




**Welcome back! Link to Attendance Form ↓**



# Pop Quiz: Containers

- Which type(s) lets you insert at the back and front equally efficiently?
- Which type(s) requires a comparison operator on the element type?
  - What type(s) can we use to get around this?
- Which is *usually* faster: `unordered_set` or `set`? Why?

# Pop Quiz: Containers (Answers)

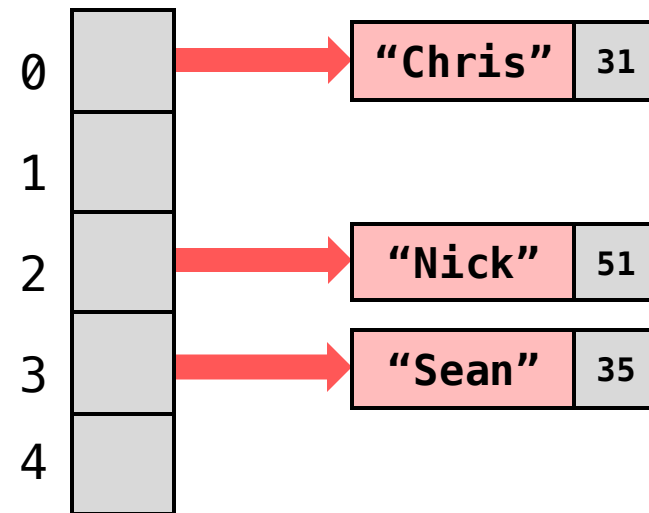
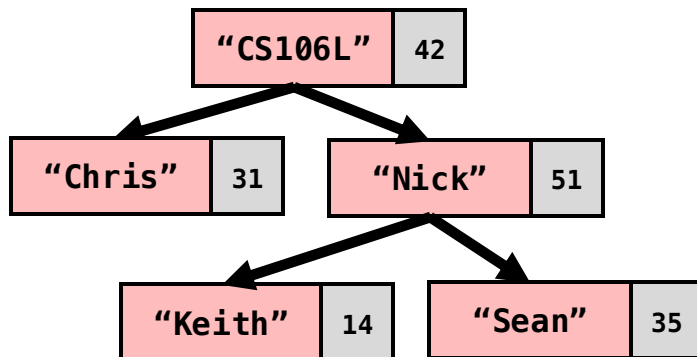
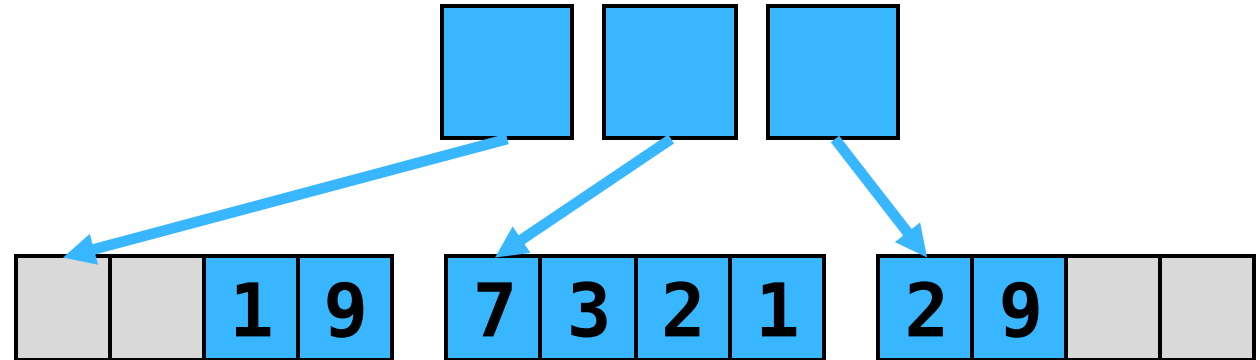
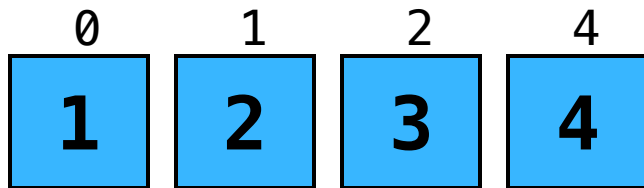
- Which type(s) lets you insert at the back and front equally efficiently?
  -  `std::deque`
- Which type(s) requires a comparison operator on the element type?
  -  `std::map`, `std::set`
- Which is *usually* faster: `unordered_set` or `set`? Why?
  -  `std::unordered_set` (Hashing + small load factor)!

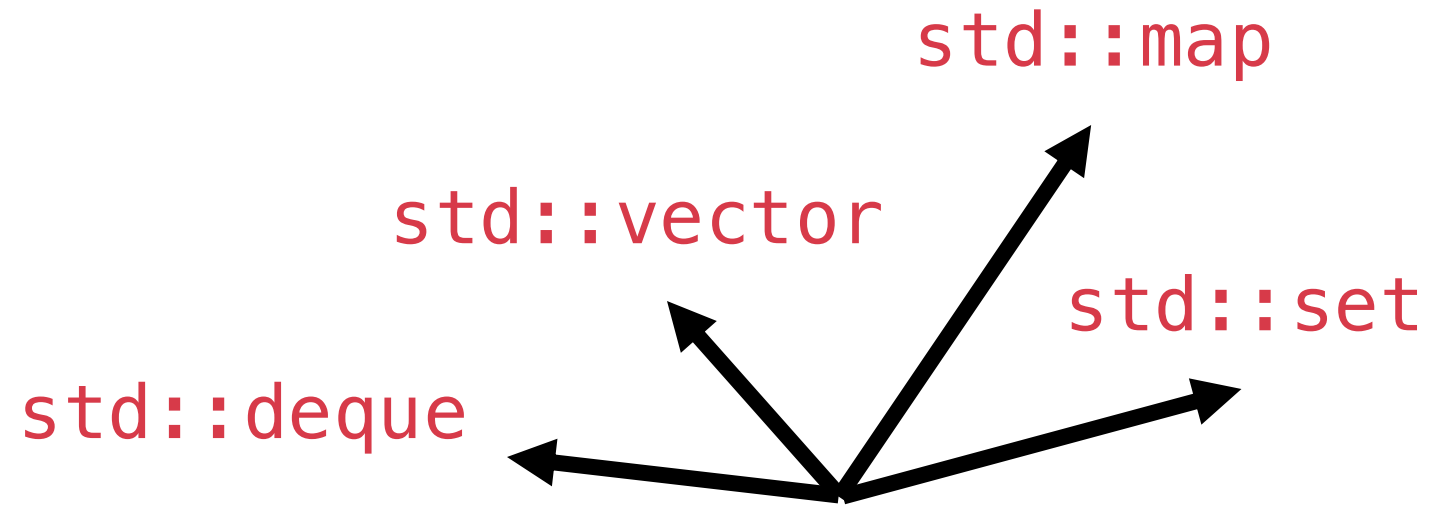
# What questions do you have?



bjarne\_about\_to\_raise\_hand

# Last Time: Containers



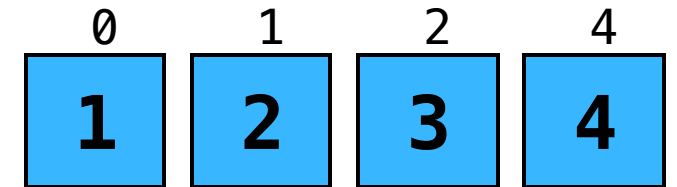


```
for (const auto& elem : container)
```

How does this work?

