

Lecture 5: Containers

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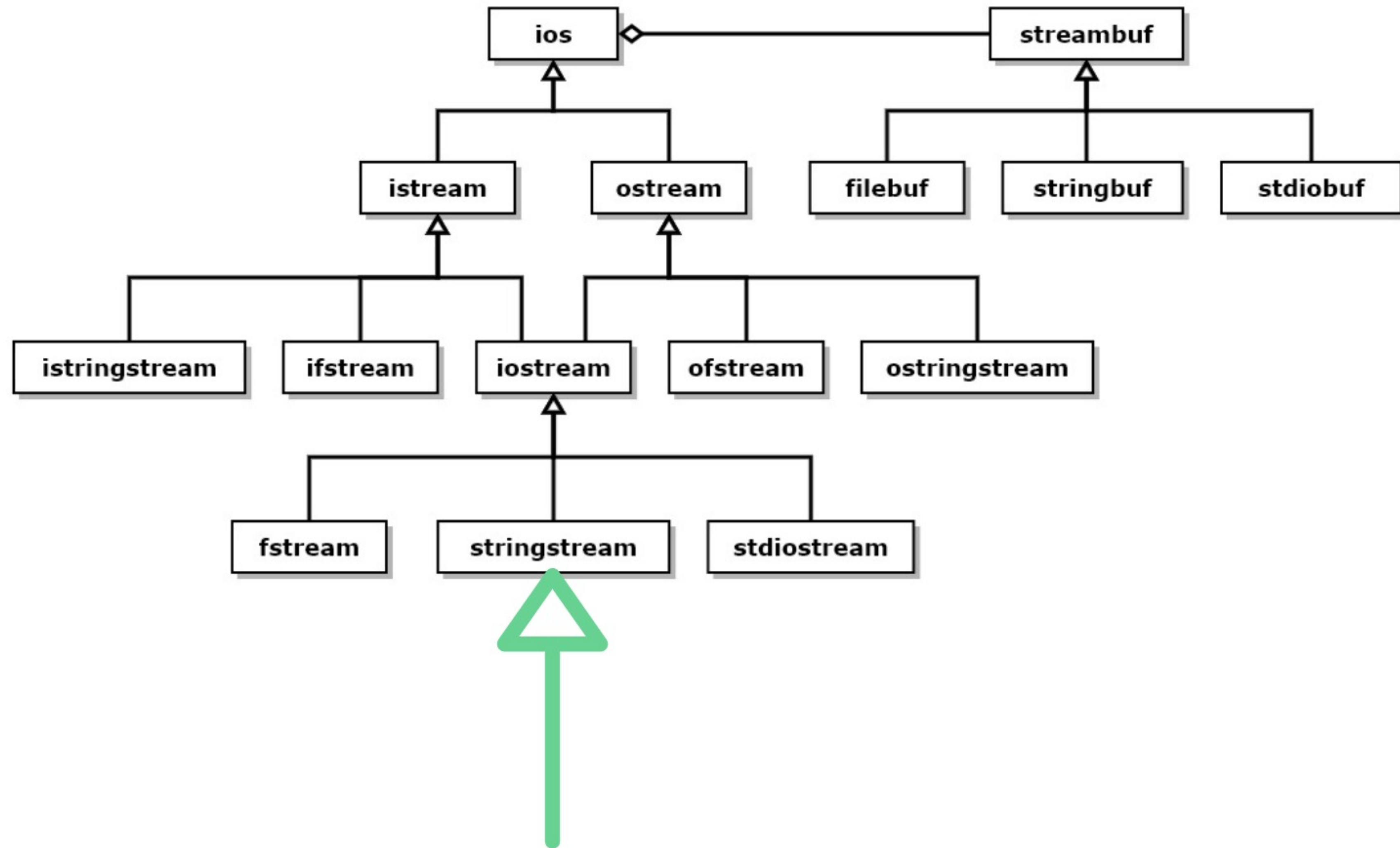
Plan

- (Recap)
 1. Space-time
 2. STL
 3. Sequence Containers
 4. Associative Containers

Recap

A `stringstream` is an...

- `istream` 
- `ostream` 



Recap

Code

Console

CPP

Run

```
1 #include <iostream>
2 #include <sstream>
3 #include <string>
4 int main() {
5     std::stringstream ss;
6     ss << 3.14f << ' ' << "hello"; // use as ostream
7
8     float pi; std::string hi;
9     ss >> pi >> hi; // use as istream
10
11     std::cout << pi << '\n' << hi << std::endl;
12 }
```

Attendance on 106l.com



[https://www.106l.com/live/containers/spirit-animal?
key=__op95hliCSsko1MJi-pUkWSO-Gaq79edorqEjt19fE](https://www.106l.com/live/containers/spirit-animal?key=__op95hliCSsko1MJi-pUkWSO-Gaq79edorqEjt19fE)



Plan

1. **Space-time**
2. STL
3. Sequence Containers
4. Associative Containers

Task - Fetch a wrench



AHA



AHA



How much stuff?





Space helps you
see and navigate



"Space is time."
- Bjarne Stroustrup

Disorganized



- Space efficient
- Slow to search
- Ex: vector

Organized



- Space inefficient
- Faster to search
- Ex: map

Plan

1. **Space-time**
2. STL
3. Sequence Containers
4. Associative Containers

Reminders

- Office hours started this morning, 10-11am in 320-220.
- Make sure to keep up with activities on cs106l.com .

Plan

1. Space-time
2. **STL**
3. Sequence Containers
4. Associative Containers

Standard Template Library (STL)

How is this different from the standard library `std`?

C++ Standard Library

streams

strings

...

**Standard Template
Library**

Standard Template Library (STL)

C++ Standard Library

streams

strings

math

...

