


Welcome to Week 3! Link to Attendance Form ↓



What type of initialization can all types use?

- Structured binding
 - `auto [first, second] = p;`
- Member-wise
 - `student.name = "Jacob"`
- Uniform initialization
 - `Student jacob { "Jacob", "NM", 21 }`


What type of initialization can all types use?

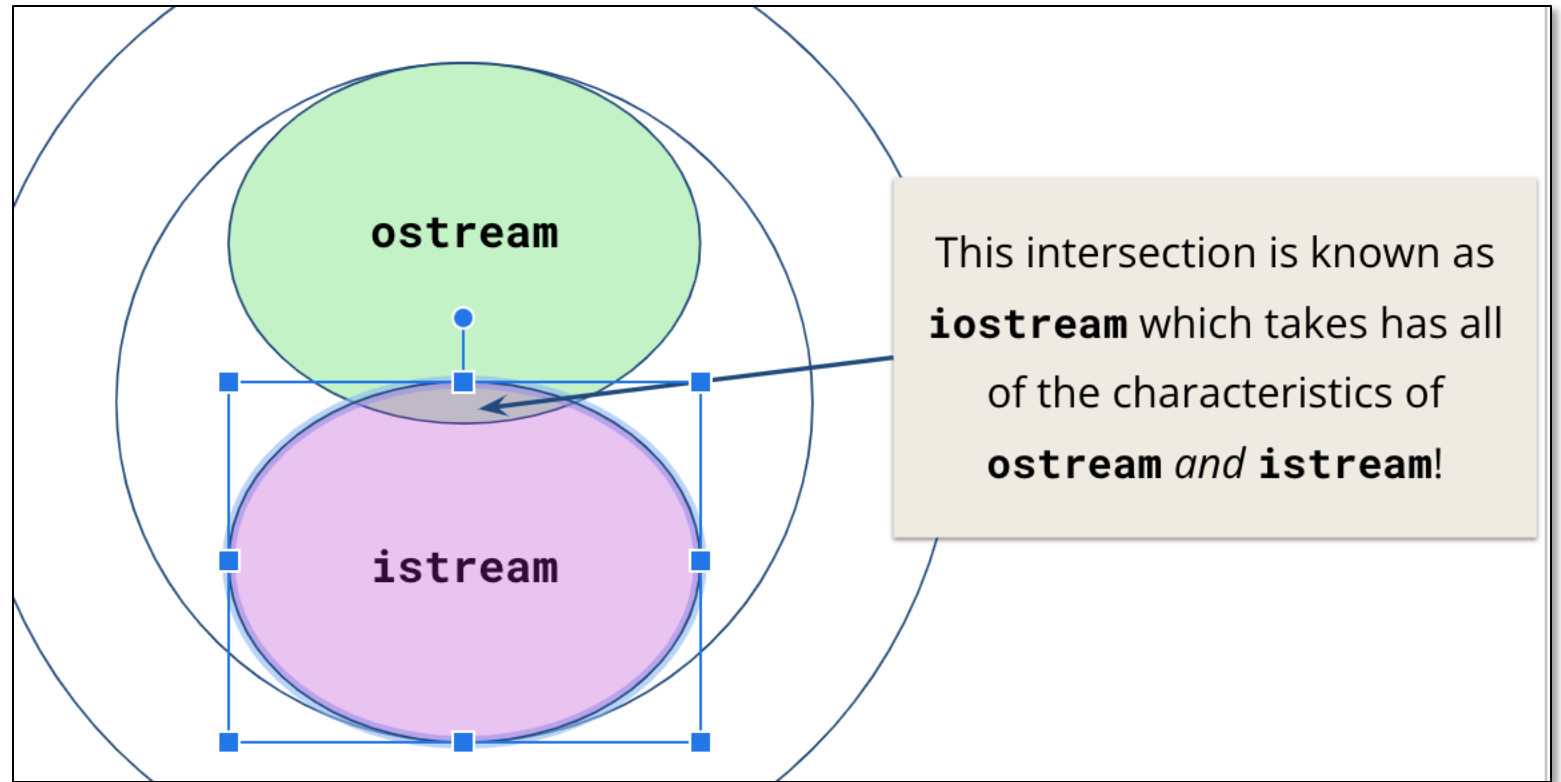
- Structured binding
 - `auto [first, second] = p;`
- Member-wise
 - `student.name = "Jacob"`
-  **Uniform initialization**
 - `Student jacob { "Jacob", "NM", 21 }`

A `stringstream` is an...

- Input stream
- Output stream
- Both!
- Neither!

A stringstream is an...

- Input stream
- Output stream
-  **Both!**
- Neither!





A Disorganized Garage





An Organized Garage

Item	Box
Tools	B1
DVDs	B2
Books	B3
Snacks	B4



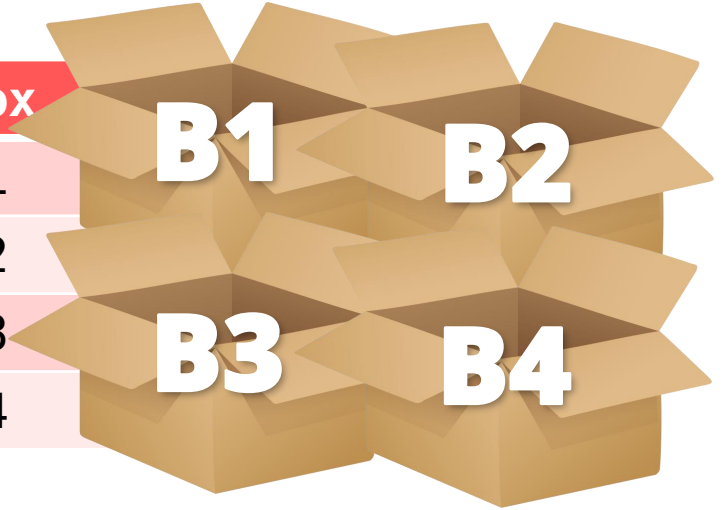
Disorganized



- Space efficient
- Slow to lookup item
- `std::vector<T>`

Organized

Item	Box
Tools	B1
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- Space inefficient
- Quick to lookup item
- `std::map<std::string, T>`

Lecture 5: Containers

Stanford CS106L, Autumn 2024

Today we're going beyond the Stanford C++ libraries!



(But we'll still make references to them)

The many containers of C++

The C++ Standard Template Library (STL)

`std::vector`

`std::set`

`std::stack`

`std::queue`

`std::map`

`std::unordered_map`

`std::unordered_set`

`std::priority_queue`

`std::deque`

`std::array`

Which container do I use?



The space-time tradeoff



“Space is time”
— Bjarne Stroustrup

[source]

Today's Agenda

- What the heck is the STL? What are templates?
 - "The Standard Template Library"
- Sequence Containers
 - A linear sequence of elements
- Associative Containers
 - A set of elements organized by unique keys

Disclaimer: We're covering a lot of material!

(try not to get lost in the details!)

But also: we can't cover everything!

(please ask us questions or reach out on Ed!)

What questions do you have?



bjarne_about_to_raise_hand

What is the STL?

STL: Standard Template Library

What are templates?



What are templates?



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

What are templates?



What are templates?



