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 }`

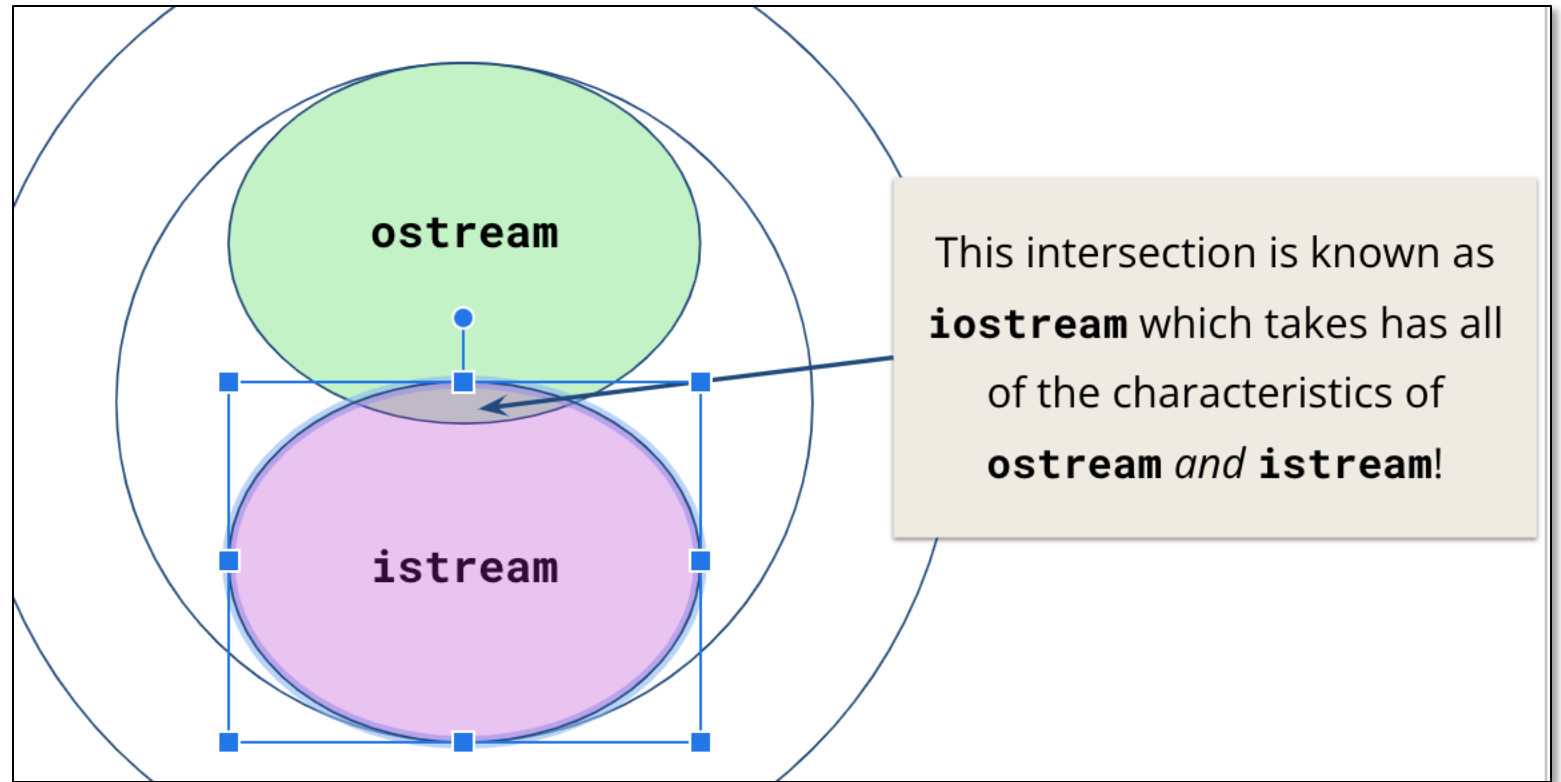# What type of initialization can all types use?

- 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!
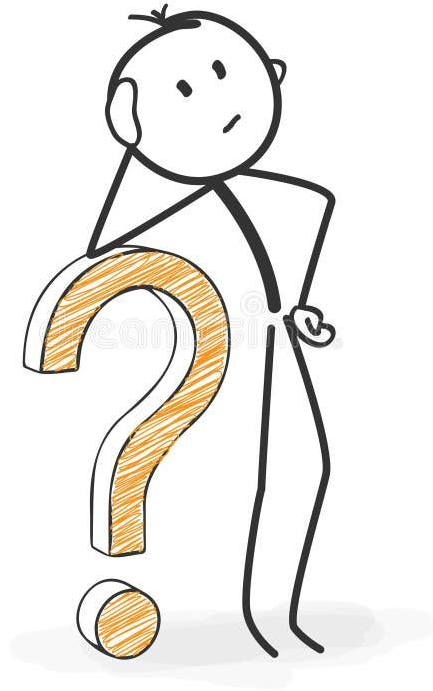
A `stringstream` is an…

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

ostream

istream

This intersection is known as `iostream` which takes has all of the characteristics of `ostream` *and* `istream`!

A Disorganized Garage

An Organized Garage

Item	Box
Tools	B1
DVDs	B2
Books	B3
Snacks	B4
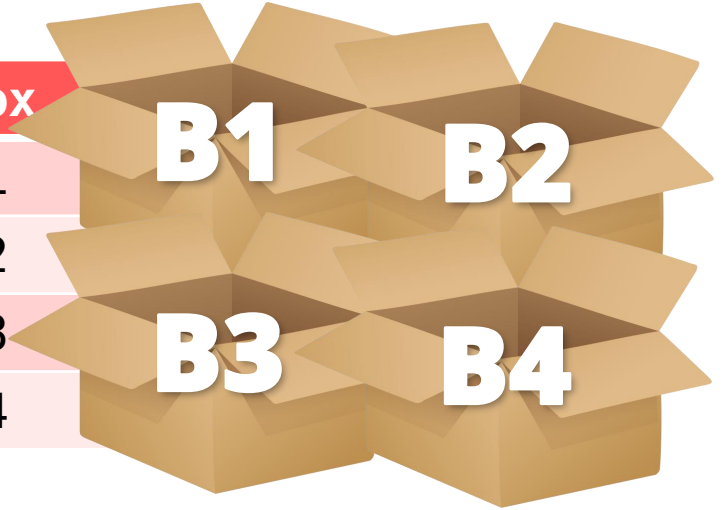
Lecture 5: Containers

Stanford CS106L, Winter 2025

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

std::map

Map

Vector

std::vector

Set

std::set

(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

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…
};
```
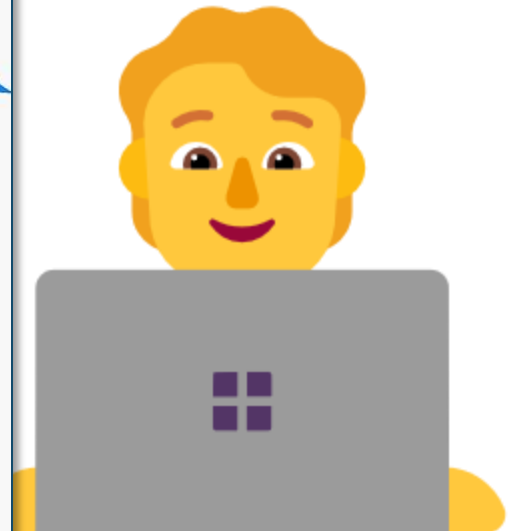
What if we could keep the logic, but change the type?

What are templates?

