Lecture 5: Containers

CS 106L, Fall '20

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!
- Recommend you review the supplemental material if you have the bandwidth :).

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

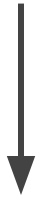
- Of type **std::istream**
- Can only **give you** data with the >> operator
  - Receives string from stream and converts it to data

```
// input: 5 abc 7
int x, z; 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
```

Streams can be converted to bool

```
stream >> temp;
if (stream.fail()) break;     // checks for fail bit OR bad bit
doSomething(temp);
```



```
stream >> temp;
if (!stream) break;           // same thing
doSomething(temp);
```

Common Read Loop

```
// here's a very common read loop:

while (stream >> temp) {
    doSomething(temp);
}
```

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)

Containers

Adaptors

Iterators

Functions

Algorithms

Key questions we will answer today

- when should each container be used?
- how is the STL different from the Stanford libraries?
- what are some best practices and common pitfalls?

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>`

C++ details we will cover

- std::vector
- std::deque/list
- std::map/unordered_map
- std::set/unordered_set
- std::stack/queue

Sequence Containers

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

Stanford vs STL Vector (a Review)

Answer on chat: what is different?

```
// Stanford
Vector<char> vec{'a', 'b', 'c'};

vec[0] = 'A';
cout << vec[vec.size()-1];

for (int i = 0; i < vec.size(); i++) {
  vec[i]++;
}

for (auto& elem : vec) {
  elem--;
}
```

```
// STL
std::vector<char> vec{'a', 'b', 'c'};

vec[0] = 'A';
cout << vec[vec.size()-1]; // or vec.back()

for (size_t i = 0; i < vec.size(); i++) {
  vec[i]++;
}

for (auto& elem : vec) {
  elem--;
}
```

Stanford vs STL Vector (a Review)

Answer on chat: what is different?

```
// Stanford
Vector<char> vec(3, 'c');
if (vec.isEmpty() || vec.size() == 3) {
  vec.clear();
}

vec[-1] = 1; // BAD, error thrown!
Vector<char> vec2(3, 'c');
if (vec == vec2) {
  vec2.remove(vec2.size()-1);
}
```

```
// STL
std::vector<char> vec(3, 'c');
if (vec.empty() || vec.size() == 3) {
  vec.clear();
}

vec[-1] = 1; // BAD, but no error thrown!
std::vector<char> vec2(3, 'c');
if (vec == vec2) {
  vec2.pop_back();
}
```

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; (*)`

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; (*)`

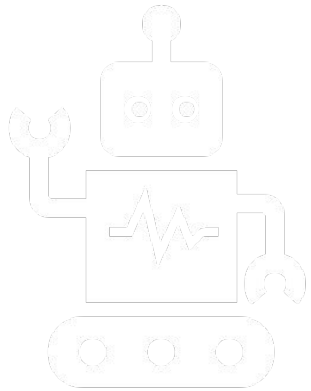
What's missing on this chart? (answer in chat)

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; (*)`

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? 🤔

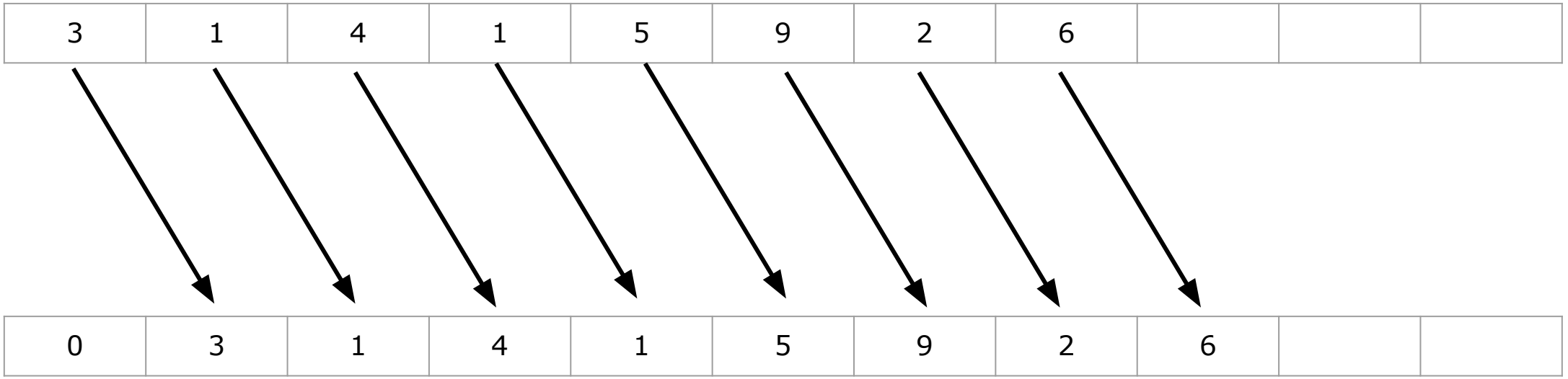
operator[] does not perform bounds checking

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
```

Live Code Demo:
InsertionSpeed

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



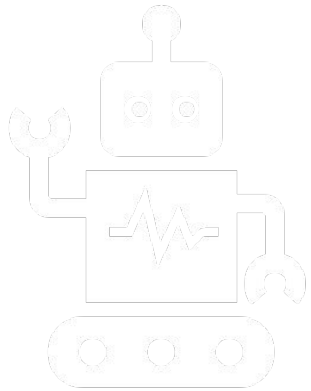
`std::vector` does not have a `push_front` function

`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

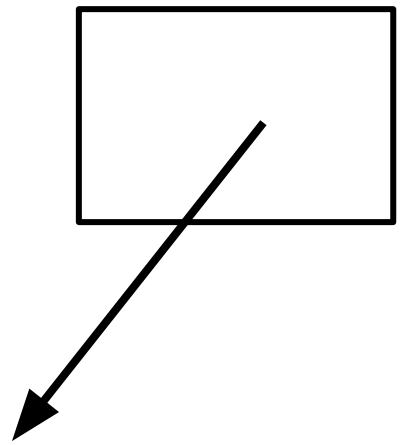
`std::deque` has the exact same functions as `std::vector` but also has `push_front` and `pop_front`.

```
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

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

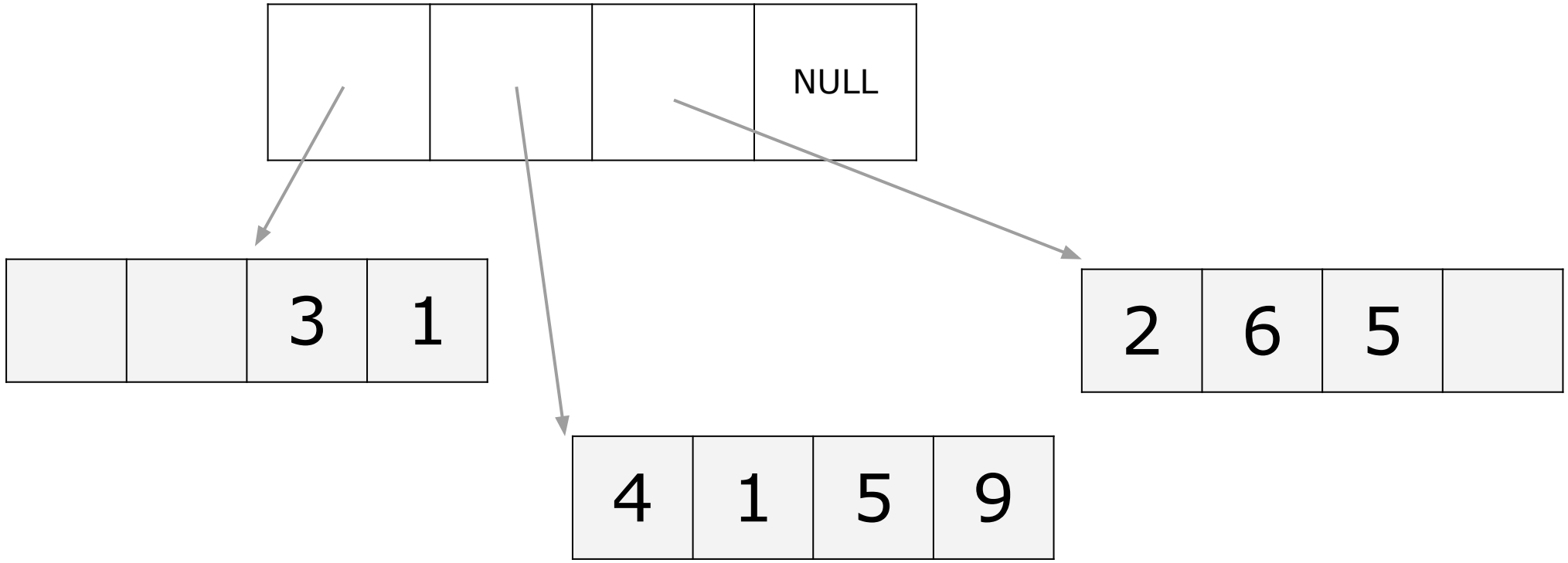
capacity = amount of space saved for the vector

0	3	1	4	1	5	9	2	6		

How is a deque implemented?