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

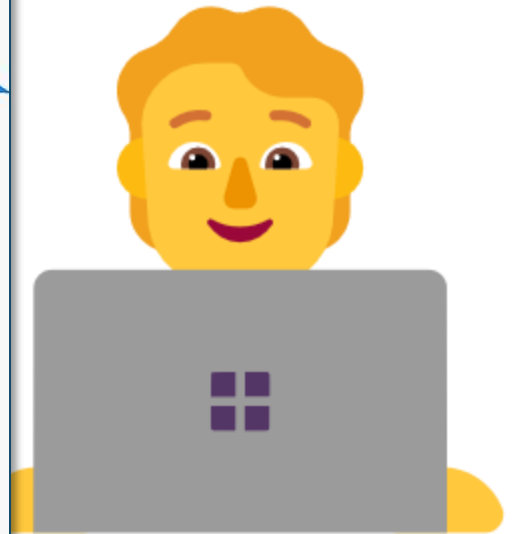

What are tem



thats kinda sus

Delivered

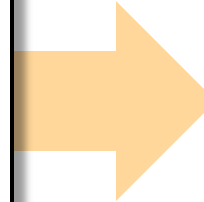
Gray Brandon



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...  
};
```

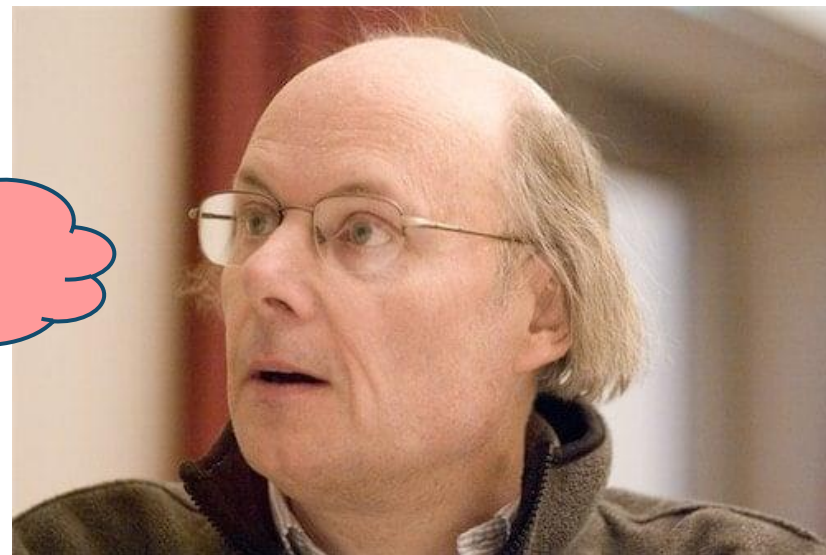
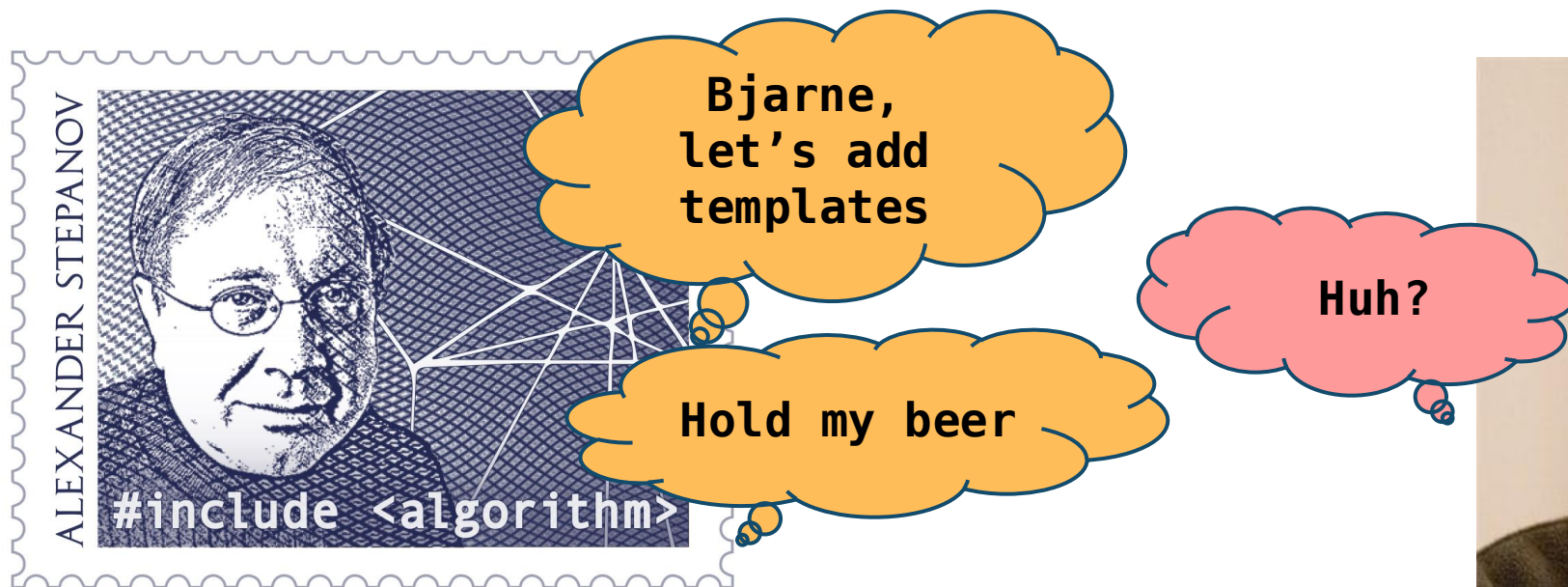


```
template <typename T>  
class vector {  
    // So satisfying.  
};  
  
vector<int> v1;  
vector<double> v2;  
vector<string> v3;
```

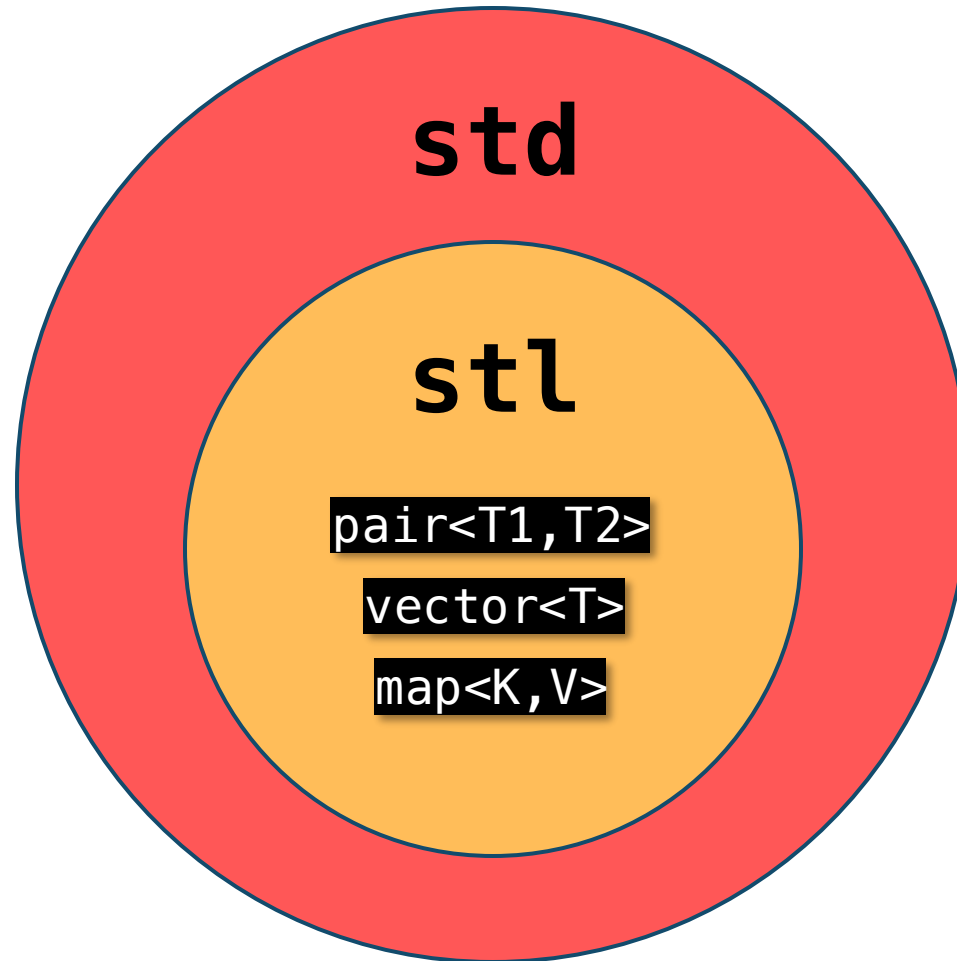
All STL containers are templates!

The Standard Template Library (STL)

- Created by Alexander Stepanov
- Added templates to C++ and built a well-known library
- This library is now known as the **STL**!



The Standard Template Library (STL)



The Standard Template Library (STL)

Containers

How do we store groups of things?

Iterators

How do we traverse containers?

Functors

How can we represent functions as objects?

Algorithms

How do we transform and modify containers in a generic way?

What questions do you have?



bjarne_about_to_raise_hand

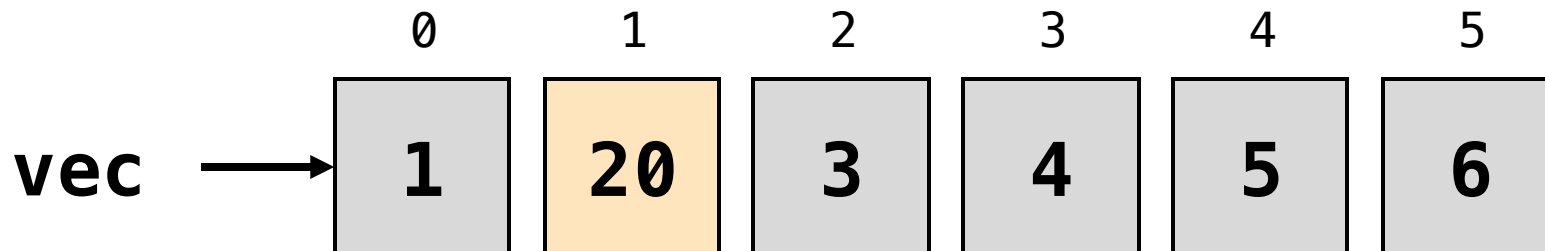
Sequence Containers

Sequence containers store a linear sequence of elements