```cpp
class IntVector {

}
```

```cpp
class DoubleVector {

}
```

```cpp
class StringVector {
    // Code to store
    // a list of
    // strings...
};
```
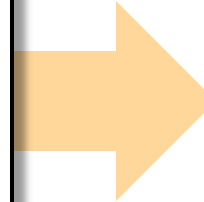
```cpp
template <typename T>
class vector {
    // So satisfying.
};

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**!
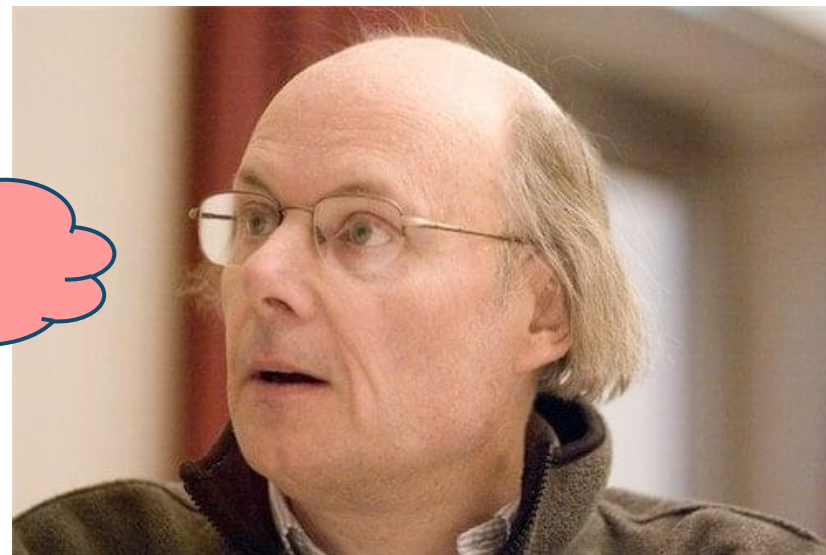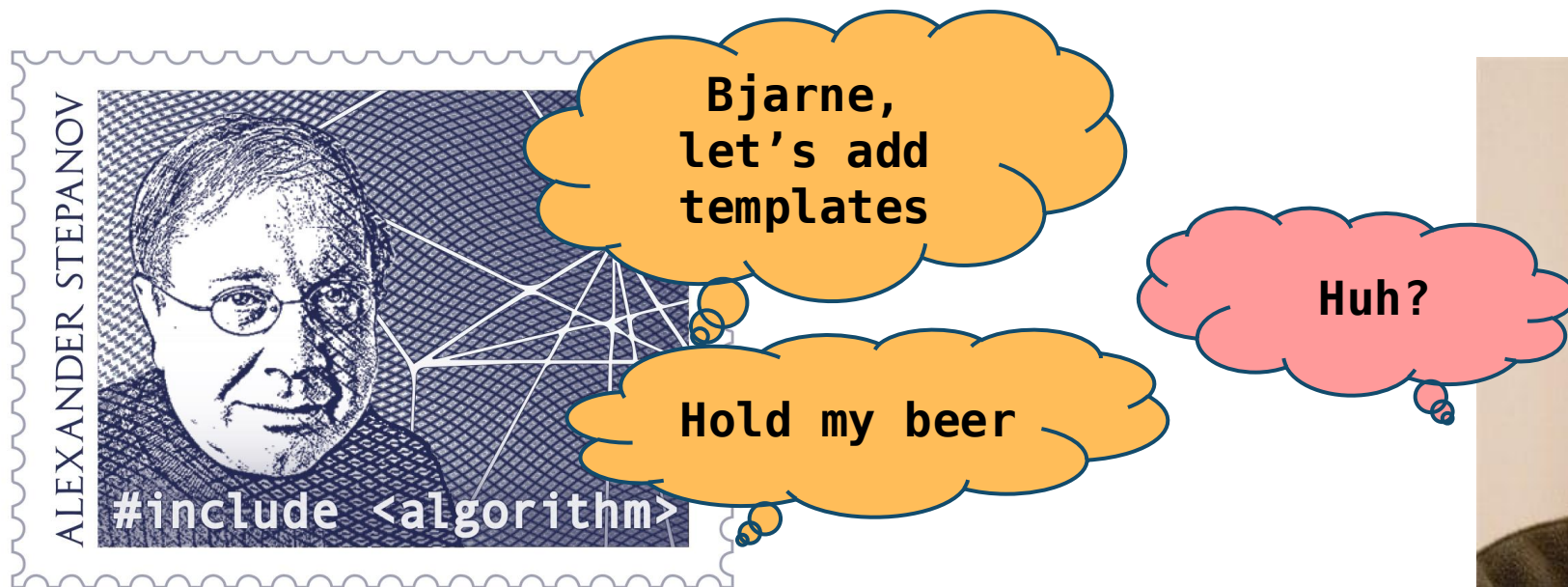
The Standard Template Library (STL)
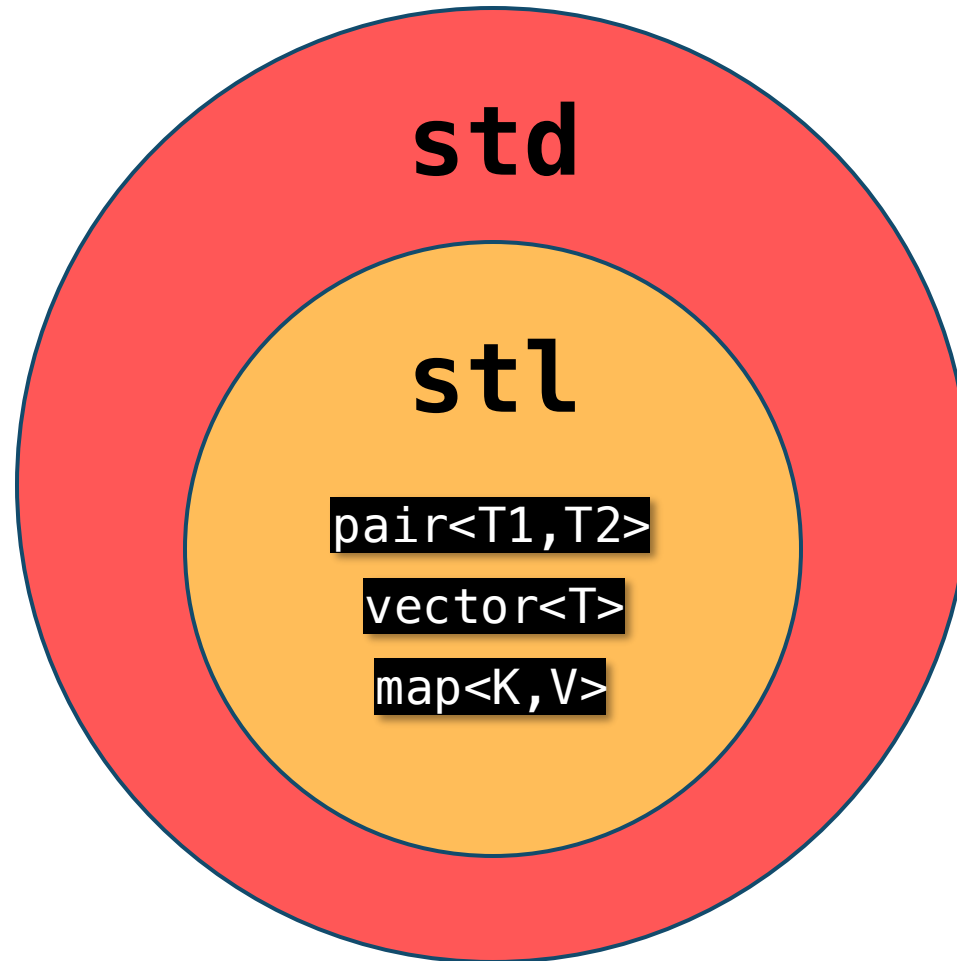
The Standard Template Library (STL)