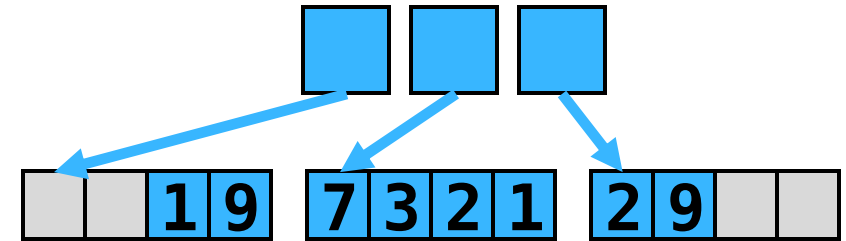
# For-each loops... huh?

```
std::vector<int> v { 1, 2, 3, 4 };  
  
for (const auto& elem : v) {  
    std::cout << elem << std::endl;  
}
```



# For-each loops... huh?

```
std::deque<int> d {  
    1, 9, 7, 3,  
    2, 1, 2, 9  
};  
  
for (const auto& elem : d) {  
    std::cout << elem << std::endl;  
}
```

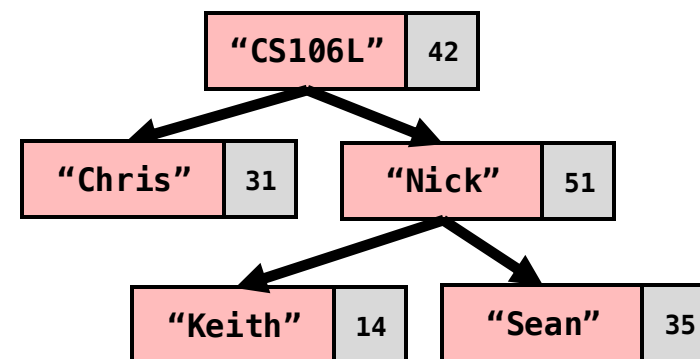




# For-each loops... huh?

```
std::map<std::string, int> m {  
    { "Chris", 31 }, { "CS106L", 42 },  
    { "Keith", 14 }, { "Nick", 51 },  
    { "Sean", 35 },  
};
```

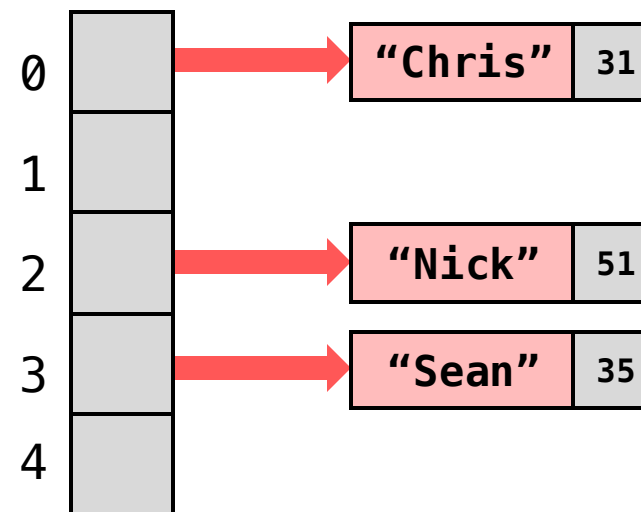
```
for (const auto& pair : m) {  
    std::cout << pair.first << " ";  
    std::cout << pair.second;  
}
```



# For-each loops... huh?

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

for (const auto& pair : m) {
    std::cout << pair.first << " ";
    std::cout << pair.second;
}
```



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



How does this work?

# Lecture 7: Iterators

CS106L, Spring 2025

# 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?*

# Today's Agenda

- Iterator Basics
  - What even is an iterator?
- Iterator Types
  - Iterators are organized by their properties
- Pointers and Memory
  - What is a pointer? What is memory?

# What questions do you have?



bjarne\_about\_to\_raise\_hand

# Iterator Basics



# Question: How do we iterate?

```
std::vector<int> v {1,2,3,4};  
for (size_t i = 0; i < v.size(); i++) {  
    const auto& elem = v[i];  
    std::cout << elem;  
}  
  
for (var-init; condition; increment) {  
    const auto& elem = /* grab element */;  
    /* do something with elem */  
}
```

# Question: How do we iterate?

`for (auto e : s)`  
is not allowed  
...for now



```
for (var-init; condition; increment)
    const auto& elem = /* grab element */;
}
```

```
std::set<int> s {1,2,3,4};
for (uhhh; ummm; what?) {
    const auto& elem = /* haeelp 🙄🙄 */;
}
```

**We need something to track where we are  
in a container... sort of like an index**

Introducing *iterators* 😎 😎

# C++ iterators are like a “claw” in a claw machine

## The claw can:

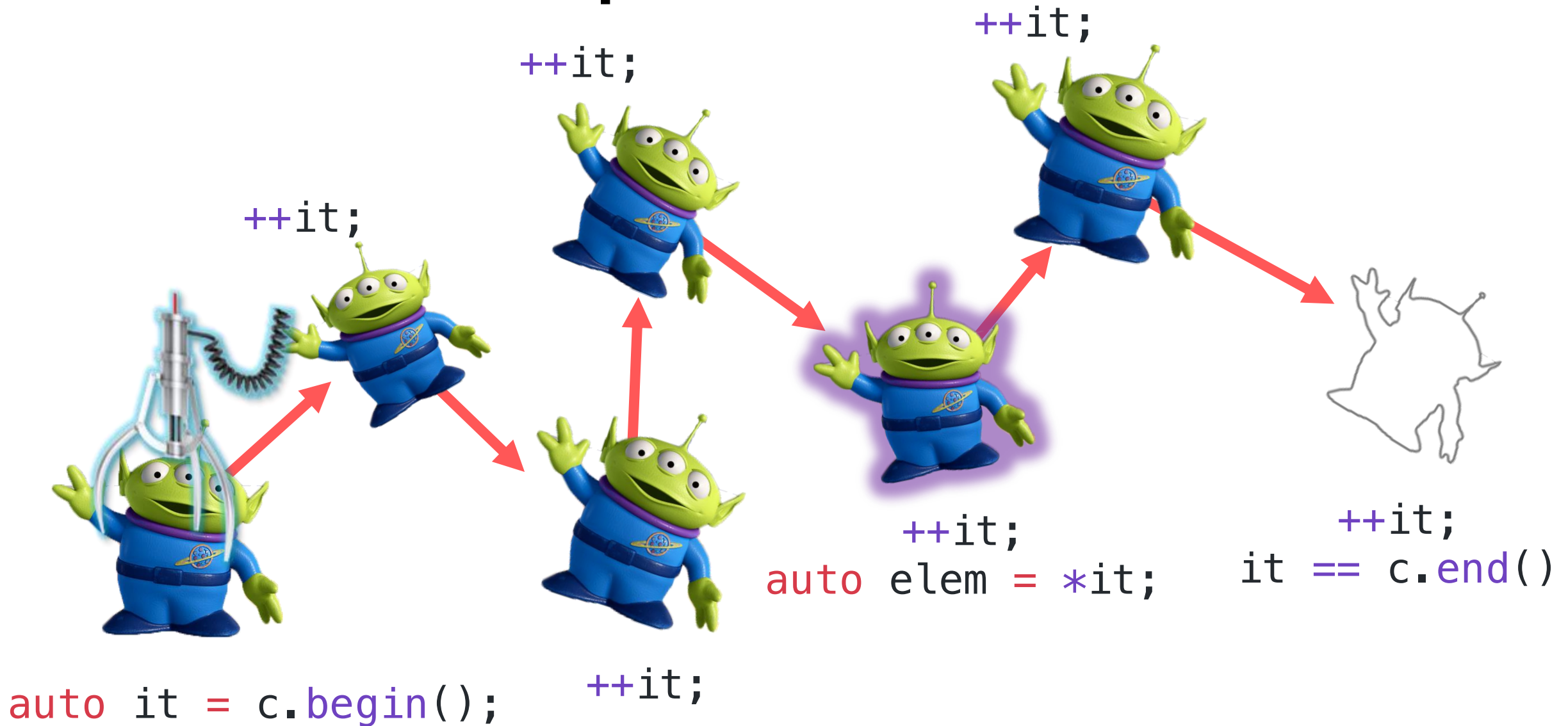
1. Grab a toy
2. Move forward
3. Check if we're done



## The machine can:

1. Tell us where to start
2. Tell us when to stop

# C++ Iterators Example



**Containers and iterators *work together* to allow iteration**

# Container Interface

`container.begin()`

Gets an iterator to  
the **first element**  
of the container  
(assuming non-empty)

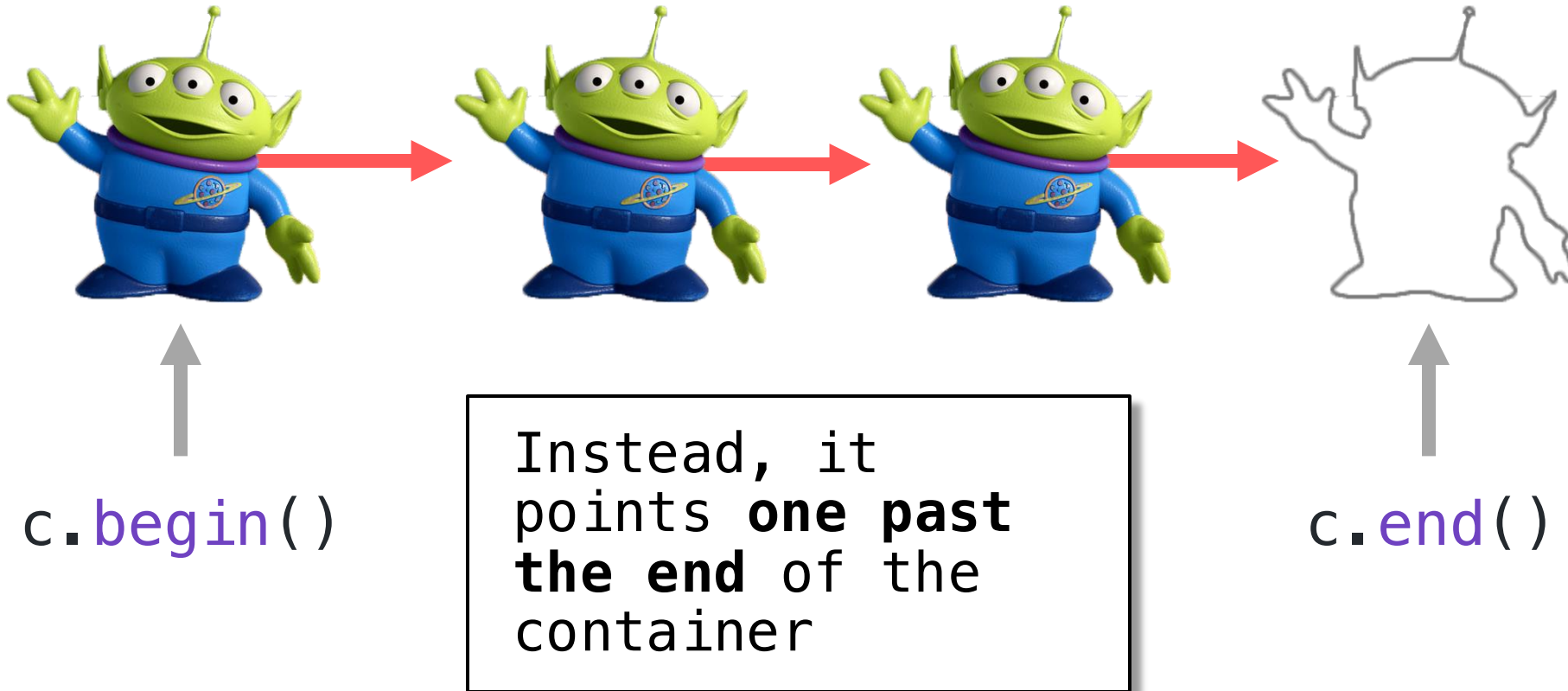
`container.end()`

Gets a **past-the-end**  
iterator

That is, an iterator to  
one element **after** the  
end of the container

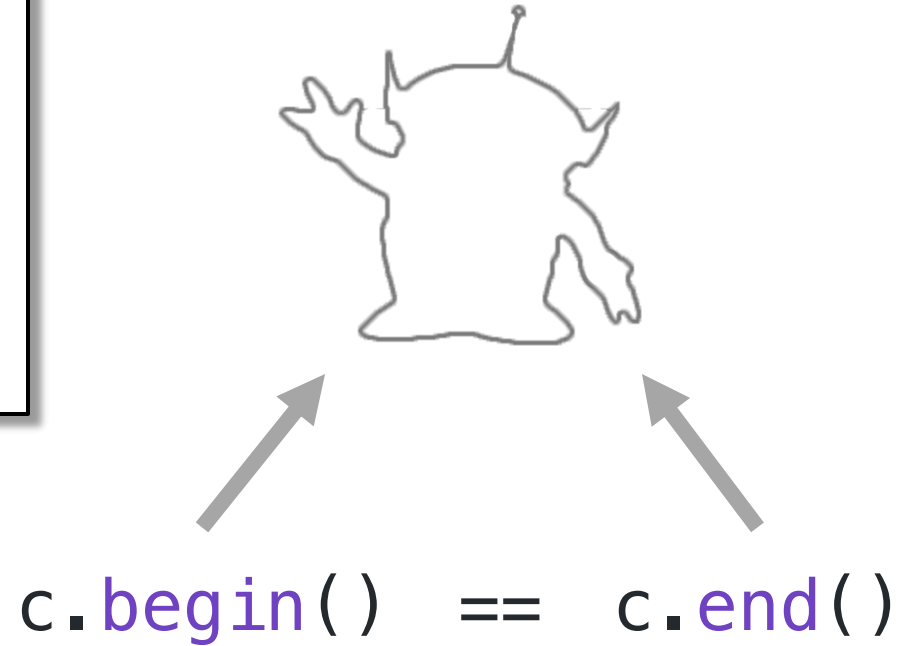


# `end()` never points to an element!



# `end()` never points to an element!

If `c` is empty,  
then `begin()` and  
`end()` are equal!



# Iterator Interface

