UCLA Samueli Computer Science

CS32: Introduction to Computer Science

# Discussion Week 7

Junheng Hao, Ramya Satish

Feb 22, 2019

# Announcement

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- Midterm Part 2 is due on Tuesday, Feb 26.
- Project 3 Part 2 is due on Thursday, February 28

# Outline

- STL (continued)
- Algorithmic Efficiency (Big-O notation)
- Sorting (1)

# STL Table list

## Check out when you need

- C++ Containers library
  - Sequence containers: `array, vector, deque, list, forward_list`
  - Container adaptors: `set, map, multiset, multimap`
  - Associate containers: `unordered_set, unordered_map`
  - Unordered associative containers: `stack, queue, priority_queue`
- Check link
  - https://en.cppreference.com/w/cpp/container#Sequence_containers

# Project 3 warmup

## Why fail on test 3?

- Pitfalls in modifying STL containers while you're traversing them, given the various iterator invalidation rules.
- Another reminder: For a container of raw pointers to dynamically allocated objects, the container operations know nothing about that: erasing an item does **NOT** call delete on the pointer.

# STL

## Iterator invalidation

<table>
<tr><th rowspan="2">Category</th><th rowspan="2">Container</th><th colspan="2">After insertion, are...</th><th colspan="2">After erasure, are...</th><th rowspan="2">Conditionally</th></tr>
<tr><th>iterators valid?</th><th>references valid?</th><th>iterators valid?</th><th>references valid?</th></tr>
<tr><td rowspan="8">Sequence containers</td><td><code>array</code></td><td colspan="2">N/A</td><td colspan="2">N/A</td><td></td></tr>
<tr><td rowspan="3"><code>vector</code></td><td colspan="2">No</td><td colspan="2">N/A</td><td>Insertion changed capacity</td></tr>
<tr><td colspan="2">Yes</td><td colspan="2">Yes</td><td>Before modified element(s)</td></tr>
<tr><td colspan="2">No</td><td colspan="2">No</td><td>At or after modified element(s)</td></tr>
<tr><td rowspan="2"><code>deque</code></td><td rowspan="2">No</td><td>Yes</td><td colspan="2">Yes, except erased element(s)</td><td>Modified first or last element</td></tr>
<tr><td>No</td><td colspan="2">No</td><td>Modified middle only</td></tr>
<tr><td><code>list</code></td><td colspan="2">Yes</td><td colspan="2">Yes, except erased element(s)</td><td></td></tr>
<tr><td><code>forward_list</code></td><td colspan="2">Yes</td><td colspan="2">Yes, except erased element(s)</td><td></td></tr>
<tr><td>Associative containers</td><td><code>set</code><br><code>multiset</code><br><code>map</code><br><code>multimap</code></td><td colspan="2">Yes</td><td colspan="2">Yes, except erased element(s)</td><td></td></tr>
<tr><td rowspan="2">Unordered associative containers</td><td rowspan="2"><code>unordered_set</code><br><code>unordered_multiset</code><br><code>unordered_map</code><br><code>unordered_multimap</code></td><td>No</td><td rowspan="2">Yes</td><td colspan="2">N/A</td><td>Insertion caused rehash</td></tr>
<tr><td>Yes</td><td colspan="2">Yes, except erased element(s)</td><td>No rehash</td></tr>
</table>