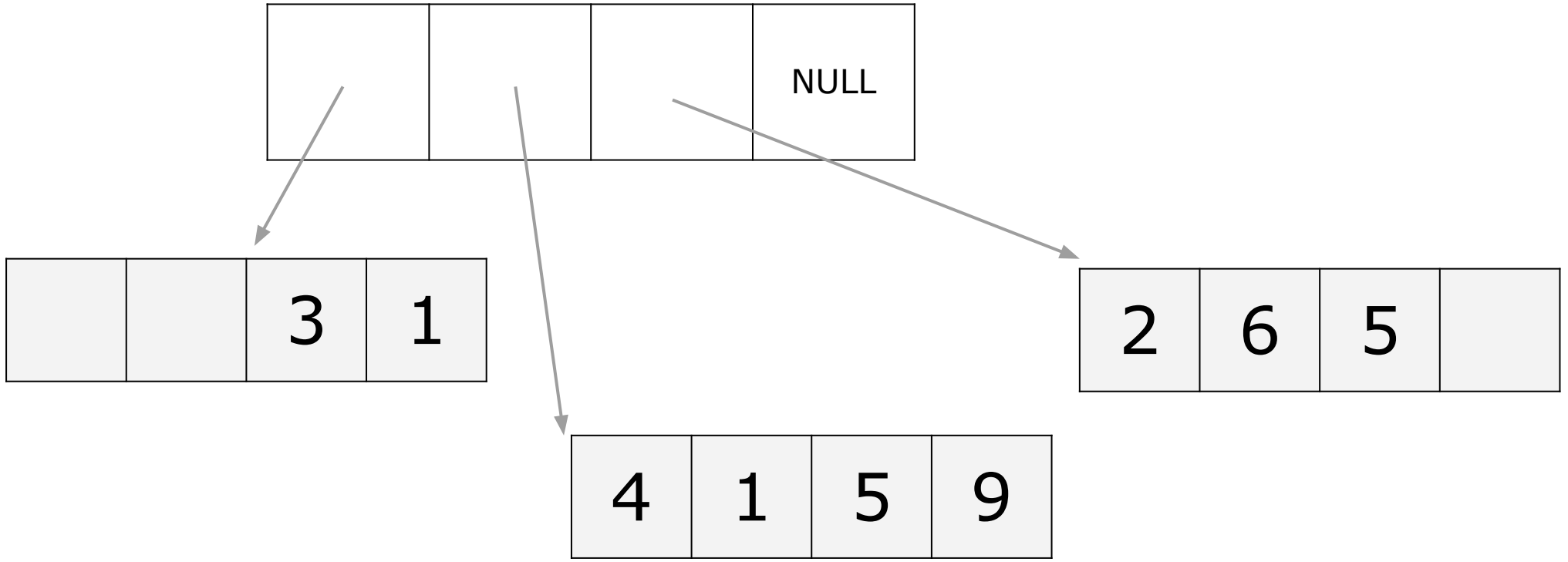
How does `std::deque<T>` work?

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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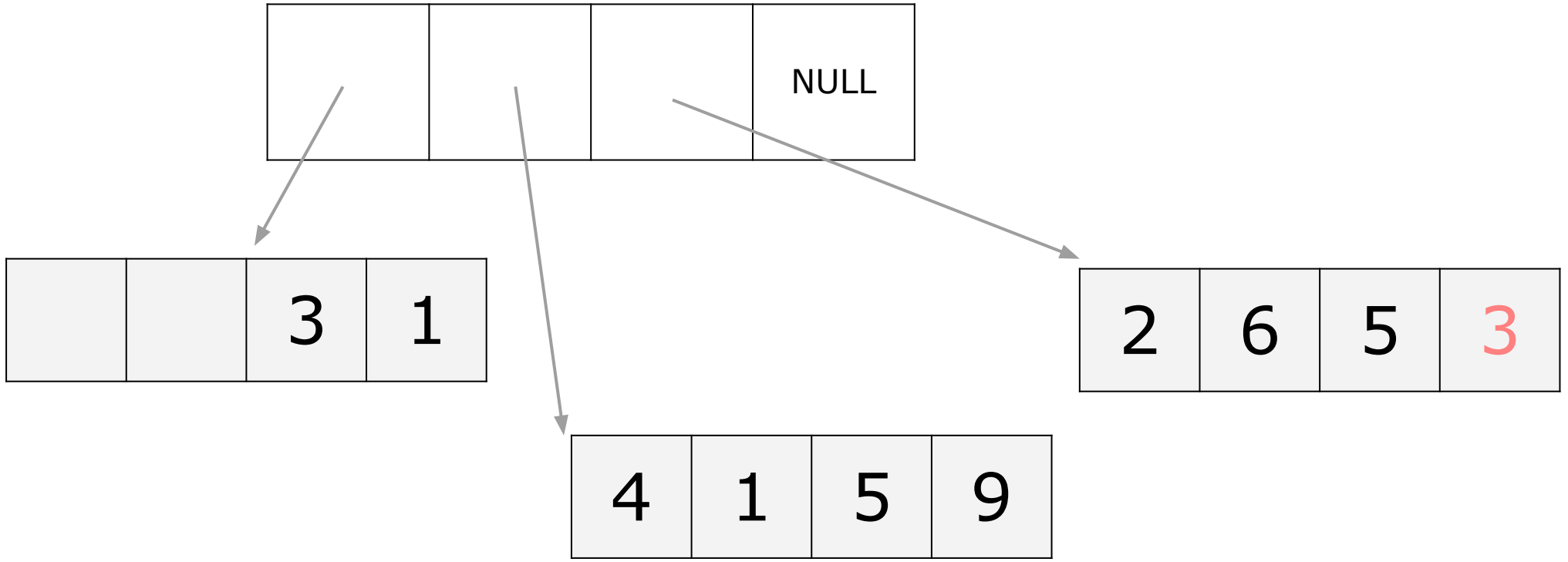
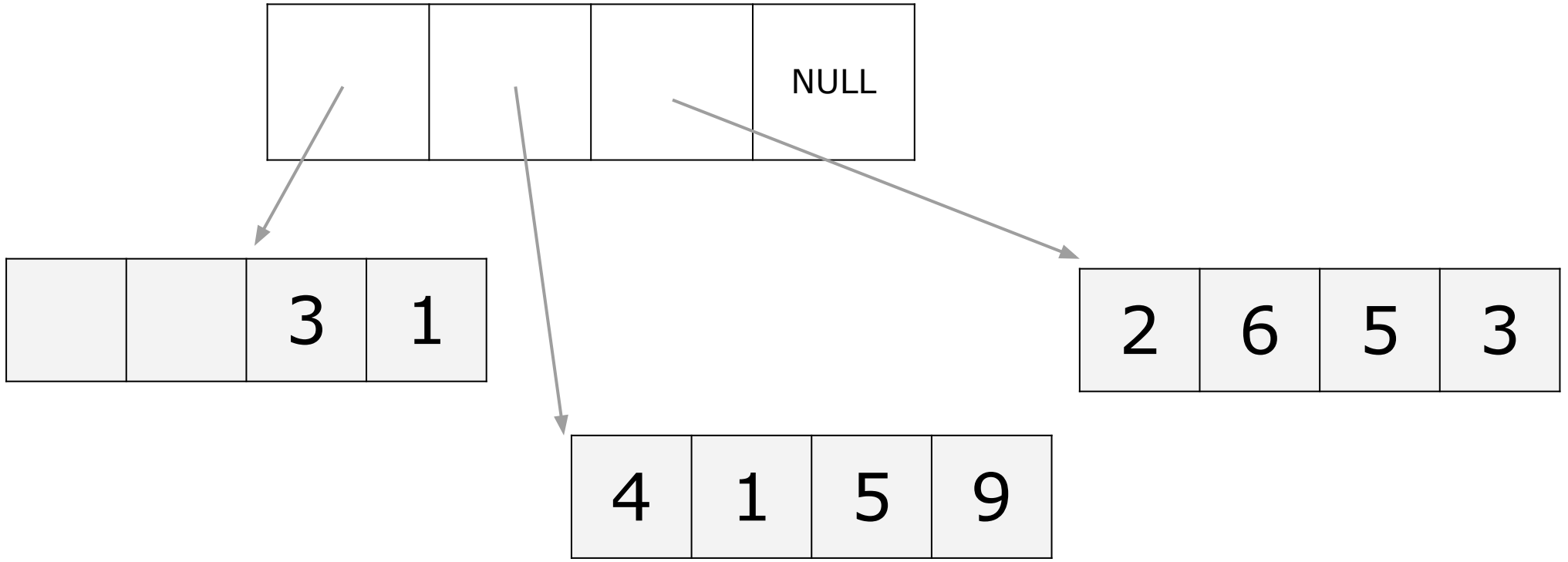


How does `std::deque<T>` work?

How would you do `push_front(1)`?