```
// Copy construction  
auto it = c.begin();
```

```
// Increment iterator forward  
++it;
```

```
// Dereference iterator -- undefined if it == end()  
auto& elem = *it;
```

```
// Equality: are we in the same spot?  
if (it == c.end()) ...
```

# We have an answer now!

```
std::set<int> s {1,2,3,4};
```

```
for (var-init; condition; increment) {  
    const auto& elem = /* grab element */;  
}
```

```
for (  
    ;  
    const auto& elem = /* grab element */;  
)
```

`for (auto e : s)`  
is not allowed  
...for now



# We have an answer now!

```
std::set<int> s {1,2,3,4};
```

```
for (var-init; condition; increment) {  
    const auto& elem = /* grab element */;  
}
```

```
for (auto it = s.begin();           ;      ) {  
    const auto& elem = /* grab element */;  
}
```

for (auto e : s)  
is not allowed  
...for now



# We have an answer now!

```
std::set<int> s {1,2,3,4};
```

```
for (var-init; condition; increment) {  
    const auto& elem = /* grab element */;  
}
```

```
for (auto it = s.begin(); it != s.end();    ) {  
    const auto& elem = /* grab element */;  
}
```

`for (auto e : s)`  
is not allowed  
...for now



# We have an answer now!

```
std::set<int> s {1,2,3,4};
```

```
for (var-init; condition; increment) {  
    const auto& elem = /* grab element */;  
}
```

```
for (auto it = s.begin(); it != s.end(); ++it) {  
    const auto& elem = /* grab element */;  
}
```

for (auto e : s)  
is not allowed  
...for now



# We have an answer now!

```
std::set<int> s {1,2,3,4};
```

```
for (var-init; condition; increment) {  
    const auto& elem = /* grab element */;  
}
```

```
for (auto it = s.begin(); it != s.end(); ++it) {  
    const auto& elem = *it;  
}
```

`for (auto e : s)`  
is not allowed  
...for now





## When you write...

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

## It's actually this:

```
auto b = s.begin();
auto e = s.end();

for (auto it = b; it != e; ++it)
{
    auto elem = *it;
    std::cout << elem;
}
```

# What questions do you have?



bjarne\_about\_to\_raise\_hand

# We have an answer now!

```
std::set<int> s {1,2,3,4};
```

```
for (var-init; condition; increment) {  
    const auto& elem = /* grab element */;  
}
```

```
for (auto it = s.begin(); it != s.end(); ++it) {  
    const auto& elem = *it;  
}
```

`for (auto e : s)`  
is not allowed  
...for now



**Guess we're done here!**



# We have an answer now!

```
std::set<int> s {1,2,3,4};
```

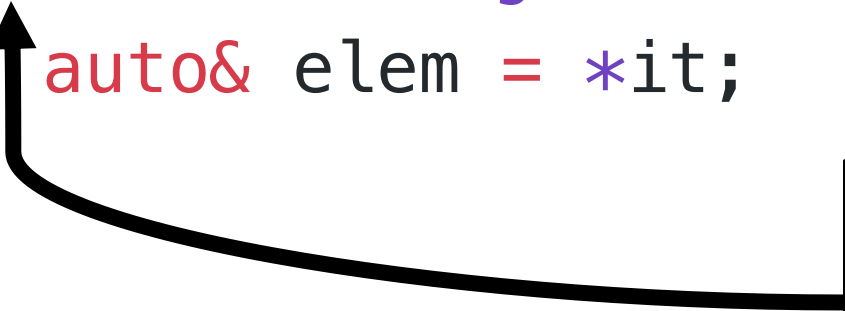
```
for (var-init; condition; increment) {  
    const auto& elem = /* grab element */;  
}
```

```
for (auto it = s.begin(); it != s.end(); ++it) {  
    const auto& elem = *it;  
}
```

for (auto e : s)  
is not allowed  
...for now



What type is  
this?



# What are the types?

Using **auto** avoids spelling out long iterator types

```
std::map<int, int> m { {1, 2}, {3, 4}, {5, 6}};  
auto it = m.begin();  
auto elem = *it;           // {1, 2}
```

```
std::map<int, int> m { {1, 2}, {3, 4}, {5, 6}};  
std::map<int, int>::iterator it = m.begin();  
std::pair<int, int> elem = *it;
```

# Remember: **using** makes a type alias

```
// Inside <map> header
template <typename K, typename V>
class std::map {
    using iterator = /* some iterator type */;
};
```

