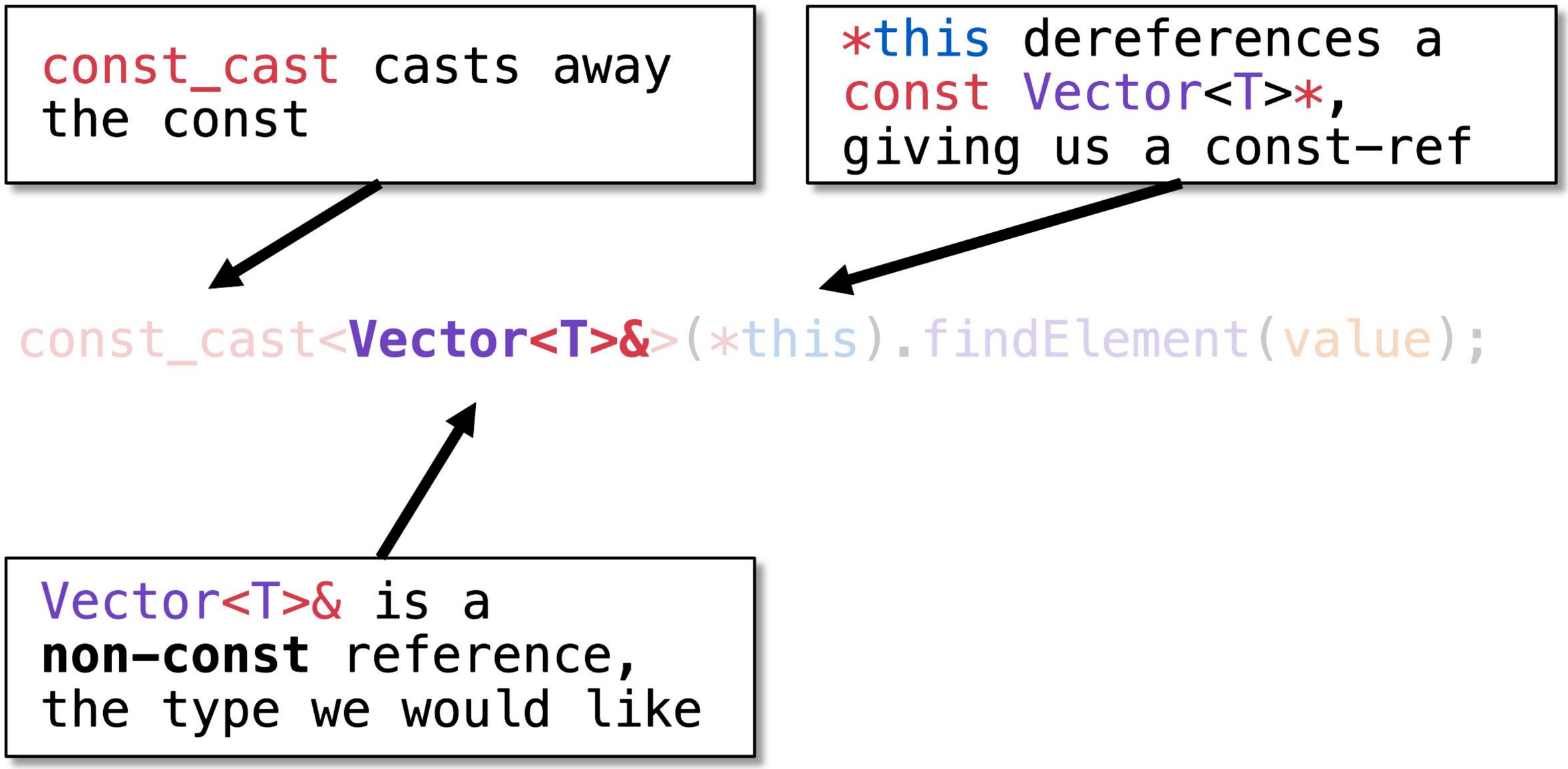
```
const_cast<Vector<T>&>(*this).findElement(value);
```

