Lecture 5: Containers

CS 106L, Winter ‘21

Today’s Agenda

- Recap: Streams
- Intro to Standard Template Library (STL)
- Sequence Containers
- Container Adaptors
- Associative Containers

Supplemental Material

- Regular slides: stuff we will go through lecture, absolutely necessary to understand future lectures.
- Supplemental material: good to know to become even more proficient in C++, but not necessary to be successful in the course!
- Feel free to review the supplemental material if you’re interested.

Recap: Streams

A stream is an abstraction for input/output

Output Streams

- Of type **`std::ostream`**
- Can only **receive** data with the **<<** operator
  - Converts data to string and **sends** it to stream

```
std::cout << 5 << std::endl;     // prints 5 to the console

std::ofstream out(“out.txt”, std::ofstream::out);
out << 5 << std::endl;           // out.txt contains 5
```

Input Streams

- Of type `std::istream`
- Can only **give you** data with the >> operator
  - Receives string from stream and converts it to data

```
// input: 5 abc 7
int x, z; std::string y;
std::cin >> x >> y >> z;                // x=5, y="xyz", z=7

// std::ifstream does the same for files
std::ifstream in("out.txt", std::ifstream::in);
in >> x >> y >> z;                      // out.txt contains 5
```

Intro to Standard Template Library (STL)

Today, we're starting a new unit on the Standard Template Library (STL)

Overview of STL (AKA Standard Template Library)

Adaptors

Containers

Iterators

Functions

Algorithms

Today, we're going to be making comparisons to these aspects of the Stanford Library:

- `Vector<T>`
- `Stack<T>, Queue<T>`
- `Map<T>, Set<T>`

Sequence Containers

1. `std::vector` - Stanford vs. STL
2. `std::vector` - safety and efficiency
3. `std::deque` vs. `std::vector`

Sequence containers store elements of a particular type in an ordered fashion

Stanford vs. STL vector: a summary

What you want to do	Stanford `Vector<int>`	`std::vector<int>`
Create an empty vector	`Vector<int> v;`	`vector<int> v;`
Create a vector with n copies of zero	`Vector<int> v(n);`	`vector<int> v(n);`
Create a vector with n copies of a value k	`Vector<int> v(n, k);`	`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();`
Get the element at index i (* does not bounds check!)	`int k = v.get(i);` `int k = v[i];`	`int k = v.at(i);` `int k = v[i]; (*)`
Check if the vector is empty	`if (v.isEmpty()) ...`	`if (v.empty()) ...`
Replace the element at index i (* does not bounds check!)	`v.get(i) = k;` `v[i] = k;`	`v.at(i) = k;` `v[i] = k; (*)`

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Add k to the end of the vector	`v.add(k);`	`v.push_back(k);`
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What’s missing on this chart?

What you want to do	Stanford `Vector<int>`	`std::vector<int>`
Create an empty vector	`Vector<int> v;`	`vector<int> v;`
Create a vector with n copies of zero	`Vector<int> v(n);`	`vector<int> v(n);`
Create a vector with n copies of a value k	`Vector<int> v(n, k);`	`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();`
Get the element at index i (* does not bounds check!)	`int k = v.get(i);` `int k = v[i];`	`int k = v.at(i);` `int k = v[i]; (*)`
Check if the vector is empty	`if (v.isEmpty()) ...`	`if (v.empty()) ...`
Replace the element at index i (* does not bounds check!)	`v.get(i) = k;` `v[i] = k;`	`v.at(i) = k;` `v[i] = k; (*)`

operator[] does not perform bounds checking

You'll see operator[] used, but rarely will you see at().

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

Stanford vs. STL vector: a summary

What you want to do	Stanford `Vector<int>`	`std::vector<int>`
Add j to the front of the vector	`v.insert(0, k);`	`v.insert(v.begin(), k);`
Insert k at some index i	`v.insert(i, k);`	`v.insert(v.begin()+i, k);`
Remove the element at index i	`v.remove(i);`	`v.erase(v.begin()+i);`
Get the sublist in indices [i, j)	`v.subList(i, j);`	`vector<int> c (v.begin()+i,v.begin()+j);`
Create a vector that is two vectors appended together.	`vector<int> v = v1 + v2;`	`// kinda complicated`

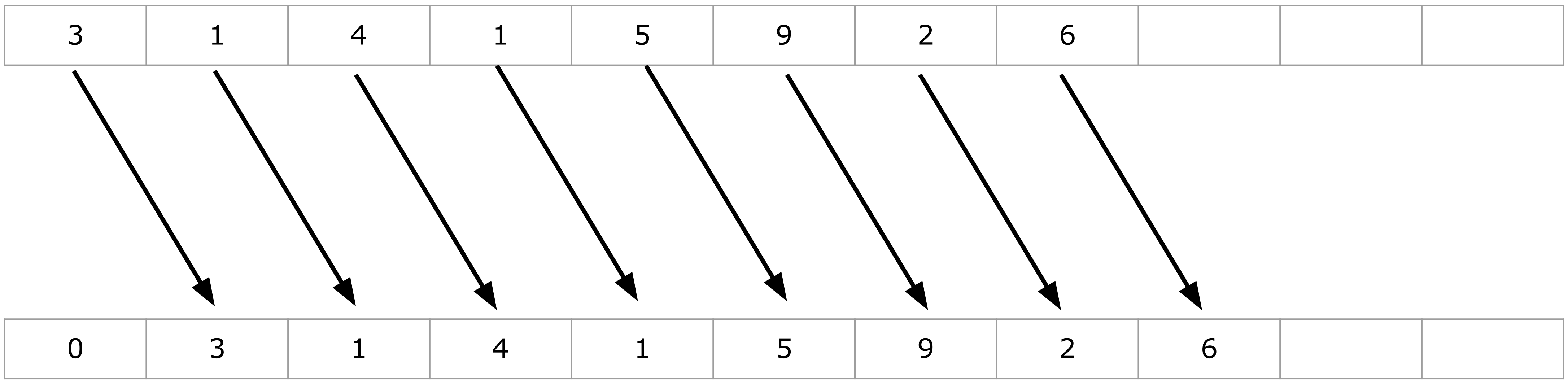
This'll require understanding **iterators**. Next lecture!

🤔 Questions? 🤔

Live Code Demo:

InsertionSpeed

`std::vector` does not have a `push_front` function



`std::vector` does not have a `push_front` function

vector does not have a push_front function

```
v.push_front(0);                // not a real function
```

Recurring C++ pattern: don't provide functions which

might be mistaken to be efficient when it's not.

🤔 Questions? 🤔

What if you really wanted fast insertion to the front?

std::deque provides fast insertion anywhere

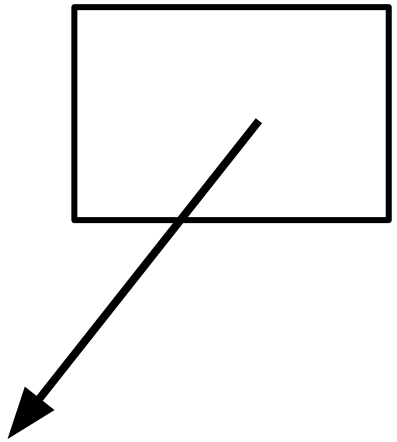
`std::deque` has the exact same functions as `std::vector` but also has `push_front` and `pop_front`.

```
std::deque<int> deq{5, 6};      // {5, 6}
deq.push_front(3);              // {3, 5, 6}
deq.pop_back();                // {3, 5}
deq[1] = -2;                    // {3, -2}
```

Live Code Demo:
DequeSpeed and VecDeqSpeed

How is a vector implemented?

how is a `std::vector` implemented?



Internally, a `std::vector` consists of an fixed-size array. The array is automatically resized when necessary. (C++ arrays will be discussed in the second half of CS 106B)

size = number of elements in the vector

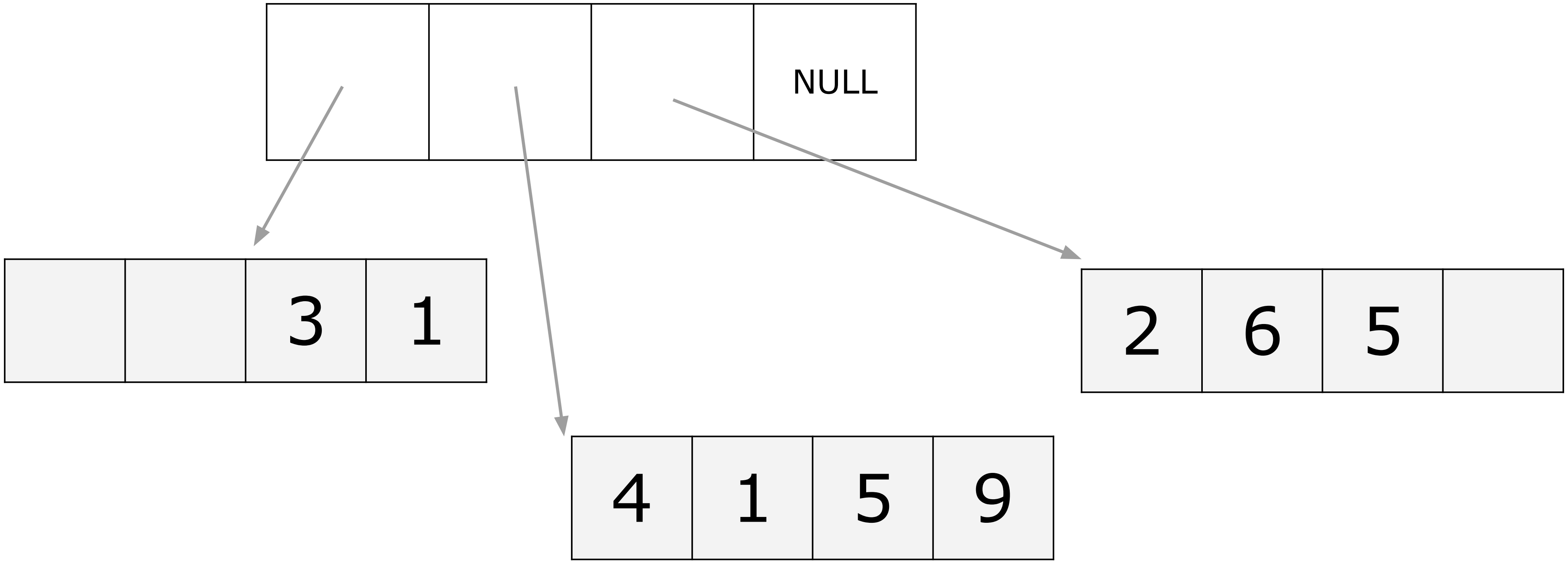
capacity = amount of space saved for the vector

0	3	1	4	1	5	9	2	6		

How is a deque implemented?