```
// Outside <map> header (e.g. main.cpp)
std::map<int, int>::iterator it = m.begin();
```



Iterator types are really long, so we like to use **auto** with iterators

**Aside: Why do we use `++it` instead of `it++`?**



## **++it** avoids making an unnecessary copy

```
// Prefix ++it  
// Increments it and returns a reference to same object  
Iterator& operator++();
```

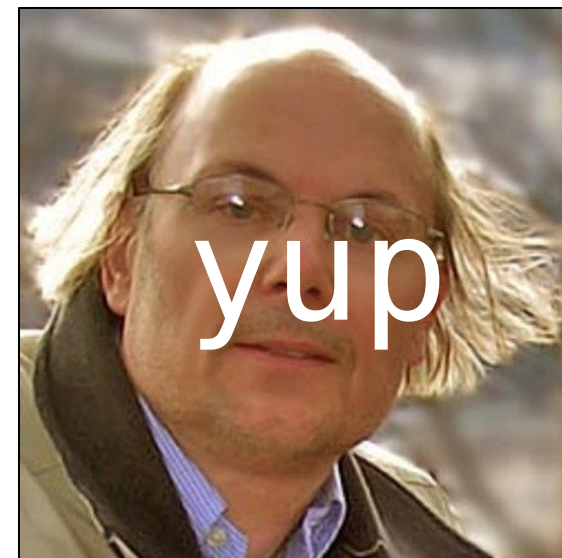
```
// Postfix it++  
// Increments it and returns a copy of the old value  
Iterator operator++(int);
```

**Remember:** an iterator is a fully-fledged object, so it's often more expensive to copy than, say, an **int**

**Does it actually make a difference?**

# Bjarne's Thoughts

“



`++i` is sometimes faster than, and is never slower than, `i++`. ... So if you're writing `i++` as a statement rather than as part of a larger expression, why not just write `++i` instead? You never lose anything, and you sometimes gain something.

[source]

# What questions do you have?

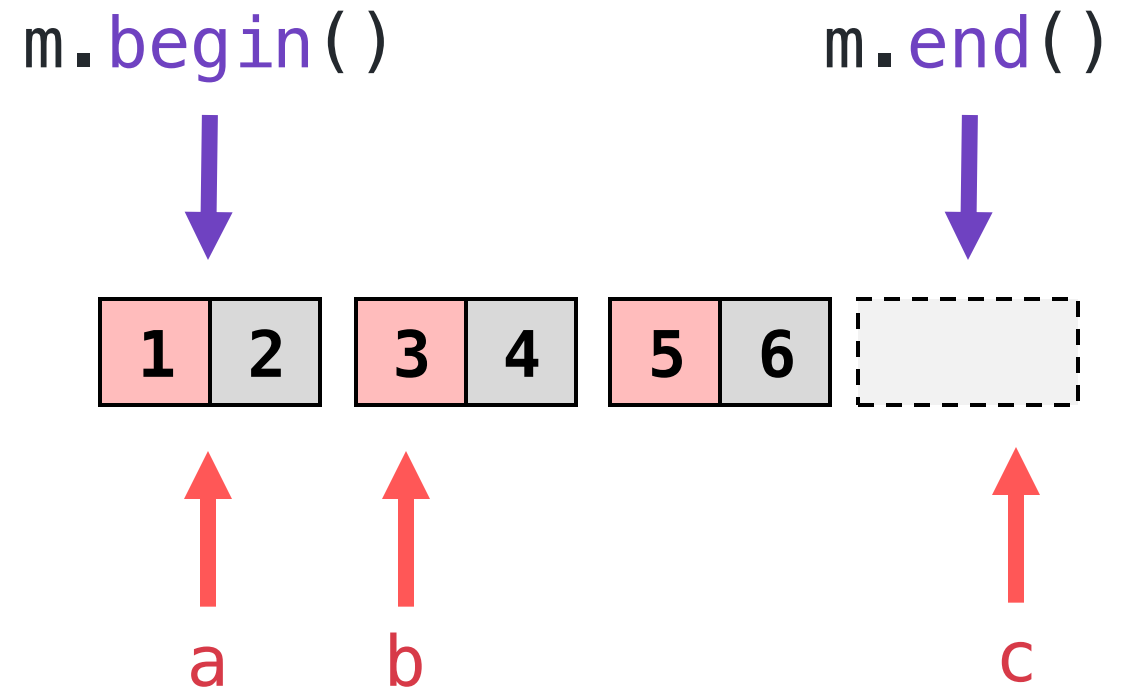


bjarne\_about\_to\_raise\_hand

# Your Turn

Trace this code with a partner to find out where each iterator points

```
std::map<int, int> m {  
    {1, 2}, {3, 4}, {5, 6}  
};  
auto a = m.begin();  
++a;  
auto b = a;  
++a;  
auto c = ++a;
```



# Iterator Types

**Not all iterators are made equal**

# All iterators provide these four operations

```
auto it = c.begin();
```

```
++it;
```

```
*it;
```

```
it == c.end()
```

## But most provide even more

```
--it; // Move backwards
```

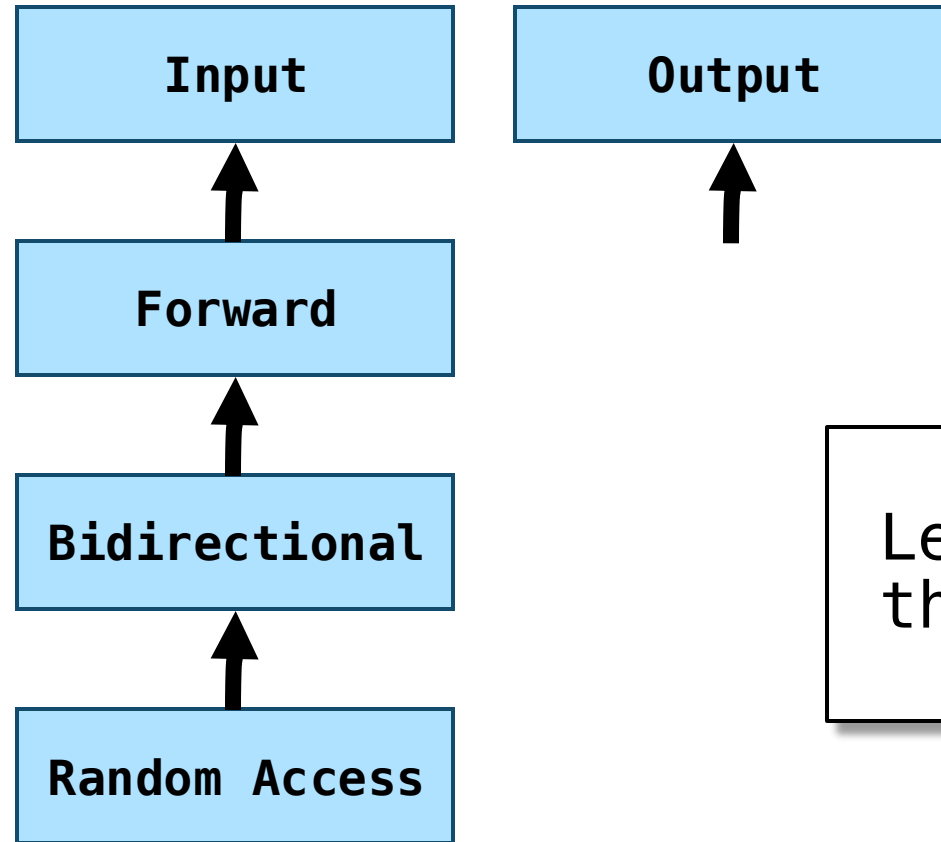
```
*it = elem; // Modify
```