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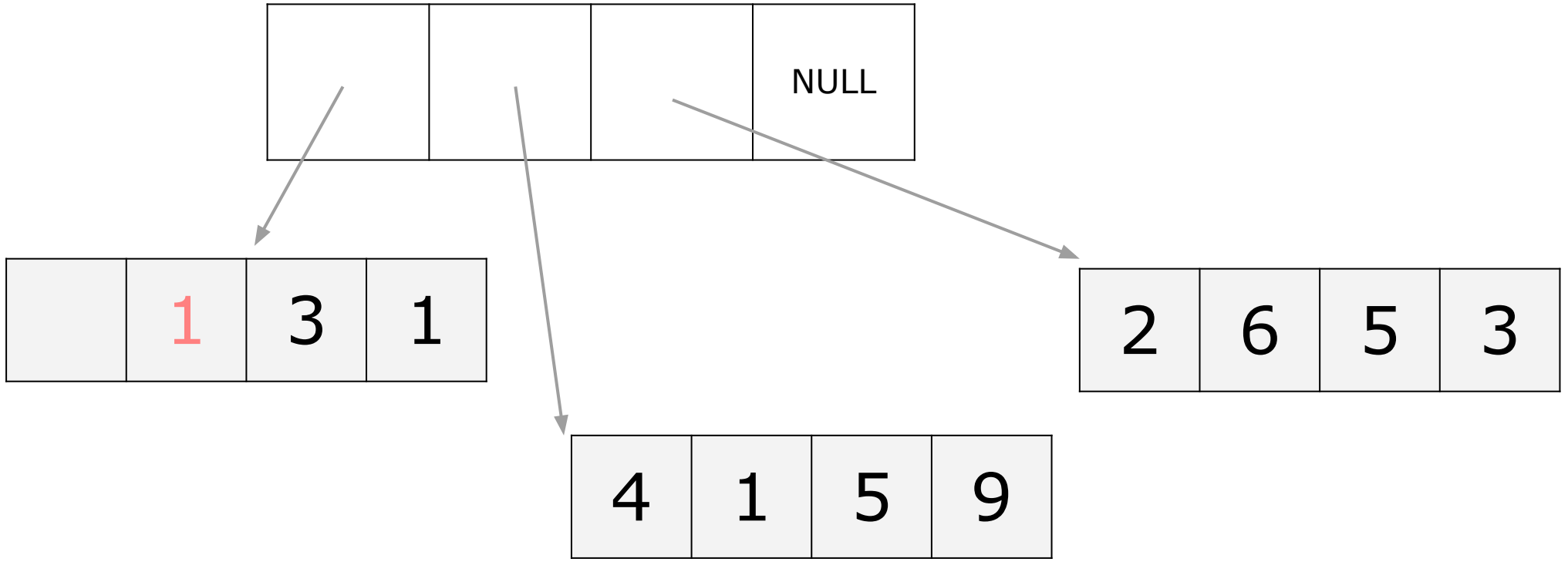
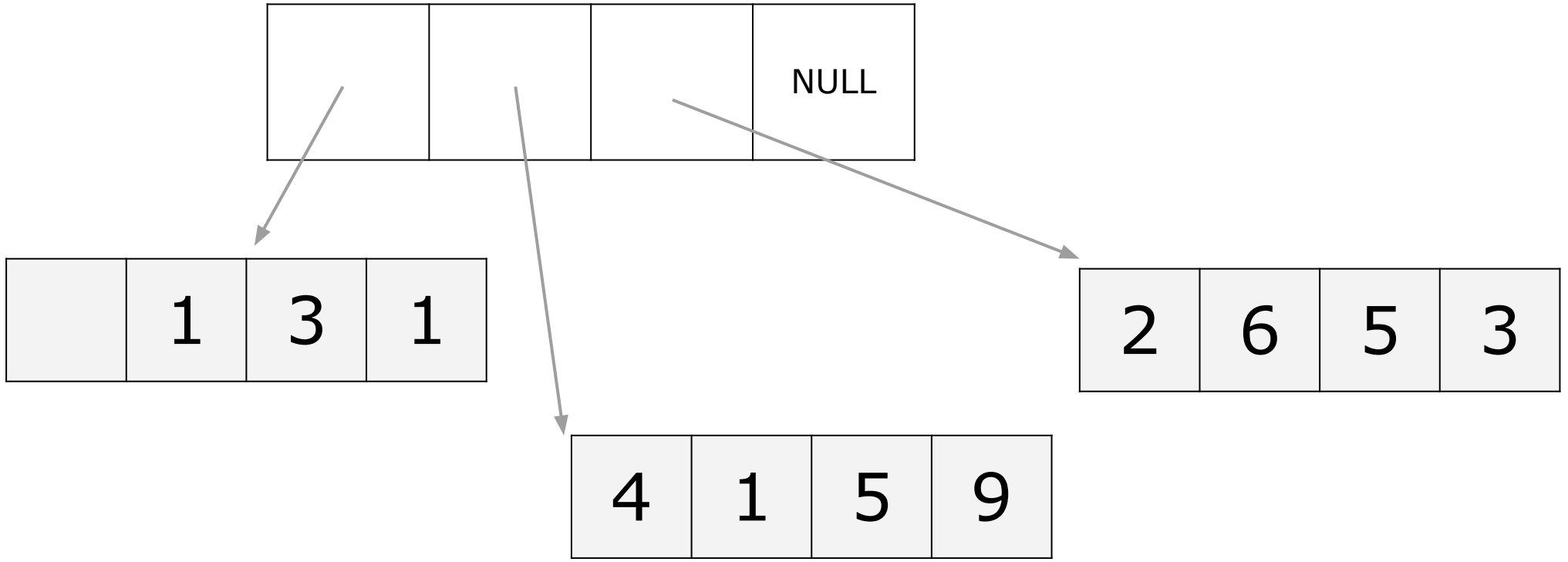


How does std::deque<T> work?

How would you do push_back(7)?



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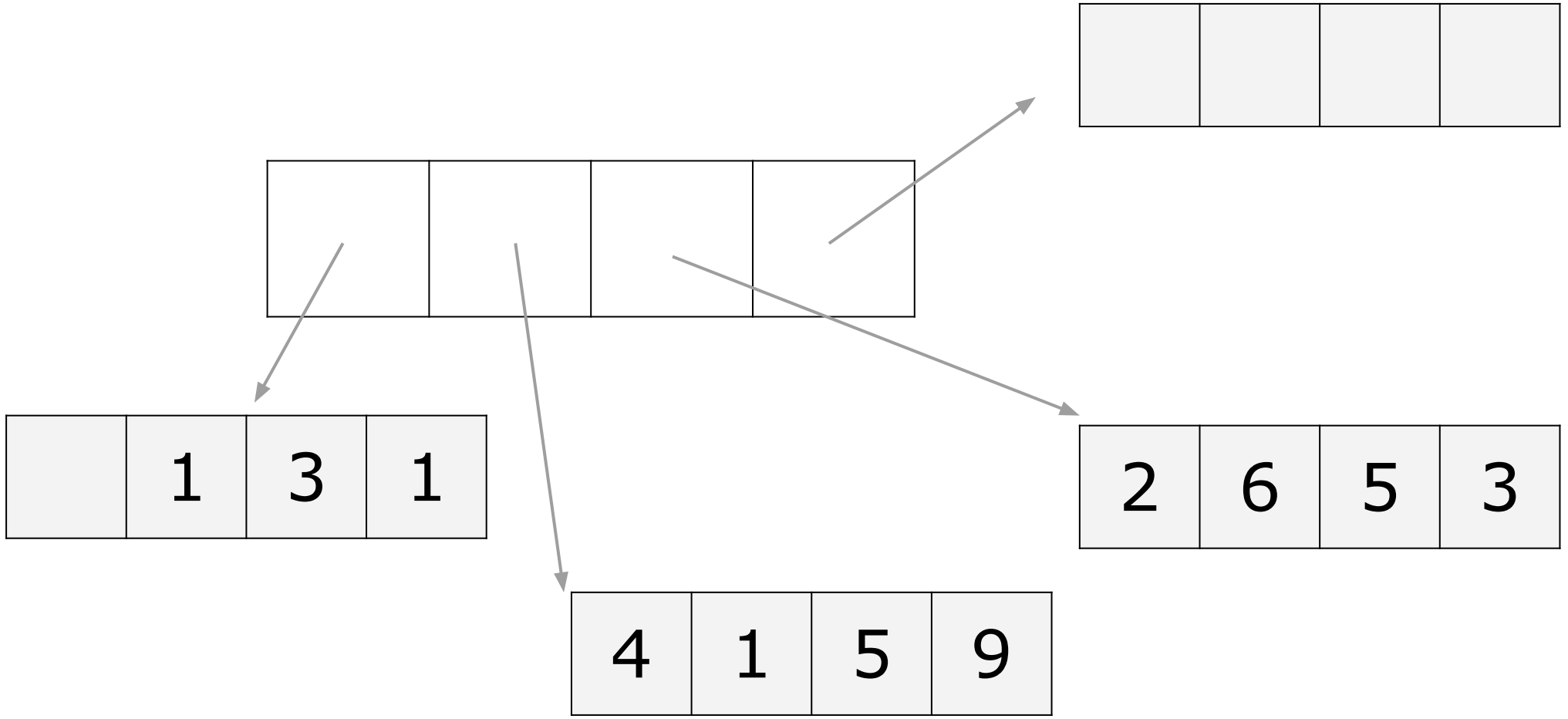

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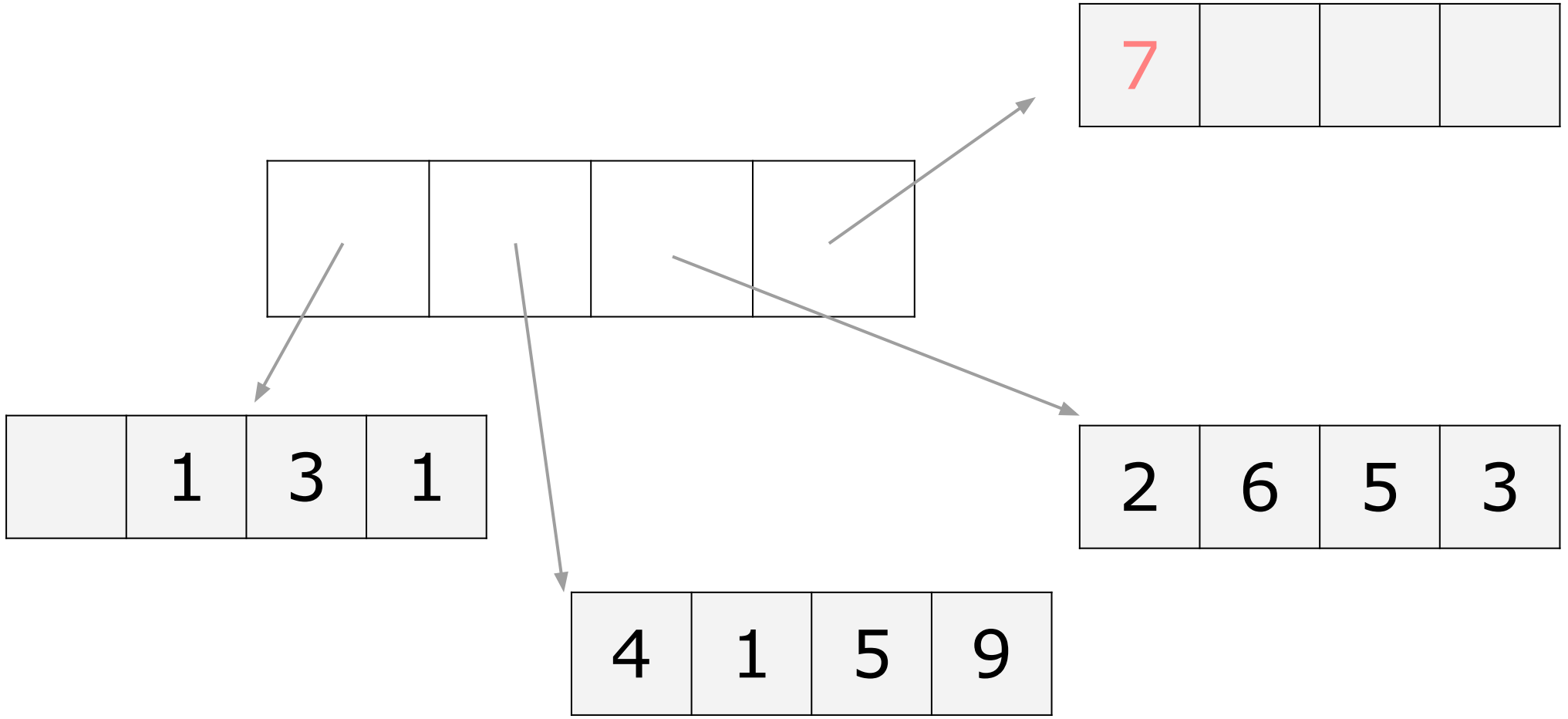