Standard Template Library

Containers

Iterators

Functors

Algorithms

Standard Template Library (STL)

C++ Standard Library

streams

strings

math

...

Standard Template Library

Containers

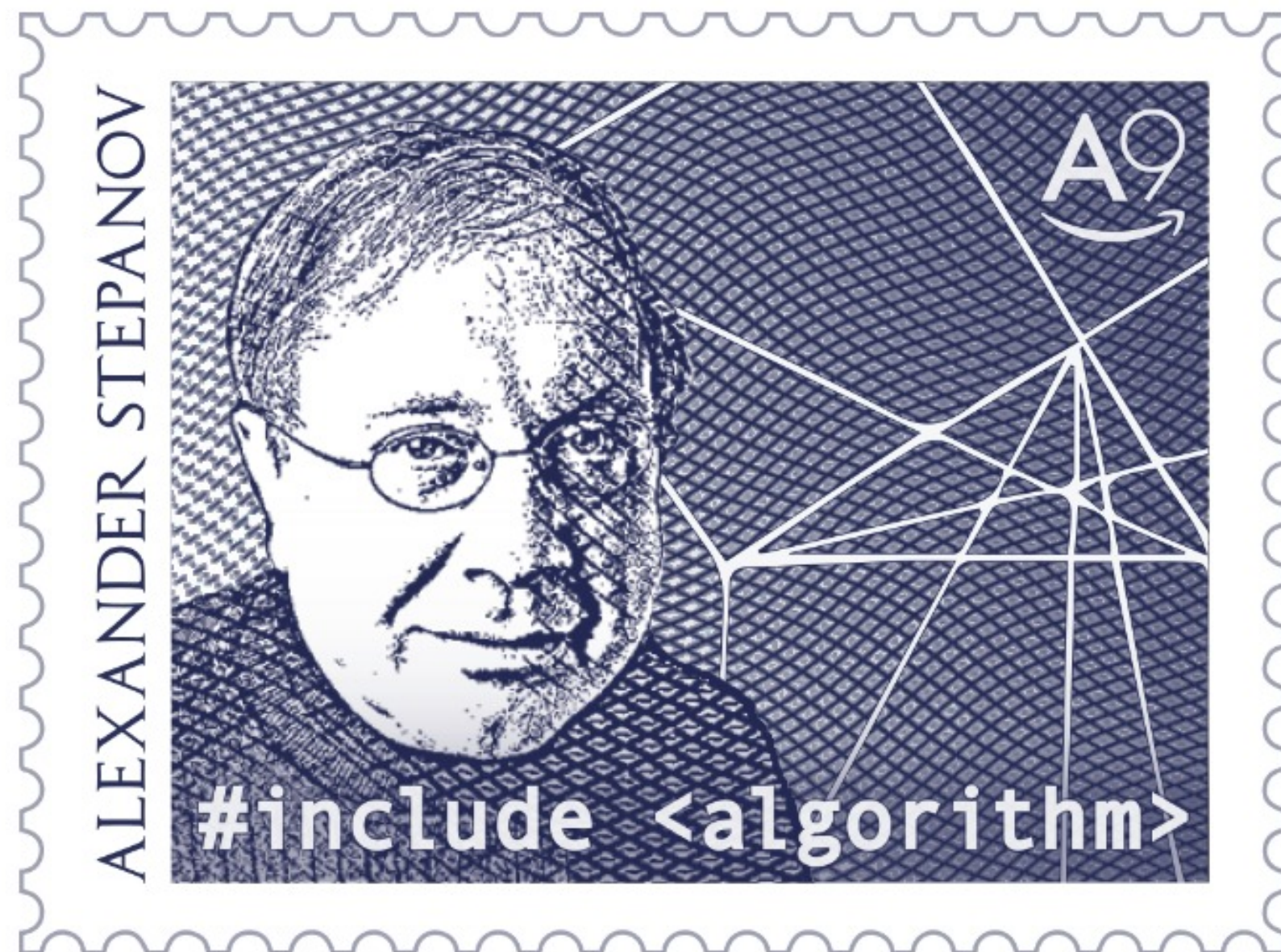
Iterators

Functors

Algorithms

Standard Template Library (STL)

- **Made by Alexander Stepanov**



Standard Template Library

Containers

Iterators

Functors

Algorithms

What does template mean?

```
1 class IntList {  
2     ...  
3 };  
4  
5 int main() {  
6     IntList ints(  
7         ints.add(10);  
8         ints.add(20);  
9  
10    assert(ints.g  
11 }
```

```
1 class StringList {  
2     ...  
3 };  
4  
5 int main() {  
6     StringList strs();  
7     strs.add("1");  
8     strs.add("2");  
9  
10    assert(strs.get(0) == "1");  
11 }
```

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```

What does template mean?

```
1 class IntList {  
2     ...  
3 };
```

```
1 class DoubleList {  
2     ...  
3 };
```

```
1 class StringList {  
2     ...  
3 };
```



```
1 // You'll learn more wk 5!  
2 template <typename T>  
3 class Vector<T> {  
4     ...  
5 }
```

```
1 #include <vector>  
2  
3 int main() {  
4     std::vector<int> ints;  
5     std::vector<double> dbls;  
6     std::vector<std::string> strs;  
7  
8     ints.push_back(1);  
9     dbls.push_back(5.4);  
10    strs.push_back("hi");  
11    std::cout << ints[0] + dbls[0];  
12 }
```

Plan

1. Space-time
2. STL
3. **Sequence Containers**
4. Associative Containers

Sequence Containers

"Sequence containers implement data structures which can be accessed sequentially."

In other words, they contain sequences.