# STL Table list

## Member function table

| | | Sequence containers | | | | | Associative containers | | | | Unordered associative containers | | | | Container adaptors | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Header | | <array> | <vector> | <deque> | <forward_list> | <list> | <set> | | <map> | | <unordered_set> | | <unordered_map> | | <stack> | <queue> | |
| Container | | **array** | **vector** | **deque** | **forward_list** | **list** | **set** | **multiset** | **map** | **multimap** | **unordered_set** | **unordered_multiset** | **unordered_map** | **unordered_multimap** | **stack** | **queue** | **priority_queue** |
| | (constructor) | (implicit) | vector | deque | forward_list | list | set | multiset | map | multimap | unordered_set | unordered_multiset | unordered_map | unordered_multimap | stack | queue | priority_queue |
| | (destructor) | (implicit) | ~vector | ~deque | ~forward_list | ~list | ~set | ~multiset | ~map | ~multimap | ~unordered_set | ~unordered_multiset | ~unordered_map | ~unordered_multimap | ~stack | ~queue | ~priority_queue |
| | operator= | (implicit) | operator= | operator= | operator= | operator= | operator= | operator= | operator= | operator= | operator= | operator= | operator= | operator= | operator= | operator= | operator= |
| | assign | | assign | assign | assign | assign | | | | | | | | | | | |
| **Iterators** | begin | begin | begin | begin | begin | begin | begin | begin | begin | begin | begin | begin | begin | begin | | | |
| | cbegin | cbegin | cbegin | cbegin | cbegin | cbegin | cbegin | cbegin | cbegin | cbegin | cbegin | cbegin | cbegin | cbegin | | | |
| | end | end | end | end | end | end | end | end | end | end | end | end | end | end | | | |
| | cend | cend | cend | cend | cend | cend | cend | cend | cend | cend | cend | cend | cend | cend | | | |
| | rbegin | rbegin | rbegin | rbegin | | rbegin | rbegin | rbegin | rbegin | rbegin | | | | | | | |
| | crbegin | crbegin | crbegin | crbegin | | crbegin | crbegin | crbegin | crbegin | crbegin | | | | | | | |
| | rend | rend | rend | rend | | rend | rend | rend | rend | rend | | | | | | | |
| | crend | crend | crend | crend | | crend | crend | crend | crend | crend | | | | | | | |
| **Element access** | at | at | at | at | | | | | at | | | | at | | | | |
| | operator[] | operator[] | operator[] | operator[] | | | | | operator[] | | | | operator[] | | | | |
| | data | data | data | | | | | | | | | | | | | | |
| | front | front | front | front | front | front | | | | | | | | | | front | top |
| | back | back | back | back | | back | | | | | | | | | top | back | |
| **Capacity** | empty | empty | empty | empty | empty | empty | empty | empty | empty | empty | empty | empty | empty | empty | empty | empty | empty |
| | size | size | size | size | | size | size | size | size | size | size | size | size | size | size | size | size |
| | max_size | max_size | max_size | max_size | max_size | max_size | max_size | max_size | max_size | max_size | max_size | max_size | max_size | max_size | | | |
| | resize | | resize | resize | resize | resize | | | | | | | | | | | |
| | capacity | | capacity | | | | | | | | bucket_count | bucket_count | bucket_count | bucket_count | | | |
| | reserve | | reserve | | | | | | | | reserve | reserve | reserve | reserve | | | |
| | shrink_to_fit | | shrink_to_fit | shrink_to_fit | | | | | | | | | | | | | |
| **Modifiers** | clear | | clear | clear | clear | clear | clear | clear | clear | clear | clear | clear | clear | clear | | | |
| | insert | | insert | insert | insert_after | insert | insert | insert | insert | insert | insert | insert | insert | insert | | | |
| | insert_or_assign | | | | | | | | insert_or_assign | | | | insert_or_assign | | | | |
| | emplace | | emplace | emplace | emplace_after | emplace | emplace | emplace | emplace | emplace | emplace | emplace | emplace | emplace | | | |
| | emplace_hint | | | | | | emplace_hint | emplace_hint | emplace_hint | emplace_hint | emplace_hint | emplace_hint | emplace_hint | emplace_hint | | | |
| | try_emplace | | | | | | | | try_emplace | | | | try_emplace | | | | |
| | erase | | erase | erase | erase_after | erase | erase | erase | erase | erase | erase | erase | erase | erase | | | |
| | push_front | | | push_front | push_front | push_front | | | | | | | | | | | |
| | emplace_front | | | emplace_front | emplace_front | emplace_front | | | | | | | | | | | |
| | pop_front | | | pop_front | pop_front | pop_front | | | | | | | | | | pop | pop |
| | push_back | | push_back | push_back | | push_back | | | | | | | | | push | push | push |
| | emplace_back | | emplace_back | emplace_back | | emplace_back | | | | | | | | | emplace | emplace | emplace |
| | pop_back | | pop_back | pop_back | | pop_back | | | | | | | | | pop | | |
| | swap | swap | swap | swap | swap | swap | swap | swap | swap | swap | swap | swap | swap | swap | swap | swap | swap |
| | merge | | | | merge | merge | merge | merge | merge | merge | merge | merge | merge | merge | | | |
| | extract | | | | | | extract | extract | extract | extract | extract | extract | extract | extract | | | |
| **List operations** | splice | | | | splice_after | splice | | | | | | | | | | | |
| | remove | | | | remove | remove | | | | | | | | | | | |
| | remove_if | | | | remove_if | remove_if | | | | | | | | | | | |
| | reverse | | | | reverse | reverse | | | | | | | | | | | |
| | unique | | | | unique | unique | | | | | | | | | | | |
| | sort | | | | sort | sort | | | | | | | | | | | |
| **Lookup** | count | | | | | | count | count | count | count | count | count | count | count | | | |
| | find | | | | | | find | find | find | find | find | find | find | find | | | |
| | contains | | | | | | contains | contains | contains | contains | contains | contains | contains | contains | | | |
| | lower_bound | | | | | | lower_bound | lower_bound | lower_bound | lower_bound | | | | | | | |
| | upper_bound | | | | | | upper_bound | upper_bound | upper_bound | upper_bound | | | | | | | |
| | equal_range | | | | | | equal_range | equal_range | equal_range | equal_range | equal_range | equal_range | equal_range | equal_range | | | |
| **Observers** | key_comp | | | | | | key_comp | key_comp | key_comp | key_comp | | | | | | | |
| | value_comp | | | | | | value_comp | value_comp | value_comp | value_comp | | | | | | | |
| | hash_function | | | | | | | | | | hash_function | hash_function | hash_function | hash_function | | | |
| | key_eq | | | | | | | | | | key_eq | key_eq | key_eq | key_eq | | | |
| **Allocator** | get_allocator | | get_allocator | get_allocator | get_allocator | get_allocator | get_allocator | get_allocator | get_allocator | get_allocator | get_allocator | get_allocator | get_allocator | get_allocator | | | |
| Container | | **array** | **vector** | **deque** | **forward_list** | **list** | **set** | **multiset** | **map** | **multimap** | **unordered_set** | **unordered_multiset** | **unordered_map** | **unordered_multimap** | **stack** | **queue** | **priority_queue** |
| | | Sequence containers | | | | | Associative containers | | | | Unordered associative containers | | | | Container adaptors | | |