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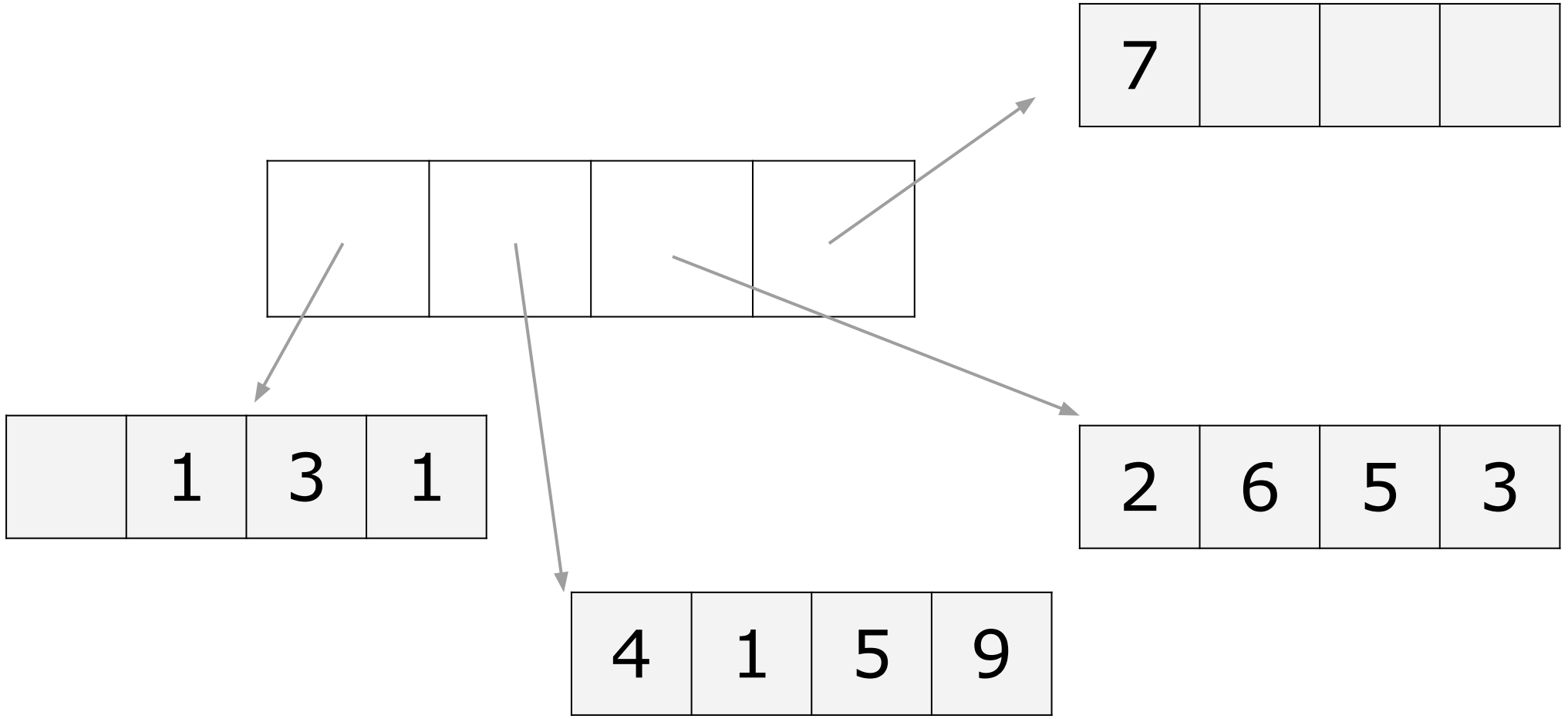
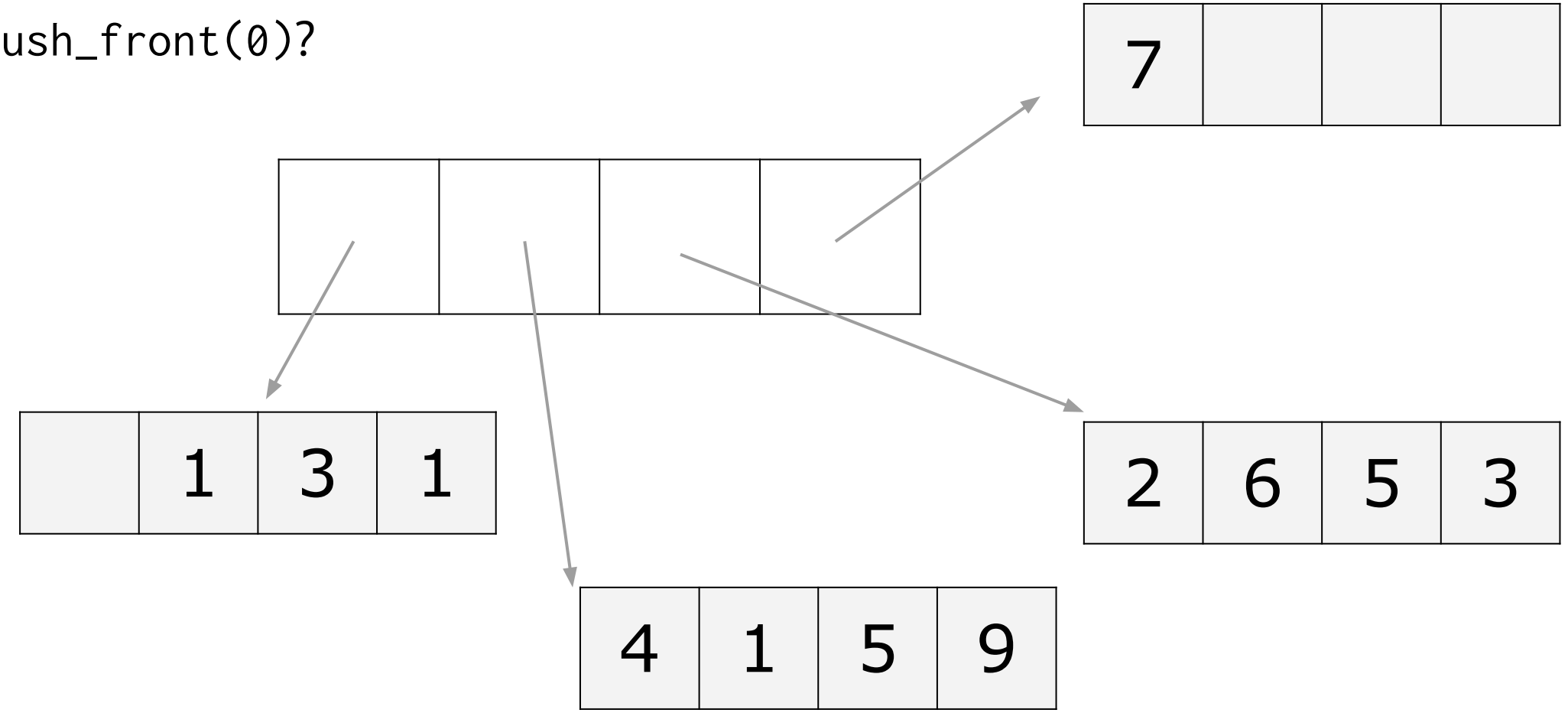


How does `std::deque<T>` work?

How would you do `push_front(8)`

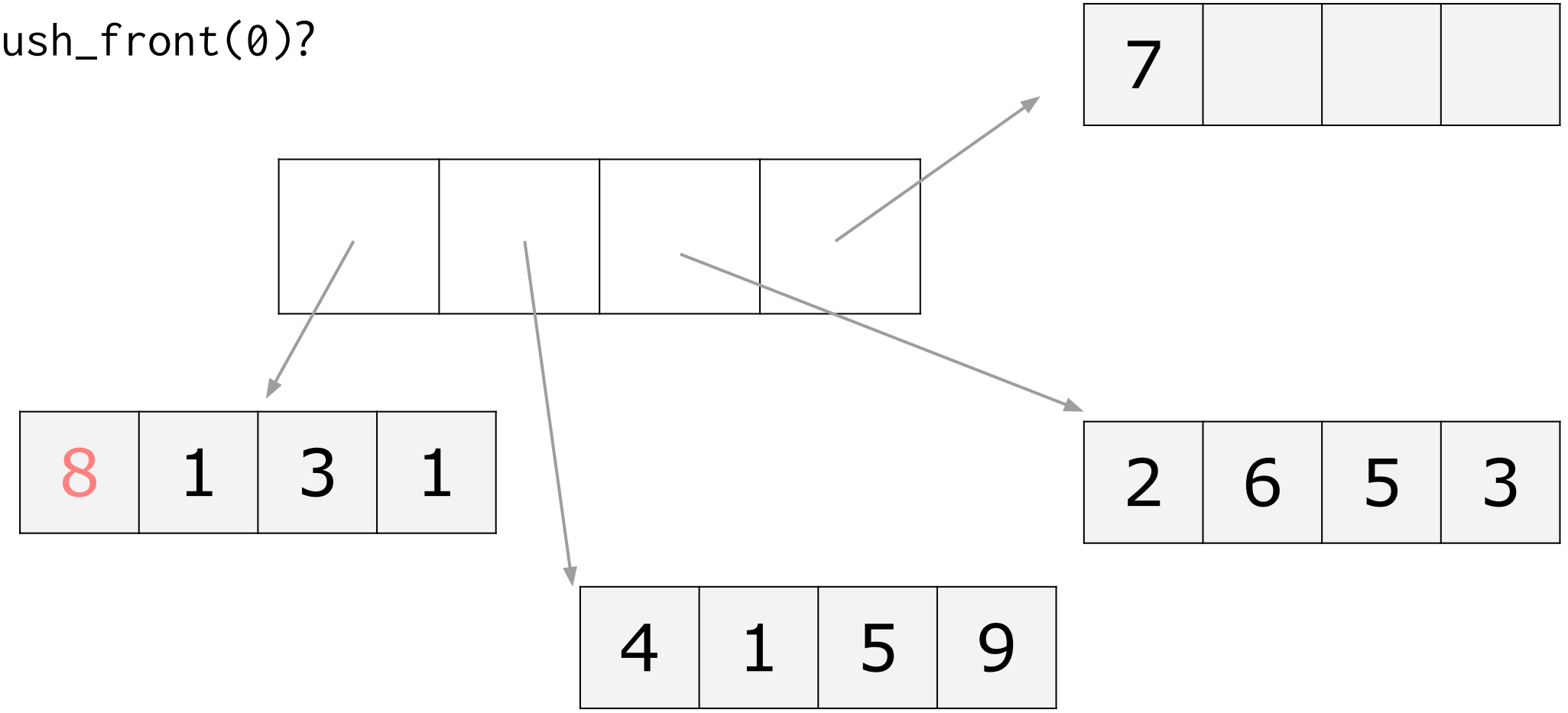
then `push_front(0)`?