<https://en.cppreference.com/w/cpp/container.html> ↗

Sequence Containers

- **Vector**
- **Deque**
- **Array**
- **List**



<https://en.cppreference.com/w/cpp/container.html> ↗

Vectors

**"A resizable
contiguous array"**

1	2	3	4	5	6
0	1	2	3	4	5

Code

Console

CPP

Run

```
1 #include <vector>
2 #include <iostream>
3 int main() {
4     std::vector<int> vec { 1, 2, 3, 4 };
5     vec.push_back(5);
6     vec.push_back(6);
7     vec[1] = 20;
8
9     for (size_t i = 0; i < vec.size(); i++) {
10         std::cout << vec[i] << " ";
11     }
12 }
```

Vectors

"A resizable
contiguous array"

1	20	3	4	5	6
0	1	2	3	4	5

Code

Console

CPP

Run

```
1 #include <vector>
2 #include <iostream>
3 int main() {
4     std::vector<int> vec { 1, 2, 3, 4 };
5     vec.push_back(5);
6     vec.push_back(6);
7     vec[1] = 20;
8
9     for (size_t i = 0; i < vec.size(); i++) {
10         std::cout << vec[i] << " ";
11     }
12 }
```

Index Checking?

- Be careful with indices
- [] doesn't check
- .at() does

```
Code Console CPP Run
1 #include <vector>
2 #include <iostream>
3 int main() {
4     std::vector<int> vec { 1, 2, 3, 4 };
5     vec.push_back(5);
6     vec.push_back(6);
7     vec[1] = 20;
8
9     for (size_t i = 0; i < 10; i++) {
10         std::cout << vec[i] << " ";
11     }
12 }
```

Index Checking?

1. You don't pay for what you don't use.
2. What you do use is just as efficient as what you could reasonably write by hand.



https://en.cppreference.com/w/cpp/language/Zero-overhead_principle.html

How do Vectors Resize?



<https://web.stanford.edu/~pseay/cs106l/vectors> ↗

106B vs. Standard Vectors

What you want to do?	Stanford Vector<int>	std::vector<int>
Create an empty vector	<code>Vector<int> v;</code>	<code>std::vector<int> v;</code>
Create a vector with n copies of 0	<code>Vector<int> v(n);</code>	<code>std::vector<int> v(n);</code>
Create a vector with n copies of value k	<code>Vector<int> v(n, k);</code>	<code>std::vector<int> v(n, k);</code>
Add k to the end of the vector	<code>v.add(k);</code>	<code>v.push_back(k);</code>
Clear vector	<code>v.clear();</code>	<code>v.clear();</code>
Check if v is empty	<code>if (v.isEmpty())</code>	<code>if (v.empty())</code>
Get the element at index i	<code>int v = v.get(i);</code> <code>int k = v[i];</code>	<code>int k = v.at(i);</code> <code>int k = v[i];</code>
Replace the element at index i	<code>v.get(i) = k;</code> <code>v[i] = k;</code>	<code>v.at(i) = k;</code> <code>v[i] = k;</code>

Practice with Vectors

Task:

Write a C++
function to calculate
the minimum value
of a vector.



Vectors Don't Reorder Well



<https://web.stanford.edu/~pseay/cs106I/vectors-insert> ↗

Dequeues

Double-ended *queue* (pronounced "deck")

Like a **vector**, with:

- **push_back**
- **pop_back**

But also has:

- **push_front**
- **pop_front**



Deque

Ex: Maintaining a list of the last 10,000 prices

[illegible]

Dequeues Behind the Scenes



<https://web.stanford.edu/~pseay/cs106l/deque> ↗

Plan

1. Space-time
2. STL
3. Sequence Containers
4. **Associative Containers**

Associative Containers

"Associative containers implement **sorted** data structures that can be **quickly searched**."



<https://en.cppreference.com/w/cpp/container.html> ↗

Maps

A map "contains
key-value pairs
with unique keys."

Python calls them
"dictionaries"



<https://en.cppreference.com/w/cpp/container/map.html> ↗

Maps

"Sequence Containers"