# *Smart Pointer

A good tool in modern C++

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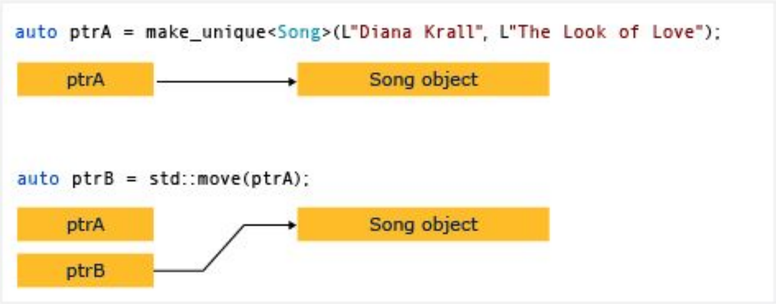
- A smart pointer is an abstract data type that simulates a pointer while providing added features, such as automatic memory management or bounds checking.
- C++ libraries provide implementations of smart pointers in the form of `unique_ptr`, `shared_ptr` and `weak_ptr`
- Trade-off by using smart pointers: may increase memory usage (for example in `list`)
- More info: [Smart pointer tutorial]

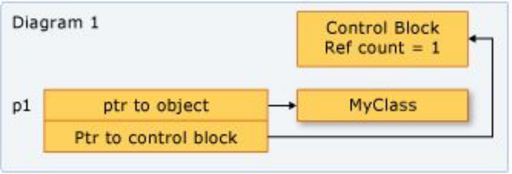
```
// normal pointers
void UseNormalPointer{
  MyClass *ptr = new MyClass();
  ptr->doSomething();
}
// We must delete ptr to avoid memory leak!
```

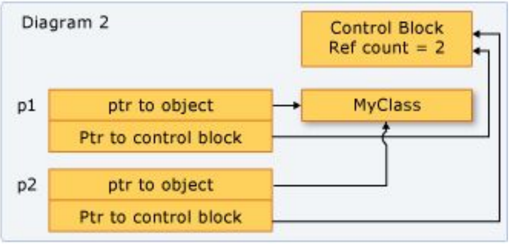
```
// smart pointers, defined in std
void UseSmartPointer{
  unique_ptr<MyClass> ptr(new MyClass());
  ptr->doSomething();
}
// ptr is deleted automatically here!
// unique_ptr:encapsulated pointer as only data member
```

# *Smart Pointer
## unique_ptr and shared_ptr

- unique_ptr
  - Allows exactly one owner of the underlying pointer.
  - Can be moved to a new owner, but not copied or shared.
  - Small and efficient (the size is one pointer as data member)
  - More about unique_ptr: [unique_ptr tutorial]
- shared_ptr
  - Reference-counted smart pointer. Use when you want to assign one raw pointer to multiple owners.
  - The size is two pointers; one for the object and one for the shared control block that contains the reference count.
  - More about shared_ptr: [shared_ptr tutorial]