```
std::vector  
#include <vector>
```

std::vector stores a list of elements

```
std::vector<int> vec { 1, 2, 3, 4 };  
vec.push_back(5);  
vec.push_back(6);  
vec[1] = 20;  
  
for (size_t i = 0; i < vec.size(); i++) {  
    std::cout << vec[i] << " ";  
}
```



Output:

1 20 3 4 5 6

Stanford vs. STL vector

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>

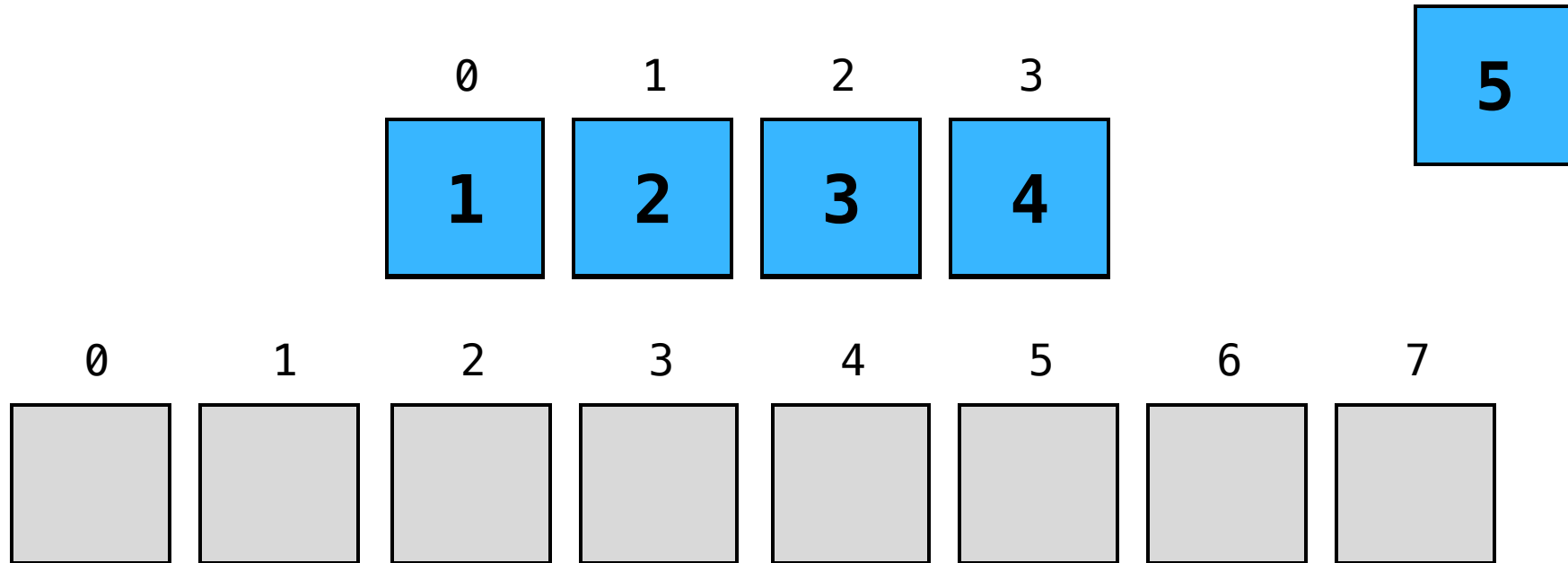
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Create a vector with n copies of 0	<code>Vector<int> v(n);</code>	<code>std::vector<int> v(n);</code>
Create a vector with n copies of value k	<code>Vector<int> v(n, k);</code>	<code>std::vector<int> v(n, k);</code>
Add k to the end of the vector	<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>

Stanford vs. STL vector

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Create an empty vector	<code>Vector<int> v;</code>	<code>std::vector<int> v;</code>
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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>

How is vector implemented?



size = 5, **capacity** = 8

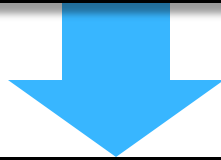
What questions do you have?



bjarne_about_to_raise_hand

Tip: Use **range-based for** when possible

```
for (size_t i = 0; i < vec.size(); i++) {  
    std::cout << vec[i] << " ";  
}
```



```
for (auto elem : vec) {  
    std::cout << elem << " ";  
}
```

- Applies for all iterable containers, not just `std::vector`

Tip: Use **const auto&** when possible

```
std::vector<MassiveType> vec { ... };  
for (auto elem : vec) ...
```



```
for (const auto& elem : v)
```

- Applies for all iterable containers, not just `std::vector`
- Saves making a potentially expensive copy of each element

Stanford vs. STL vector

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); int k = v[i];</code>	<code>int k = v.at(i); int k = v[i];</code>
Replace the element at index i	<code>v.get(i) = k; v[i] = k;</code>	<code>v.at(i) = k; v[i] = k;</code>

operator[] does not perform bounds checking