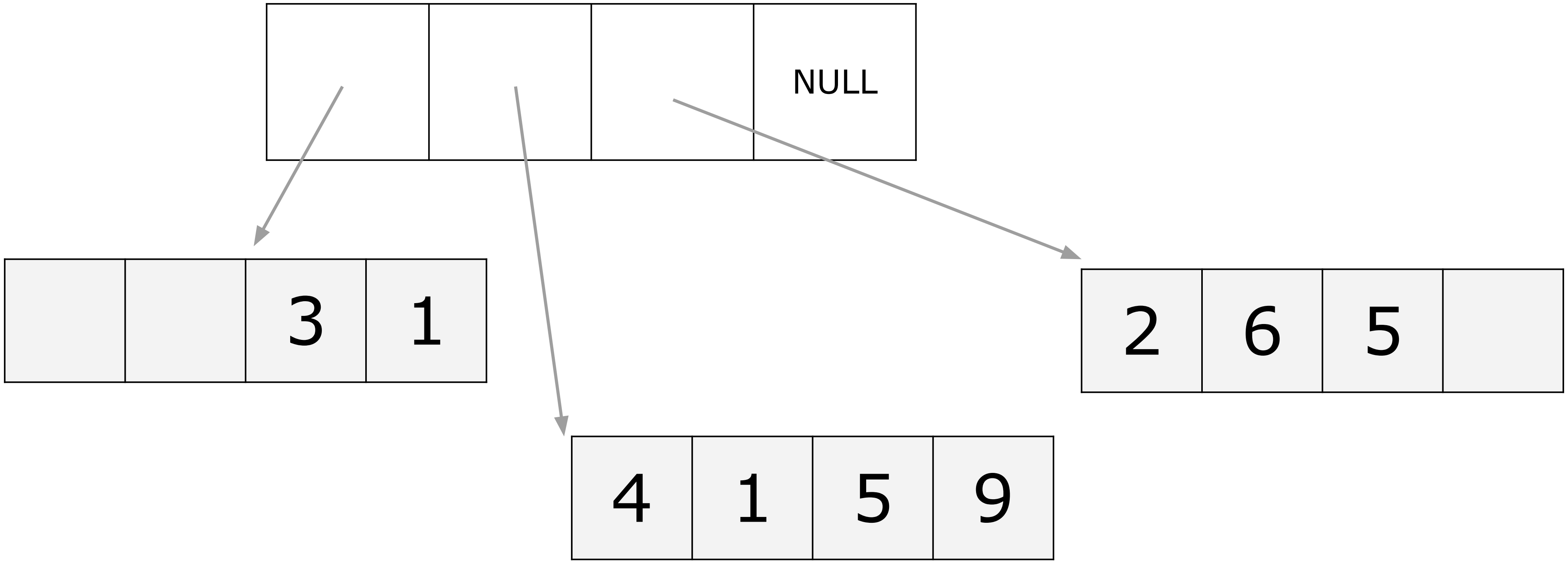
How does `std::deque<T>` work?

There is no single specific implementation of a deque, but one common one might look like this:



How does `std::deque<T>` work?

How would you do `push_back(3)`?



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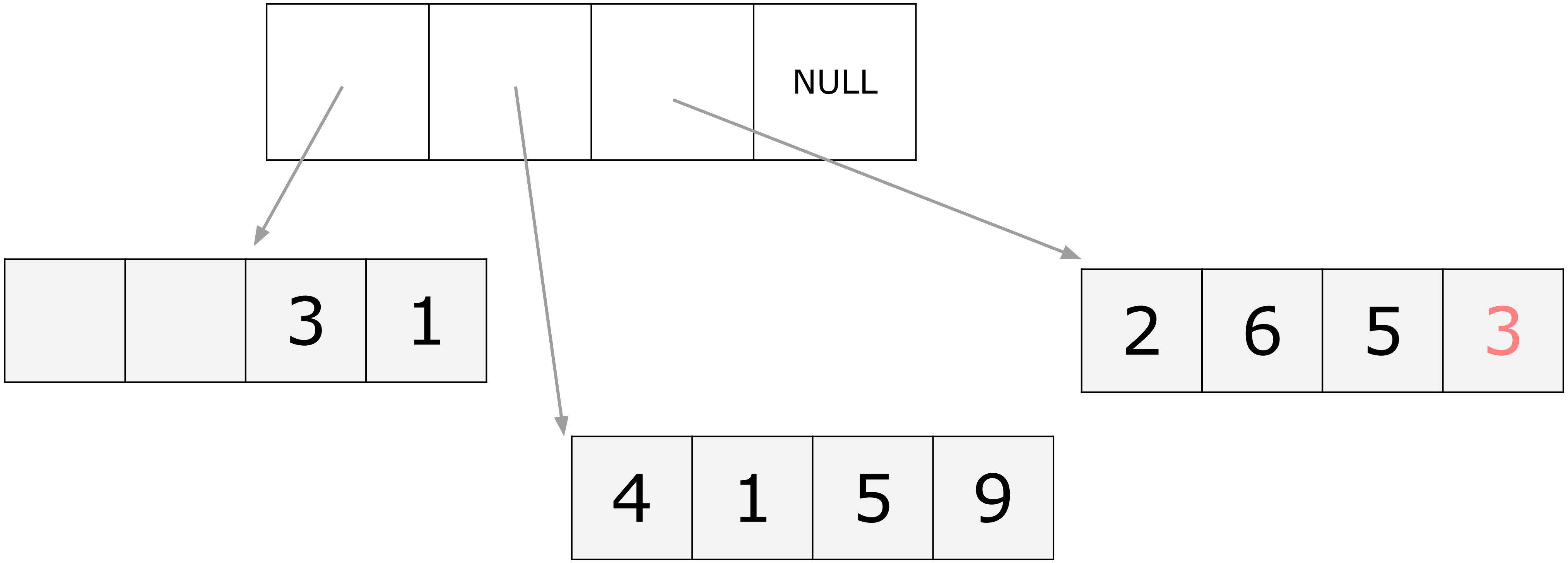

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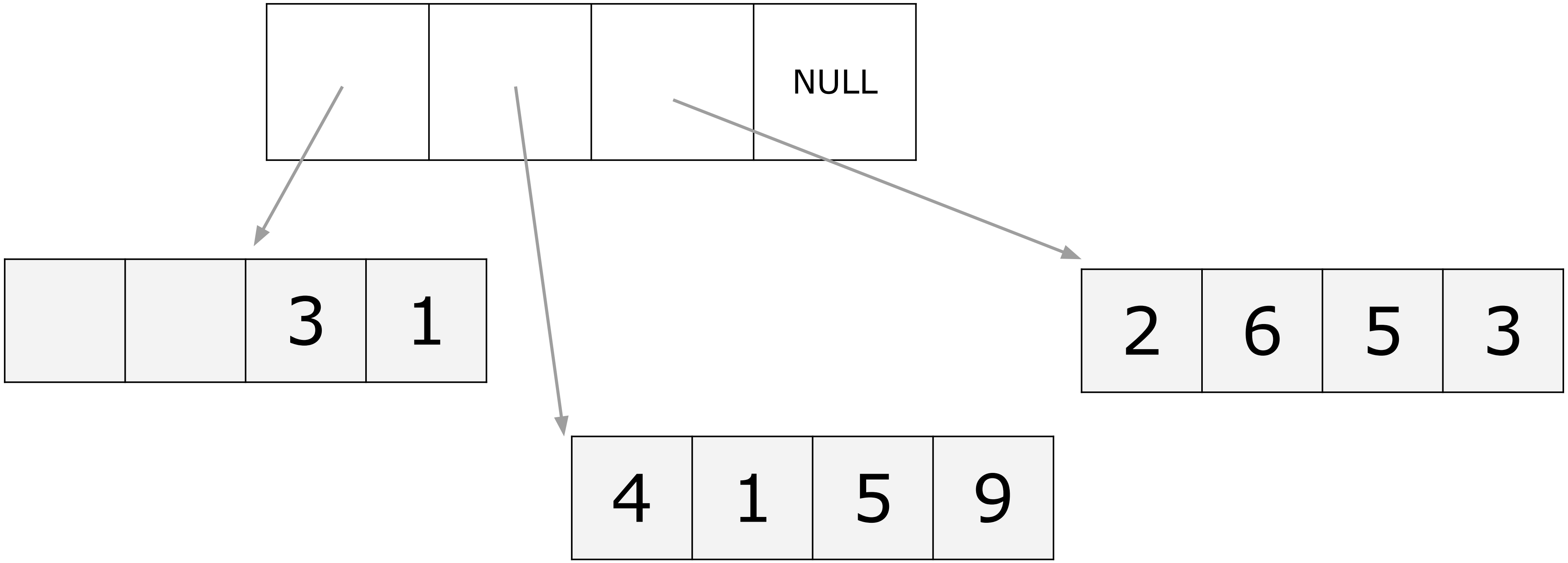

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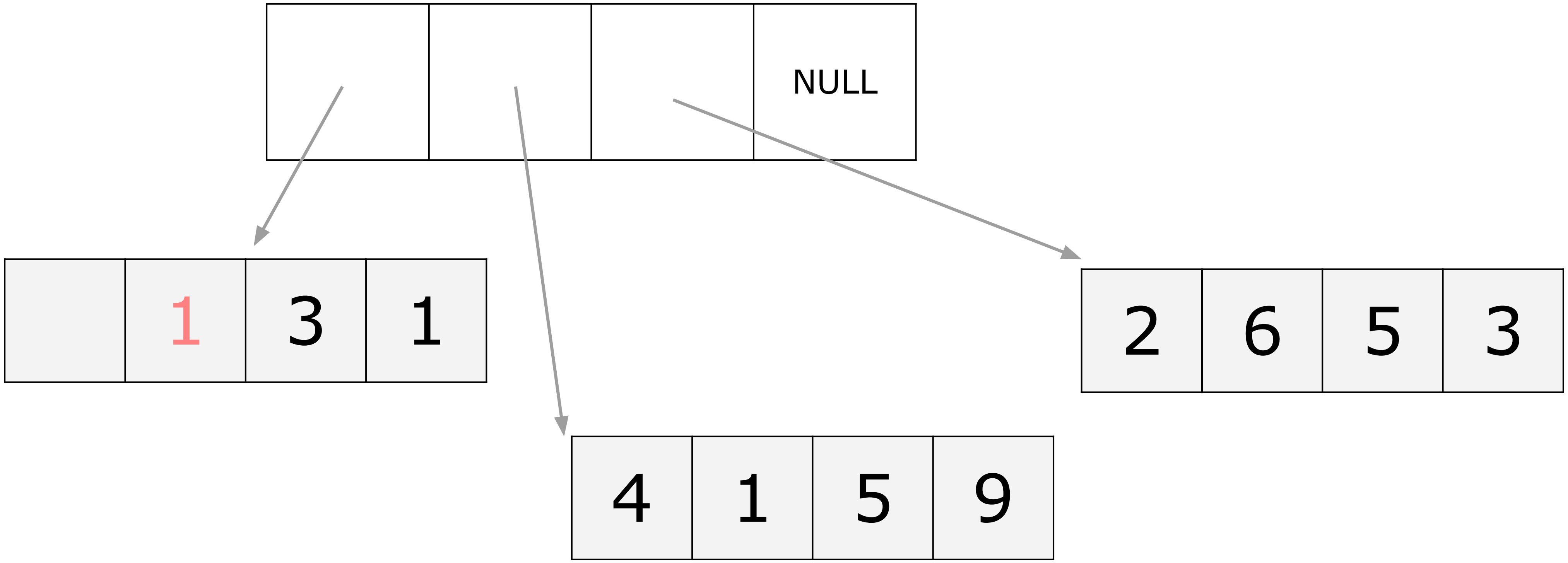
How would you do `push_front(1)`?