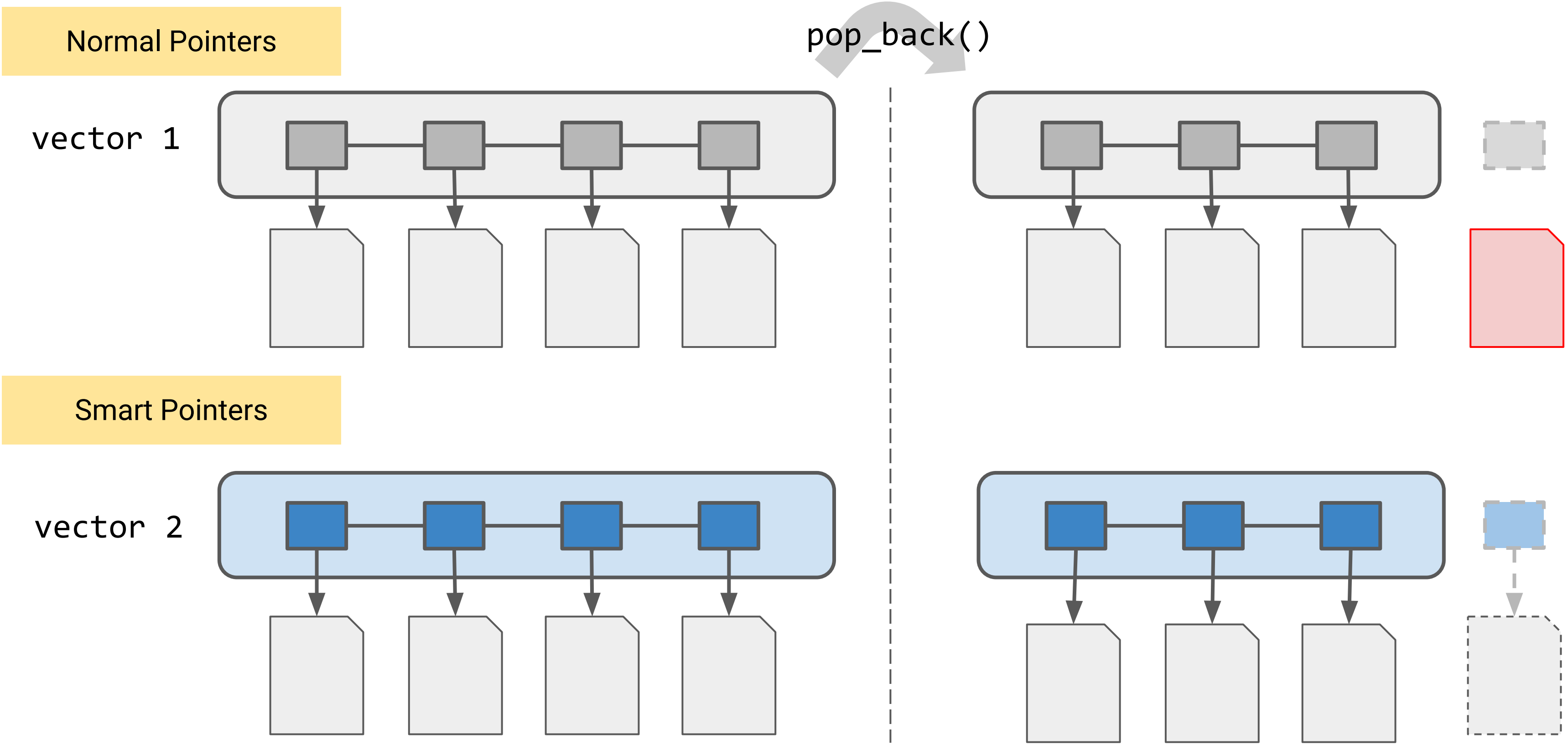
# Exercise

Try to implement a `unique_ptr`?

```
template<class T>
class unique_ptr {
 public:
  unique_ptr(T* p) : ptr_(p) {}
  ~unique_ptr() {
    delete ptr_;
  }
 private:
  T* ptr_;
};
```

# Pointers vs Smart Pointers

Example: Container of pointers



# Algorithm Efficiency

## Note: Complexity of a program

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- Quantify the efficiency of a program.
- The magnitude of time and space cost for an algorithm given certain size of input.
  - Time complexity: quantifies the run time.
  - Space complexity: quantifies the usage of the memory (or sometimes hard disk drives, cloud disk drives, etc.).
- Naturally, the size of input determines how long a program runs.
  - Often, the larger the size of input, the longer the run time. But not always that case.
  - Consider: sort an array of 1,000 items and 1,000,000 items vs get size of an array of 1,000 items and 1,000,000 items
- Big-O notation

# Big-O Notation

## Formal definition

If you are interested in formal definition, check here.