```
std::vector<int> vec{5, 6}; // {5, 6}
vec[1] = 3;                // {5, 3}
vec[2] = 4;                // undefined behavior
vec.at(2) = 4;             // Runtime error
```

Zero-overhead principle

The *zero-overhead principle* is a C++ design principle that states:

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.

[\[cppreference\]](#)

What questions do you have?



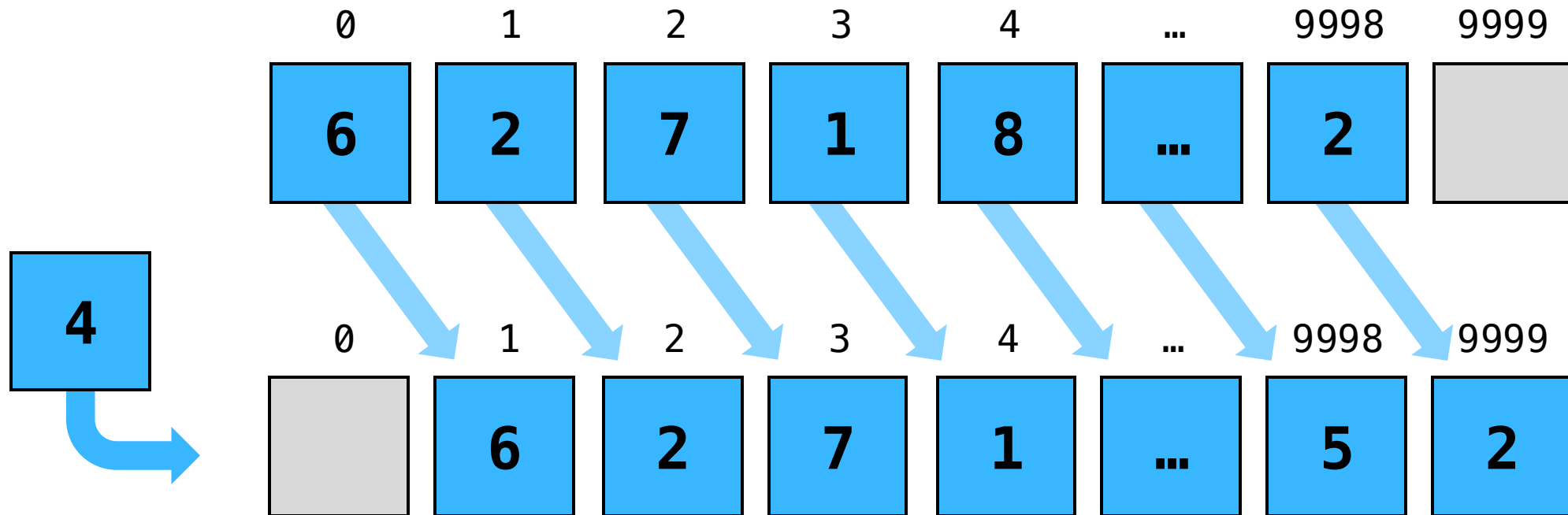
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Trick question!

`std::vector` has no `push_front`!

A hypothetical `push_front`...

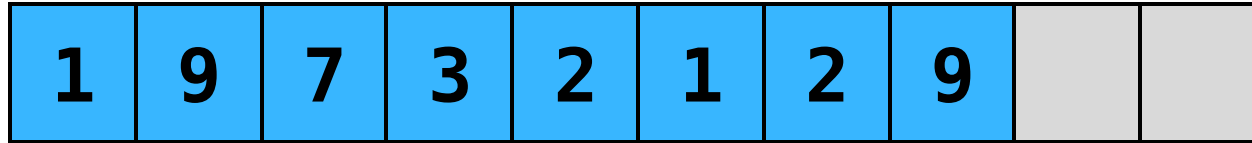


SLOW!!!


```
std::deque  
#include <deque>
```


**A deque has the same interface as vector,
except we can push_front / pop_front**

How is **deque** implemented?

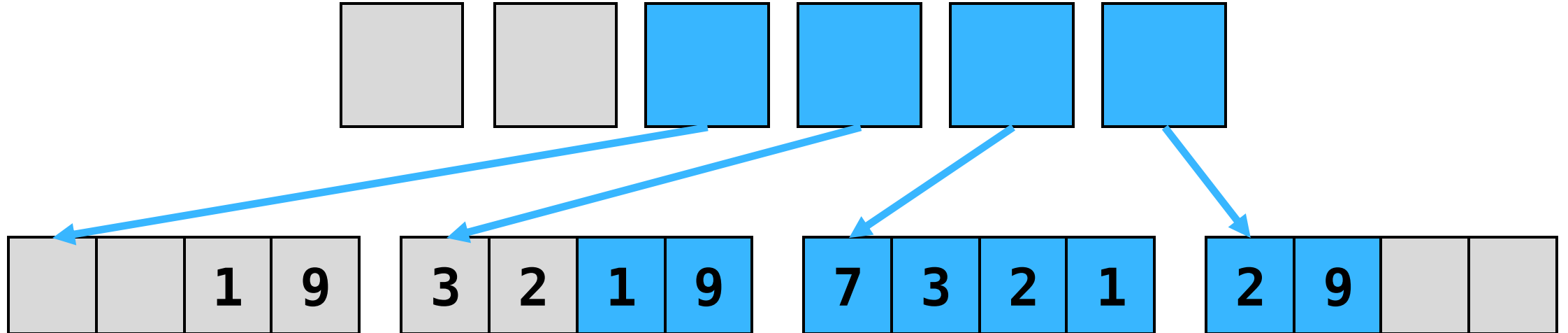


The problem with **vector** is that we have a single chunk of memory

So... let's split it up!

How is **deque** implemented?

Array of arrays



Separate subarrays
allocated independently

What questions do you have?



bjarne_about_to_raise_hand

Announcements

- Assignment 1 due Friday!
 - Submission instructions will posted tonight
- OH times announced
 - Fabio 3-4pm Wednesdays on Zoom
 - Jacob 1-2:30pm Fridays in Thornton 208

Associative Containers

Associative containers organize elements by unique keys

```
std::map  
#include <map>
```

`std::map` maps keys to values

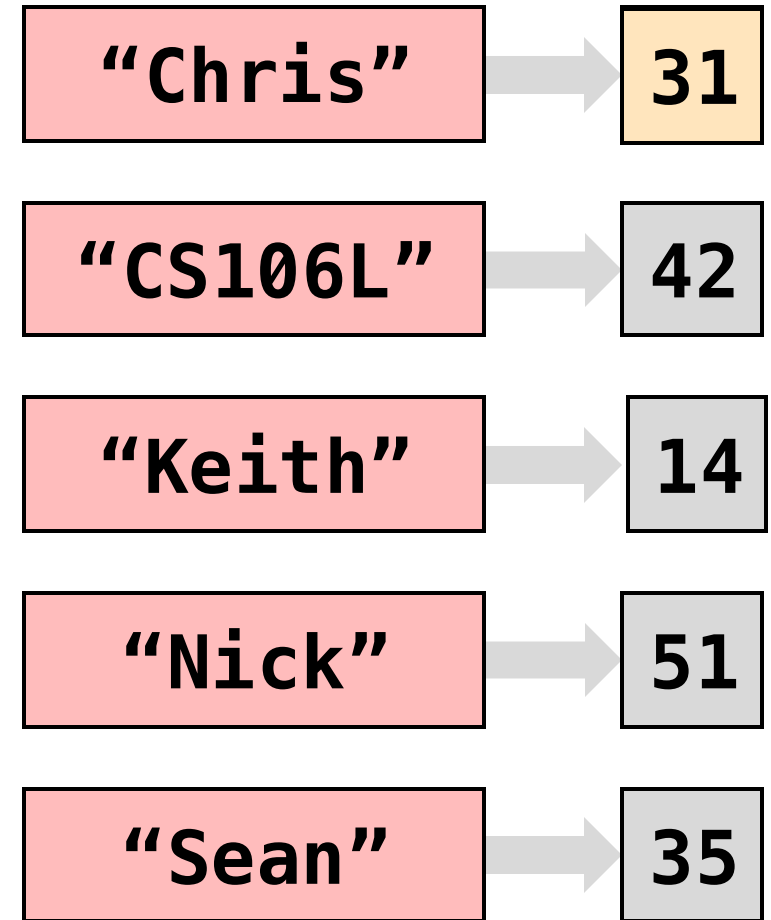


- Equivalent of a Python dictionary
- Sometimes called an **associative array**

`std::map` maps keys to values

```
std::map<std::string, int> map {  
    { "Chris", 2 },  
    { "CS106L", 42 },  
    { "Keith", 14 },  
    { "Nick", 51 },  
    { "Sean", 35 },  
};
```

```
int sean = map["Sean"]; // 35  
map["Chris"] = 31;
```



Stanford vs. STL map

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;

Stanford vs. STL map

What you want to do?	Stanford Map<char, int>	std::map<char, int>
Create an empty map	<code>Map<char, int> m;</code>	<code>std::map<char, int> m;</code>
Add key k with value v into the map	<code>m.put(k, v);</code> <code>m[k] = v;</code>	<code>m.insert({k, v});</code> <code>m[k] = v;</code>
Remove key k from the map	<code>m.remove(k);</code>	<code>m.erase(k);</code>

Stanford vs. STL map

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())

Stanford vs. STL map

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;