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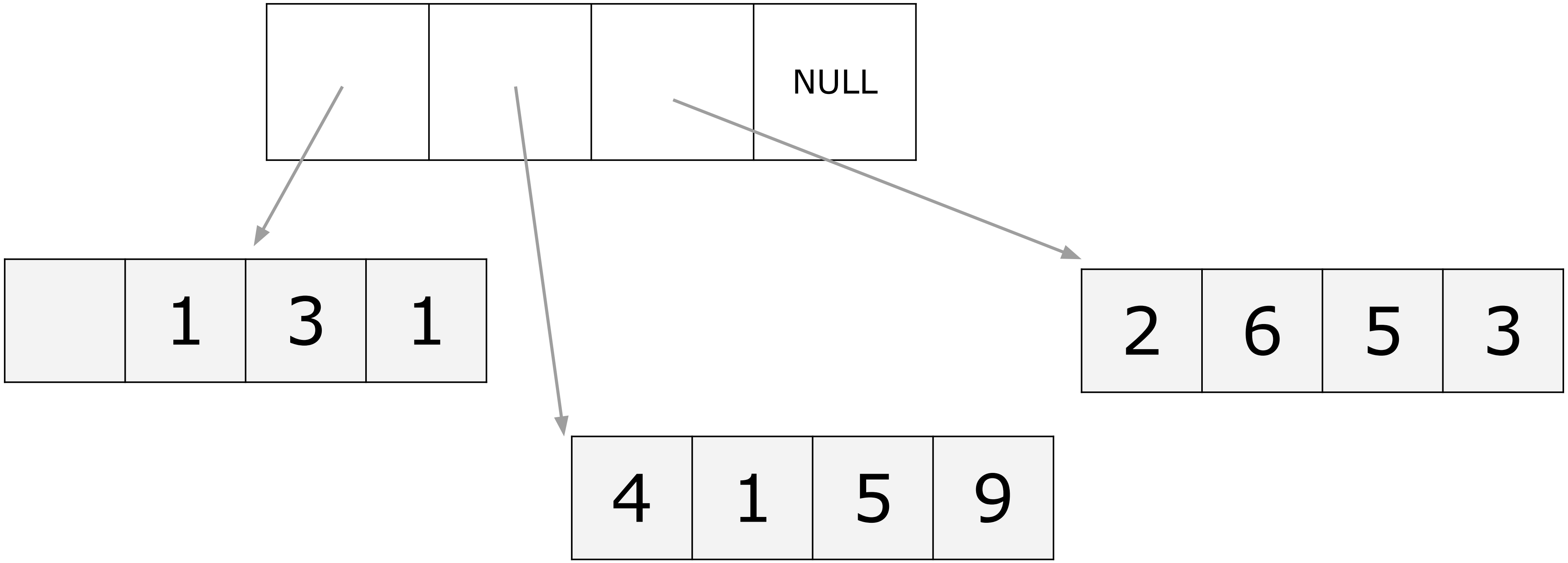
How would you do `push_back(7)`?



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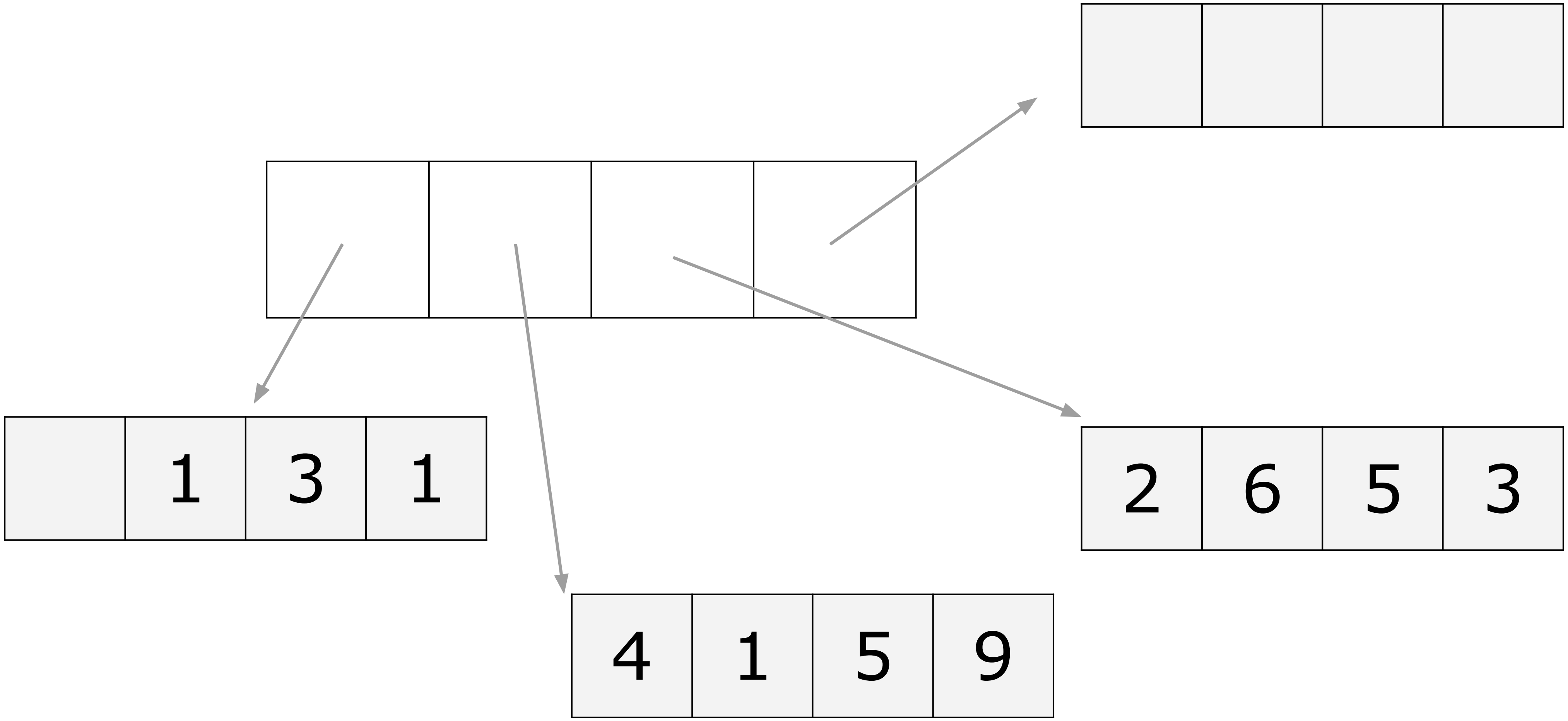