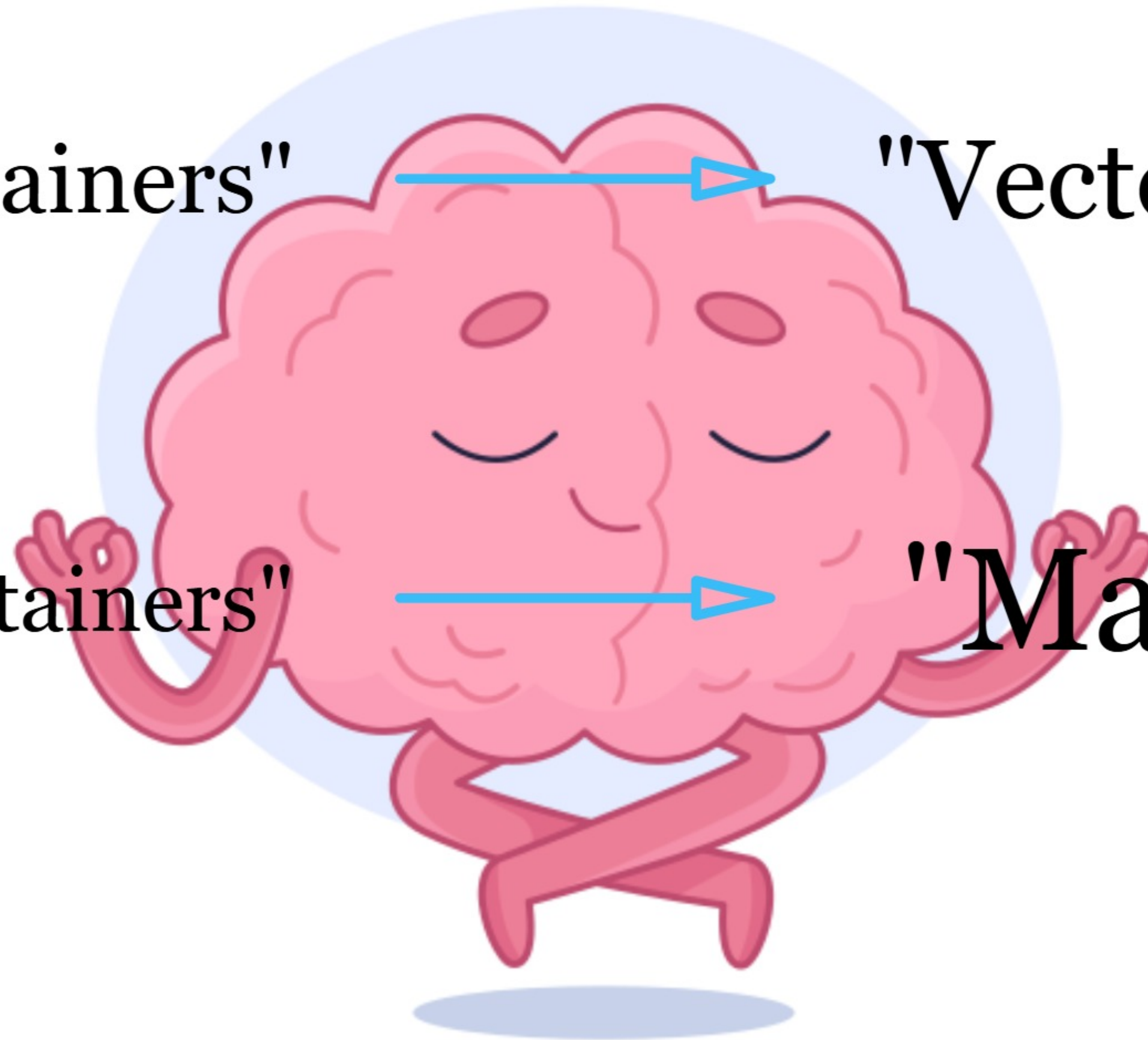


"Vectors & Deques"

"Associative Containers"



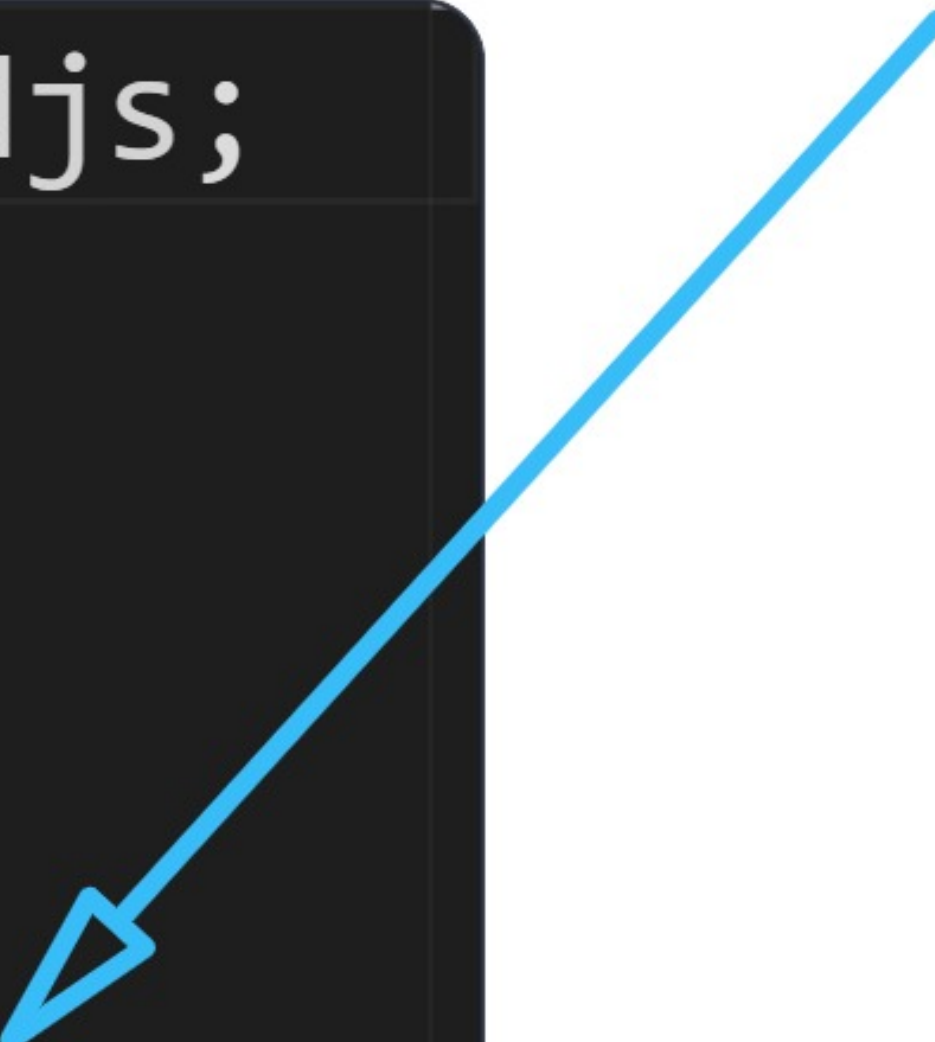
"Maps & Sets"



Maps

We can do this:

```
1 std::map<int, char*> adjs;  
2 adjs[106] = "awesome";  
3 adjs[103] = "mathy";  
4 adjs[107] = "deep";  
5  
6 std::cout << adjs[106];
```



How is it efficient?

It sorts the
pairs by
their keys...