```
std::map<K, V>
```

stores a collection of

```
std::pair<const K, V>
```

*(I encourage you to think about why K is const.
What would happen if we could modify a key?)*

map as a collection of pair

We can iterate through the key-value pairs using a range based for loop

```
std::map<std::string, int> map;  
  
for (auto kv : map) {  
    // kv is a std::pair<const std::string, int>  
    std::string key = kv.first;  
    int value = kv.second;  
}
```

map as a collection of pair

Structured bindings come in handy when iterating a map

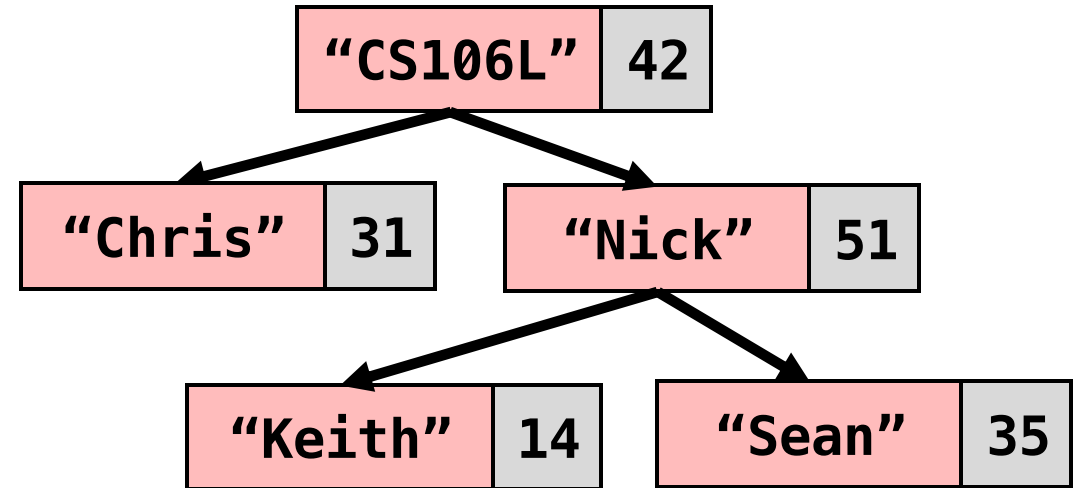
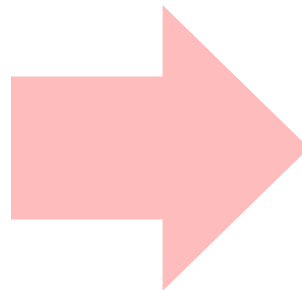
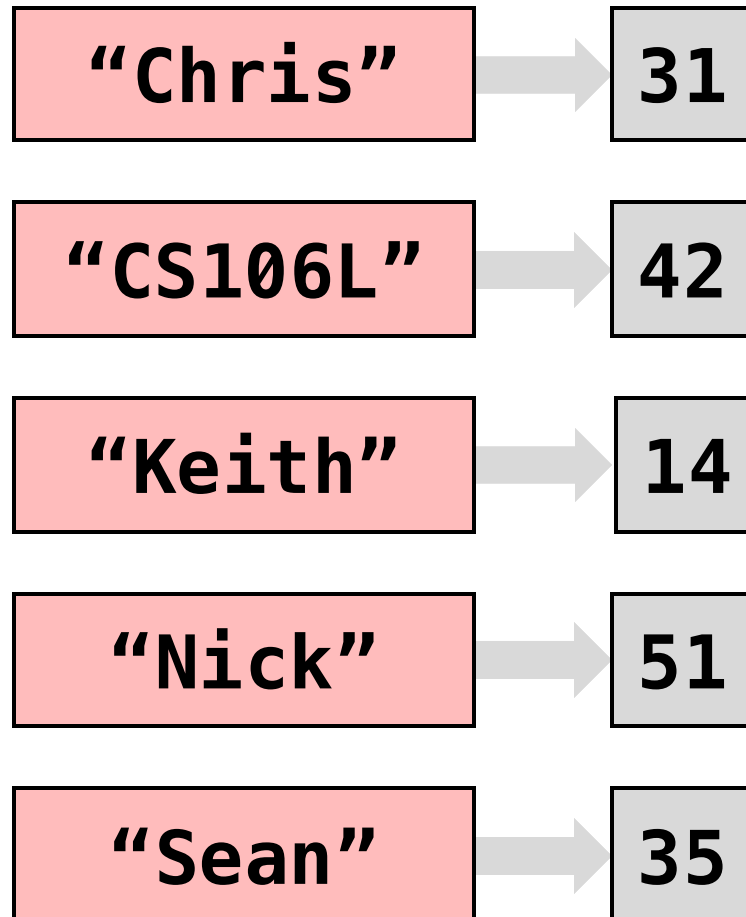
```
std::map<std::string, int> map;  
  
for (const auto& [key, value] : map) {  
    // key has type const std::string&  
    // value has type const int&  
}
```

What questions do you have?



bjarne_about_to_raise_hand

How is **map** implemented?

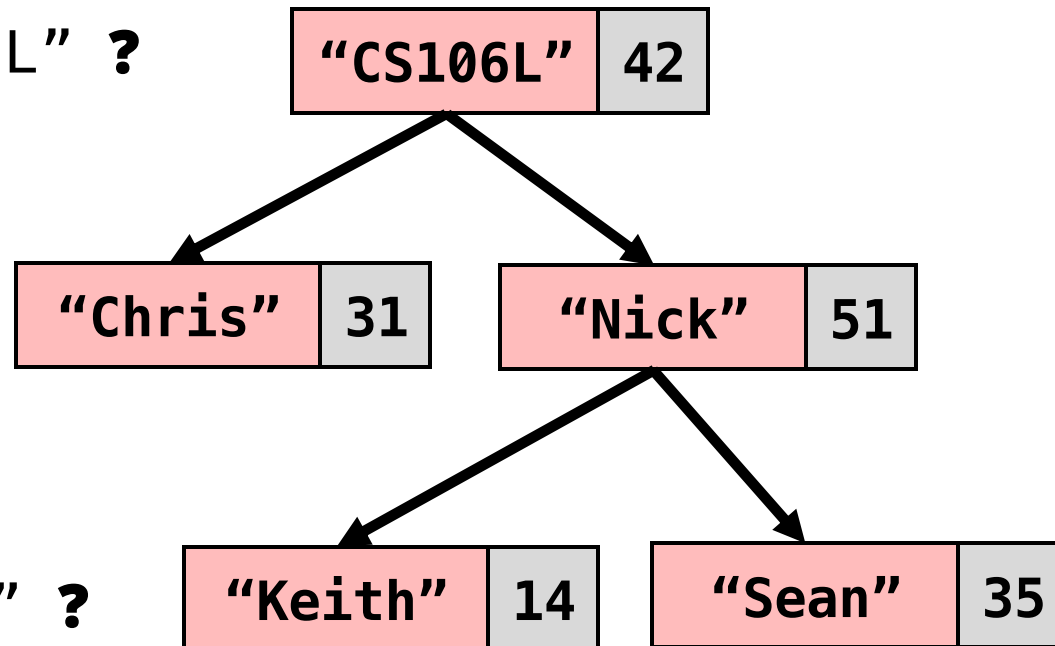


Binary Search Tree
(technically a *red-black tree*)

What is `map["Keith"]`?

"Keith" < "CS106L" ?

No! Go right



"Keith" < "Keith" ?

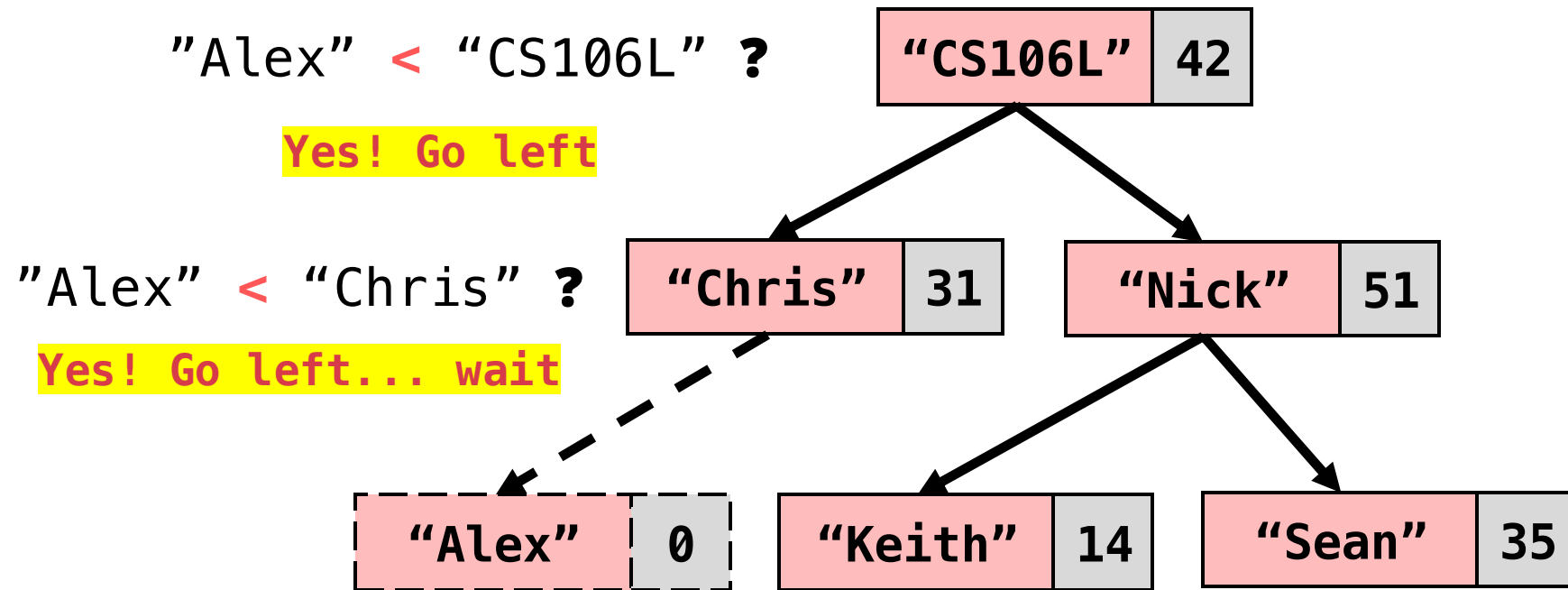
Hey look, you found me!

`map["Keith"] = 14`

"Keith" < "Nick" ?

Yes! Go left

What is `map["Alex"]`?




`map["Alex"] = 0`

(Note: "Alex" was default-inserted into the map)

`std::map<K, V>` requires `K` to have an `operator<`

`std::map<K, V>` requires `K` to have an `operator<`