```
it += n; // Rand. access
```

```
it1 < it2 // Is before?
```



# Iterator types determine their functionality

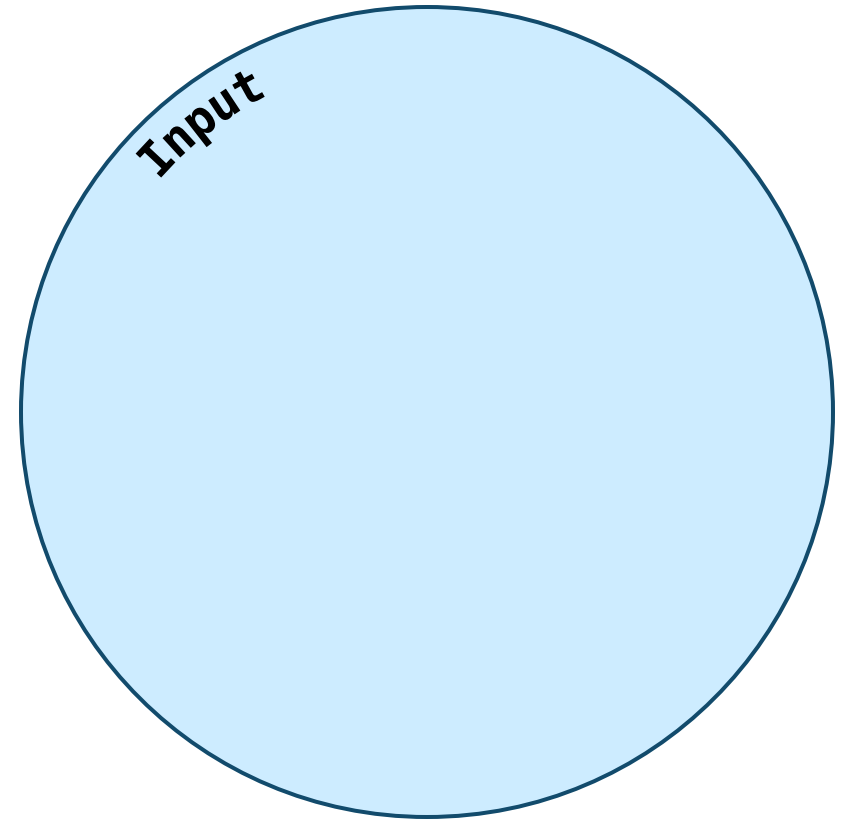


Let's unpack  
this!

# Input Iterators

- Most basic kind of iterator
- Allows us to read elements

```
auto elem = *it;
```



**Vivid Venn Diagram of  
Vexing Iterators**

# Input Iterators: operator->

If the element is a struct, we can access its members with ->

```
struct Bibble {  
    int zarf;  
};
```

*Bibble*, v.  
“To eat and/or drink noisily”

```
std::vector<Bibble> v {...};  
auto it = v.begin();  
int m = (*it).zarf;  
int m = it->zarf;
```

// Exactly the same as prev!



# Input Iterators

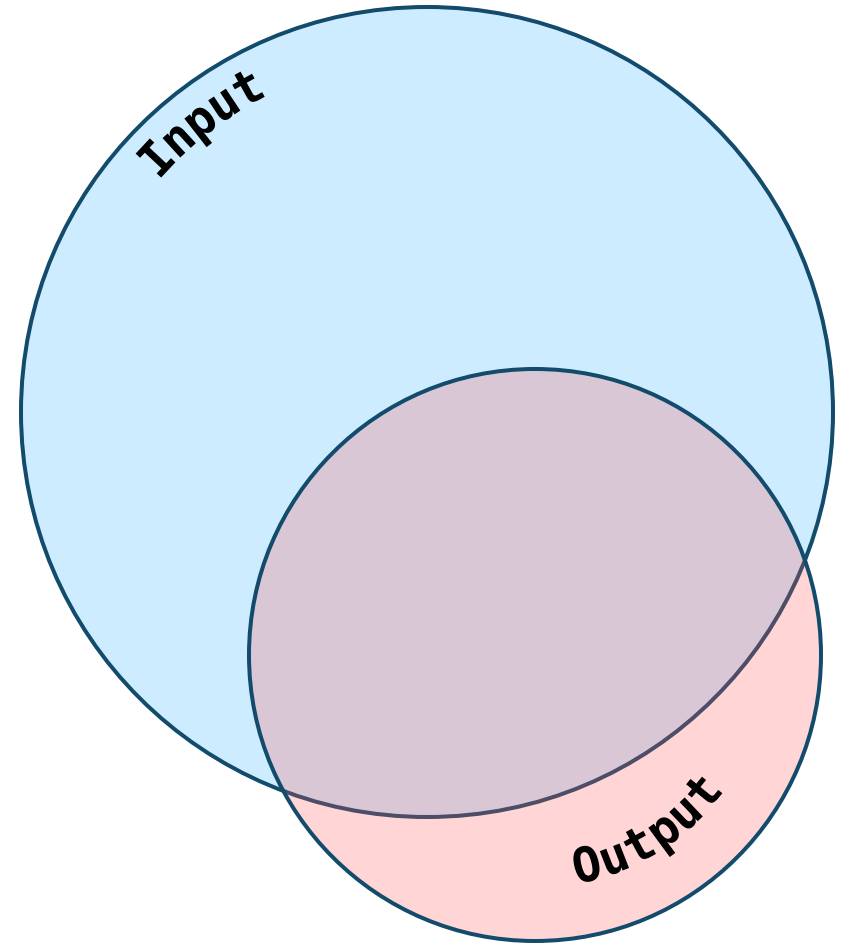
- Most basic kind of iterator
- Allows us to read elements

```
auto elem = *it;
```

# Output Iterator

Allows us to write elements

```
*it = elem;
```



**Vivid Venn Diagram of  
Vexing Iterators**

# Forward Iterator

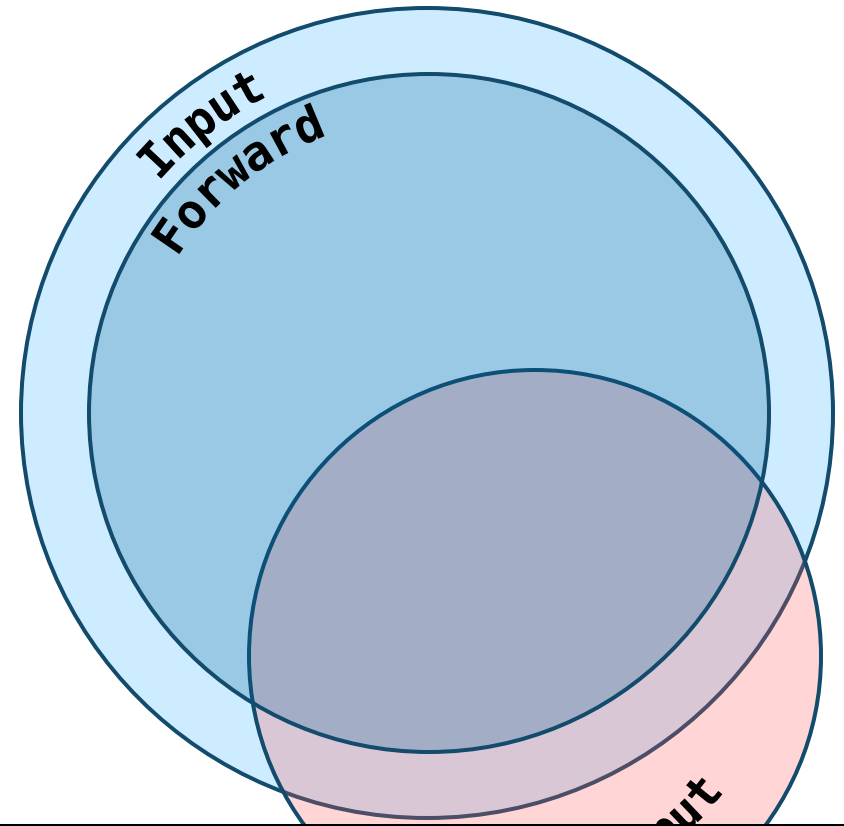
- An input iterator that allows us to make multiple passes
- All STL container iterators fall here

Multi-pass guarantee

`it1 == it2`



`++it1 == ++it2`



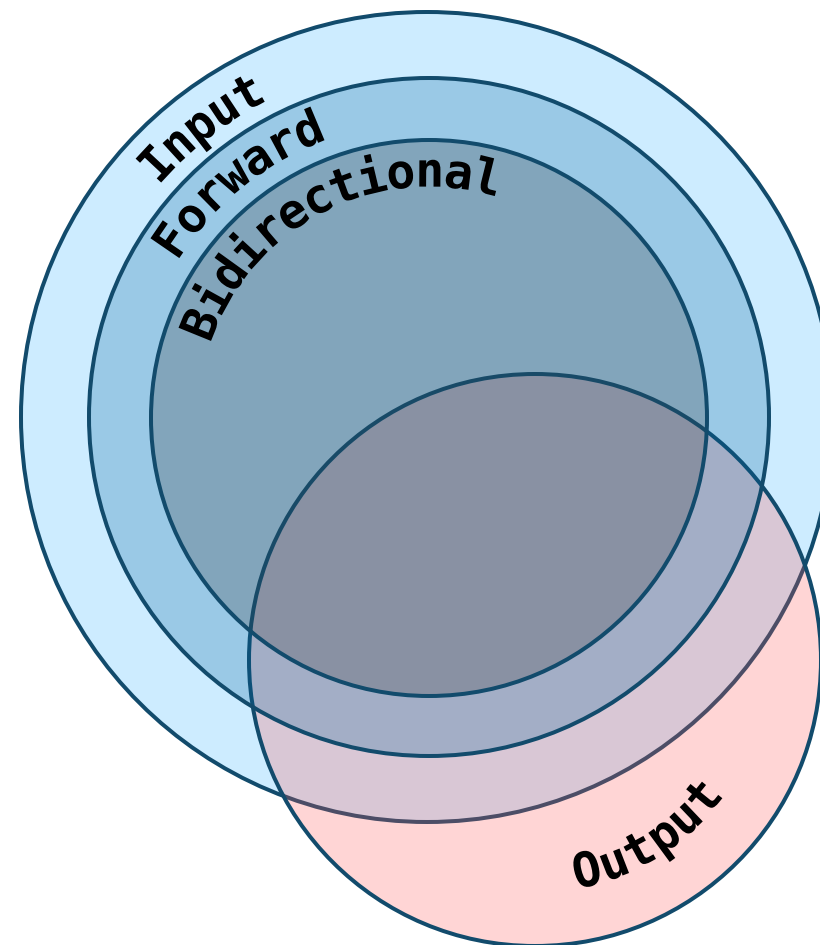
What kind of data structure might not want a multi-pass iterator?

**Streams!!!**

# Bidirectional Iterators

- Allows us to move forwards *and* backwards
- `std::map`, `std::set`