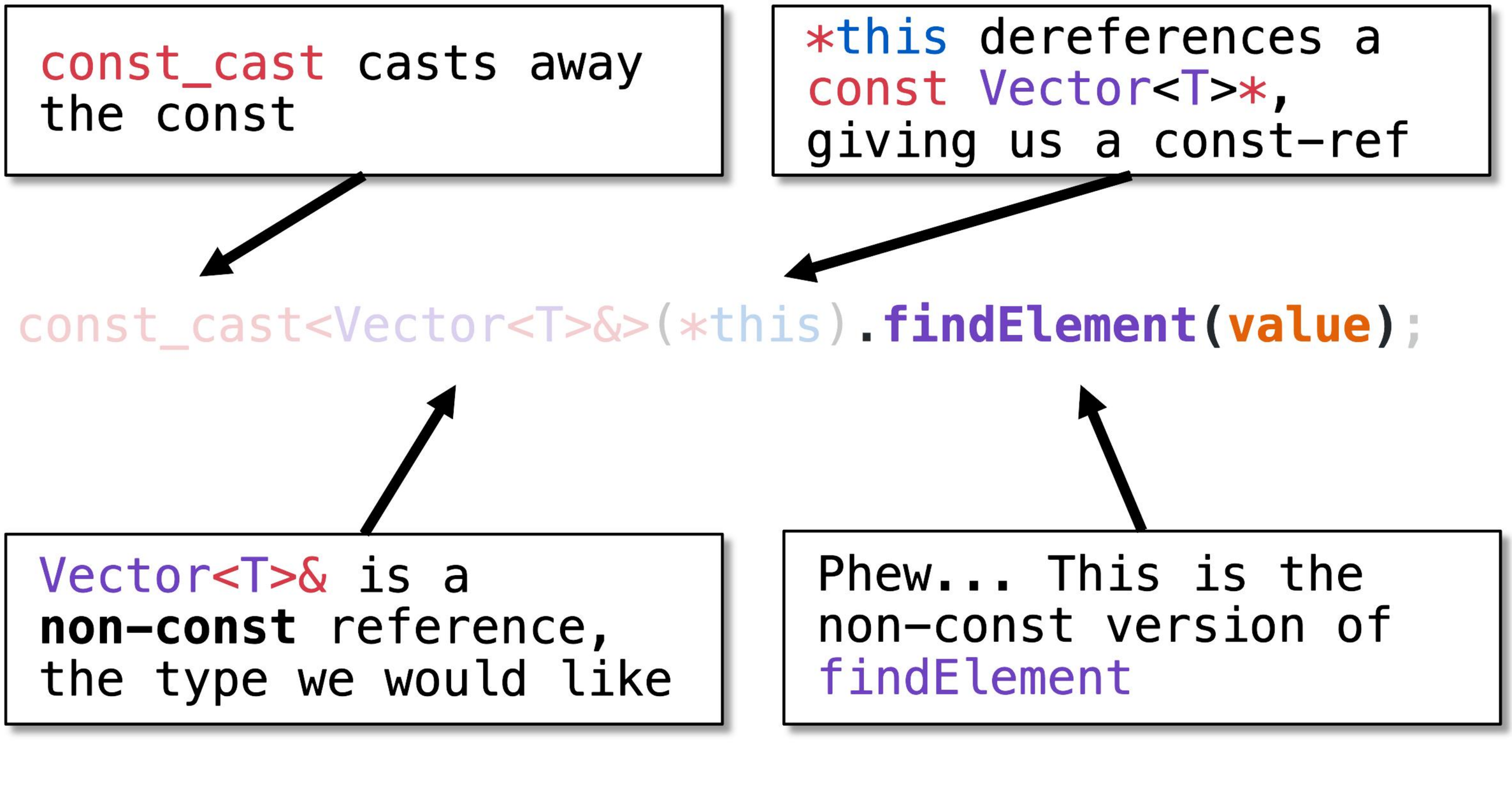
`const_cast` casts away the const

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



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


const_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` 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");
}