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

How would you do `push_front(8)`

then `push_front(0)`?



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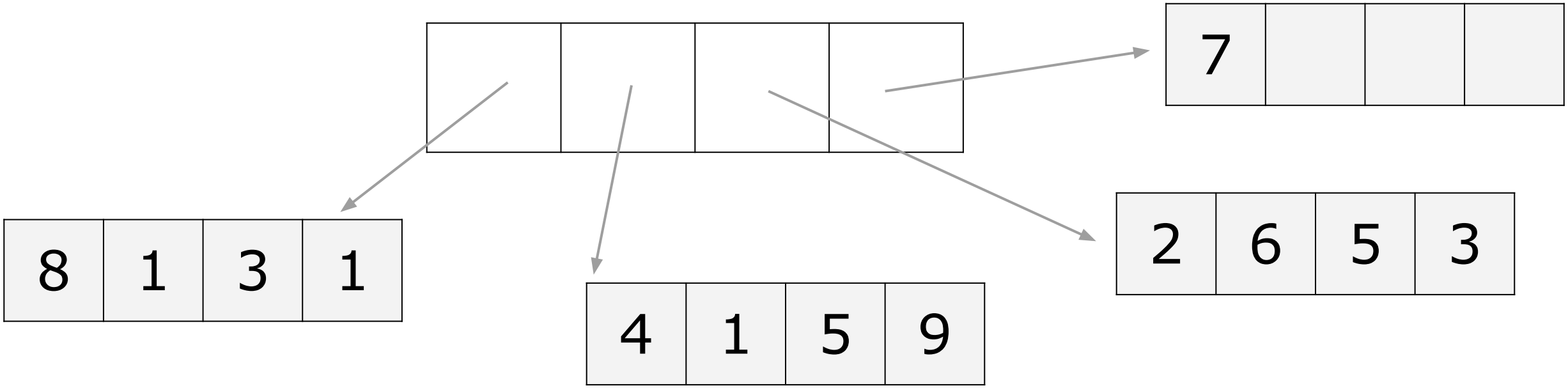

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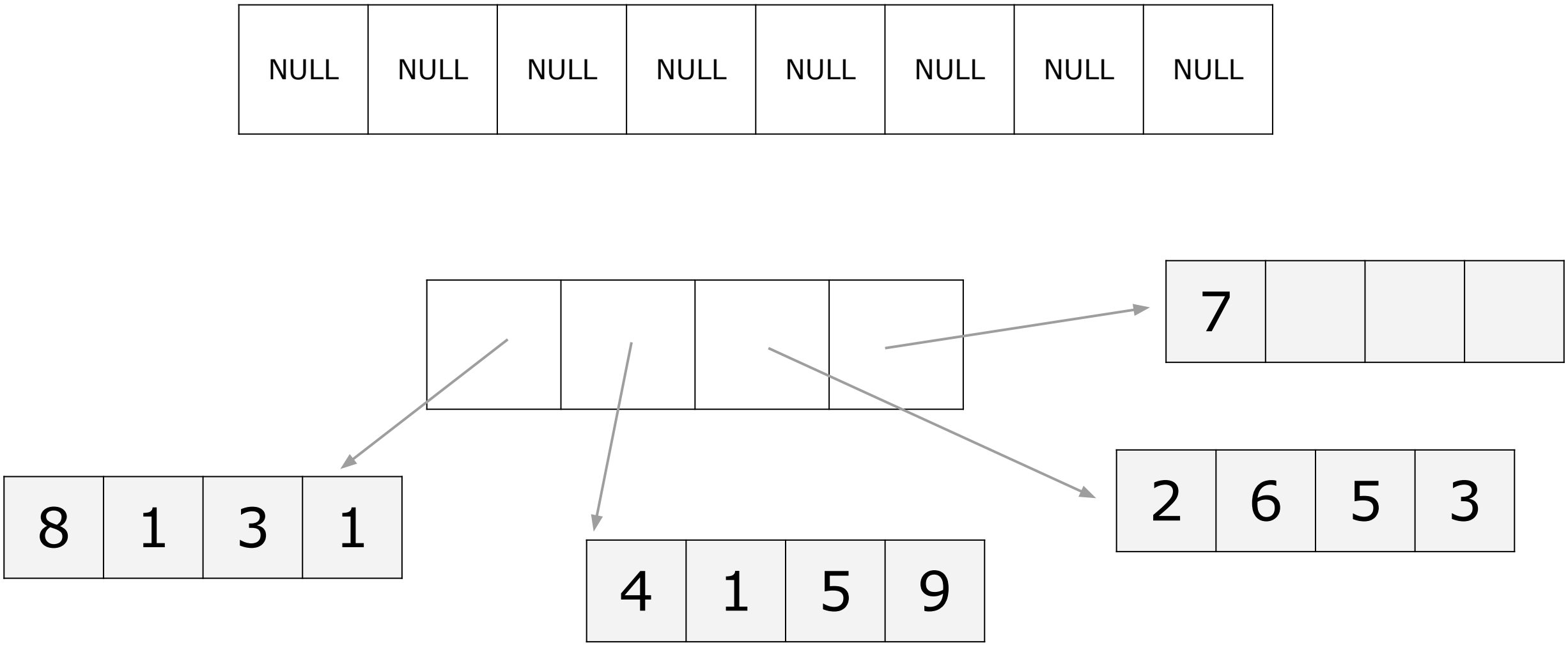

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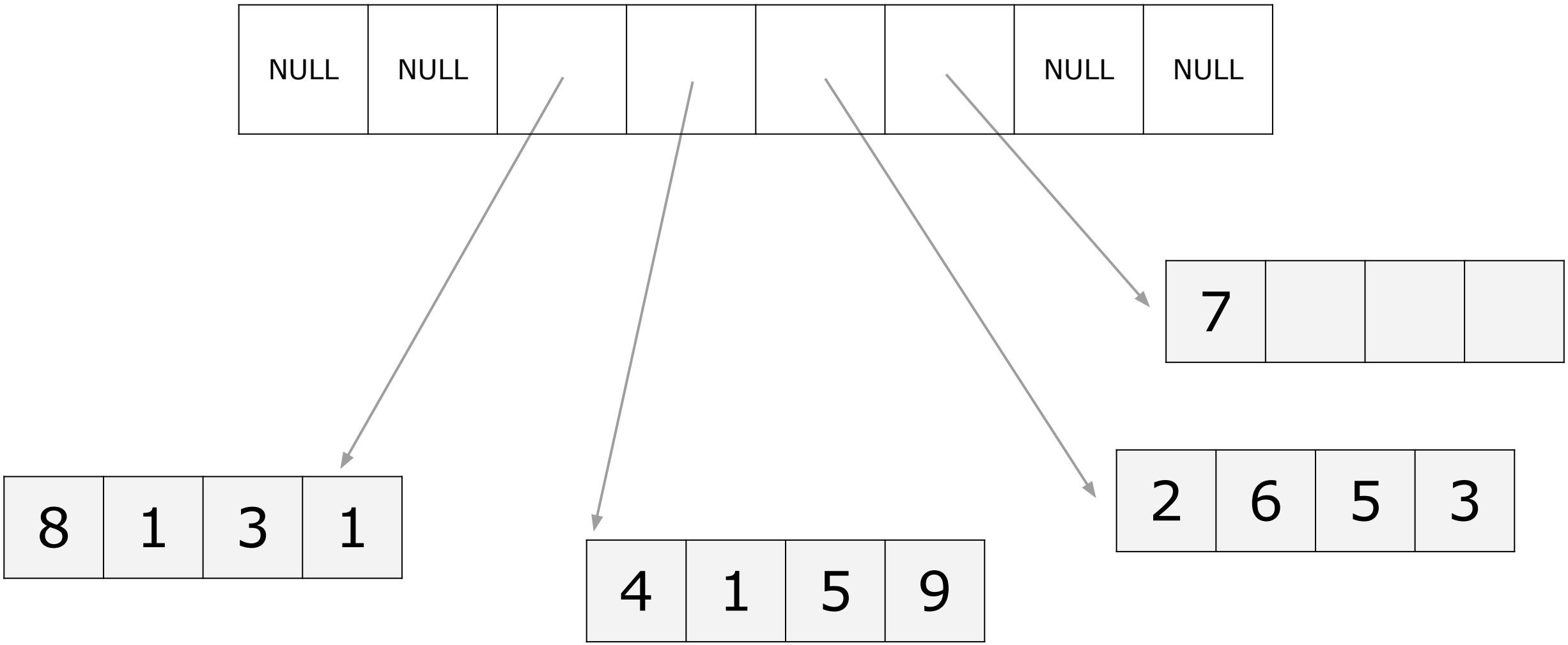