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

```cpp
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] << " ";
}
```

	0	1	2	3	4	5
vec →	1	20	3	4	5	6
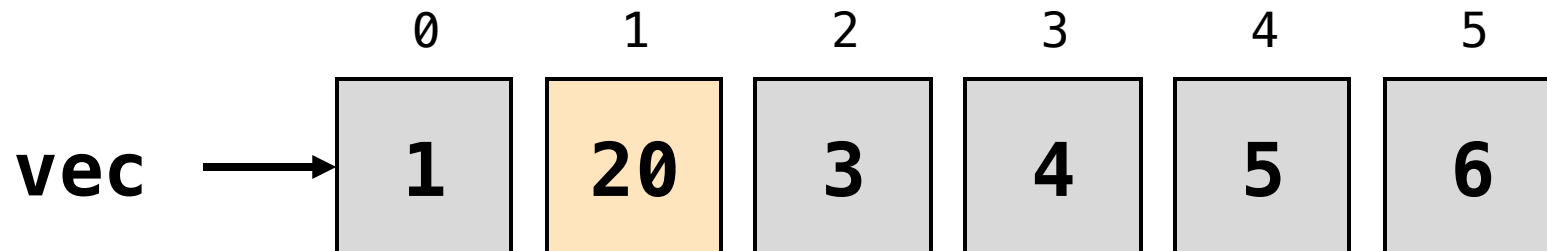
Output:
1 20 3 4 5 6

Stanford vs. STL vector

What you want to do?	Stanford Vector<int>	std::vector<int>
Create an empty vector	Vector<int> v;	std::vector<int> v;
Create a vector with **n** copies of **0**	Vector<int> v(n);	std::vector<int> v(n);
Create a vector with **n** copies of value **k**	Vector<int> v(n, k);	std::vector<int> v(n, k);

Stanford vs. STL vector

What you want to do?	Stanford Vector<int>	std::vector<int>
Create an empty vector	Vector<int> v;	std::vector<int> v;
Create a vector with **n** copies of **0**	Vector<int> v(n);	std::vector<int> v(n);
Create a vector with **n** copies of value **k**	Vector<int> v(n, k);	std::vector<int> v(n, k);
Add **k** to the end of the vector	v.add(k);	v.push_back(k);
Clear vector	v.clear();	v.clear();
Check if **v** is empty	if (v.isEmpty())	if (v.empty())

Stanford vs. STL vector

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

How is vector implemented?
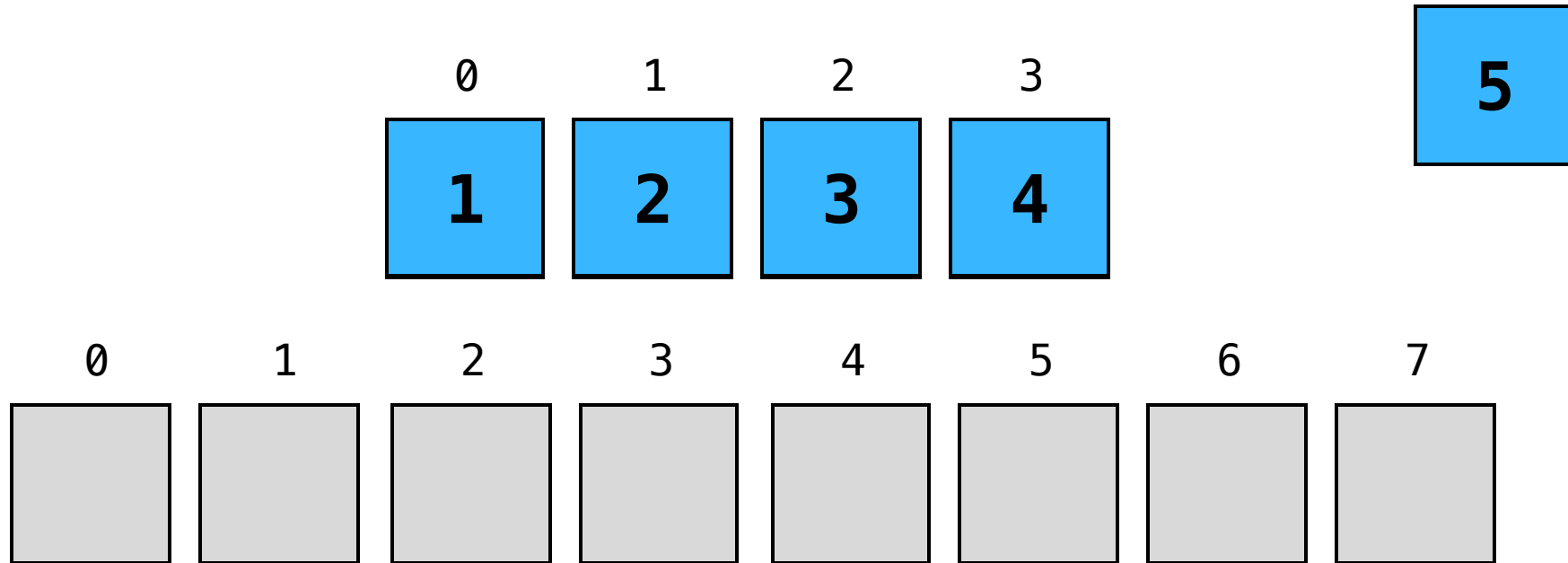
size = 5, capacity = 8

What questions do you have?

bjarne_about_to_raise_hand

Tip: Use range-based for when possible

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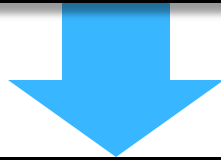
```cpp
for (auto elem : vec) {
    std::cout << elem << " ";
}
```

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

Tip: Use `const auto&` when possible

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

⬇

```cpp
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	`Vector<int> v;`	`std::vector<int> v;`
Create a vector with **n** copies of **0**	`Vector<int> v(n);`	`std::vector<int> v(n);`
Create a vector with **n** copies of value **k**	`Vector<int> v(n, k);`	`std::vector<int> v(n, k);`
Add **k** to the end of the vector	`v.add(k);`	`v.push_back(k);`
Clear vector	`v.clear();`	`v.clear();`
Check if **v** is empty	`if (v.isEmpty())`	`if (v.empty())`
Get the element at index **i**	`int v = v.get(i);` `int k = v[i];`	`int k = v.at(i);` `int k = v[i];`
Replace the element at index **i**	`v.get(i) = k;` `v[i] = k;`	`v.at(i) = k;` `v[i] = k;`

operator[] does not perform bounds checking

```cpp
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.

What questions do you have?

bjarne_about_to_raise_hand

`std::vector` is not the best for all cases...

- Suppose we need to observe the last 10,000 prices of a stock
- What might be concerning about the code below?

```cpp
void receivePrice(vector<double>& prices, double price)
{

  prices.push_front(price);
  if (prices.size() > 10000)
    prices.pop_back();    // Remove last price
                          // so we don't exceed 10k
}
```

Trick question!

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

A hypothetical push_front...