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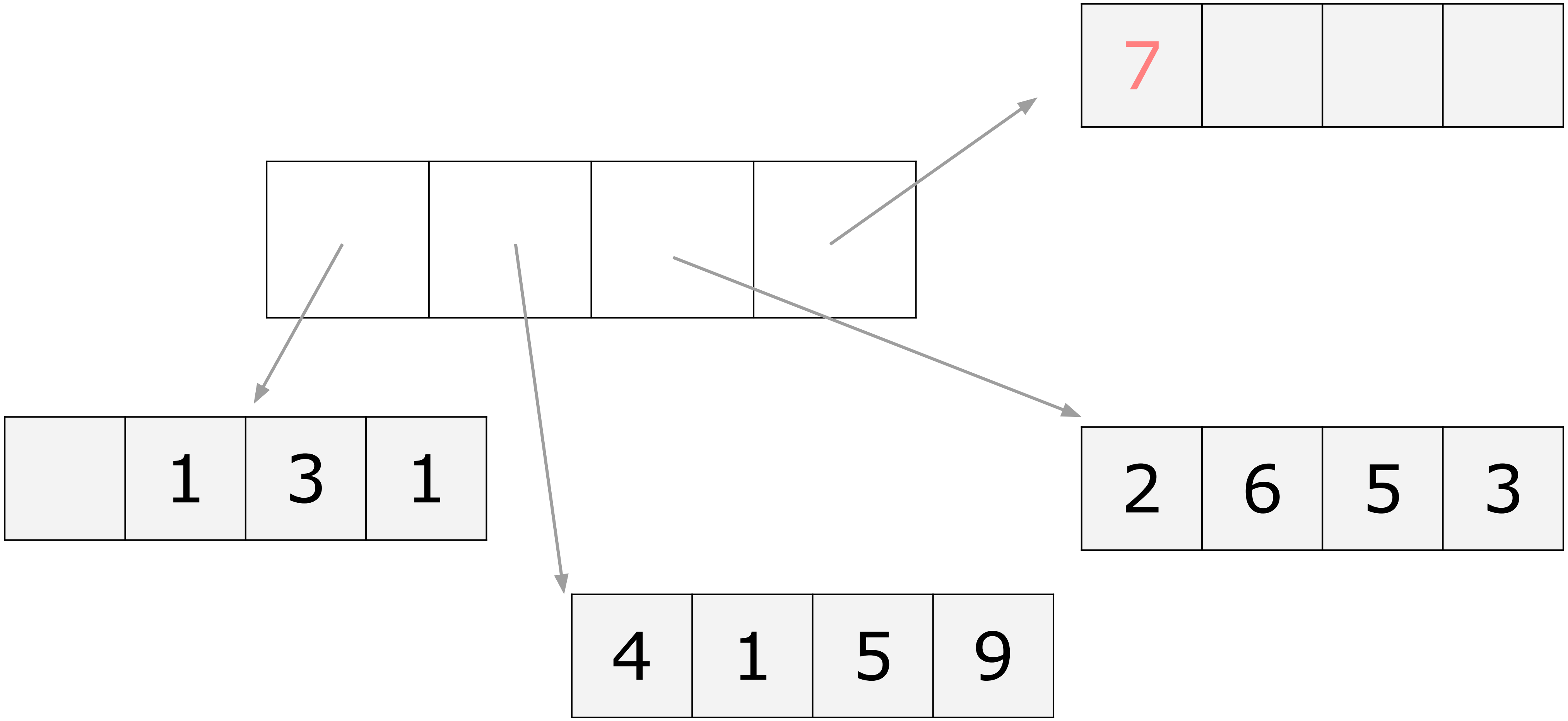
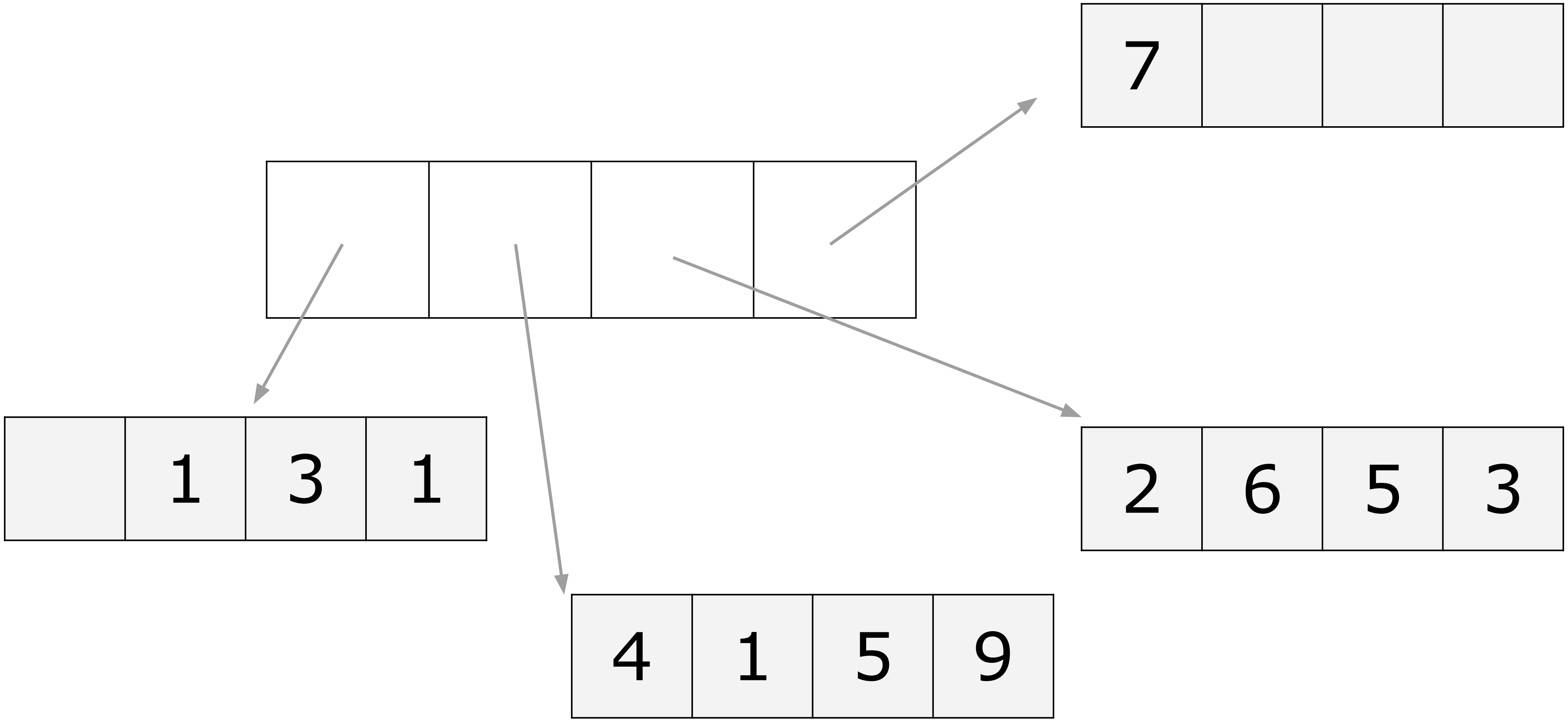
How would you do `push_back(7)`?



How does `std::deque<T>` work?

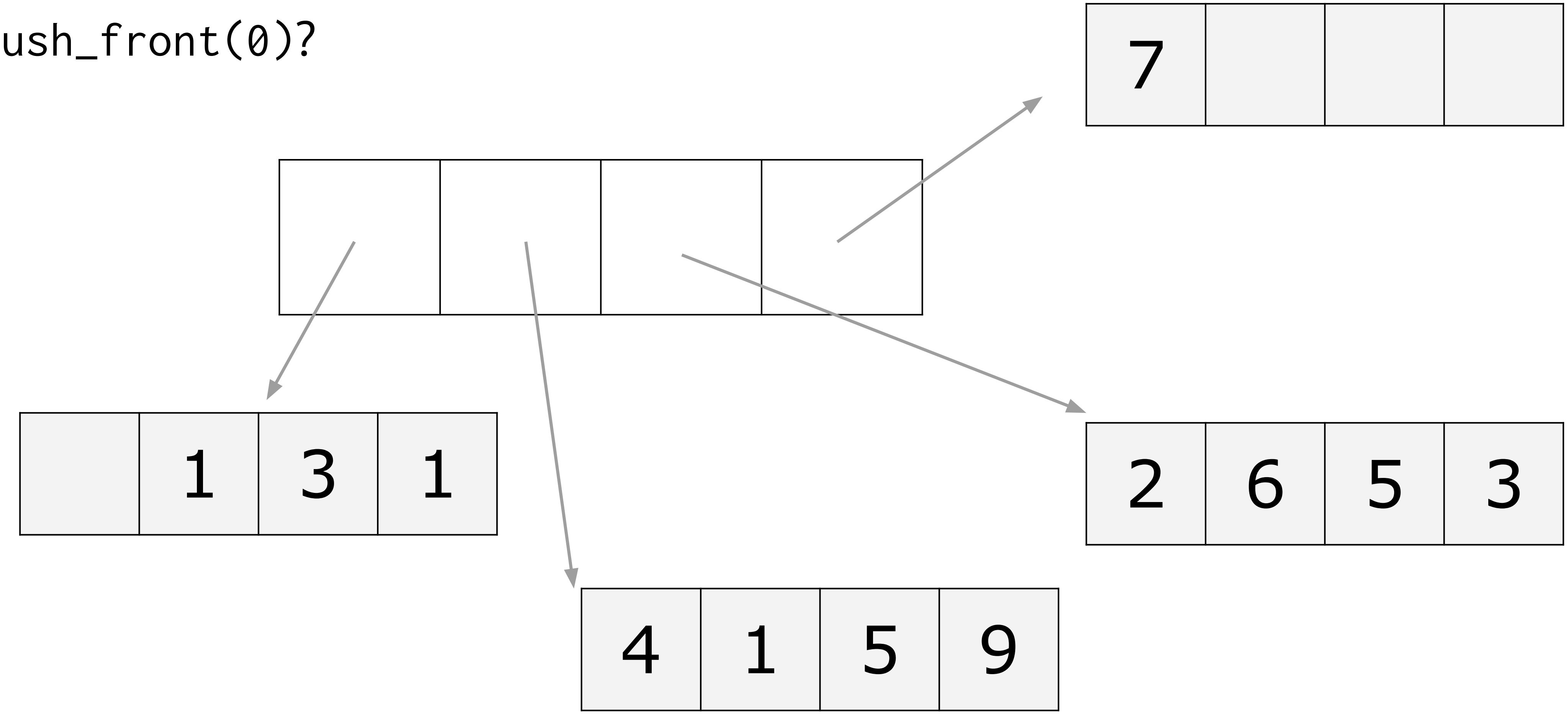
How would you do `push_back(7)`?



How does `std::deque<T>` work?

How would you do `push_front(8)`

then `push_front(0)`?



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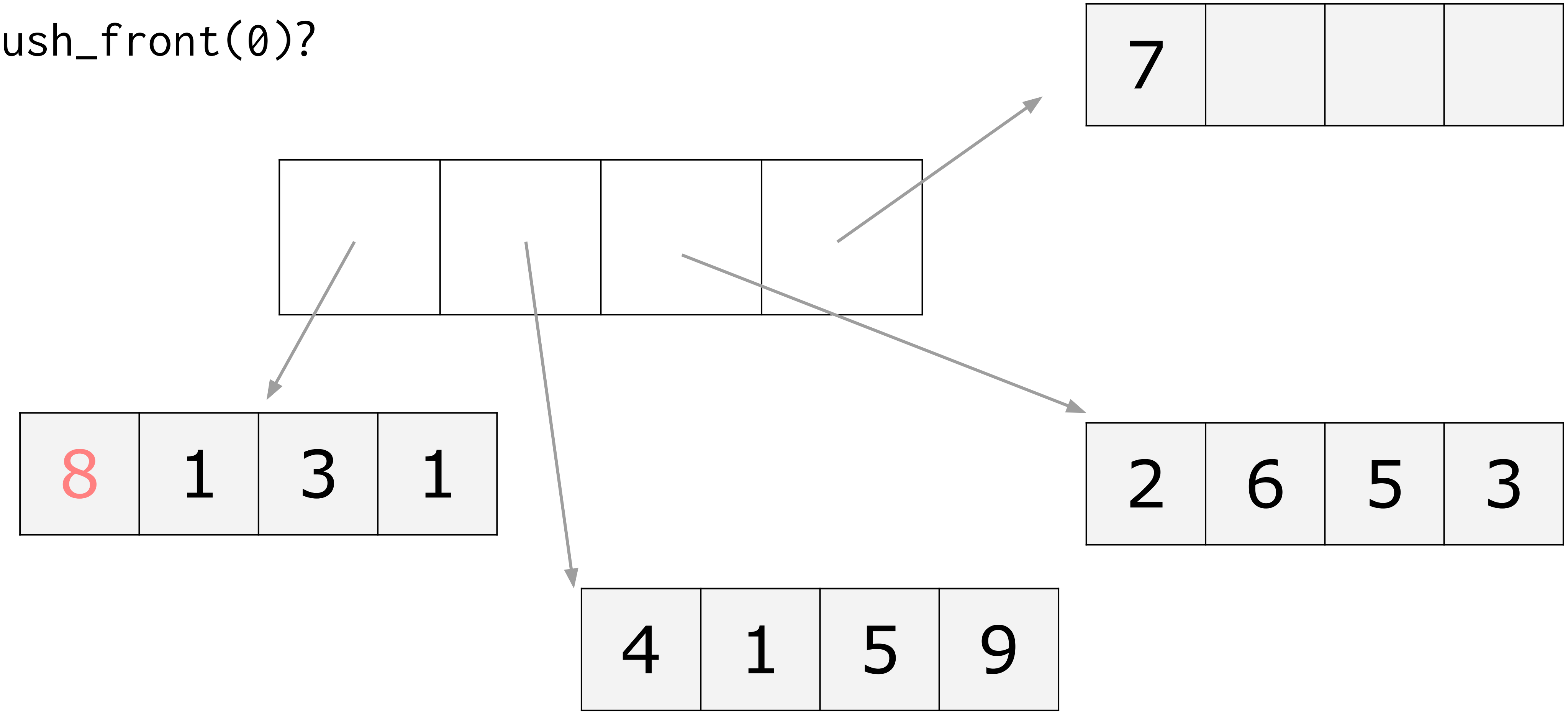
How would you do `push_front(8)`

then `push_front(0)`?