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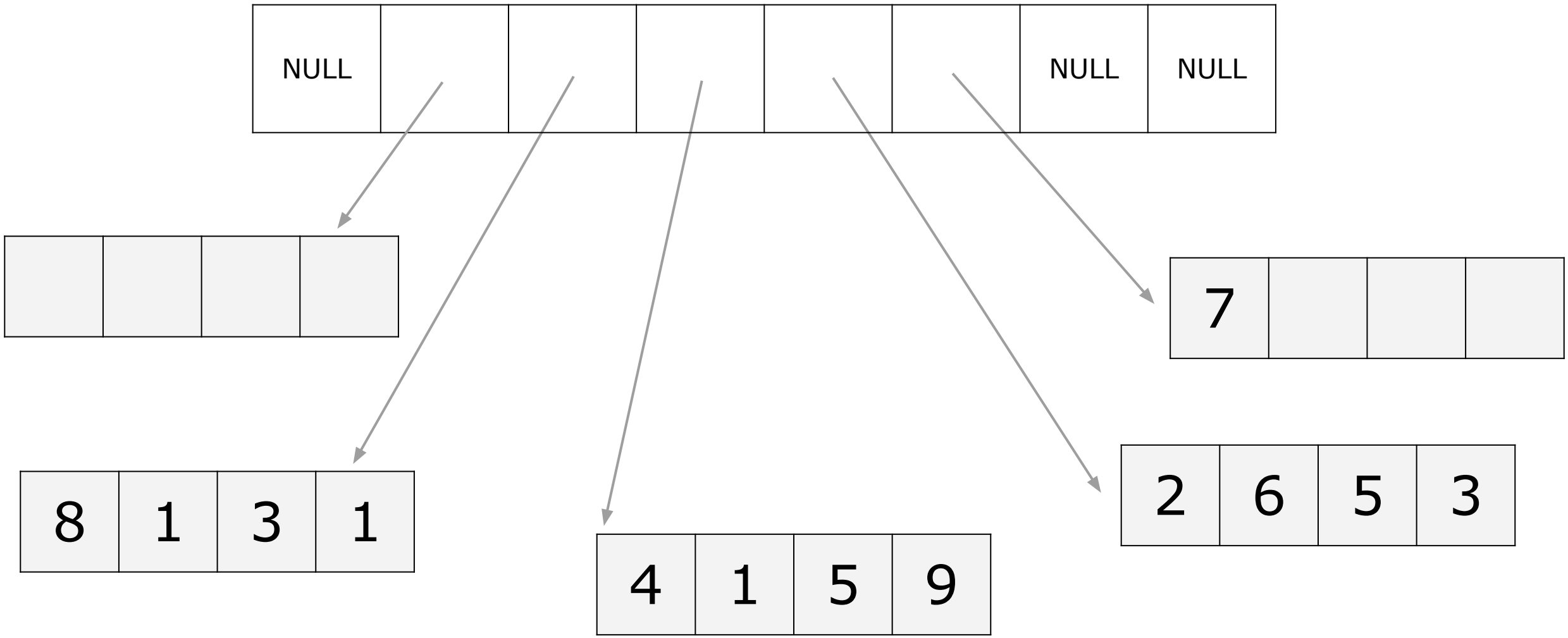
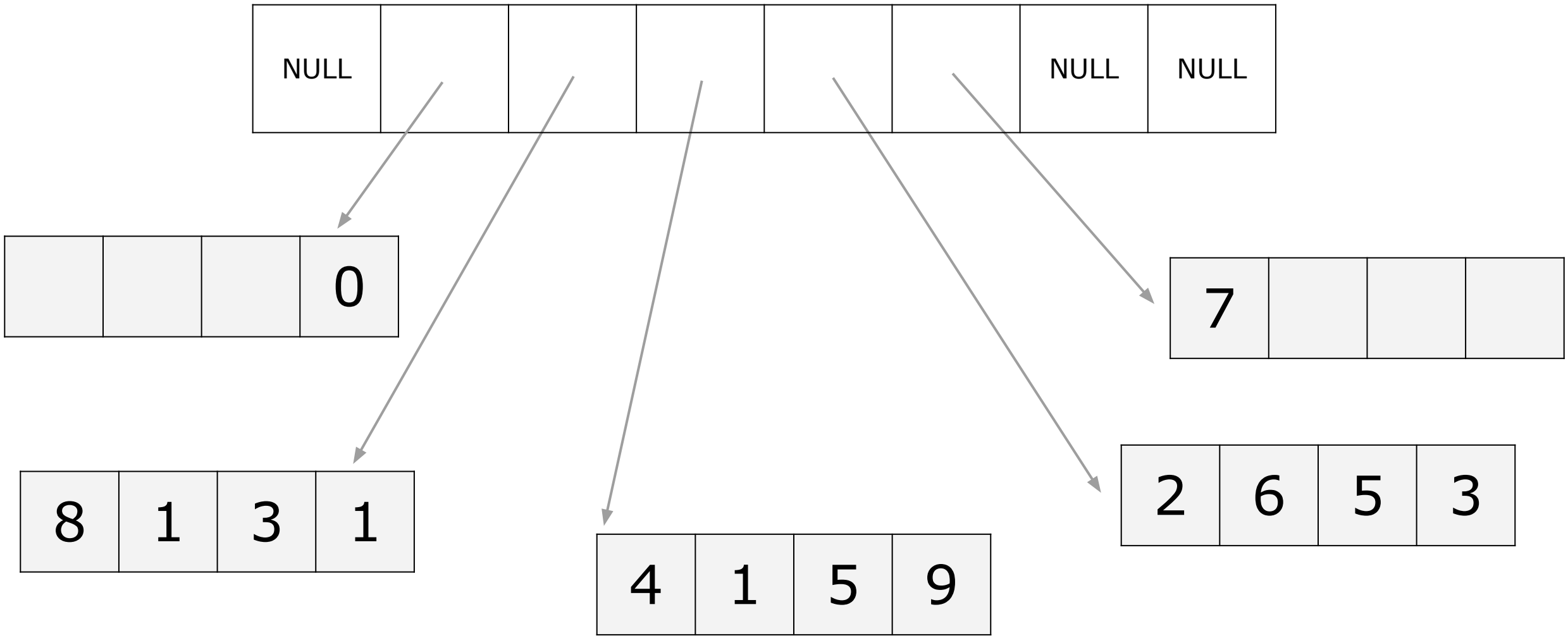


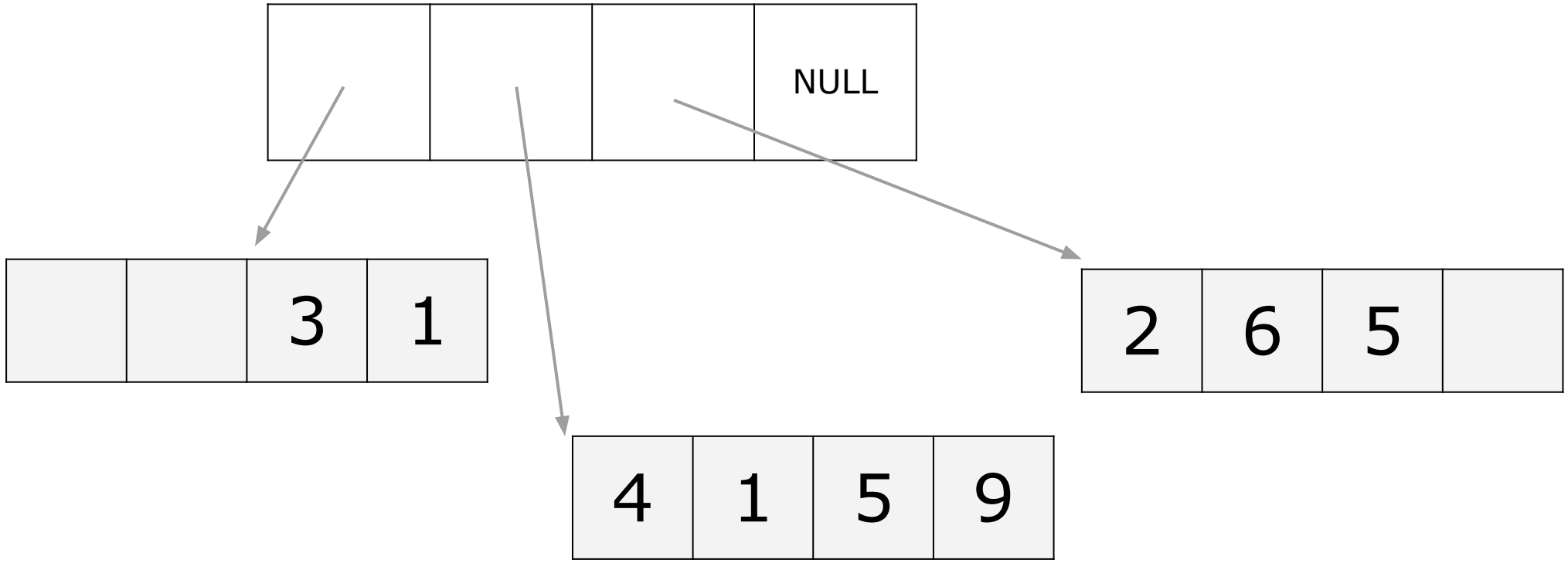
How does `std::deque<T>` work?



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!

Supplemental Material

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.

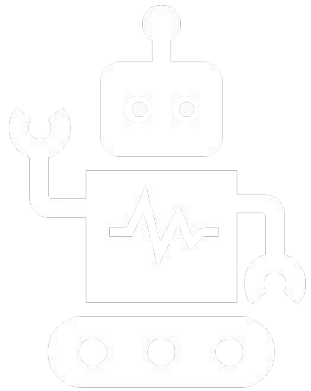
Live Code Demo:

`VecDecSpeed` (measuring access speed in the middle of a container)

Summary from the ISO Standard

"vector is the type of sequence that should be used by default... deque is the data structure of choice when most insertions and deletions take place at the beginning or at the end of the sequence."