SLOW!!!

std::deque
`#include <deque>`

std::deque

- A deque ("deck") is a double-ended queue
- Allows efficient insertion/removal at either end

```cpp
void receivePrice(deque<double>& prices, double price)
{

  prices.push_front(price);   // Super fast
  if (prices.size() > 10000)
    prices.pop_back();        // Remove last price
                              // so we don't exceed 10k
}
```
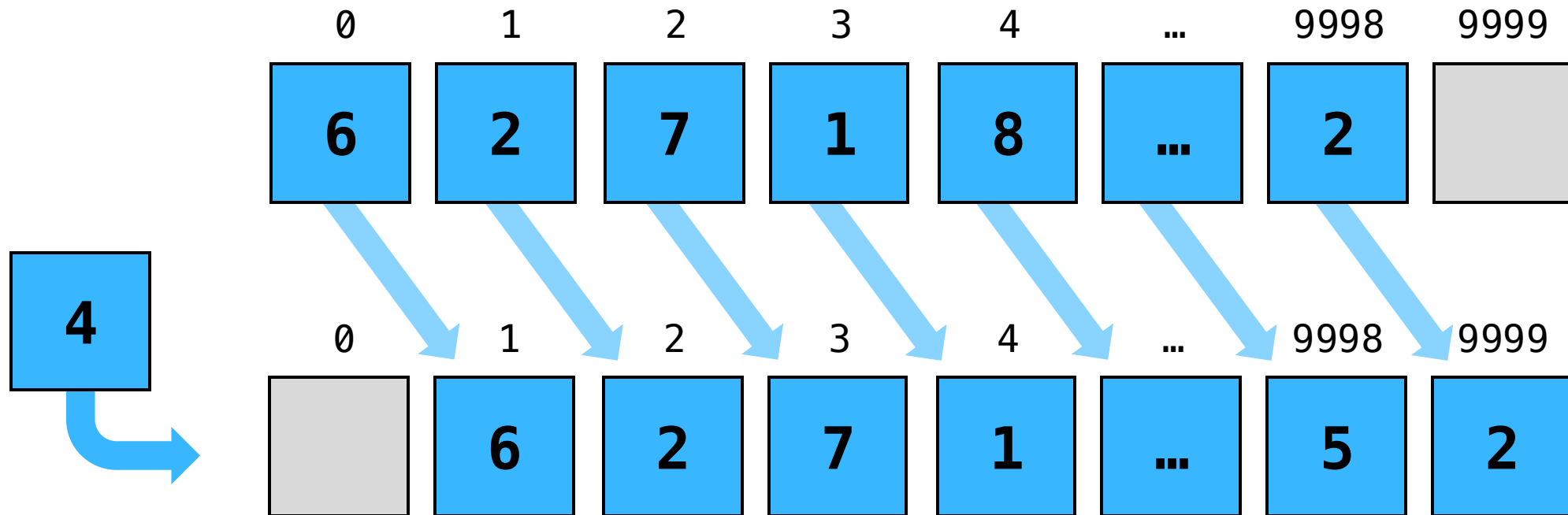
A **deque** has the same interface as `vector`,
except we can `push_front` / `pop_front`

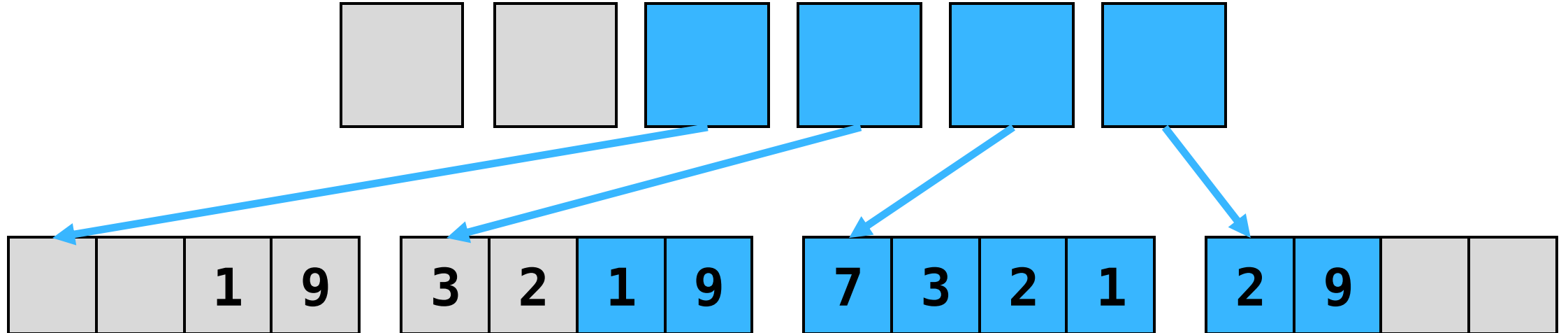# How is deque implemented?

| 1 | 9 | 7 | 3 | 2 | 1 | 2 | 9 | | |
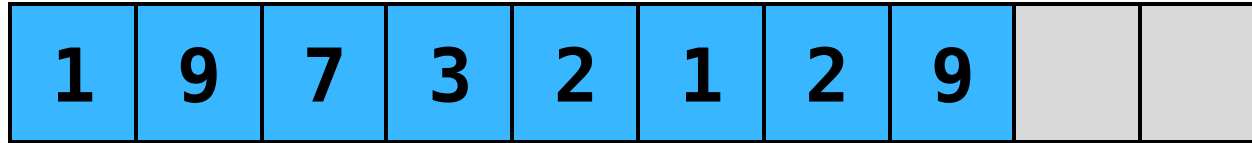
The problem with **vector** is that we have a single chunk of memory

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!
- A0 grades are out!
    - Let us know if anything looks fishy
    - Same goes for attendance grades!
- Watch for OH announcements
    - Jacob's Friday OH this week (1/24) will be earlier, ~1:30pm

Associative Containers

Associative containers organize elements by unique keys

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

`std::map` maps keys to values

```
"CS106L!"  ⟶  std::map<std::string, int>  ⟶  42
```
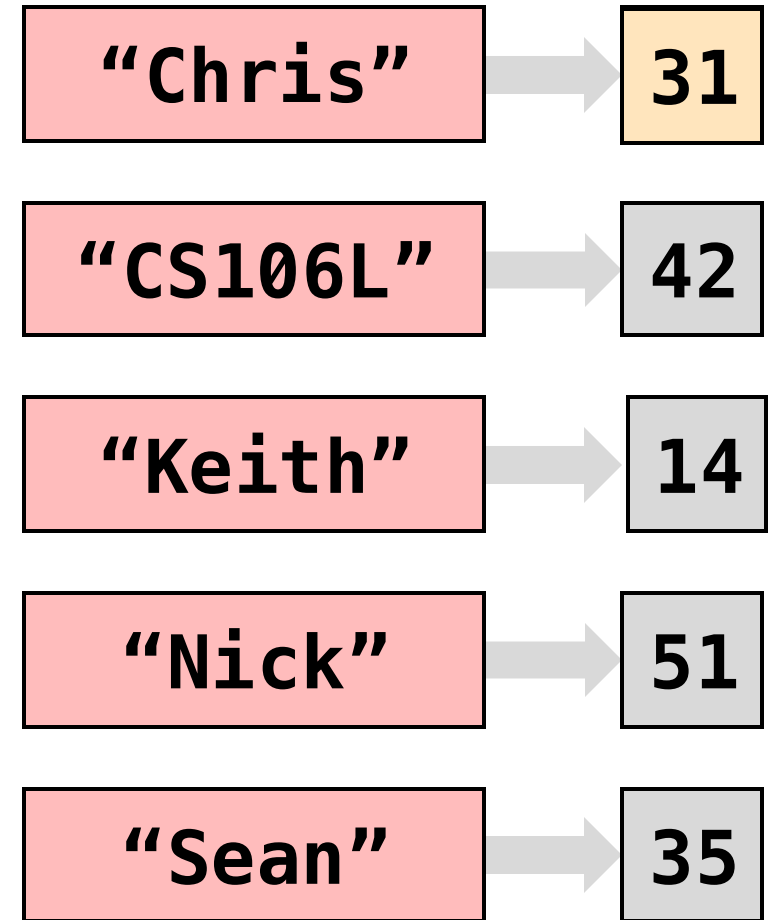
- Equivalent of a Python dictionary
- Sometimes called an **associative array**