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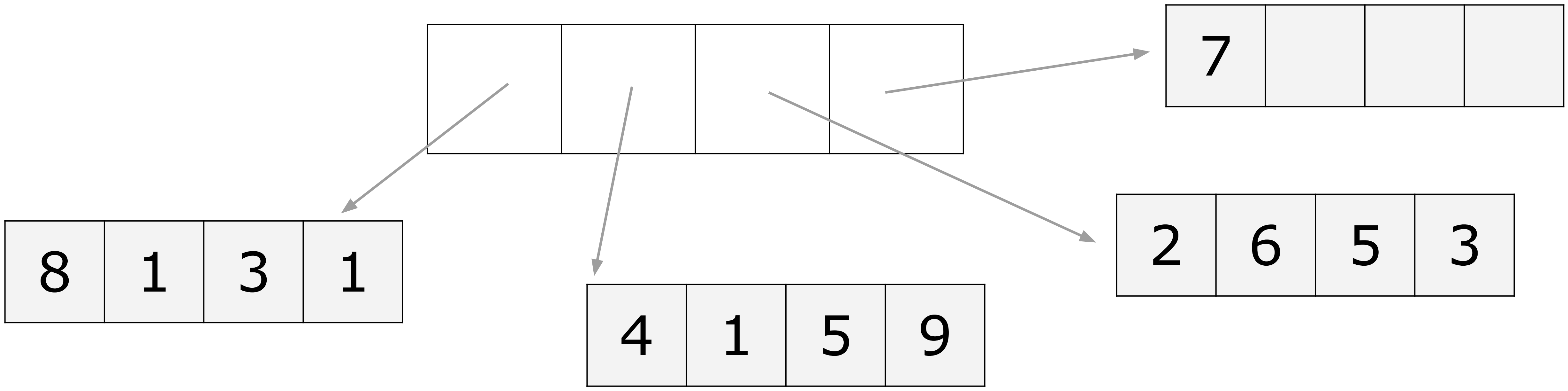
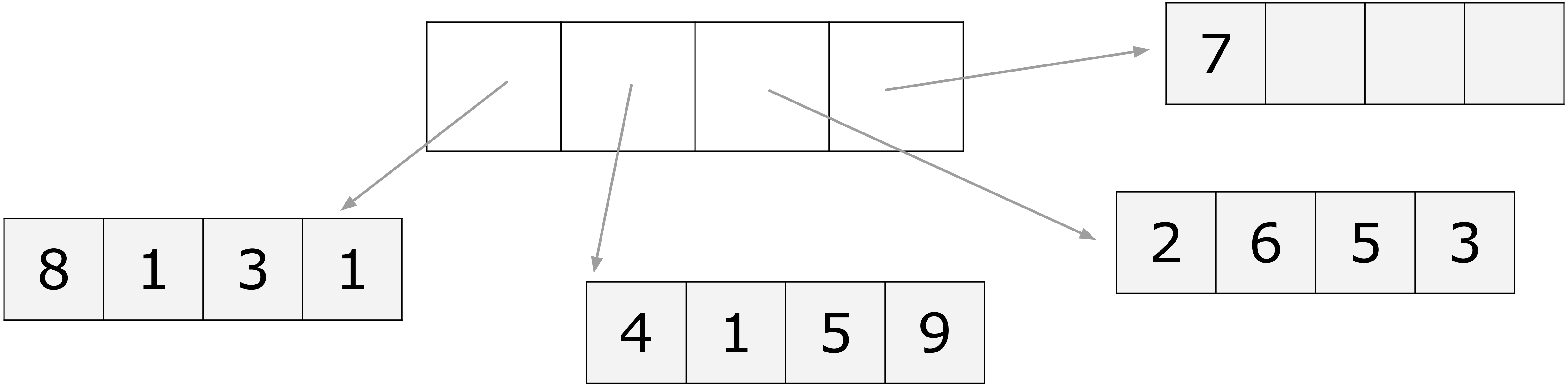


Supplemental Material

How does `std::deque<T>` work?

NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL



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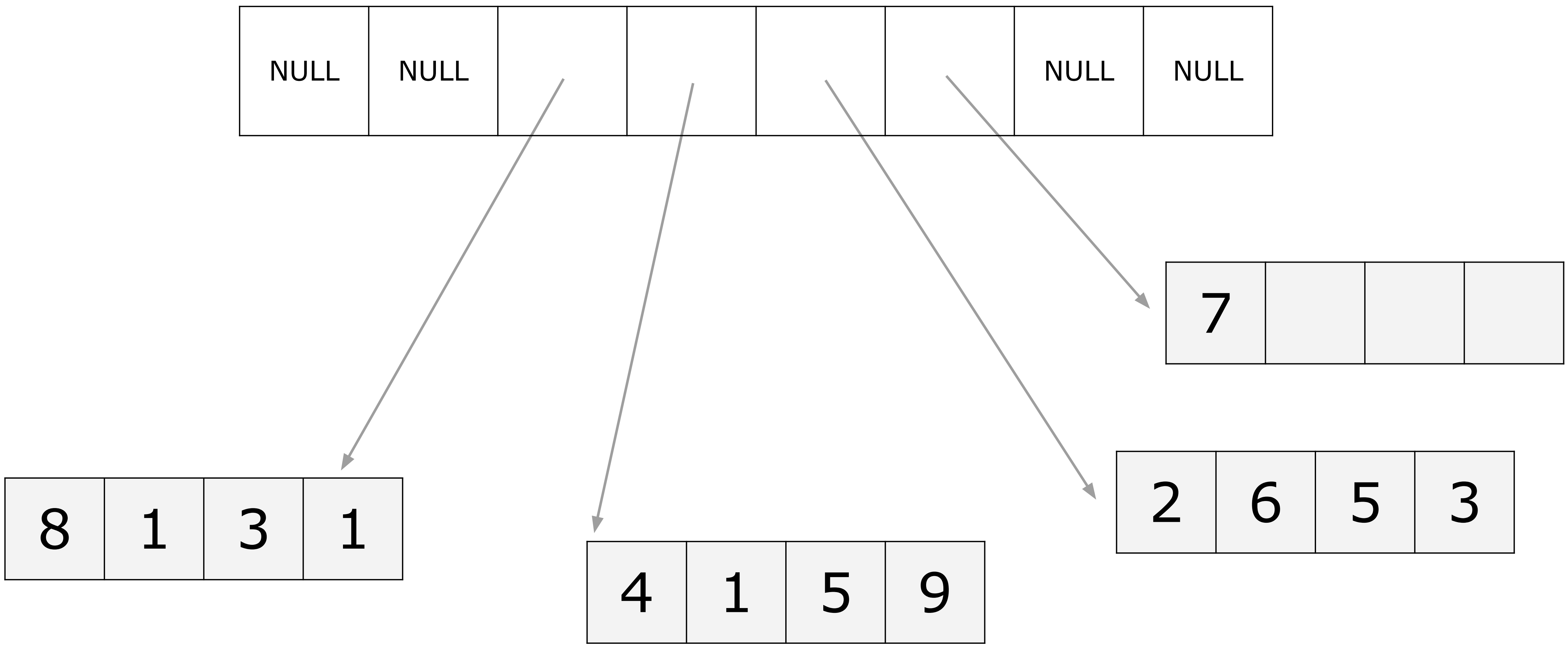

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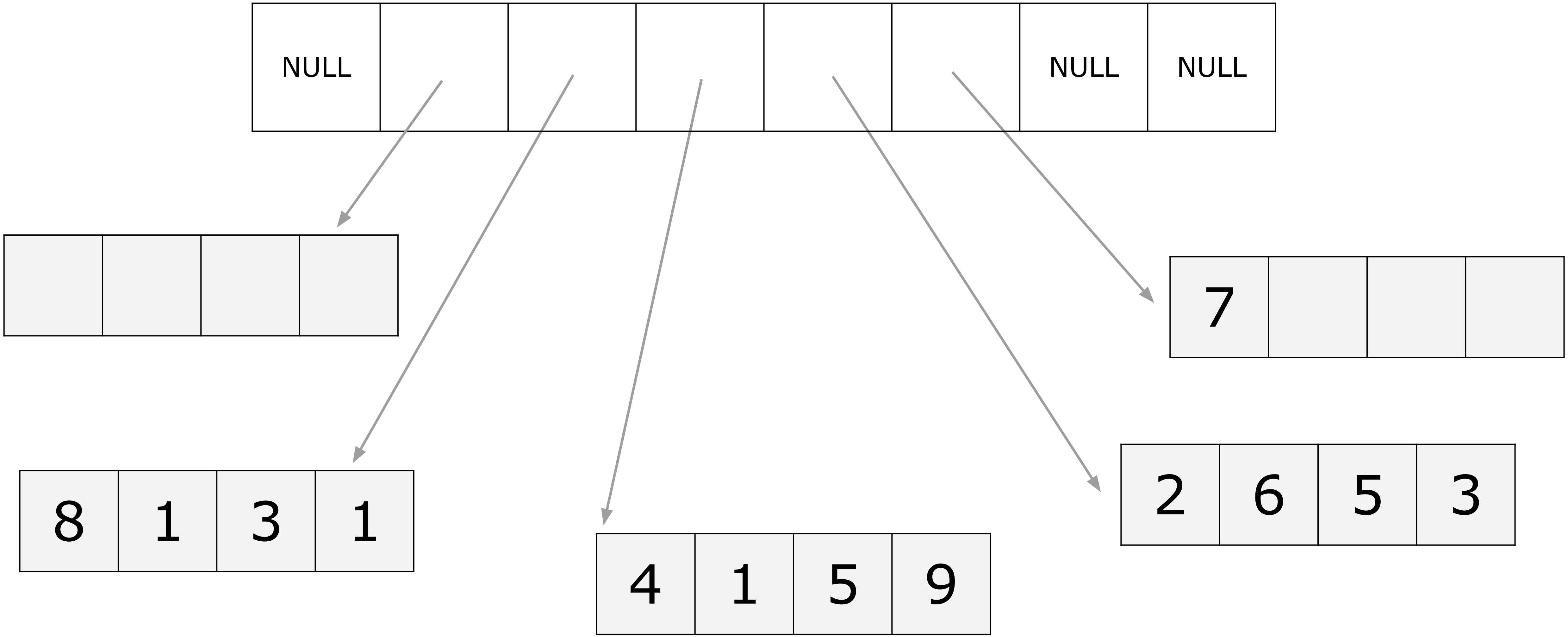