```
//  OKAY – int has operator<  
std::map<int, int> map1;
```

```
//  ERROR – std::ifstream has no operator<  
std::map<std::ifstream, int> map2;
```

What questions do you have?



bjarne_about_to_raise_hand

```
std::set  
#include <set>
```

std::set stores a collection of unique items

```
std::set<std::string> set {  
    "CS106L!",  
    "Keith",  
    "Sean",  
    "Nick",  
    "Chris"  
};
```

≈

{
 "CS106L!"
 "Keith"
 "Sean"
 "Nick"
 "Chris"
}

Stanford vs. STL set

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

std::set is an amoral std::map

std::set is an std::map without values

How is **set** implemented?

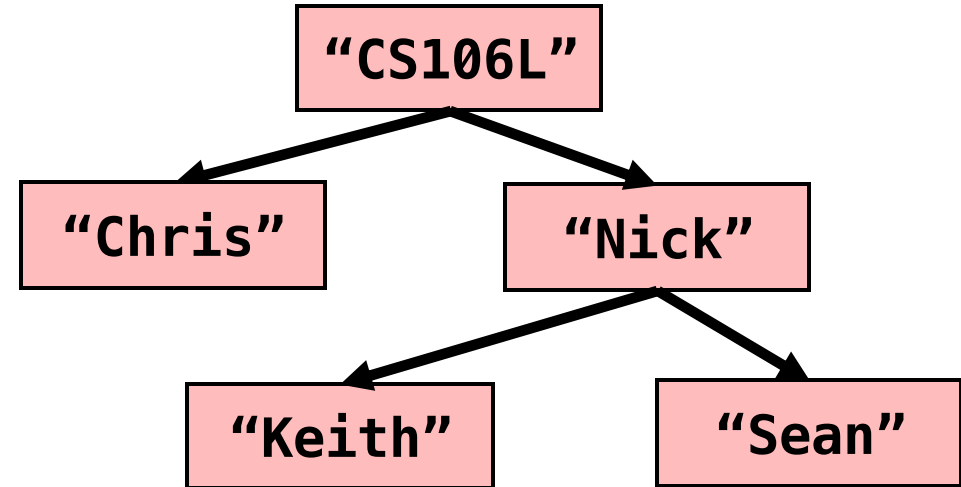
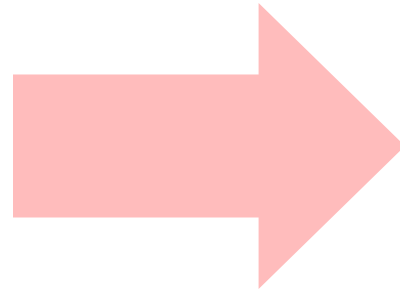
"Chris"

"CS106L"

"Keith"

"Nick"

"Sean"



Binary Search Tree
(technically a *red-black tree*)

But wait... **map** and **set** have an alter ego 🥷 🥷

std::unordered_map and **std::unordered_set**

```
#include <unordered_map>
```

```
#include <unordered_set>
```

std::unordered_map

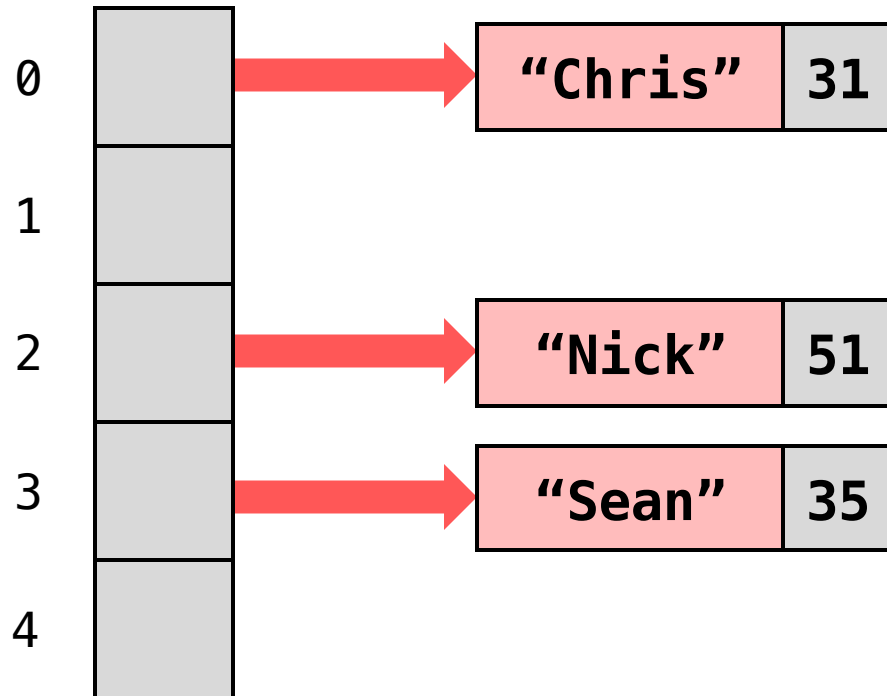
- You can think of `unordered_map` as an optimized version of `map`
- It has the same interface as `map`

```
std::unordered_map<std::string, int> map {  
    { "Chris", 2 },  
    { "Nick", 51 },  
    { "Sean", 35 },  
};
```