Maps

Code Console

CPP

Run

```
1 #include <map>
2 #include <iostream>
3 int main () {
4     std::map<int, char> preston {
5         {16, 'p'}, {18, 'r'}, {5, 'e'},
6         {19, 's'}, {20, 't'}, {15, 'o'}, {14, 'n'}
7     };
8     for (const auto& pair : preston) {
9         std::cout << pair.first << ' '
10         << pair.second << std::endl;
11     }
12 }
```

A map is a collection of pairs,
so here is uniform initialization of
pairs.

We loop over each pair.

The pairs are sorted by key.

Maps

A `std::map<K, V>` is a collection of `std::pair<const K, V>`

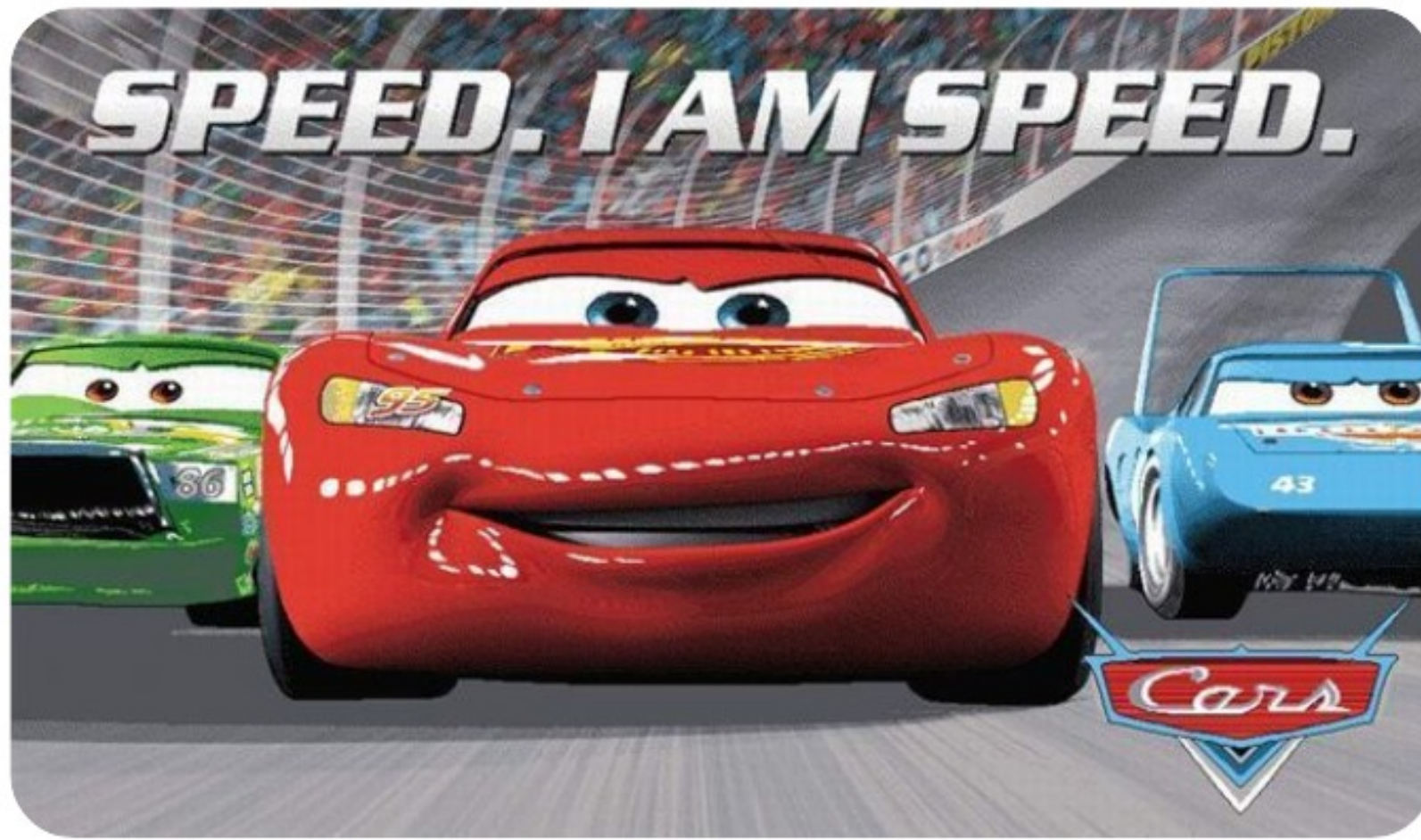
```
Code Console CPP Run
1 for (const auto& pair : myMap) {
2     auto key = pair.first;
3     auto value = pair.second;
4 }
```

↓ Structured binding 👍

```
Code Console CPP Run
1 for (const auto& [key, value] : myMap) {
2
3 }
```

Maps Storage - Red Black Trees

- Stores pairs in a **binary search tree** (BST)
- Specifically, it uses a **Red-Black Tree**, guaranteeing maximum depth of $2 \log(n)$
- This makes search **$O(\log(n))$**



<https://web.stanford.edu/~pseay/cs106l/maps-rbt> ↗

Maps - Auto Insertion

We can do this:

```
1 std::map<std::string, int> fav_num;  
2 fav_num["Preston"] = 2;  
3  
4 std::cout << "Preston's is " << fav_num["Preston"] <<  
5 " and Emily's is " << fav_num["Emily"] << '\n';
```

"Ummmm... we never defined that???"



The map automatically inserts the default value of the object.