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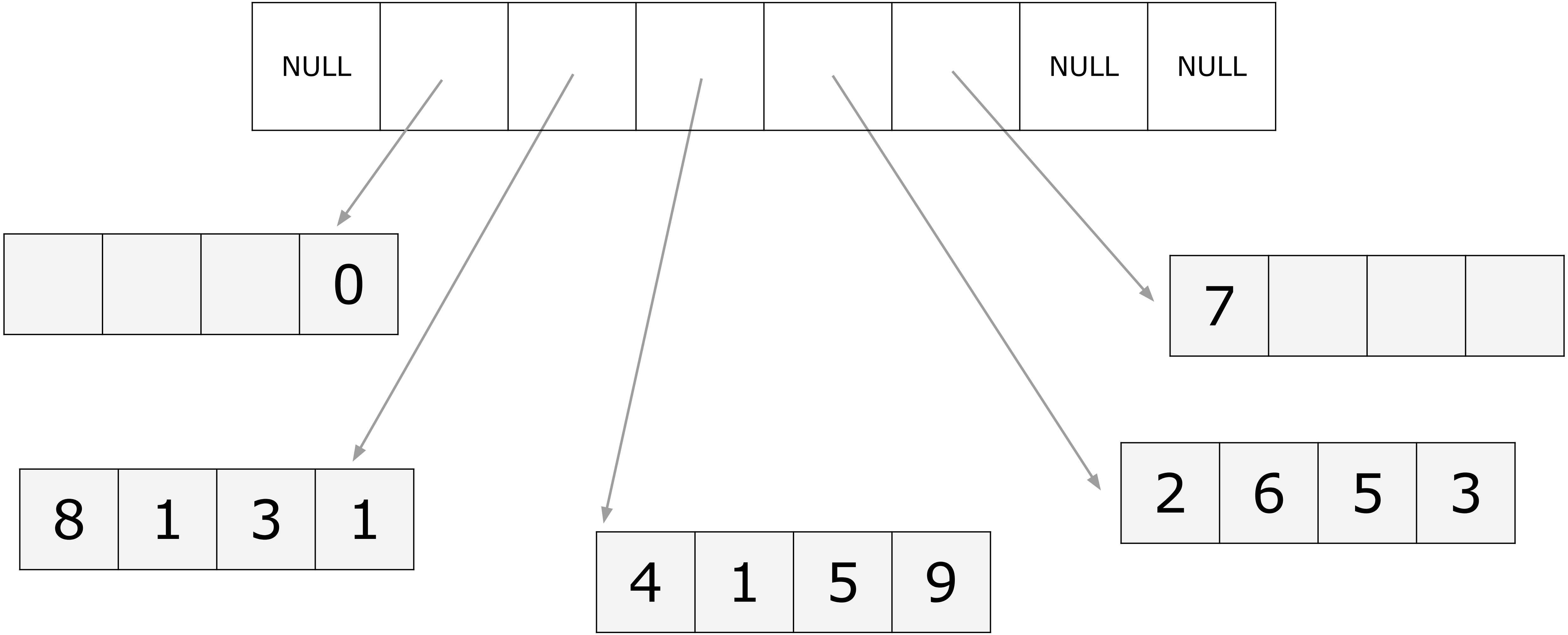
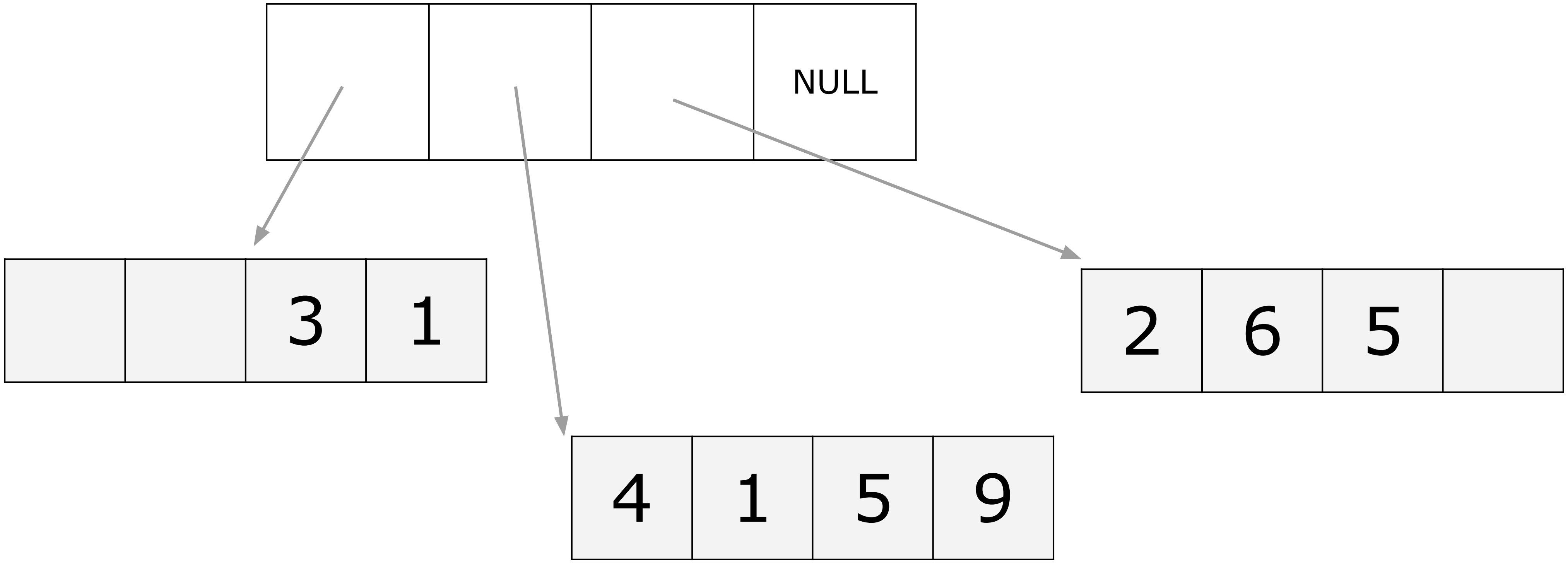


How does `std::deque<T>` work?

Difficult question that we won't answer in class:

How fast is inserting? Is it better of worse than a `std::vector<T>`?



std::list is kinda like std::stack + std::queue

`std::list` provides fast insertion anywhere in the sequence given an iterator pointing to that location, but you can't index into it like you can for a `std::deque` or `std::vector`

```
std::list<int> list{5, 6};      // {5, 6}
list.push_front(3);
list.pop_back(4);
```

Sidenote: usually a doubly-linked list. There's also a forward_list that's a singly-linked list. Linked lists will be covered at the end of 106B, so don't fret if you don't understand this sidenote at ll!

When to use which sequence container?

	`std::vector`	`std::deque`	`std::list`
Indexed Access	Super Fast	Fast	Impossible
Insert/remove front	Slow	Fast	Fast
Insert/remove back	Super Fast	Very Fast	Fast
Ins/rem elsewhere	Slow	Fast	Very Fast
Memory	Low	High	High
Splicing/Joining	Slow	Very Slow	Fast
Stability * (Iterators, concurrency)	Poor	Very Poor	Good

Sidenote: color-wise vector might not look great, but remember that indexed access and inserting to the back are the most common uses of sequence containers.

* Don't worry if you have no idea what we mean by Stability here. This is a fairly advanced concept, and we may (or may not) introduce it later in the course.

🤔 Questions? 🤔

Summary of Sequence Containers

- vector: use for most purposes
- deque: frequent insert/remove at front
- list: very rarely - if need splitting/joining

best practices: if possible, reserve before insert

What's the best way to create a vector of the first 1,000,000 integers?

```
std::vector<int> vec;

for (size_t i = 0; i < 1000000; ++i) {
  vec.push_back(i);
}
```

Problem: internally the array is resized and copied many times.

best practices: if possible, reserve before insert

What's the best way to create a vector of the first 1,000,000 integers?

```
std::vector<int> vec;
vec.reserve(1000000);
for (size_t i = 0; i < 1000000; ++i) {
  vec.push_back(i);
}
```

Problem: internally the array is resized and copied many times.

Other best practices that we won't go over.

- Consider using shrink_to_fit if you don't need the memory.
- Call empty(), rather than check if size() == 0.
- Don't use vector<bool> ("noble failed experiment")
- A ton of other stuff after we talk about iterators!

- If curious, ask us on Piazza :)!

Summary of Supplemental Material

It's easy to write inefficient code.

Know about the common pitfalls - prevent as much resizing as much as possible.

Container Adaptors

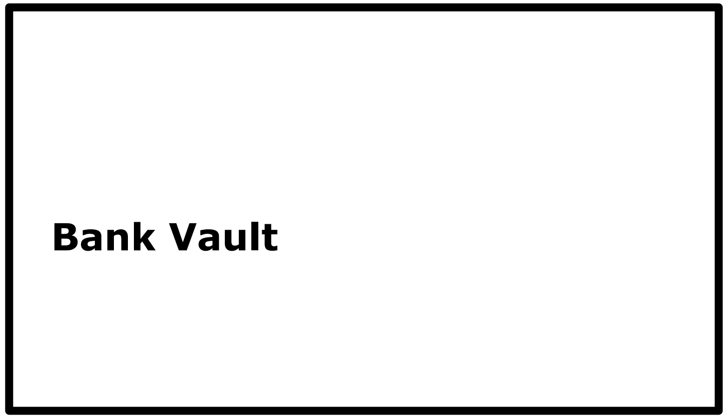
1. What is a container adaptor?
2. `std::stack` and `std::queue`

What is a wrapper (in general)?

- A wrapper for an object changes how external users can interact with that object.

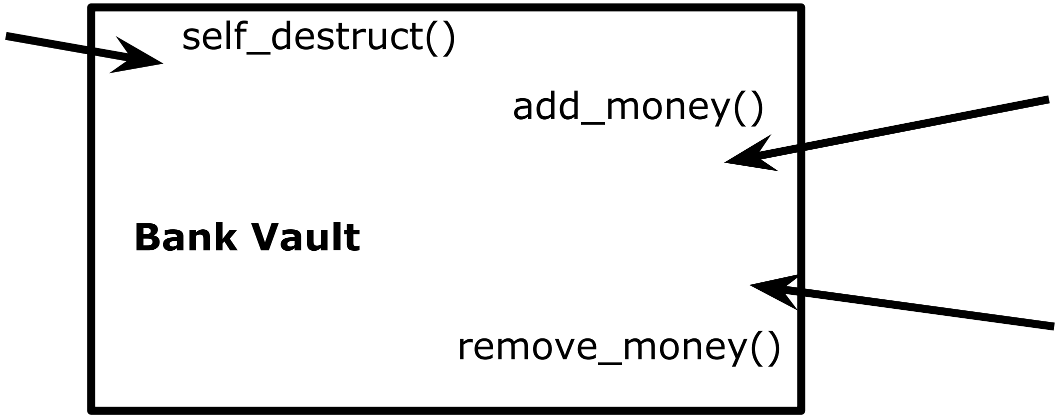
What is a wrapper (in general)?

- Here is a bank vault.