```
int sean = map["Sean"]; // 35  
map["Chris"] = 31;
```

How is `unordered_map` implemented?

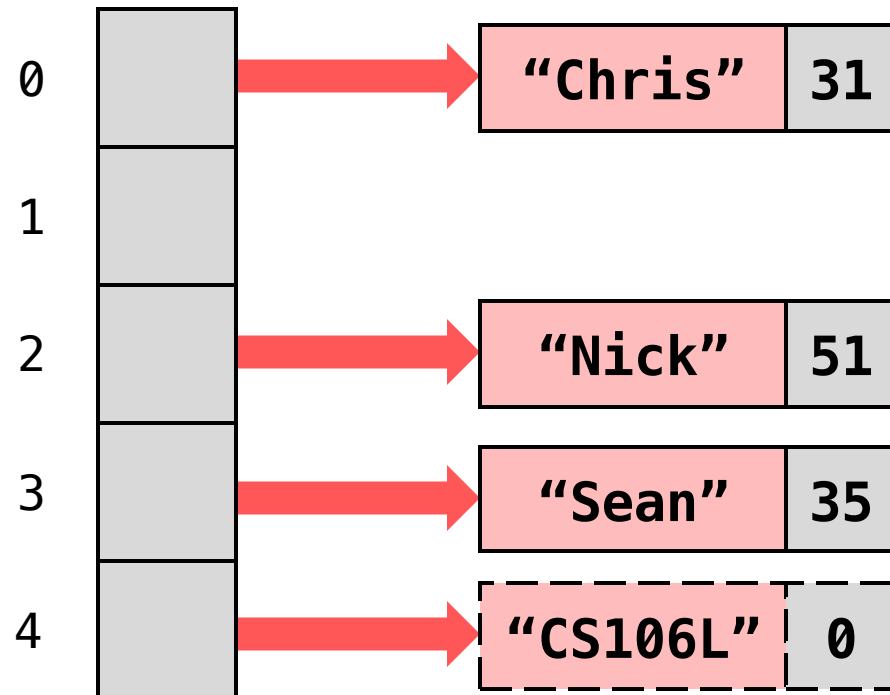
- Remember, map is a collection of `std::pair`
- `unordered_map` stores a collection of n "buckets" of pairs



```
std::unordered_map  
<std::string, int> map {  
    { "Chris", 31 },  
    { "Nick", 51 },  
    { "Sean", 35 },  
};
```

How is `unordered_map` implemented?

- To add a key/value, we feed the key through a **hash function**
- The hash, modulo the bucket count, determines the pair's bucket no.



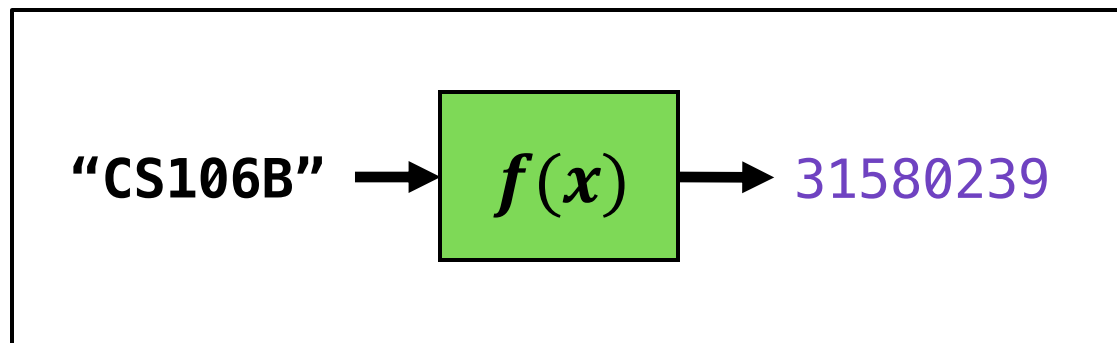
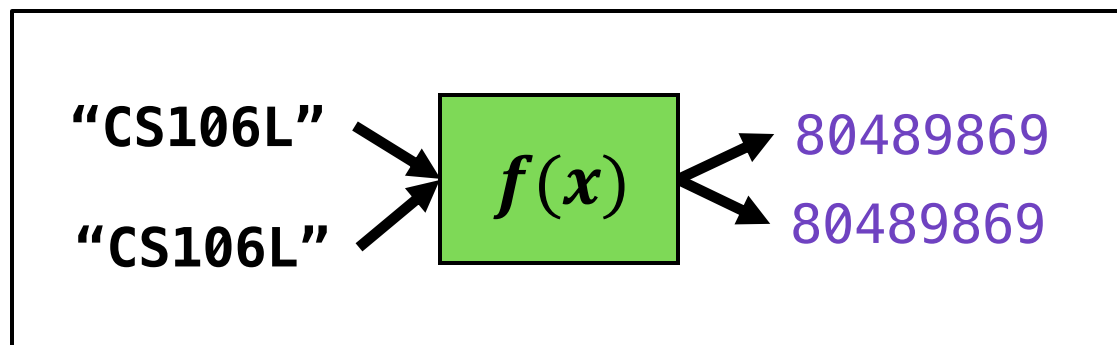
```
int x = map["CS106L"];
```

"CS106L" → $f(x)$ → 80489869

80489869 mod 5 = 4

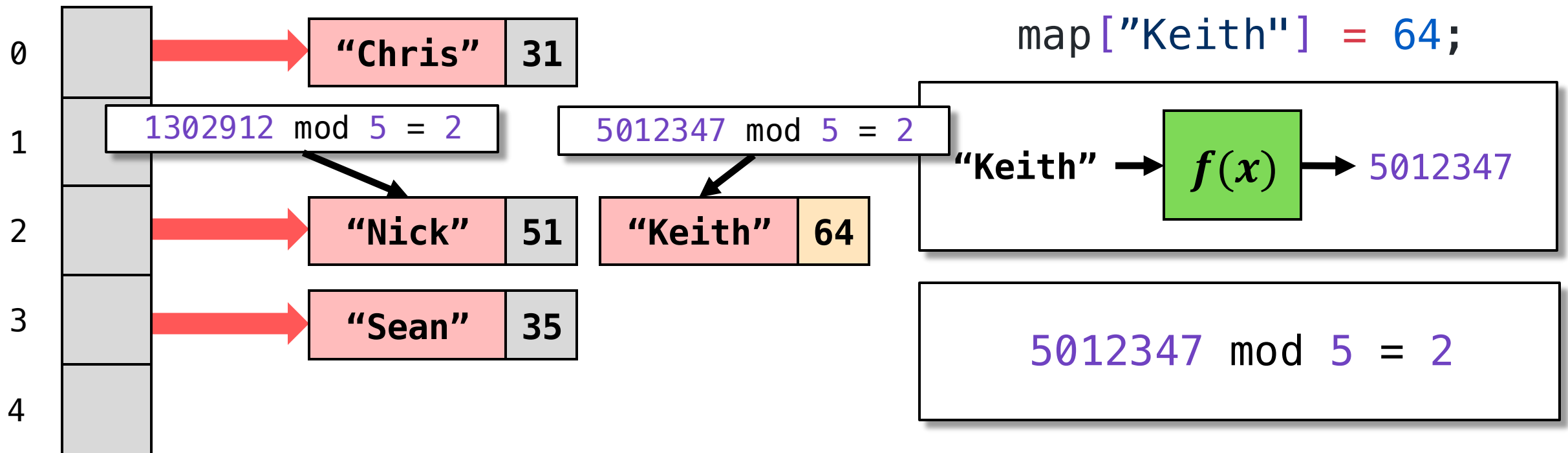
What is a hash function?

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



How is `unordered_map` implemented?

- If two keys hash to the same bucket, we get a **hash collision**
- During lookup, we loop through bucket and check key equality
 - Two keys with the same hash are not necessarily equal!



`std::unordered_map<K, V>` requires **K** to have a hash function (and equality)

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;
```

(We will learn more about this syntax later!)