`std::map` maps keys to values

```cpp
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	`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);`

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

```cpp
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

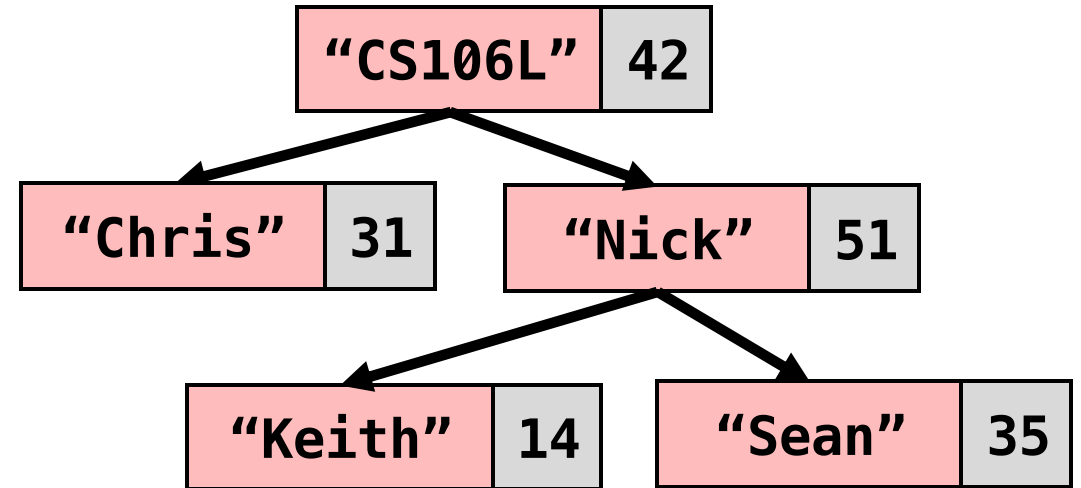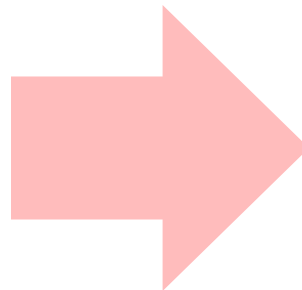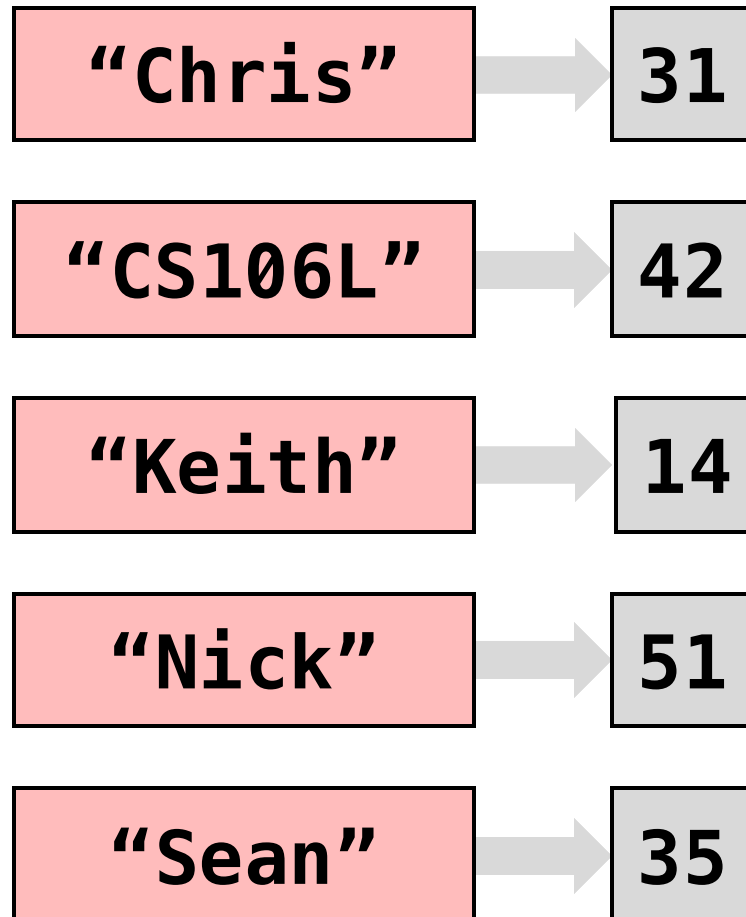Structured bindings come in handy when iterating a map

```cpp
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?
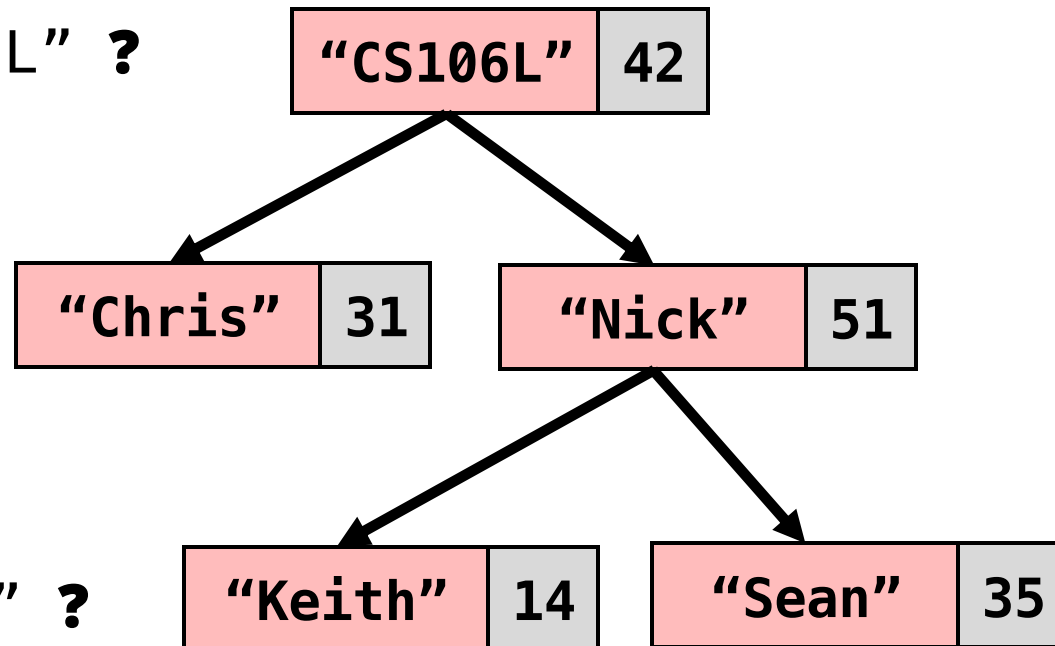
bjarne_about_to_raise_hand

How is map implemented?

"Chris" → 31

"CS106L" → 42

"Keith" → 14

"Nick" → 51

"Sean" → 35

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

What is map["Keith"]?

"Keith" **<** "CS106L" **?**

No! Go right

"CS106L"	42

"Chris"	31

"Nick"	51

"Keith" **<** "Nick" **?**

Yes! Go left

"Keith" **<** "Keith" **?**

"Keith"	14

"Sean"	35

Hey look, you found me!

map["Keith"] = 14

What is map["Alex"]?

"Alex" **<** "CS106L" **?**

Yes! Go left

"CS106L" | 42

"Alex" **<** "Chris" **?**

Yes! Go left... wait

"Chris" | 31

"Nick" | 51

"Alex" | 0

"Keith" | 14

"Sean" | 35
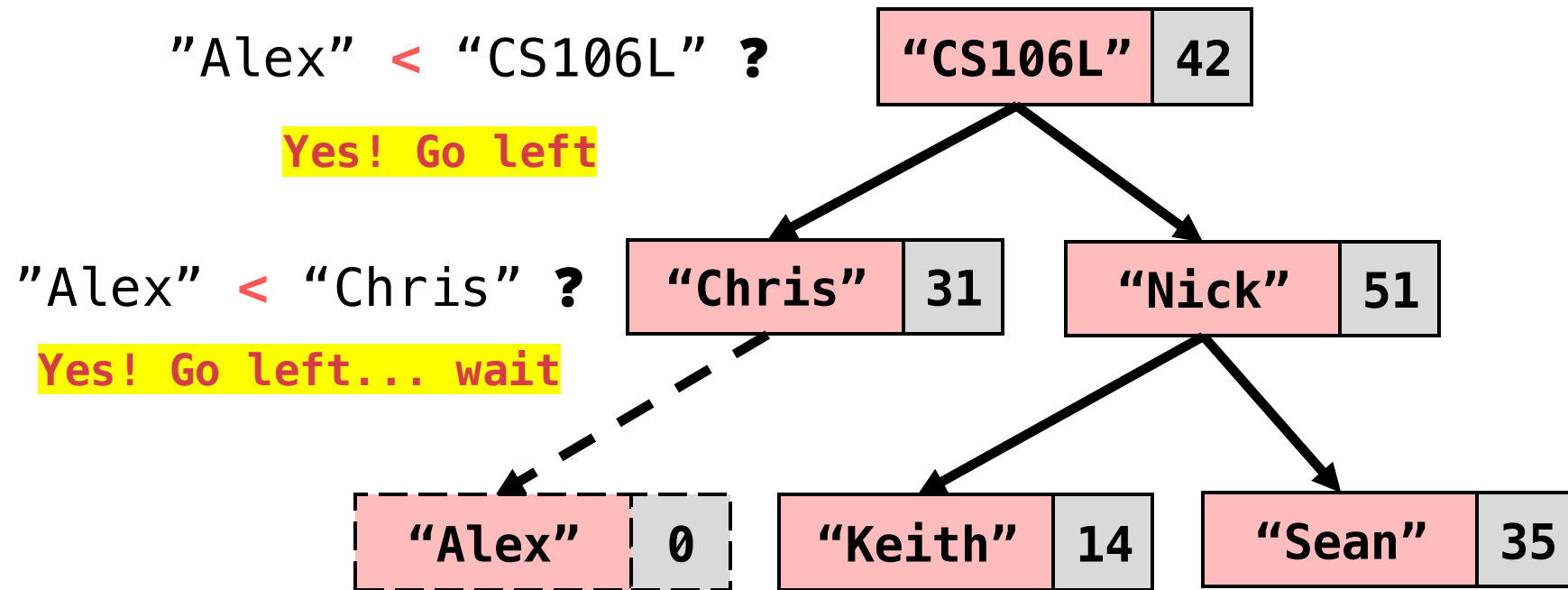
map["Alex"] = 0
(Note: "Alex" was default-inserted into the map)

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

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