(It actually does this every time, even on **line 2**)

Sets

Amoral maps

Maps without values

Unique Objects



<https://web.stanford.edu/~pseay/cs106I/sets-rbt> ↗

Map Syntax

What you want to do?	Stanford Map<char, int>	std::map<char, int>
Create an empty map	Map<char, int> m;	std::map<char, int> m;
Add key k with value v into the map	m.put(k, v); m[k] = v;	m.insert({k, v}); m[k] = v;
Remove key k from the map	m.remove(k);	m.erase(k);
Check if k is in the map (* C++20)	if (m.containsKey(k))	if (m.count(k)) if (m.contains(k)) (*)
Check if the map is empty	if (m.isEmpty())	if (m.empty())
Retrieve or overwrite value associated with key k (auto-insert default if doesn't exist)	int i = m[k]; m[k] = i;	int i = m[k]; m[k] = i;

Set Syntax

What you want to do?	Stanford Set<char>	std::set<char>
Create an empty set	Set<char> s;	std::set<char> s;
Add k to the set	s.add(k);	s.insert(k);
Remove k from the set	s.remove(k);	s.erase(k);
Check if k is in the set (* C++20)	if (s.contains(k))	if (s.count(k)) if (s.contains(k)) (*)
Check if the set is empty	if (s.isEmpty())	if (s.empty())

Practice with Associative Containers

Task:

Write a C++
function to find
"Supersponsors."



Practice

Code Console

CPP

Run

```
1 #include <iostream>
2 #include <vector>
3 #include <string>
4 #include <map>
5 #include <set>
6
7 std::set<std::string> findDoubleAgents(std::map<std::string, std::set<std::string>>
  departments) {
8     std::set<std::string> seen, doubleAgents;
9
10    // Your code here
11
12    return doubleAgents;
13 }
14
15 int main() {
16     std::map<std::string, std::set<std::string>> company = {
```

There are also versions with non-unique keys...

Associative containers

Associative containers implement sorted data structures that can be quickly searched ($O(\log n)$ complexity).

set	collection of unique keys, sorted by keys (class template)
map	collection of key-value pairs, sorted by keys, keys are unique (class template)
multiset	collection of keys, sorted by keys (class template)
multimap	collection of key-value pairs, sorted by keys (class template)

The Caveat of Associative Containers

"Wait... how do they get sorted?"

std::map

Defined in header `<map>`

```
template<
    class Key,
    class T,
    class Compare = std::less<Key>,
class Allocator = std::allocator<std::pair<const Key, T>>
> class map;
```

This is how... they must be comparable, so it uses the "less than" comparator by default.

"How do we make memory for it?"

The Caveat of Associative Containers

Not all elements
are comparable
by default...

`int, double, string`

`ifstream, Course`

Plan

1. Space-time
2. STL
3. Sequence Containers
4. **Associative Containers**

Plan

1. Space-time
2. STL
3. Sequence Containers
4. Associative Containers
 - **Bonus - Unordered Associative Containers**

Containers library

The Containers library is a generic collection of classes implement common data structures like queues, lists, containers:

- sequence containers,
- associative containers,
- unordered associative containers, (since C++11)

Unordered Associative Containers

map

unordered_map



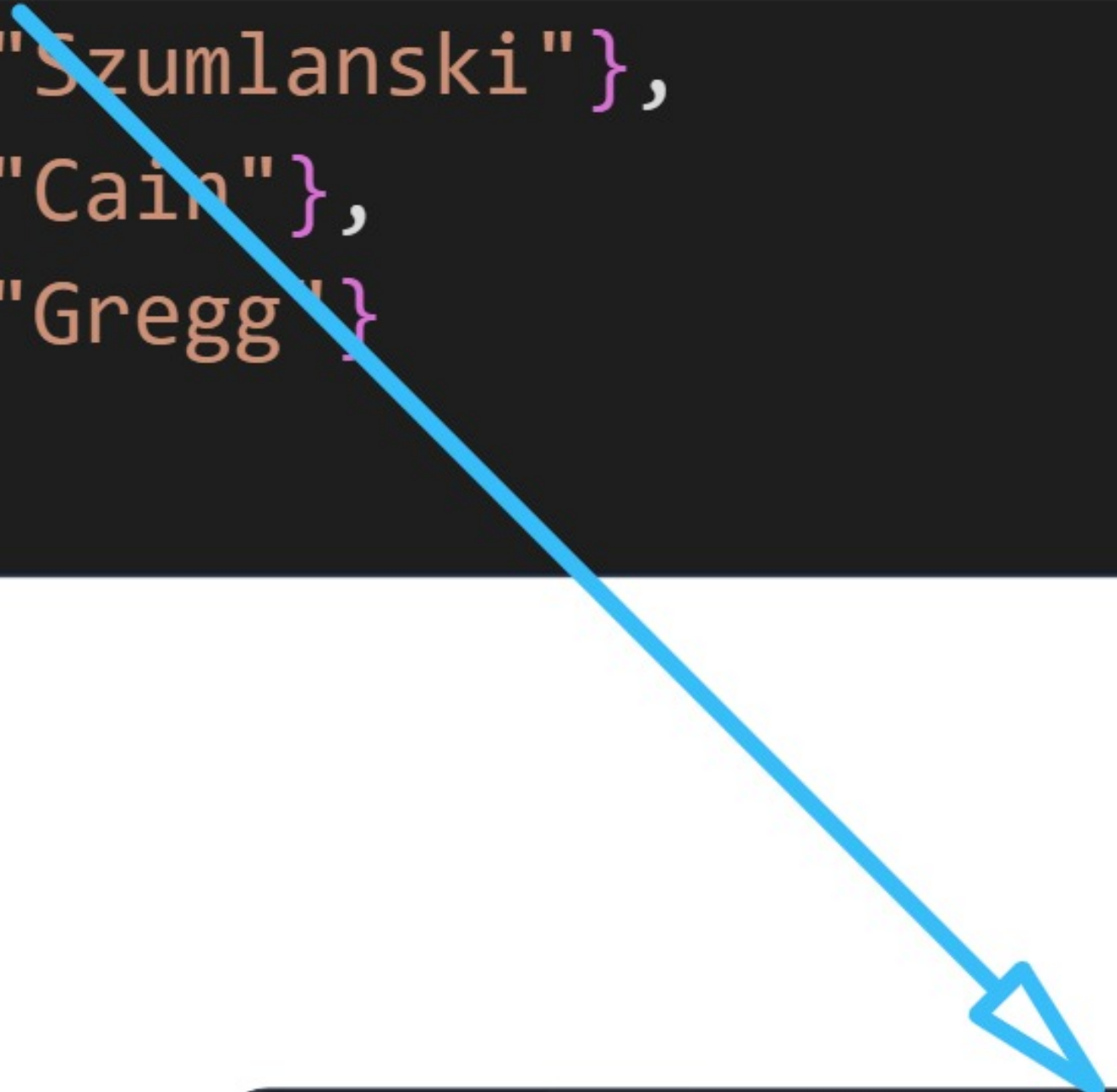
set

unordered_set

Essentially optimized versions of map and set.