什么时候用deque和vector



🤔 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

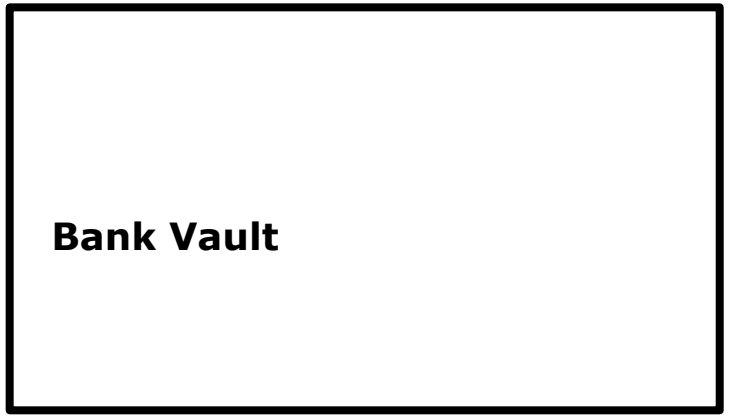
1. What is a container adaptor?
2. `std::stack` and `std::queue`

What is a wrapper (in general)?

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

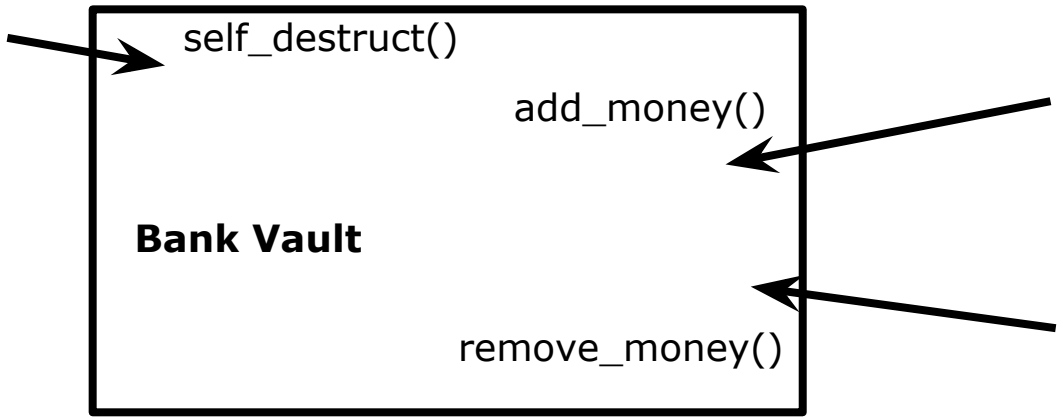
What is a wrapper (in general)?

- Here is a bank vault.



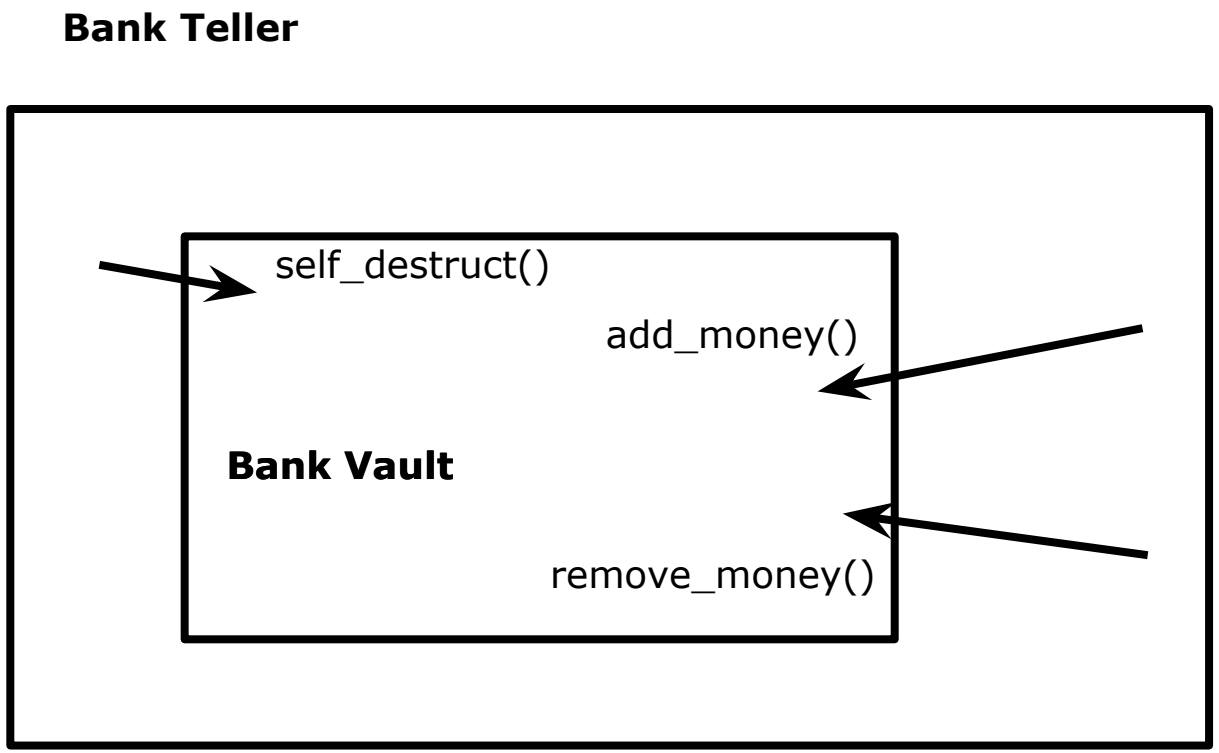
What is a wrapper (in general)?

- 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.



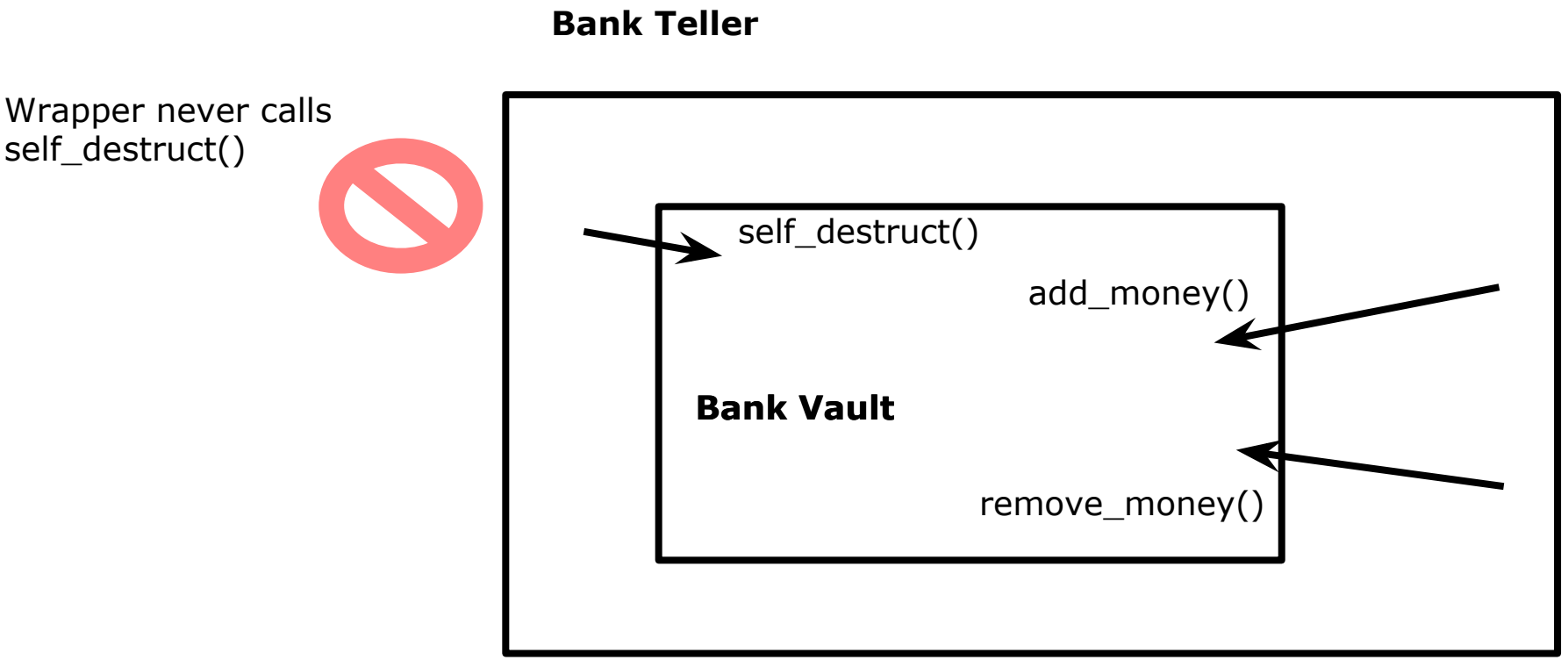
What is a wrapper (in general)?

- 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



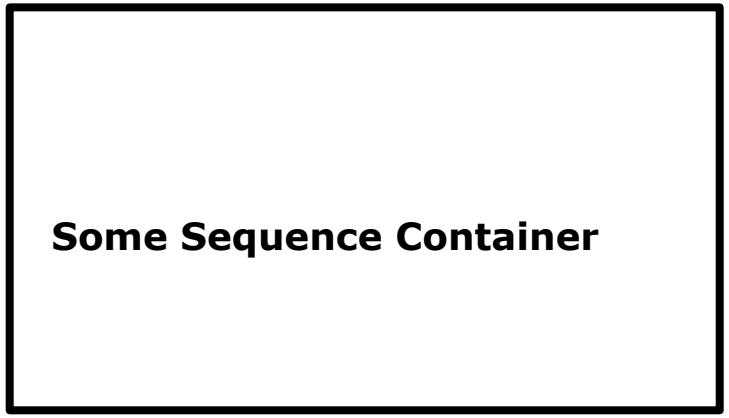
This is exactly what a wrapper in C++ does!