`std::unordered_map<K, V>` requires **K** to be hashable

```
//  OKAY – int is hashable
```

```
std::unordered_map<int, int> map1;
```

```
//  ERROR – std::ifstream is not hashable
```

```
std::unordered_map<std::ifstream, int> map2;
```

Most basic types (`int`, `double`, `string`) are hashable by default

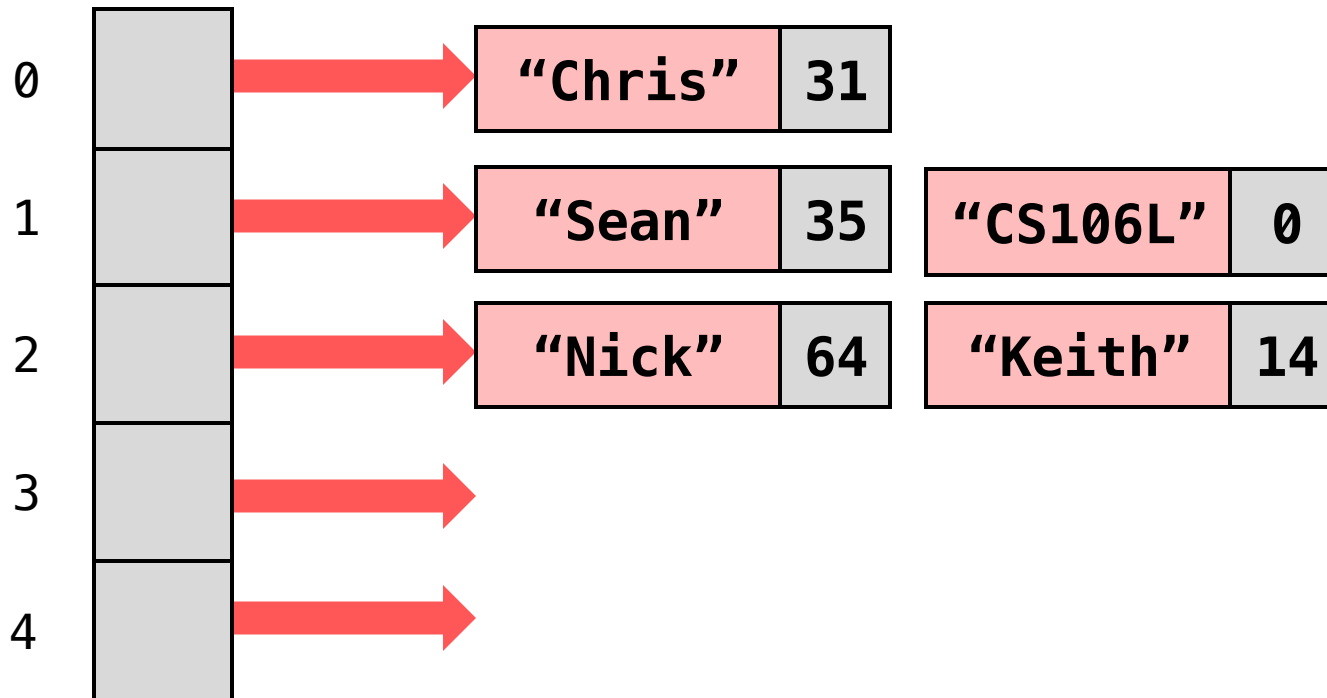
What questions do you have?



bjarne_about_to_raise_hand

Why use `std::unordered_map`?

- **Load factor:** average number items per bucket
- `unordered_map` allows super fast lookup by keeping load factor small
- If load factor gets too large (above 1.0 by default), we **rehash**



Load Factor: 1.66

Load Factor: 1.0

Fun C++ Trivia: `max_load_factor`

You can control the max load factor before rehashing

```
std::unordered_map<std::string, int> map;  
  
double lf = map.load_factor(); // Get current load factor  
map.max_load_factor(2.0); // Set the max load factor  
  
// Now the map will not rehash until load factor exceeds 2.0  
// You should almost never need to do this,  
// but it's a fun fact (good for parties!)
```

What makes a good hash function?

A good hash function minimizes the chance of a hash collision

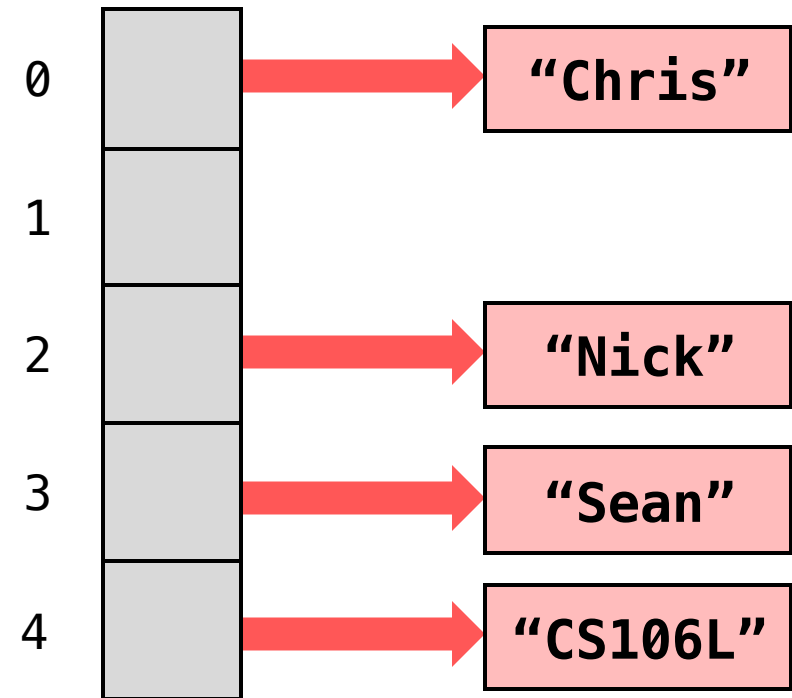
```
// ❌ The worst possible hash

template <>
struct std::hash<MyType>
{
    std::size_t operator()(const MyType& k) const
    {
        return 0;
    }
};
```

(Don't worry too much about this syntax. We'll learn more later)

unordered_set is an **unordered_map** without values

```
std::unordered_set  
<std::string> set {  
    "Chris",  
    "Nick",  
    "Sean",  
    "CS106L"  
};
```



When to use `unordered_map` vs. `map`?

- `unordered_map` is *usually* faster than `map`
- However, it uses more memory (organized vs. disorganized garage)
- If your key type has no total order (`operator<`), use `unordered_map`!
- If you must choose, `unordered_map` is a safe bet

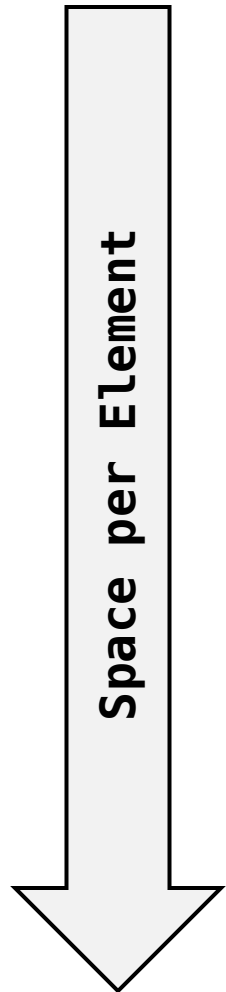
What questions do you have?



bjarne_about_to_raise_hand

Recap

Summary of Data Structures



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

Some more containers if you're curious!

std::array

A fixed-size array of items

std::list

A doubly linked list

std::multiset (+unordered)

A set that can contain duplicates

std::multimap (+unordered)

Can contain multiple values for the same key

Recap

- What the heck is the STL? What are templates?
 - "The Standard Template Library"
- Sequence Containers
 - A linear sequence of elements
 - `std::vector`, `std::deque`
- Associative Containers
 - A set of elements organized by unique keys
 - `std::map`, `std::set`, `std::unordered_map`, `std::unordered_set`