```cpp
// ✅ 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"
};
```

$\approx$

$$\left\{ \begin{array}{l} \text{``CS106L!''} \\ \text{``Keith''} \\ \text{``Sean''} \\ \text{``Nick''} \\ \text{``Chris''} \end{array} \right\}$$

Stanford vs. STL set

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())`

`std::set` is an amoral `std::map`

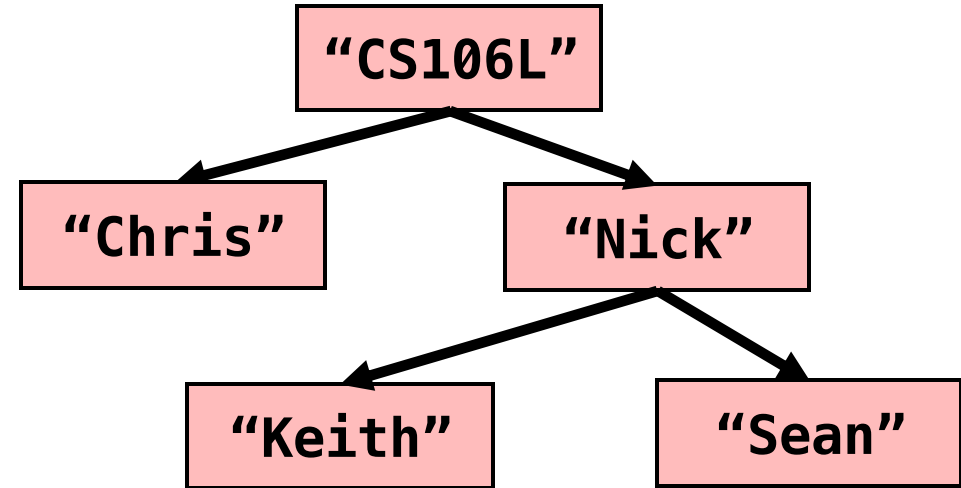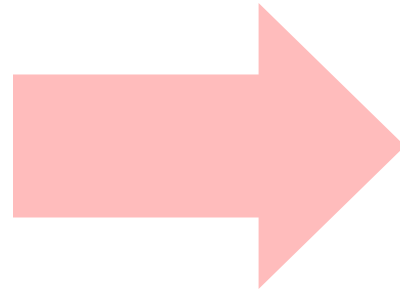`std::set` is an `std::map` without values

How is set implemented?

"Chris"

"CS106L"

"Keith"

"Nick"

"Sean"