Unordered Associative Containers

```
1 std::map<int, std::string> courses{
2     {103, "Szumlanski"},
3     {107, "Cain"},
4     {109, "Gregg"}
5 };
```



Drop-in replacement

```
1 std::unordered_map<int, std::string> courses{
2     {103, "Szumlanski"},
3     {107, "Cain"},
4     {109, "Gregg"}
5 };
```

The Caveat - Hashing

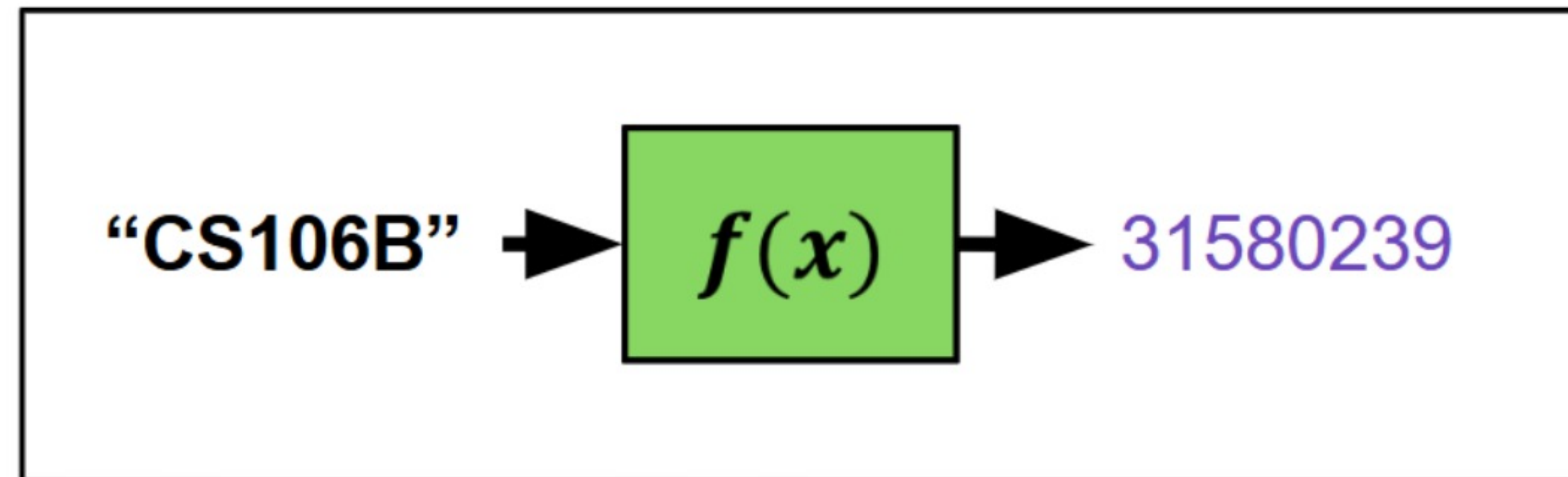
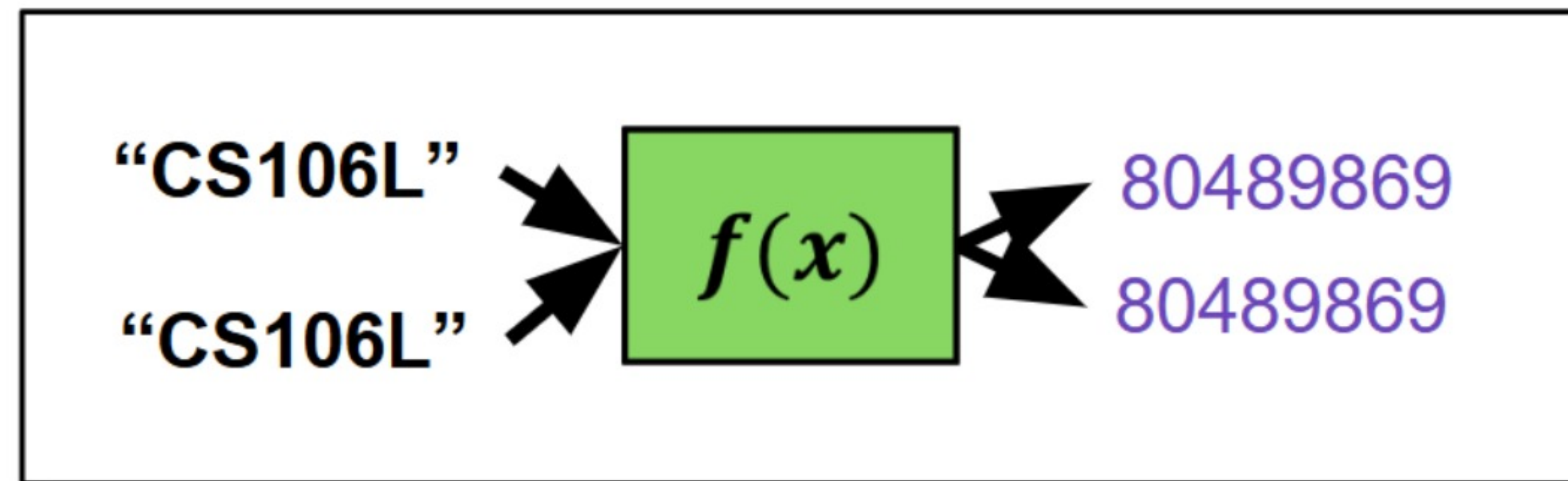
std::unordered_map

Defined in header `<unordered_map>`

```
template<
    class Key,
    class T,
    class Hash = std::hash<Key>,
    class KeyEqual = std::equal_to<Key>,
    class Allocator = std::allocator<std::pair<const Key, T>>
> class unordered_map;
```

What is a hash function?