Well, you can simply understand as how many operations given input size of `n` regardless of the constant.

No need to memorize definitions.

Example: if your program takes,

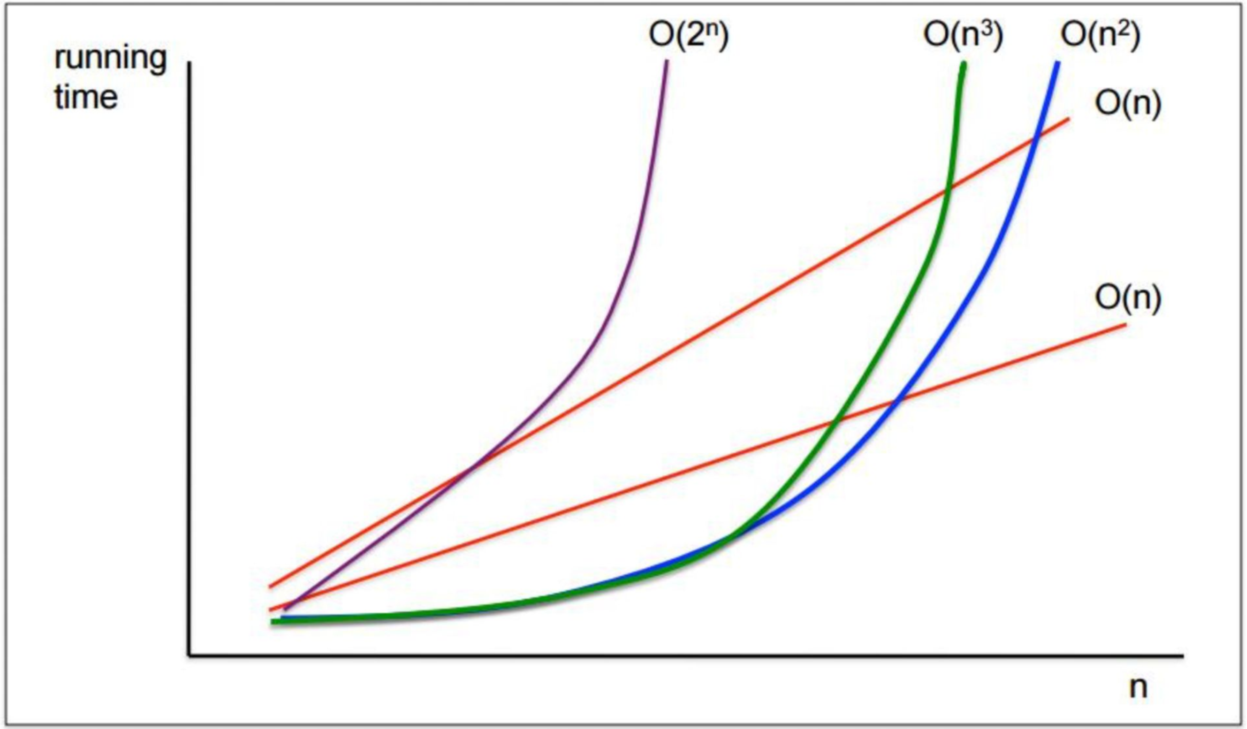
- about `n` steps → `O(n)`
- about `2n` steps → `O(n)`
- about `n^2` steps → `O(n^2)`
- about `3n^2+10n` steps → `O(n^2)`
- about `2^n` steps → `O(2^n)`

Question: What is the speed of growth for typical function?

`f(n) = log(n) / n / n^2 / 2^n / n!`

# Big-O Notation

## Growth speed



# Big-O Arithmetic

How to determine the entire program?

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Generally,

- If things happen sequentially, we add Big-Os;
- If one thing happen with another, then we multiply Big-Os.
- Watch the LOOPS in your programs!

Rules:

$$O(f(n)) + O(g(n)) = O(\max(f(n), g(n)))$$

$$O(f(n)) \times O(g(n)) = O(f(n) \times g(n))$$

# Efficiency Analysis

## Example 1: Linear Search

- Linear search: Look for one item in an unsorted array
- Best cases? Average cases? Worst cases?
- What if the array is ordered?

```
int linear_search(array arr, size n, value v)
{
  for (int i=0; i<n; i++)
  {
    if (arr[i] == v)
      return i;
  }
  return -1;
}
```

# Efficiency Analysis

Example 2: Enumerate all pairs

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- Task: Find all pairs from one array (Note: [1,2] and [2,1] are considered different pairs)

```
int all_pairs(array arr, size n, value v)
{
  for (int i=0; i<n; i++)
  {
    for (int j=0; i<n; j++)
    {
      if (i != j)
        cout << “Pair:” << arr[i] << “and” << arr[j] <<endl;
    }
  }
  return -1;
}
```