```
              ┌──────────┐
              │ "CS106L" │
              └──────────┘
             ↙            ↘
      ┌─────────┐      ┌────────┐
      │ "Chris" │      │ "Nick" │
      └─────────┘      └────────┘
                      ↙          ↘
               ┌─────────┐   ┌────────┐
               │ "Keith" │   │ "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**

```cpp
#include <unordered_map>
#include <unordered_set>
```
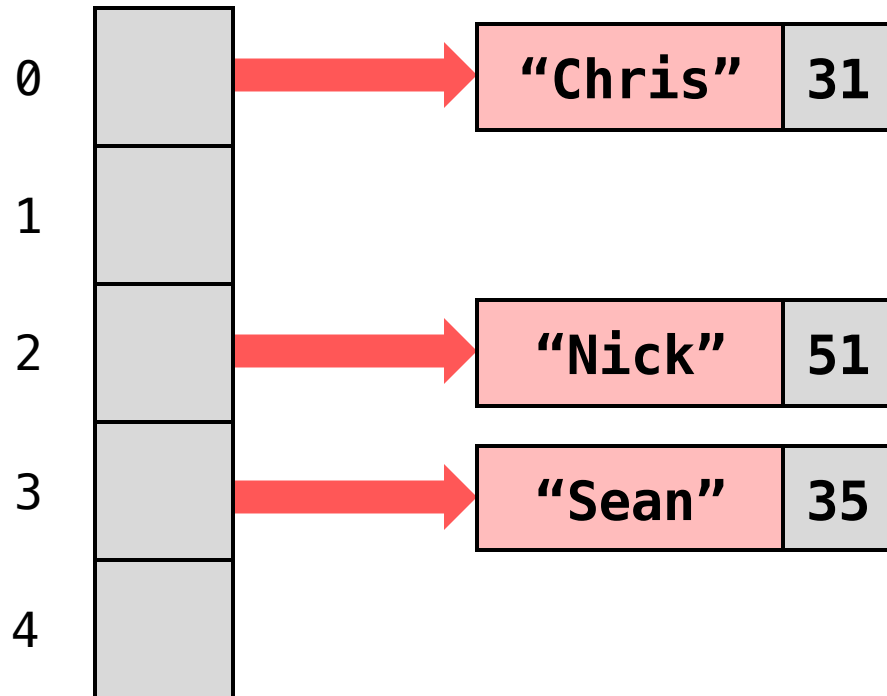
std::unordered_map

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

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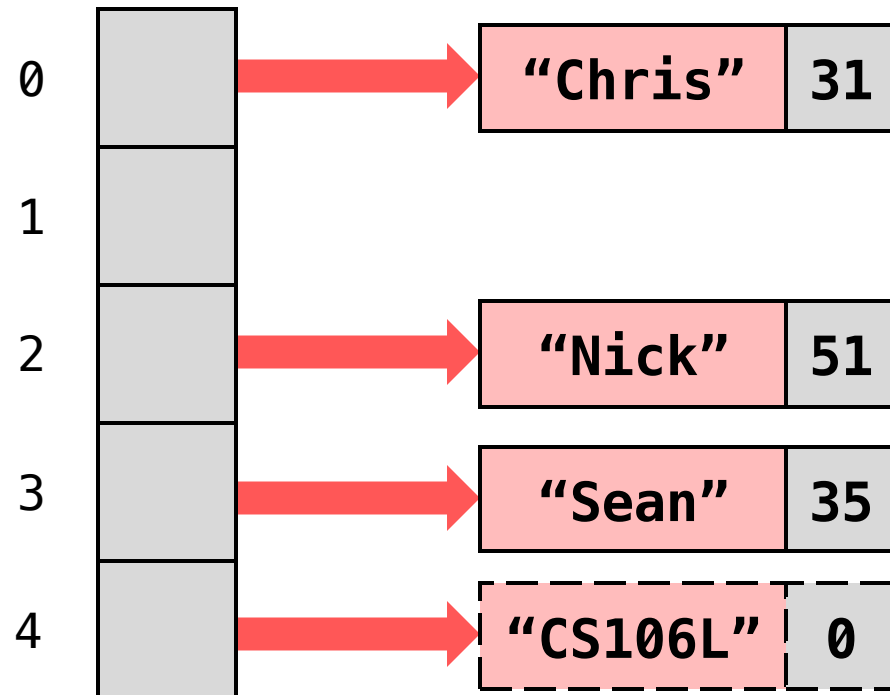
- Remember, `map` is a collection of `std::pair`
- `unordered_map` stores a collection of n "buckets" of pairs


```
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.
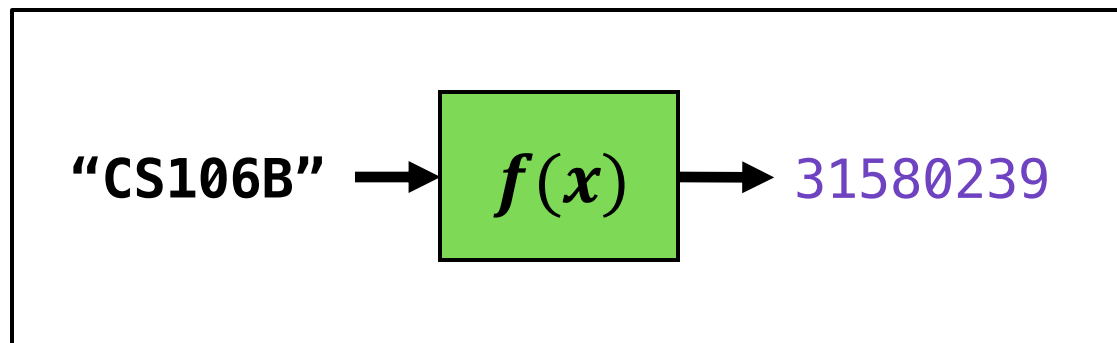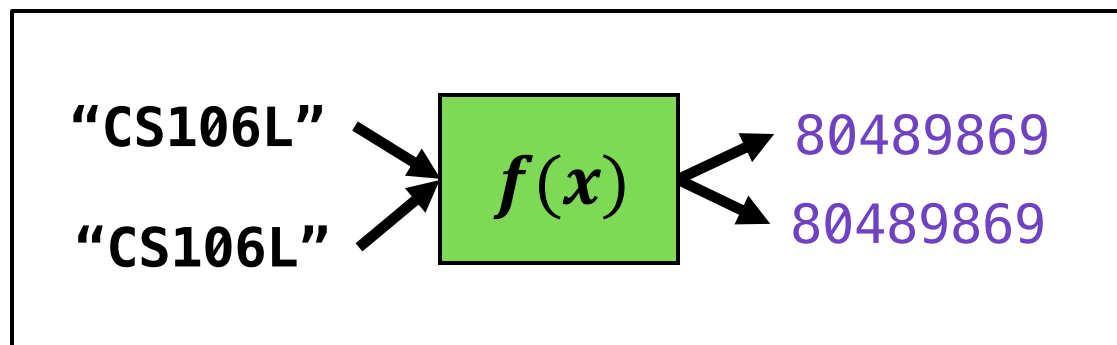


```
int x = map["CS106L"];
```

"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

"CS106L" → $f(x)$ → 80489869
"CS106L" → $f(x)$ → 80489869

"CS106B" → $f(x)$ → 31580239

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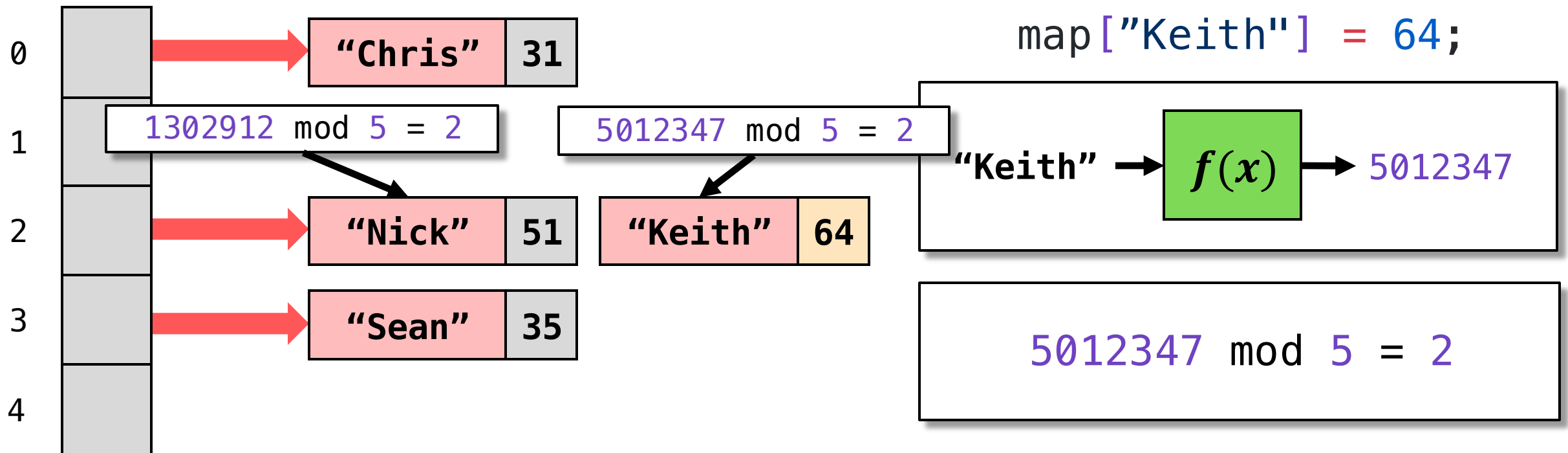
std::unordered_map<K, V> requires K to have a hash function (and equality)

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