- “Scrambles” a key into a `size_t` (64 bit)
- Small changes in the input should produce large changes in the output



Unordered Map Implementation

Hash
Table



<https://web.stanford.edu/~pseay/cs106I/hash-map> ↗

Speed



Vectors

$O(n)$



Maps

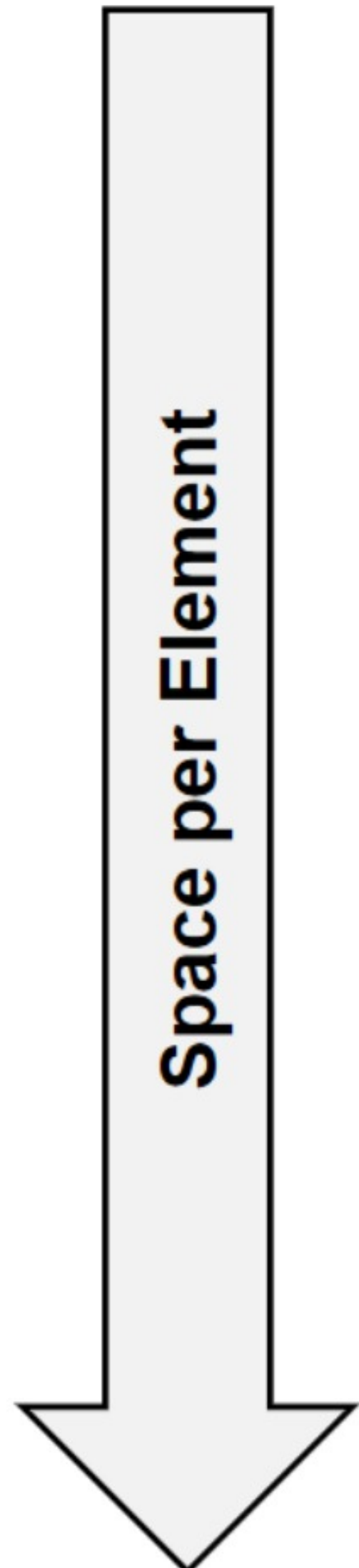
Unordered Maps

$O(\log(n))$

$O(1)$

Recap

Summary of Data Structures



	i^{th} element	Search	Insertion	Erase
std::vector	Very Fast	Slow	Slow	Slow
std::deque	Fast	Slow	Fast (front/back) Slow (all others)	Fast (front/back) Slow (all others)
std::set	Slow	Fast	Fast	Fast
std::map	Slow	Fast	Fast	Fast
std::unordered_set	N/A	Very Fast	Very Fast	Very Fast
std::unordered_map	N/A	Very Fast	Very Fast	Very Fast

More Data Structures = More Fun

Sequence containers

Sequence containers implement data structures which can be accessed sequentially.

array (C++11)	fixed-sized inplace contiguous array (class template)
vector	resizable contiguous array (class template)
inplace_vector (C++26)	resizable, fixed capacity, inplace contiguous array (class template)
hive (C++26)	collection that reuses erased elements' memory (class template)
deque	double-ended queue (class template)
forward_list (C++11)	singly-linked list (class template)
list	doubly-linked list (class template)

Container adaptors

Container adaptors provide a different interface for sequential containers.

stack	adapts a container to provide stack (LIFO data structure) (class template)
queue	adapts a container to provide queue (FIFO data structure) (class template)
priority_queue	adapts a container to provide priority queue (class template)
flat_set (C++23)	adapts a container to provide a collection of unique keys, sorted by keys (class template)
flat_map (C++23)	adapts two containers to provide a collection of key-value pairs, sorted by unique keys (class template)
flat_multiset (C++23)	adapts a container to provide a collection of keys, sorted by keys (class template)
flat_multimap (C++23)	adapts two containers to provide a collection of key-value pairs, sorted by keys (class template)

Associative containers

Associative containers implement sorted data structures that can be quickly searched ($O(\log n)$ complexity).

set	collection of unique keys, sorted by keys (class template)
map	collection of key-value pairs, sorted by keys, keys are unique (class template)
multiset	collection of keys, sorted by keys (class template)
multimap	collection of key-value pairs, sorted by keys (class template)

Unordered associative containers (since C++11)

Unordered associative containers implement unsorted (hashed) data structures that can be quickly searched ($O(1)$ average, $O(n)$ worst-case complexity).

unordered_set (C++11)	collection of unique keys, hashed by keys (class template)
unordered_map (C++11)	collection of key-value pairs, hashed by keys, keys are unique (class template)
unordered_multiset (C++11)	collection of keys, hashed by keys (class template)
unordered_multimap (C++11)	collection of key-value pairs, hashed by keys (class template)

cppreference.com

Summary

1. **Space-time**

- Tradeoffs

2. **STL**

- Standard Template Library

3. **Sequence Containers**

- Ex: `vector`, `deque`, ...

4. **(Unordered) Associative Containers**

- Ex: `(unordered_)` `map`, `set`, ...