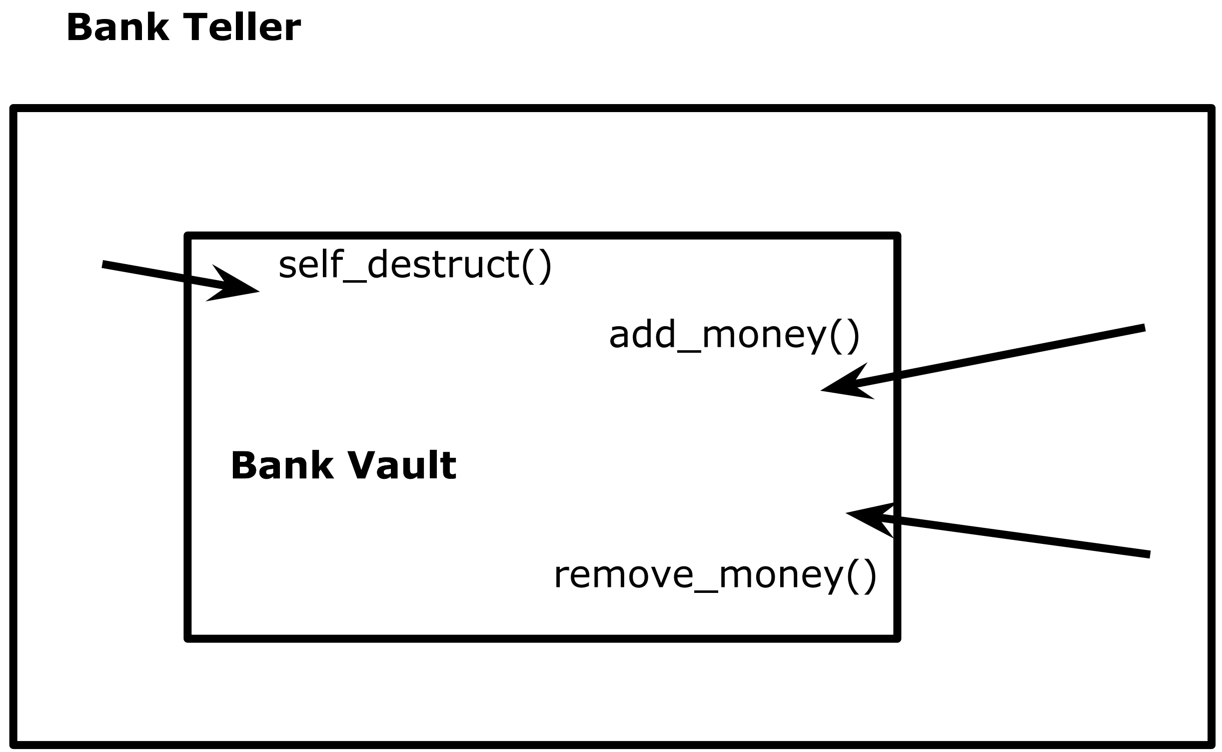
What is a wrapper (in general)?

- There are many ways you can interact with a bank vault. It would be bad if people outside the bank could interact in these manners freely.



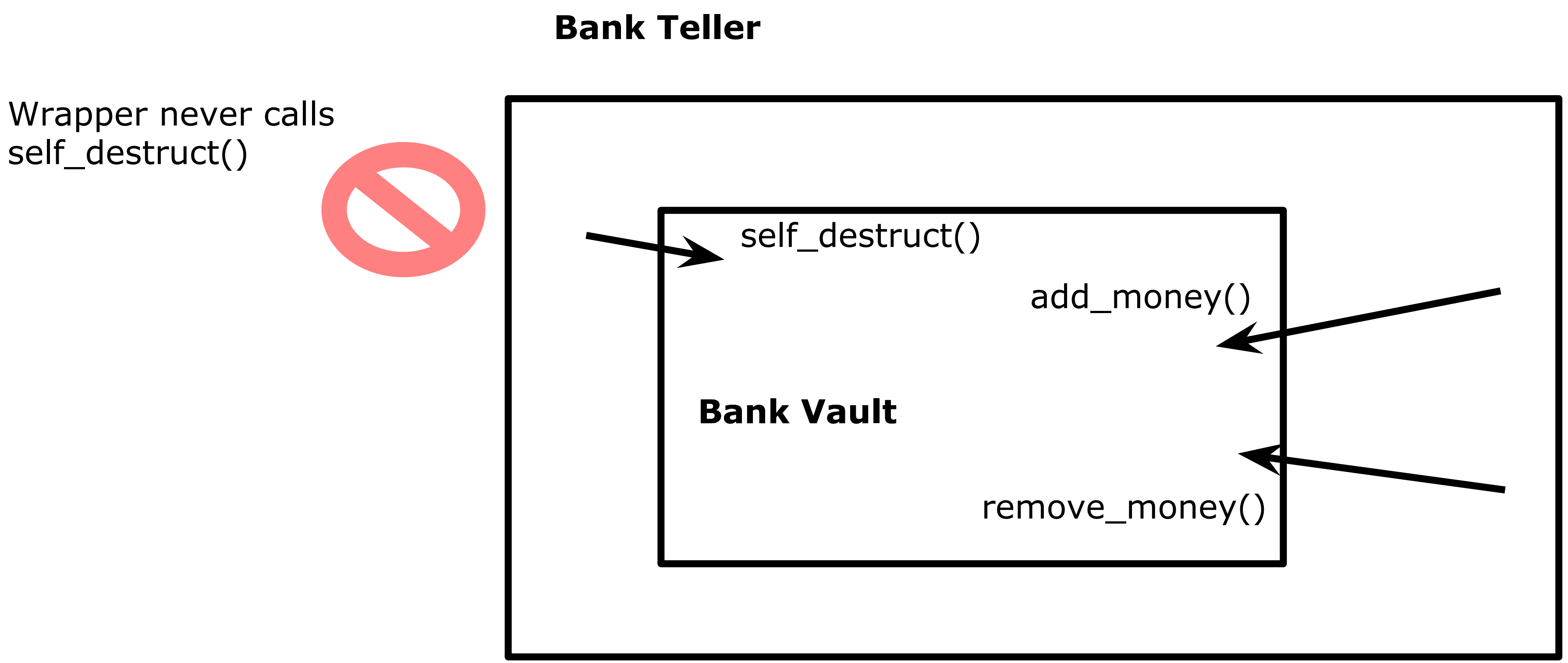
What is a wrapper (in general)?

- The bank teller limits your access to the money stored in the vault



What is a wrapper (in general)?

- The bank teller is in charge of forwarding your request to the actual bank vault itself



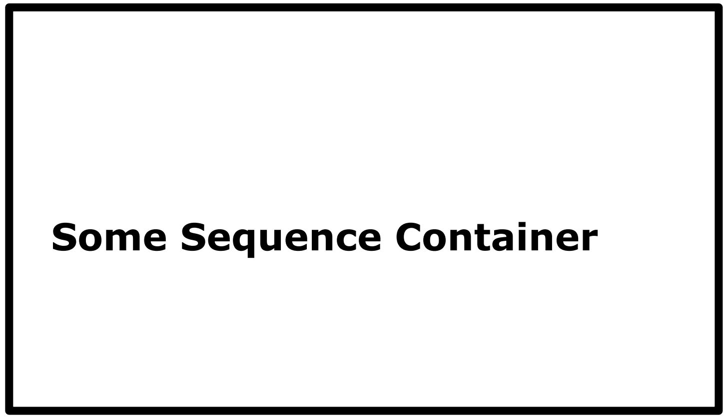
This is exactly what a wrapper in C++ does!

What’s a container adaptor?

- **Container adaptors** provide a different interface for sequence containers. You can choose what the underlying container is!

How do you design a stack?

- **Container adaptors** provide a different interface for sequence containers. You can choose what the underlying container is!



How do you design a stack?

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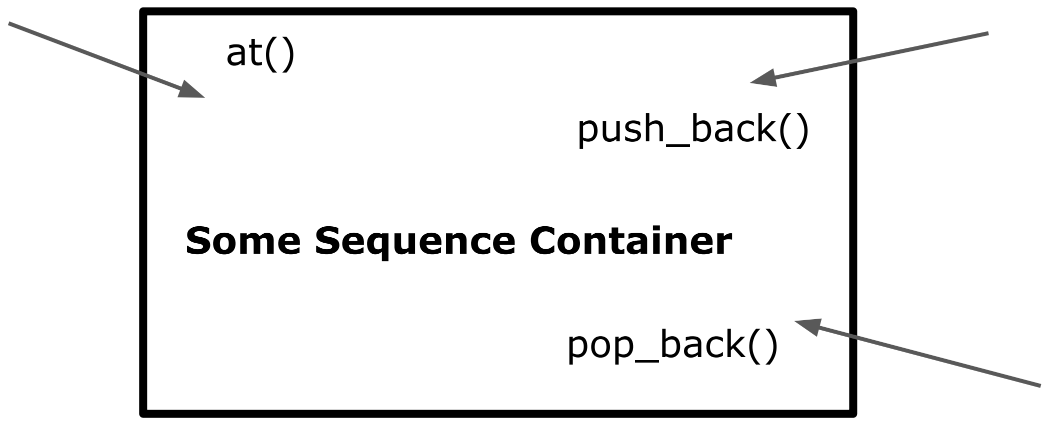

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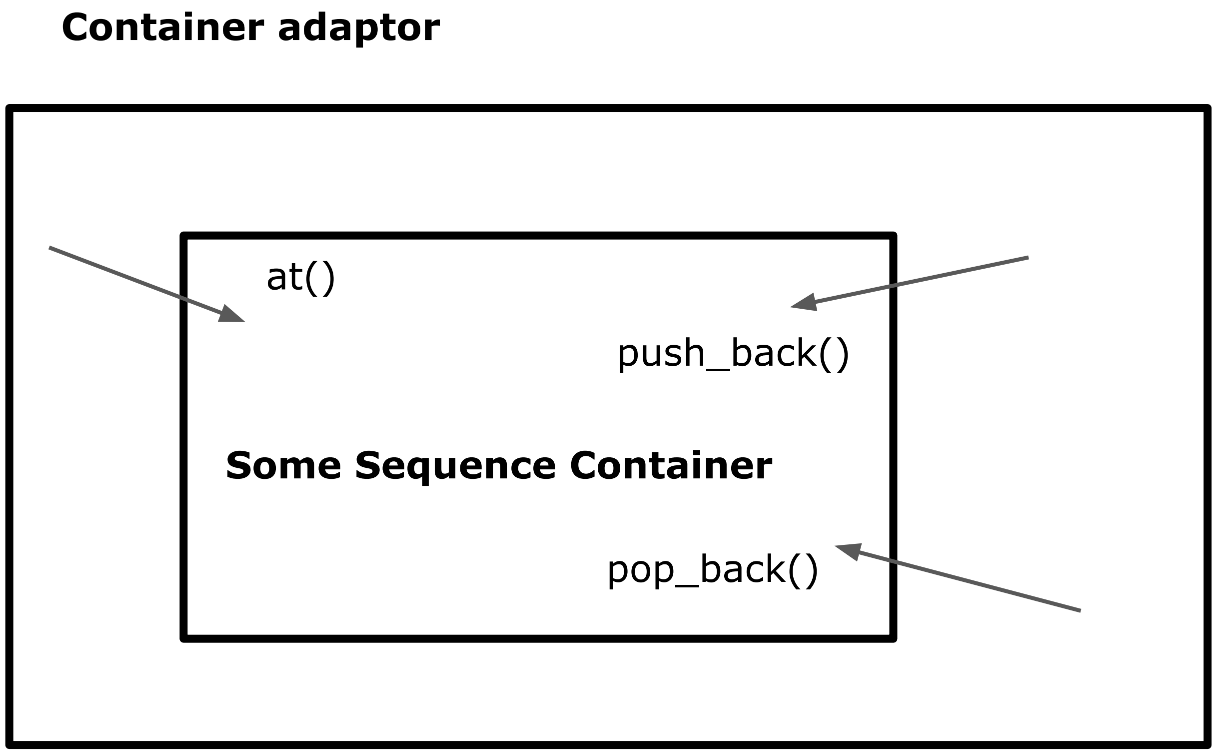

How do you design a stack?