# Efficiency Analysis

## Example 3: Binary search

- Task: Look for one item in a sorted array

```
// this is pseudo code
int binary_search(array arr, value v, start_index s, end_index e)
{
  if (s > e) return -1
  find the middle point i=(s+e)/2
  if (arr[i] == v) return i
  else if (arr[i] < v) return binary_search(arr, v, i+1, e)
  else return binary_search(arr, v, s, i-1)
}
```

# Big-O and Complexity

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| Big O | Name | n = 128 |
|---|---|---|
| $O(1)$ | constant | 1 |
| $O(\log n)$ | logarithmic | 7 |
| $O(n)$ | linear | 128 |
| $O(n \log n)$ | "n log n" | 896 |
| $O(n^2)$ | quadratic | 16192 |
| $O(n^k)$, k >= 1 | polynomial | |
| $O(2^n)$ | exponential | $10^{40}$ |
| $O(n!)$ | factorial | $10^{214}$ |

Question: Can you find an algorithms with `O(n!)` complexity?

# Sorting
## Introduction

Most important algorithm ever!

Methods:

- Selection sort
- Bubble sort
- Insertion sort
- Merge sort
- Quick sort

Focus on:

1. Steps for each sorting algorithm
2. Runtime complexity for worst cases, best cases and average cases
3. Space complexity
4. How about additional assumptions, such as the array is “almost sorted” / “reversed” arrays

# Sorting

## Selection sort

**Steps:**

| | | | | |
|---|---|---|---|---|
| 4 | 3 | 1 | 5 | 2 |
| 1 | 3 | 4 | 5 | 2 |
| 1 | 2 | 4 | 5 | 3 |
| 1 | 2 | 3 | 5 | 4 |
| 1 | 2 | 3 | 4 | 5 |

**Idea:** Find the smallest item in the unsorted portion and place it in the front.

**Runtime complexity:**

Average: $O(n^2)$

Worst: $O(n^2)$

Best: $O(n^2)$

**Space complexity:** $O(1)$

# Sorting

## Insertion sort

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**Steps:**

| | | | | |
|---|---|---|---|---|
| 4 | 3 | 1 | 5 | 2 |
| 3 | 4 | 1 | 5 | 2 |
| 1 | 3 | 4 | 5 | 2 |
| 1 | 3 | 4 | 5 | 2 |
| 1 | 2 | 3 | 4 | 5 |