What's a container adaptor? 容器适配器

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

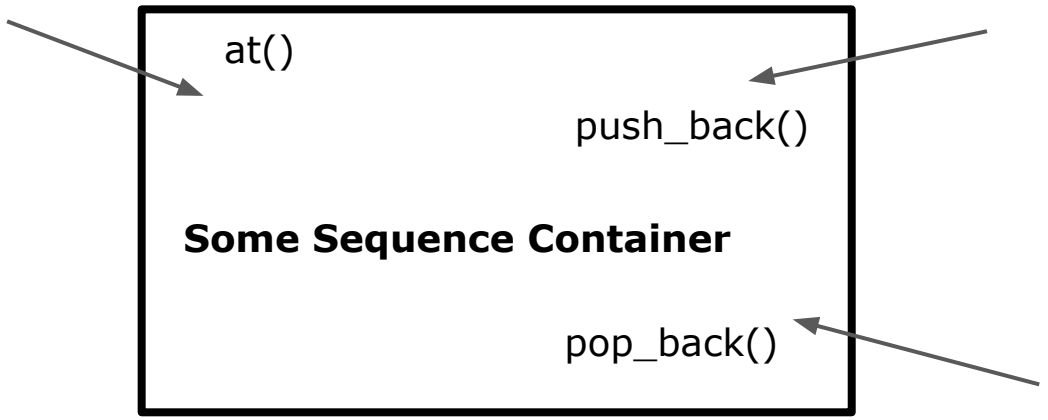
How do you design a stack?

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



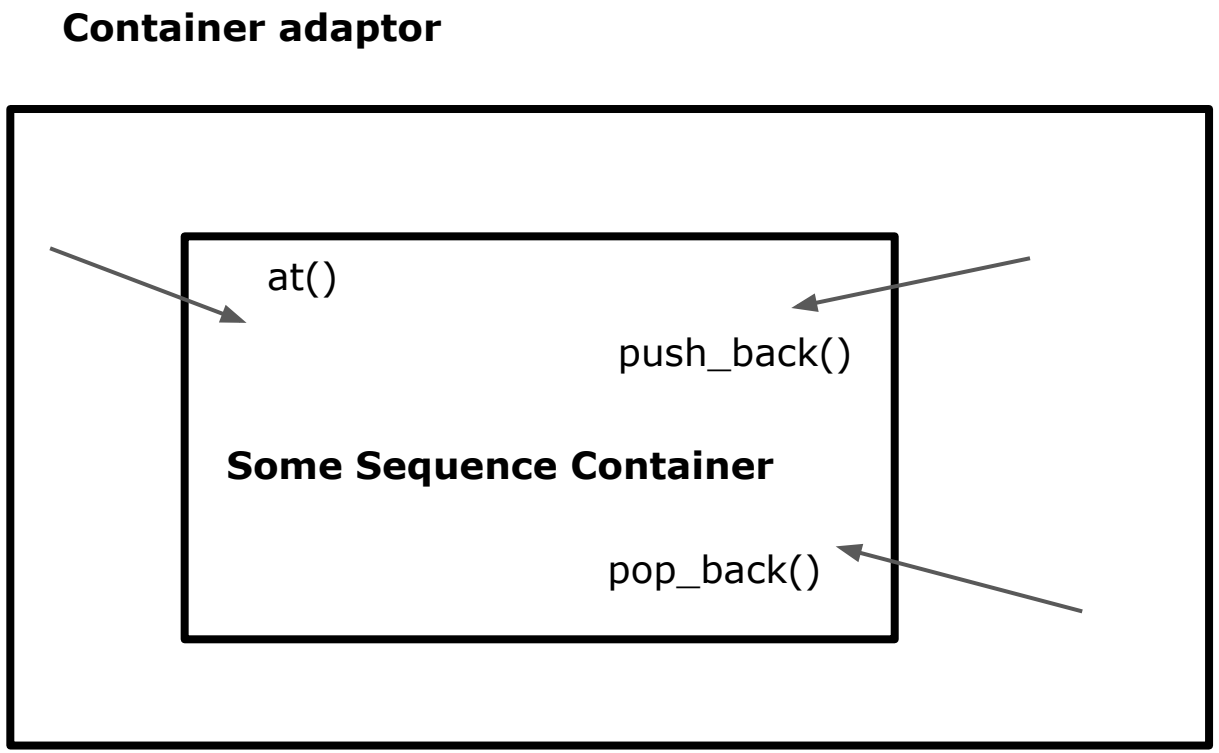
How do you design a stack?

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



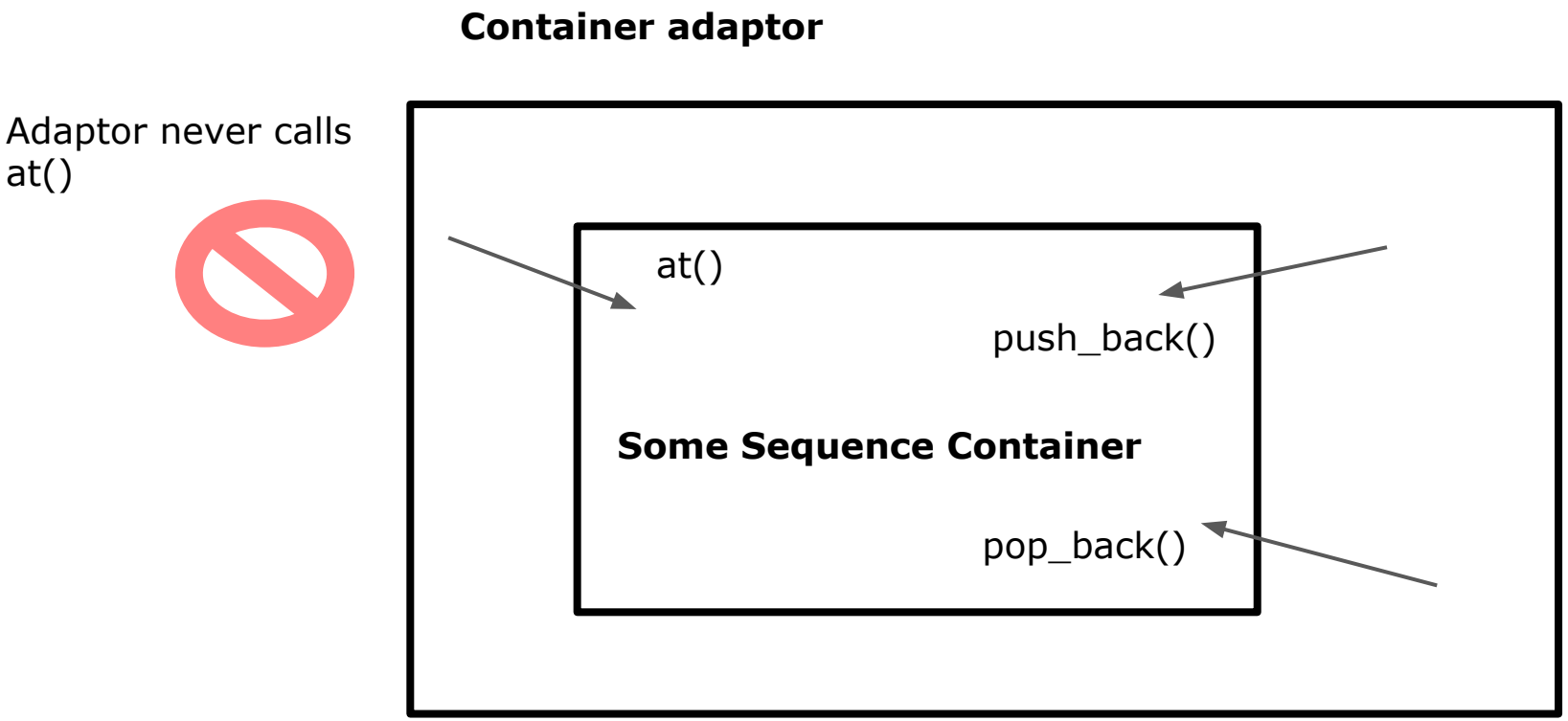
How do you design a stack?

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



How do you design a stack?

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



Quiz Question (answer in chat)

Which data structure should we use to implement a stack? How about a queue?

A. std::vector<T>

B. std::deque<T>

C. Both are equally good

D. Both are equally bad

Believe it or not, `std::deque` is actually the preferred choice for both of these!

Concrete Example

std::stack

Defined in header <stack>

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

Why deque as opposed to vector or list?

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;
```

No surprise

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
```

Deep Dive Into `std::stack` documentation

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


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.

关联容器

Associative Containers

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

Stanford vs. STL set: a summary

文本

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()) ...`

Answer on chat: what is different?

Stanford vs. STL set: a summary

What you want to do	Stanford `Set<int>`	`std::set<int>`
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Check if the set is empty	`if (s.isEmpty()) ...`	`if (s.empty()) ...`

There are functions for size, ==, !=, clear, etc.

STL does not have member functions for subset, difference, union, intersection, etc, but there are STL algorithms!

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

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


std::map<std::set<int>, int> map1;     // OKAY - comparable
std::map<std::function, 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.

Summary of Associative Containers

set: membership

map: key/value pairs

set/map require comparison operator

map stores std::pairs

auto-insertion = useful but be careful

unordered/multi stuff - know they exist

We've run into a few problems with STL containers

Concrete things we haven't been able to do yet...

- how to insert an element at a certain position in a vector?
- how do we create sublists of a vector? how about for a set?
- how do we iterate over all the elements in an associative container?

Ideas we want to move toward (we'll know how to do these by the end of the class!)

- can I write a function that works for any container?
- can I operate over a container while completing ignoring the container?

Summary

- `std::vector` methods are very similar to Stanford Vector
- `std::vector` indexing has `[]` and `at()` functions. only `at()` does error-checking
- `std::deque` is like vector, inserting to front is fast, other operations slower
- `std::stack` and `std::queue` adapt a deque to their unique interface
- `std::set is` like Stanford Set. Main difference: `count()` instead of `contains()`
- `std::map` kinda like Stanford Map, but internally stores `pair<K, V>`
- `std::map`'s `operator[]` has auto-insertion, but `at()` does not
- `set/map` require a comparison operator (since they are internally sorted)
- you should practice using these containers yourself
- you should read the STL documentation for more details

Next time

Iterators