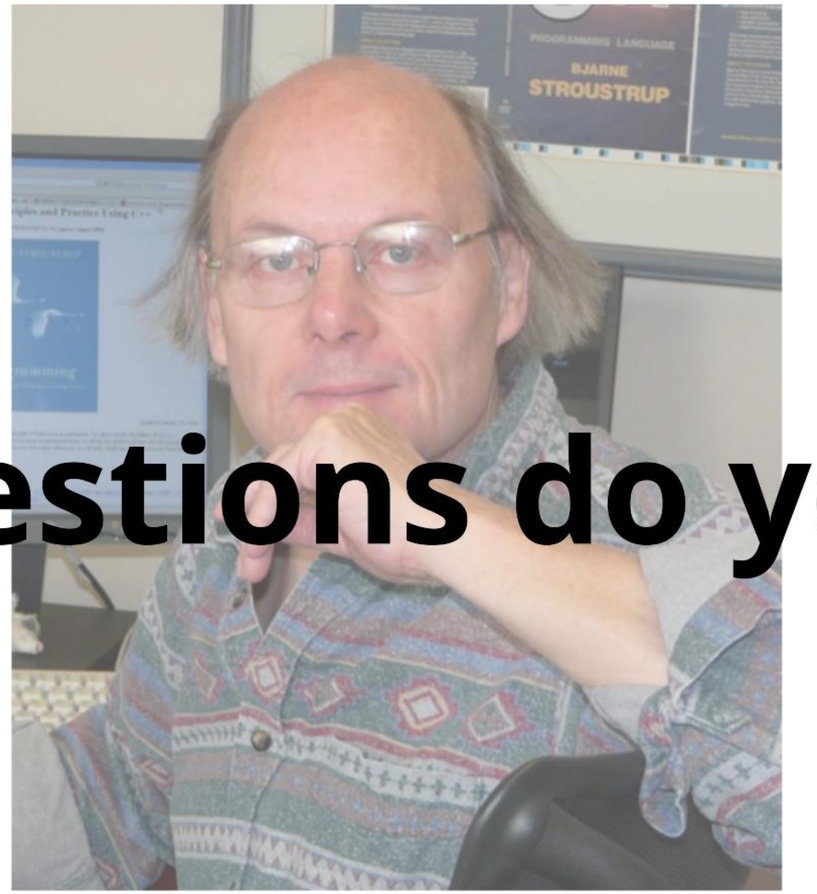
template <typename T>
const T& Vector<T>::findElement(const T& value) const {
   return const_cast<Vector<T>&>(*this).findElement(value);
}
```

When to use `const_cast`?

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

What questions do you have?



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`const_cast` makes an *entire* object mutable

A C++ party trick: mutable keyword

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

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

A C++ party trick: mutable keyword

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

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

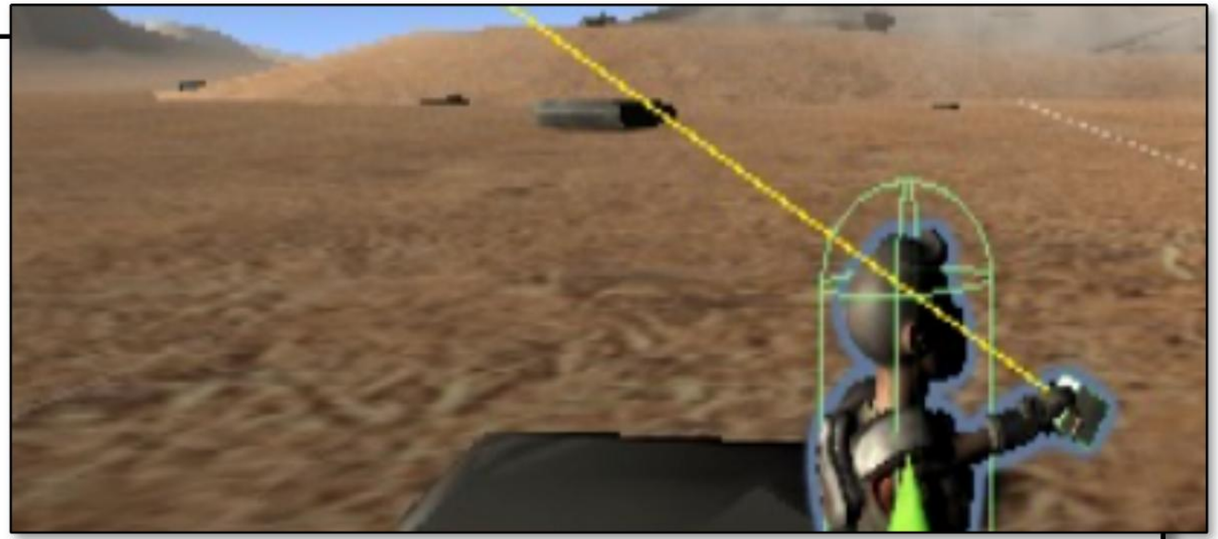
const MutableStruct cm;
// cm.dontTouchThis = 42;   // ❌ Not allowed, cm is const
cm.iCanChange = 3.14;       // ✅ Ok, iCanChange is mutable
```

`mutable` example: storing debug info

```
struct CameraRay {
   Point origin;
   Direction direction;

}
```

`mutable` example: storing debug info



```
struct CameraRay {
   Point origin;
   Direction direction;

}

void renderRay(const CameraRay& ray) {

   /* Rendering logic goes here ... */
}
```

Recap

Meme of the Day

Meme of the Day

Meme of the Day

Meme of the Day

What We Covered

What We Covered

- Template Classes
  - Template classes generalize logic across types!
- Code Demo
  - We implemented an `IntVector`, and then 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

End of slide show, click to exit.