**Idea:** Pick one from the unsorted part and place it in the right position.

**Runtime complexity:**

Average: $O(n^2)$

Worst: $O(n^2)$

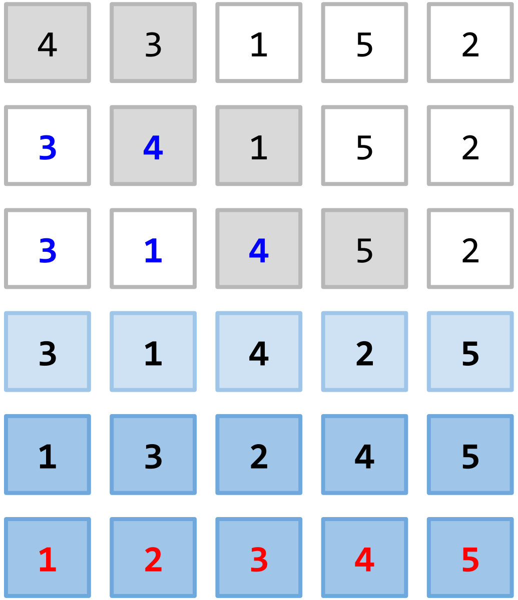
Best: $O(n)$

**Space complexity:** $O(1)$

# Sorting

## Bubble sort

**Steps:**




**Idea:** Well, just “bubble” as its name

**Runtime complexity:**

Average: $O(n^2)$

Worst: $O(n^2)$

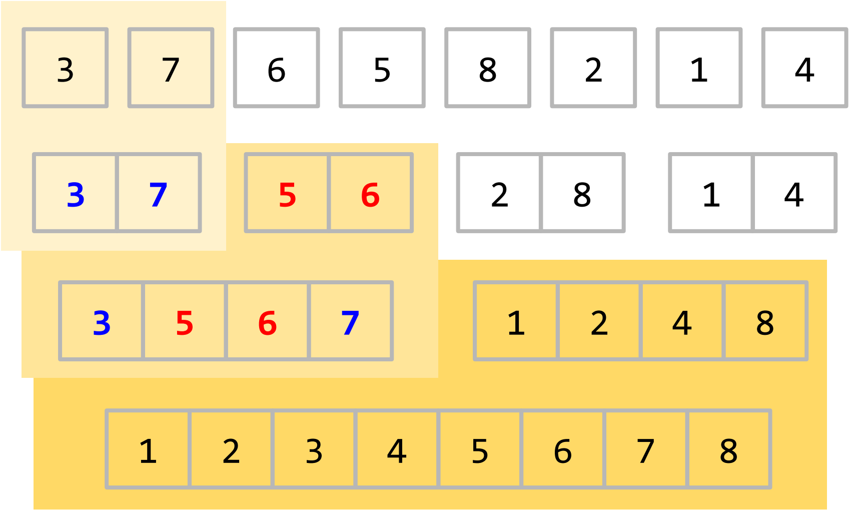
Best: $O(n)$

**Space complexity:** $O(1)$

# Sorting

## Merge sort

**Steps:**




**Idea:** Divide and conquer

**Runtime complexity:**

Average: $O(n \log n)$

Worst: $O(n \log n)$

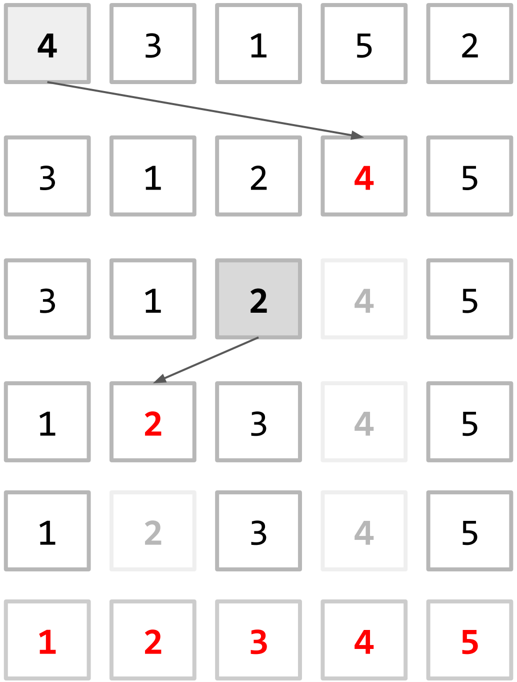
Best: $O(n \log n)$

**Space complexity:** $O(n)$

# Sorting

## Quicksort

**Steps:**




**Idea: Set a pivot. Numbers less then pivot are placed to front while other to end.**

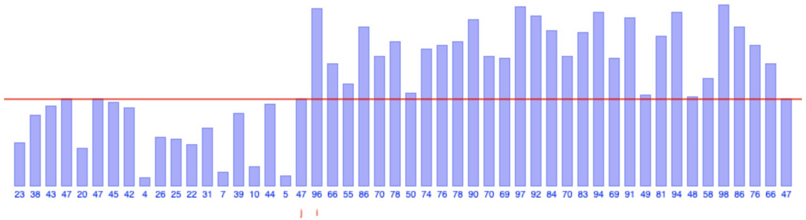
**Runtime complexity:**

Average: $O(n \log n)$

Worst: $O(n^2)$

Best: $O(n \log n)$

**Space complexity:** $O(\log n)$



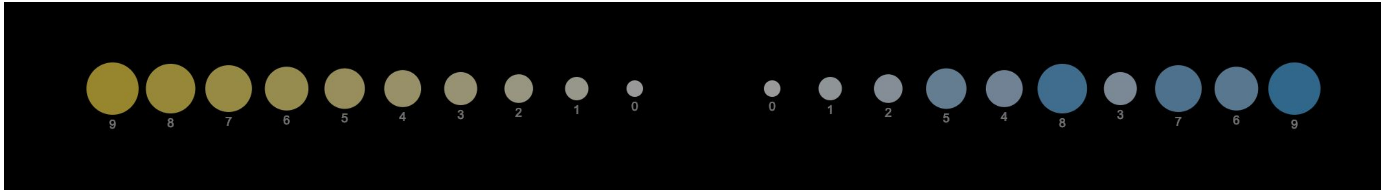
# Sorting

## Other methods and complexity?



- O(n log n) is faster than O(n^2) → Merge sort is more efficient than selection, insertion and bubble sort in runtime.
- O(n log n) is best average complexity that a general sorting algorithm can achieve.
- With more information about the data provided, you can sometimes sort things almost linearly.

Question: What is the complexity of these sorting algorithms if you know the array is **reversed**? What if the array is **almost already sorted**?