```
auto it = m.end();  
  
// Get last element  
--it;  
auto& elem = *it;
```



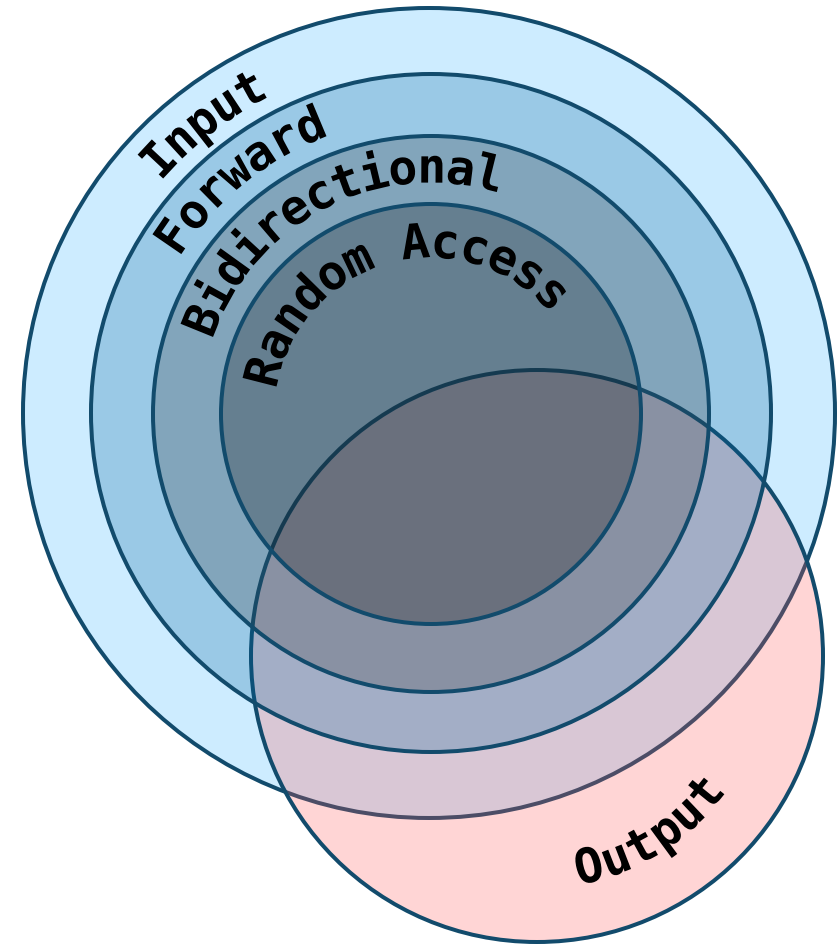
Vivid Venn Diagram of  
Vexing Iterators

# Random Access Iterators

- Allows us to quickly skip forward and backward
- `std::vector`, `std::deque`

```
auto it2 = it + 5; // 5 ahead
auto it3 = it2 - 2; // 2 back

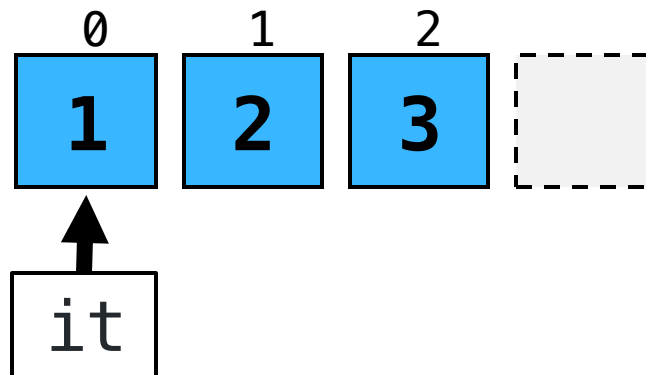
// Get 3rd element
auto& second = *(it + 2);
auto& second = it[2];
```



Vivid Venn Diagram of  
Vexing Iterators

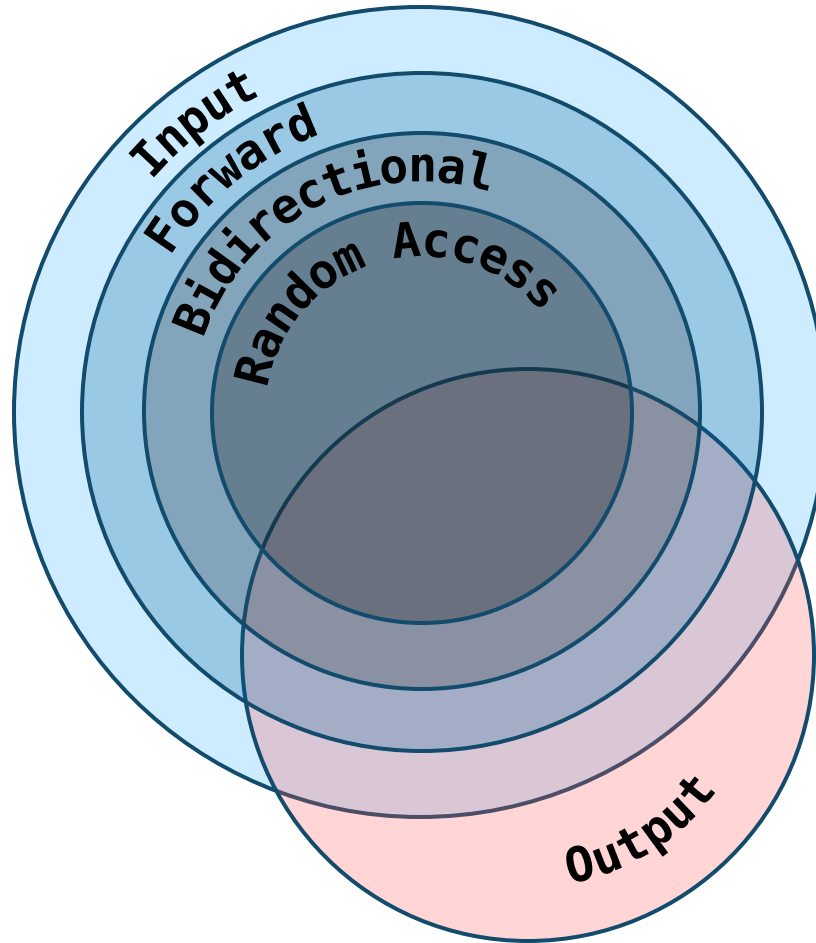
# Be careful not to go out of bounds

```
std::vector<int> v { 1, 2, 3 };  
auto it = v.begin();  
it += 3;  
int& elem = *it; // Undefined behaviour
```





# STL Iterator Types



**Why does it matter?**

# Why does it matter?

As we'll soon see, some algorithms require a certain iterator type!