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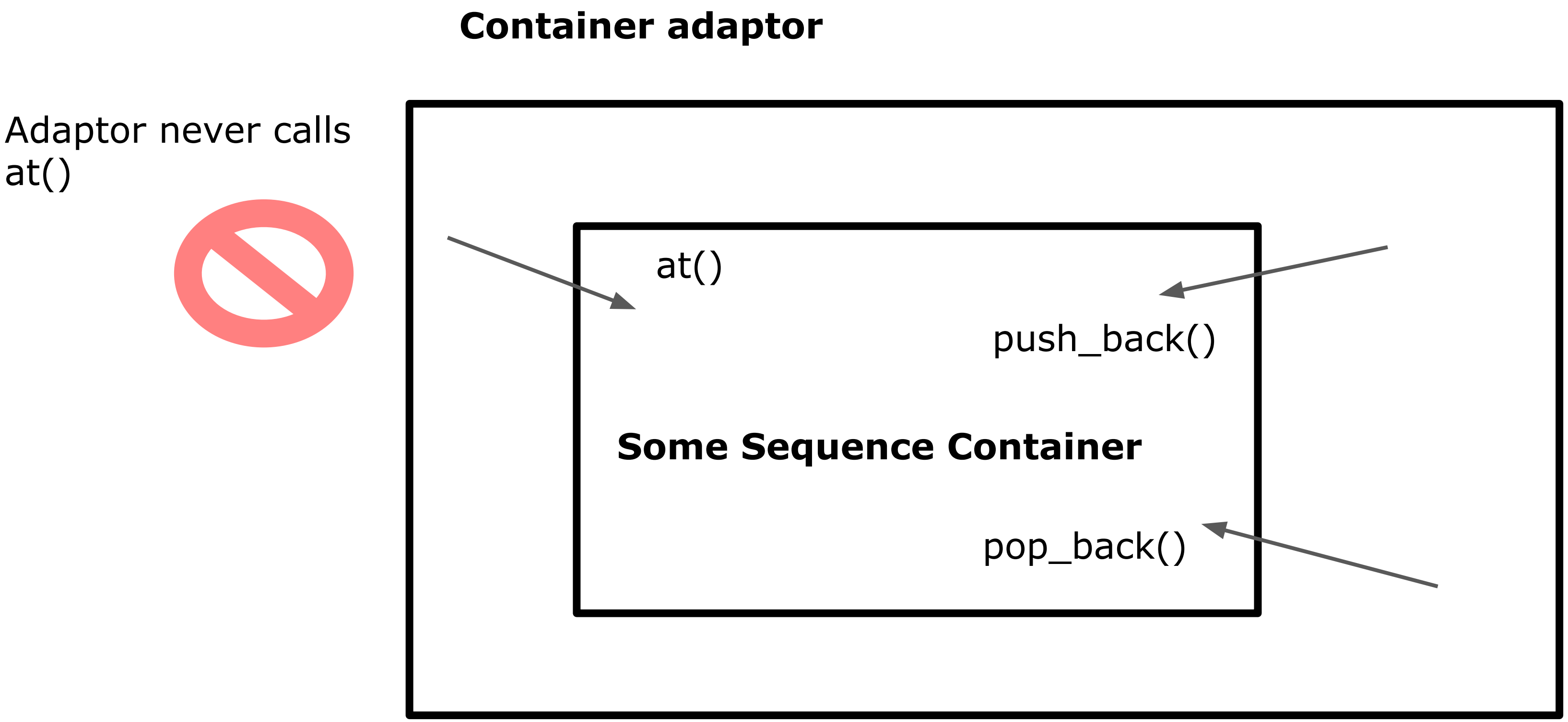

std::stack and std::queue

std::stack

Defined in header <stack>

```
template<
    class T,
    class Container = std::deque<T>
> class stack;
```

The `std::stack` class is a container adapter that gives the programmer the functionality of a stack - specifically, a LIFO (last-in, first-out) data structure.

The class template acts as a wrapper to the underlying container - only a specific set of functions is provided. The stack pushes and pops the element from the back of the underlying container, known as the top of the stack.

std::queue

Defined in header <queue>

```
template<
    class T,
    class Container = std::deque<T>
> class queue;
```

The `std::queue` class is a container adapter that gives the programmer the functionality of a queue - specifically, a FIFO (first-in, first-out) data structure.

The class template acts as a wrapper to the underlying container - only a specific set of functions is provided. The queue pushes the elements on the back of the underlying container and pops them from the front.

Concrete Example

std::stack

Defined in header <stack>

```
template<
    class T,
    class Container = std::deque<T>
> class stack;
```

The `std::stack` class is a container adapter that gives the programmer the functionality of a stack - specifically, a LIFO (last-in, first-out) data structure.

The class template acts as a wrapper to the underlying container - only a specific set of functions is provided. The stack pushes and pops the element from the back of the underlying container, known as the top of the stack.

```
std::stack<int> stack_d;                       // Container = std::deque

std::stack<int, std::vector<int>> stack_v;     // Container = std::vector

std::stack<int, std::list<int>> stack_l;       // Container = std::list
```

Some member functions of std::stack

https://en.cppreference.com/w/cpp/container/stack

(constructor)	constructs the `stack` (public member function)
(destructor)	destructs the `stack` (public member function)
`operator=`	assigns values to the container adaptor (public member function)
Element access	
`top`	accesses the top element (public member function)
Capacity	
`empty`	checks whether the underlying container is empty (public member function)
`size`	returns the number of elements (public member function)
Modifiers	
`push`	inserts element at the top (public member function)
`emplace` (C++11)	constructs element in-place at the top (public member function)
`pop`	removes the top element (public member function)
`swap`	swaps the contents (public member function)

🤔 Questions? 🤔

You'll be using std::priority_queue for A1!

std::priority_queue

Defined in header <queue>

```
template<
    class T,
    class Container = std::vector<T>,
    class Compare = std::less<typename Container::value_type>
> class priority_queue;
```

A priority queue is a container adaptor that provides constant time lookup of the largest (by default) element, at the expense of logarithmic insertion and extraction.

A user-provided `Compare` can be supplied to change the ordering, e.g. using `std::greater<T>` would cause the smallest element to appear as the `top()`.

Working with a `priority_queue` is similar to managing a heap in some random access container, with the benefit of not being able to accidentally invalidate the heap.

One of the CS 106B assignments is basically to write this container adaptor.

Associative Containers

1. `std::set` functions
2. `std::map` functions and auto-insertion
3. type requirements

Stanford vs. STL set: a summary

What you want to do	Stanford `Set<int>`	`std::set<int>`
Create an empty set	`Set<int> s;`	`set<int> 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()) ...`

Stanford vs. STL set: a summary

What you want to do	Stanford Set<int>	std::set<int>
Create an empty set	Set<int> s;	set<int> 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()) ...

Stanford vs. STL map: a summary

What you want to do	Stanford `Map<int, char>`	`std::map<int, char>`
Create an empty map	`Map<int, char> m;`	`map<int, char> 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 (error if does not exist)	`Impossible` `(put does auto-insert)`	`char c = m.at(k);` `m.at(k) = v;`
Retrieve or overwrite value associated with key k (auto-insert if DNE)	`char c = m[k];` `m[k] = v;`	`char c = m[k];` `m[k] = v;`

Stanford vs. STL map: a summary

What you want to do	Stanford `Map<int, char>`	`std::map<int, char>`
Create an empty map	`Map<int, char> m;`	`map<int, char> 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 (error if does not exist)	`Impossible` `(put does auto-insert)`	`char c = m.at(k);` `m.at(k) = v;`
Retrieve or overwrite value associated with key k (auto-insert if DNE)	`char c = m[k];` `m[k] = v;`	`char c = m[k];` `m[k] = v;`

STL maps stores std::pairs.

The underlying type stored in a

`std::map<K, V>`

is a

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

sidenote: why is the key const? You should think about this, and you'll need a good answer when A2 rolls around.

Stanford/STL sets + maps require comparison operator

By default, the type (for sets) or key-type (for maps) must have a comparison (<) operator defined

(There is an alternative that we will cover in ~2 lectures)

```
std::set<int> set1;     // OKAY - comparable
std::set<std::ifstream> set2;          // ERROR - not comparable


std::map<int, int> map1;     // OKAY - comparable
std::map<std::ifstream, int> map2;    // ERROR - not comparable
```

🤔 Questions? 🤔

Iterating over the elements of a STL set/map.

- Exactly the same as in CS 106B - no modifying the container in the loop!
- The elements are ordered based on the operator< for element/key.
- Because maps store pairs, each element m is an std::pair that you can use structured binding on.

```
for (const auto& element : s) {
  // do stuff with key
}


for (const auto& [key, value] : m) {
  // do stuff with key, value
}
```

unordered_map and unordered_set

Each STL set/map comes with an unordered sibling. Their usage is the same, with two differences:

- Instead of a comparison operator, the element (set) or key (map) must have a hash function defined for it (you'll learn more in Assignment 2).
- The unordered_map/unordered_set is generally faster than map/set.

Don't worry too much about these just yet - you'll implement unordered_map in assignment 2!

multimap, multiset (+ unordered siblings)

Each STL set/map (+ unordered_set/map) comes with an multi- cousin. Their usage is the same, with two differences:

- You can have multiple of the same element (set) or key (map).
- insert, erase, and retrieving behave differently (since they may potentially have to retrieve multiple elements/values).

I've actually never used these before. Let us know if you actually ever use one. Otherwise, let's not spend too much time on this.

Recap

- Sequence containers
  - std::vector and std::deque
- Container adaptors
  - std::stack and std::queue
- Associative containers
  - std::map and std::set

Next time

Iterators