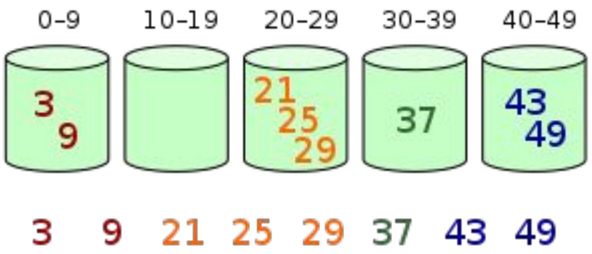


# Sorting

## Other methods and complexity?

There are many other sorting methods:

- Shell sort (shell 1959, Knuth 1973, Ciura 2001)
- Quicksort 3-way
- Heap sort
- Bucket sort



# Sorting

## Why sorting is important?

Sorting is the most important and basic algorithm. Many other real-world problems are somewhat based on sorting, including:

Sorting Algorithms Animations: https://www.toptal.com/developers/sorting-algorithms
Other good demos:
https://www.cs.usfca.edu/~galles/visualization/ComparisonSort.html
http://sorting.at/

# Sorting

## Variant sorting problems

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Question: How about get the *K-th* largest numbers in one array?

Leetcode question #215

Hint:

1. How to find the k-th largest numbers by merge sort and quicksort (or other sort methods)? What are the average and worst complexity?
2. What data structures is good to use?

# Big-O Notation

## Big-O Complexity Chart

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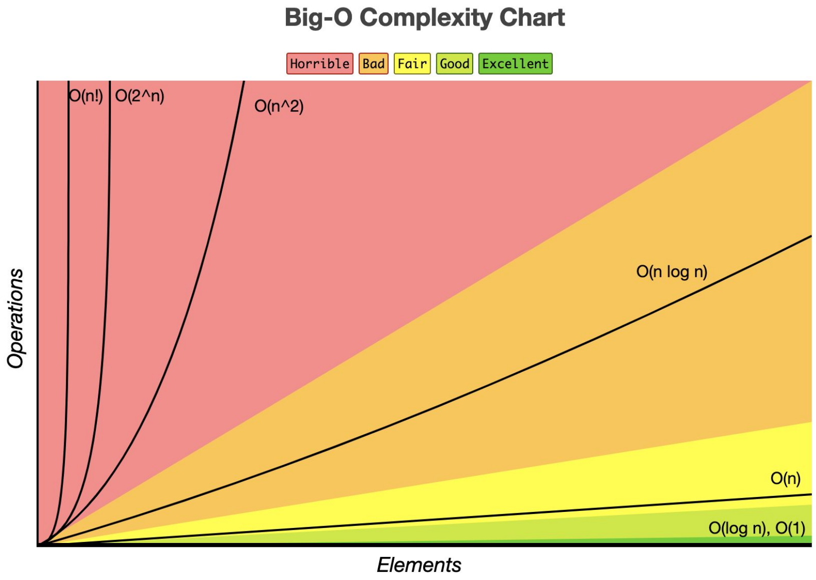


### Array Sorting Algorithms

| Algorithm | Time Complexity | | | Space Complexity |
|---|---|---|---|---|
| | Best | Average | Worst | Worst |
| Quicksort | Ω(n log(n)) | Θ(n log(n)) | O(n^2) | O(log(n)) |
| Mergesort | Ω(n log(n)) | Θ(n log(n)) | O(n log(n)) | O(n) |
| Timsort | Ω(n) | Θ(n log(n)) | O(n log(n)) | O(n) |
| Heapsort | Ω(n log(n)) | Θ(n log(n)) | O(n log(n)) | O(1) |
| Bubble Sort | Ω(n) | Θ(n^2) | O(n^2) | O(1) |
| Insertion Sort | Ω(n) | Θ(n^2) | O(n^2) | O(1) |
| Selection Sort | Ω(n^2) | Θ(n^2) | O(n^2) | O(1) |
| Tree Sort | Ω(n log(n)) | Θ(n log(n)) | O(n^2) | O(n) |
| Shell Sort | Ω(n log(n)) | Θ(n(log(n))^2) | O(n(log(n))^2) | O(1) |
| Bucket Sort | Ω(n+k) | Θ(n+k) | O(n^2) | O(n) |
| Radix Sort | Ω(nk) | Θ(nk) | O(nk) | O(n+k) |
| Counting Sort | Ω(n+k) | Θ(n+k) | O(n+k) | O(k) |
| Cubesort | Ω(n) | Θ(n log(n)) | O(n log(n)) | O(n) |

# Thank you!

Q & A