```
std::vector<int> vec{1,5,3,4};  
std::sort(vec.begin(), vec.end());  
// ✓ begin/end are random access  
  
std::unordered_set<int> set {1,5,3,4};  
std::sort(set.begin(), set.end());  
// ✗ begin/end are bidirectional
```

# Why have multiple iterator types?

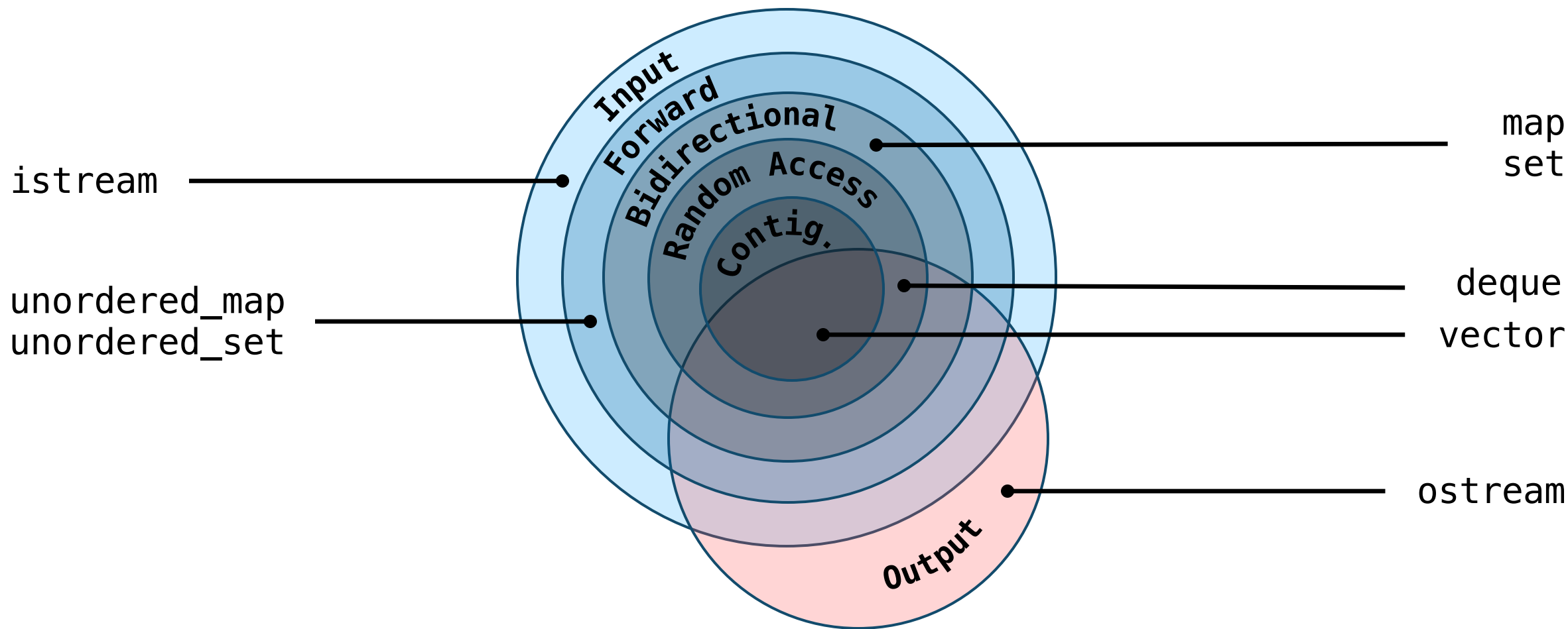
- **Goal:** provide a uniform abstraction over all containers
- **Caveat:** the way that a container is implemented affects how you iterate through it
  - Skipping ahead 5 steps (random access) is a lot easier/faster when you have a sequence container (**vector**, **deque**) than associative (**map**, **set**)
  - C++ generally avoids providing you with slow methods by design, so that's why you can't do random access on a **map::iterator**

# What questions do you have?



bjarne\_about\_to\_raise\_hand

# STL Iterator Types



# Pointers and Memory

**An iterator points to a container element**

**A pointer points to any object**

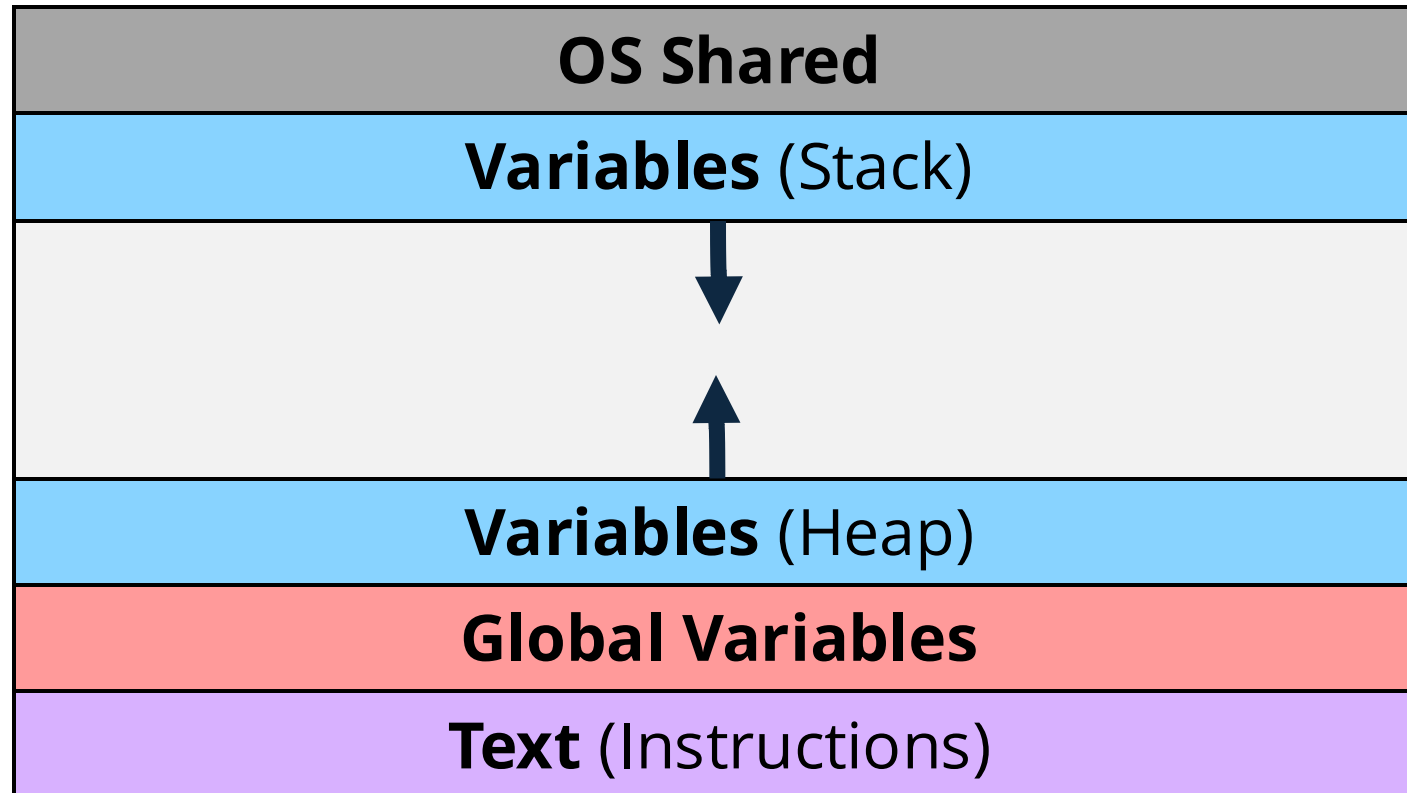


# Memory Basics



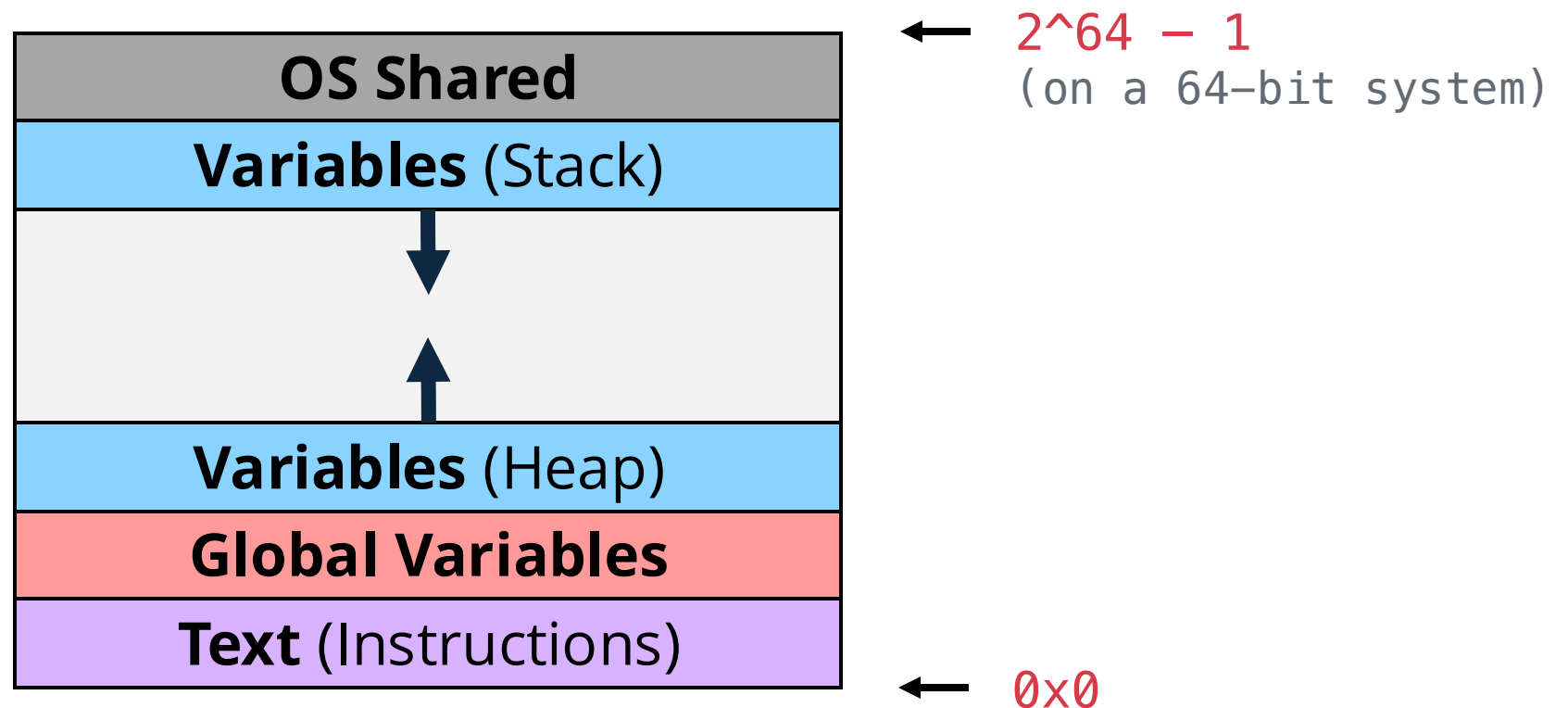
# Memory Basics

- Every variable lives somewhere in memory
- All the places something could live form the **address space**



# Memory Basics

- Memory is usually byte-addressable, with each byte numbered from 0
- 1 byte = 8 bits



# Memory Basics

- The **address** of an object is the location of its lowest byte
- For example, an integer always uses 32 bits = 4 bytes