```cpp
// ✅ OKAY — int is hashable
std::unordered_map<int, int> map1;

// ❌ ERROR — std::ifstream is not hashable
std::unordered_map<std::ifstream, int> map2;
```

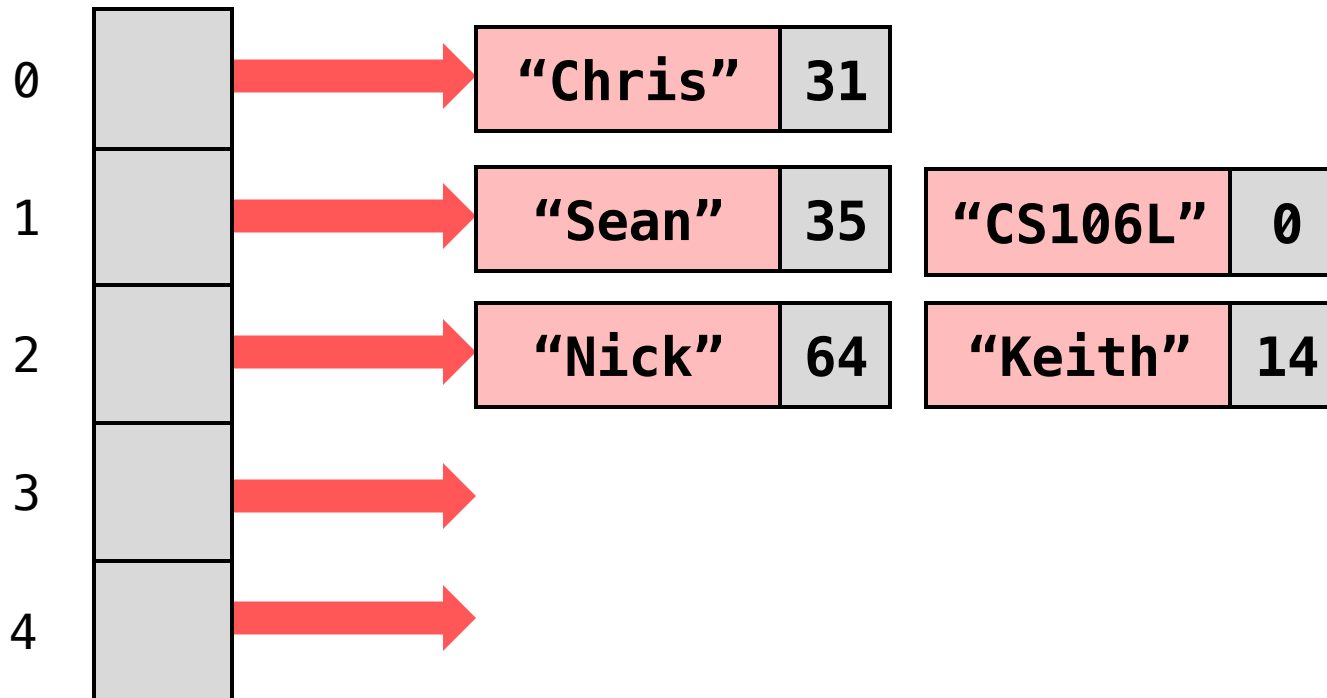Most basic types (`int, double, string`) are hashable by default

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**

Fun C++ Trivia: max_load_factor

You can control the max load factor before rehashing

```cpp
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?

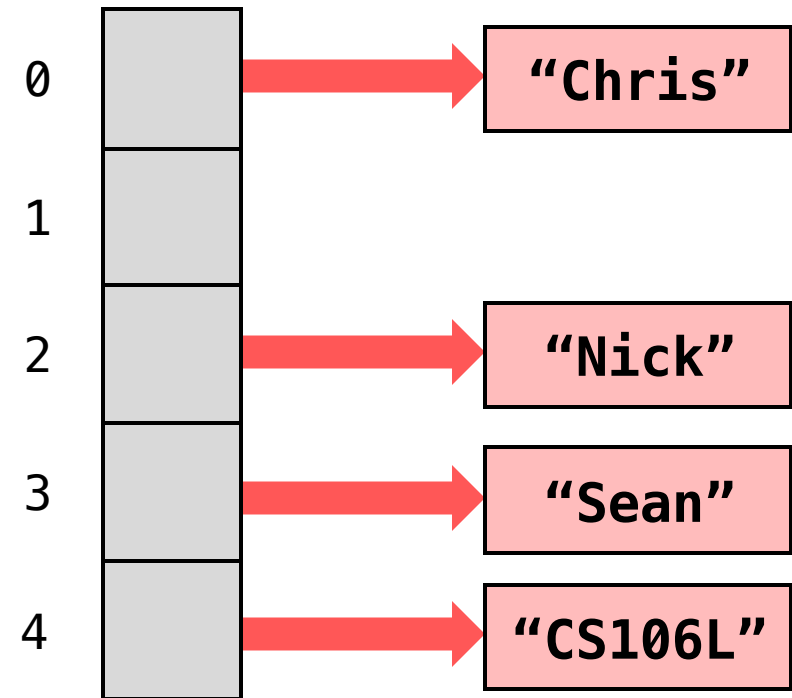A good hash function minimizes the chance of a hash collision

```cpp
// ❌ 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"
};
```

0 → "Chris"

1

2 → "Nick"

3 → "Sean"

4 → "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`!
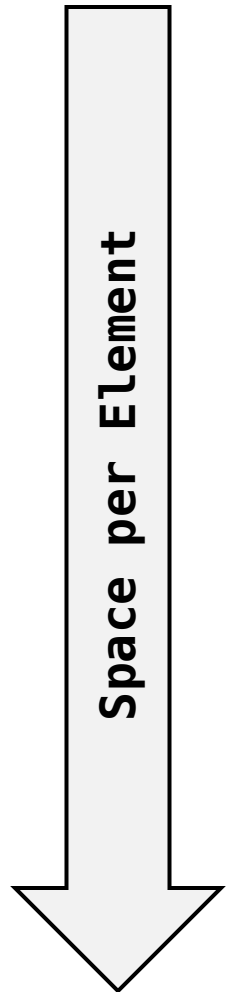- If you must choose, `unordered_map` is a safe bet

What questions do you have?

bjarne_about_to_raise_hand

Recap

Summary of Data Structures

Space per Element (↓)

	ith 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

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`