```
int x = 106; // 32 bits
```

0x10 is the  
address of x

x's memory

00000000	00000000	00000000	01101010
----------	----------	----------	----------

0x10

0x11

0x12

0x13

# What questions do you have?



bjarne\_about\_to\_raise\_hand

**How do we get the address of a variable in C++?**

**Pointers!** 🙌 🙌 🙌

# A pointer is the **address** of a variable

```
int x = 106;  
int* px = &x;
```

`int*` means `px`  
is a pointer  
to an `int`

`&` is the  
address of  
operator

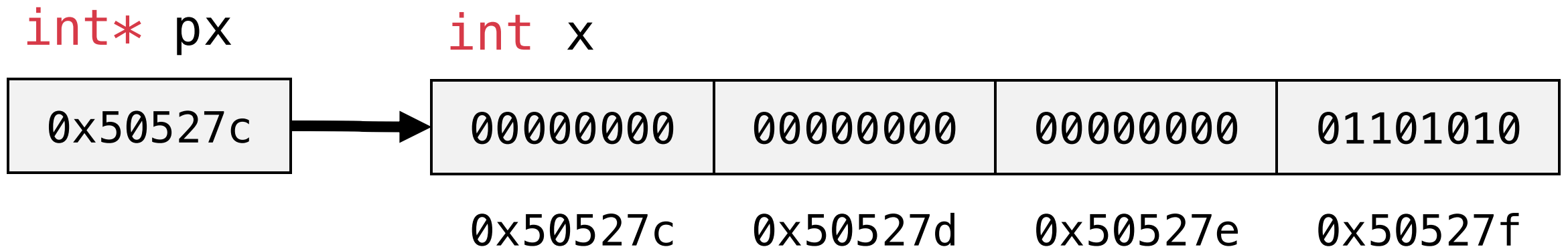
```
std::cout << x << std::endl;    // 106  
std::cout << *px << std::endl;  // 106  
std::cout << px << std::endl;   // 0x50527c
```



MAN, I SUCK AT THIS GAME.  
CAN YOU GIVE ME  
A FEW POINTERS?



# A pointer is just a number!



# What questions do you have?



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`int* px`

`int x`



# We can have pointers to all kinds of things!

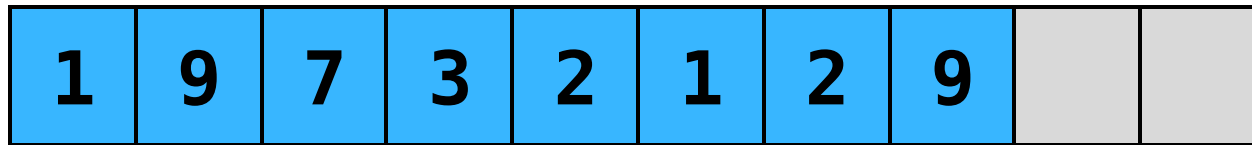
```
int x = 106;  
int* px = &x;
```

```
StanfordID id { "jtrb" };  
StanfordID* p = &id;  
auto name = p->name;
```

```
std::vector<int> v;  
std::vector<int>* p = &v;
```

```
std::vector<int> v {  
    1, 2, 3, 4, 5  
};  
int* arr = &v[0];
```

# Recall: a vector is a contiguous array

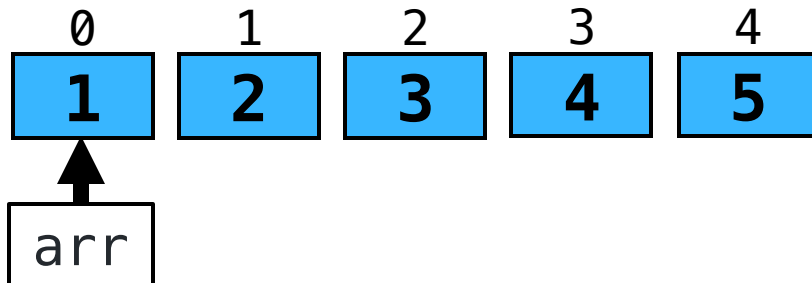


A **vector** is a single chunk  
of memory

# Array pointer

```
std::vector<int> v {1,2,3,4,5};
```

```
int* arr = &v[0];    std::cout << *arr << " ";  
arr += 1;            std::cout << *arr << " ";  
++arr;               std::cout << *arr << " ";  
arr += 2;            std::cout << *arr << " ";  
if (arr == &v[4])   std::cout << "At last index";
```



Output:

1 2 3 5 At last index

# Notice anything?

```
std::vector<int> v {1,2,3,4,5};  
  
int* arr = &v[0];           // Copy construction  
arr += 1;                   // Random access  
++arr;                      // Move pointer forward  
arr += 2;                   // Random access  
if (arr == &v[4])          // Pointer comparison
```



# We could do the same thing with iterators!

```
auto it = v.begin();    std::cout << *it << " ";
it += 1;               std::cout << *it << " ";
++it;                 std::cout << *it << " ";
it += 2;               std::cout << *it << " ";
if (it == --v.end())   std::cout << "At last element";
```

**Iterators** have a similar interface to **pointers**

## Recall: **iterator** is a type alias

```
template <typename T>
class vector {
    using iterator = /* some iterator type */;;

    // Implementation details...
};
```

**T\*** is the backing type for **vector<T>::iterator**

```
template <typename T>
class vector {
    using iterator = T*;

    // Implementation details...
};
```

In the real STL implementation, the actual type is not **T\***.  
But for all intents and purposes, you can think of it this way.

# What questions do you have?



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# Recap

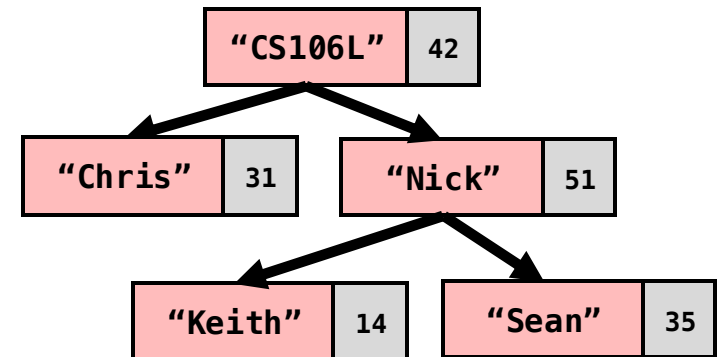
# What we covered

- Iterator Basics
  - An iterator allows us to step forward through a container
- Iterator Types
  - Input, Output, Forward, Bidirectional, Random Access
- Pointers and Memory
  - A pointer points to an arbitrary C++ object in memory
  - Pointers and iterators have the same interface

# So how do we implement other iterators?

```
template <typename K, typename V>
class map {
    using iterator = ????????;

    // Implementation details...
};
```





# Classes

**We'll learn about them next time**