C++ Data Structures and Algorithms Cheat Sheet

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1.2 Vector `std::vector`

Use for * Simple storage * Adding but not deleting * Serialization * Quick lookups by index * Easy conversion to C-style arrays * Efficient traversal (contiguous CPU caching)

Do not use for * Insertion/deletion in the middle of the list * Dynamically changing storage * Non-integer indexing

Time Complexity

Operation	Time Complexity
Insert Head	`O(n)`
Insert Index	`O(n)`
Insert Tail	`O(1)`
Remove Head	`O(n)`
Remove Index	`O(n)`
Remove Tail	`O(1)`
Find Index	`O(1)`

Operation	Time Complexity
Find Object	`O(n)`

Example Code ```c++ std::vector v;

//-------------------------------- // General Operations //--------------------------------

// Size unsigned int size = v.size();

// Insert head, index, tail v.insert(v.begin(), value); // head v.insert(v.begin() + index, value); // index v.push_back(value); // tail

// Access head, index, tail int head = v.front(); // head head = v[0]; // or using array style indexing

int value = v.at(index); // index value = v[index]; // or using array style indexing

int tail = v.back(); // tail tail = v[v.size() - 1]; // or using array style indexing

// Iterate for(std::vector::iterator it = v.begin(); it != v.end(); it++) { std::cout << *it << std::endl; }

// Remove head, index, tail v.erase(v.begin()); // head v.erase(v.begin() + index); // index v.pop_back(); // tail

// Clear v.clear();

````
 -------------------------------------------------------
### 1.3 Deque `std::deque`
**Use for**
* Similar purpose of `std::vector`
* Basically `std::vector` with efficient `push_front` and `pop_front`

**Do not use for**
* C-style contiguous storage (not guaranteed)

**Notes**
* Pronounced 'deck'
* Stands for **D**ouble **E**nded **Que**ue

**Example Code**
```c++
std::deque<int> d;

//---------------------------------
// General Operations
//---------------------------------

// Insert head, index, tail
d.push_front(value);                    // head
d.insert(d.begin() + index, value);     // index
d.push_back(value);                     // tail

// Access head, index, tail
int head = d.front();       // head
int value = d.at(index);    // index
int tail = d.back();        // tail

// Size
unsigned int size = d.size();

// Iterate
for(std::deque<int>::iterator it = d.begin(); it != d.end(); it++) {
    std::cout << *it << std::endl;
}

// Remove head, index, tail
d.pop_front();                  // head
d.erase(d.begin() + index);     // index
d.pop_back();                   // tail

// Clear
d.clear();
````
````

1.4 List `std::list` and `std::forward_list`

Use for * Insertion into the middle/beginning of the list * Efficient sorting (pointer swap vs. copying)

Do not use for * Direct access

Time Complexity

Operation	Time Complexity
Insert Head	`O(1)`
Insert Index	`O(n)`
Insert Tail	`O(1)`
Remove Head	`O(1)`
Remove Index	`O(n)`
Remove Tail	`O(1)`
Find Index	`O(n)`
Find Object	`O(n)`

Example Code ```c++ std::list l;

//-------------------------------- // General Operations //--------------------------------

// Insert head, index, tail l.push_front(value); // head l.insert(l.begin() + index, value); // index l.push_back(value); // tail

// Access head, index, tail int head = l.front(); // head int value = std::next(l.begin(), index); // index int tail = l.back(); // tail

// Size unsigned int size = l.size();

// Iterate for(std::list::iterator it = l.begin(); it != l.end(); it++) { std::cout << *it << std::endl; }

// Remove head, index, tail l.pop_front(); // head l.erase(l.begin() + index); // index l.pop_back(); // tail

// Clear l.clear();

//-------------------------------- // Container-Specific Operations //--------------------------------

// Splice: Transfer elements from list to list // splice(iterator pos, list &x) // splice(iterator pos, list &x, iterator i) // splice(iterator pos, list &x, iterator first, iterator last) l.splice(l.begin() + index, list2);

// Remove: Remove an element by value l.remove(value);

// Unique: Remove duplicates l.unique();

// Merge: Merge two sorted lists l.merge(list2);

// Sort: Sort the list l.sort();

// Reverse: Reverse the list order l.reverse();

```
-------------------------------------------------------
### 1.5 Map `std::map` and `std::unordered_map`
**Use for**
* Key-value pairs
* Constant lookups by key
* Searching if key/value exists
* Removing duplicates
* `std::map`
    * Ordered map
* `std::unordered_map`
    * Hash table

**Do not use for**
* Sorting

**Notes**
* Typically ordered maps (`std::map`) are slower than unordered maps (`std::unordered_map`)
* Maps are typically implemented as *binary search trees*
```

````
**Time Complexity**

**`std::map`**

| Operation           | Time Complexity |
|---------------------|-----------------|
| Insert              |     `O(log(n))` |
| Access by Key       |     `O(log(n))` |
| Remove by Key       |     `O(log(n))` |
| Find/Remove Value   |     `O(log(n))` |

**`std::unordered_map`**

| Operation           | Time Complexity |
|---------------------|-----------------|
| Insert              |          `O(1)` |
| Access by Key       |          `O(1)` |
| Remove by Key       |          `O(1)` |
| Find/Remove Value   |              -- |

**Example Code**
```c++
std::map<std::string, std::string> m;

//---------------------------------
// General Operations
//---------------------------------

// Insert
m.insert(std::pair<std::string, std::string>("key", "value"));

// Access by key
std::string value = m.at("key");

// Size
unsigned int size = m.size();

// Iterate
for(std::map<std::string, std::string>::iterator it = m.begin(); it != m.end(); it++) {
    std::cout << *it << std::endl;
}

// Remove by key
m.erase("key");

// Clear
m.clear();

//---------------------------------
// Container-Specific Operations
//---------------------------------

// Find if an element exists by key
bool exists = (m.find("key") != m.end());

// Count the number of elements with a certain key
unsigned int count = m.count("key");
````

1.6 Set `std::set`

Use for * Removing duplicates * Ordered dynamic storage

Do not use for * Simple storage * Direct access by index
````

Notes * Sets are often implemented with binary search trees

Time Complexity

Operation	Time Complexity
Insert	`O(log(n))`
Remove	`O(log(n))`
Find	`O(log(n))`

Example Code ```c++ std::set s;

//-------------------------------- // General Operations //--------------------------------

// Insert s.insert(20);

// Size unsigned int size = s.size();

// Iterate for(std::set::iterator it = s.begin(); it != s.end(); it++) { std::cout << *it << std::endl; }

// Remove s.erase(20);

// Clear s.clear();

//-------------------------------- // Container-Specific Operations //--------------------------------

// Find if an element exists bool exists = (s.find(20) != s.end());

// Count the number of elements with a certain value unsigned int count = s.count(20);

````
-------------------------------------------------------
### 1.7 Stack `std::stack`
**Use for**
* First-In Last-Out operations
* Reversal of elements

**Time Complexity**

| Operation    | Time Complexity |
|--------------|-----------------|
| Push         |          `O(1)`  |
| Pop          |          `O(1)`  |
| Top          |          `O(1)`  |

**Example Code**
```c++
std::stack<int> s;

//--------------------------------
// Container-Specific Operations
//--------------------------------

// Push
s.push(20);

// Size
unsigned int size = s.size();

// Pop
s.pop();

// Top
int top = s.top();
````

1.8 Queue `std::queue`

Use for * First-In First-Out operations * Ex: Simple online ordering system (first come first served) * Ex: Semaphore queue handling * Ex: CPU scheduling (FCFS)

Notes * Often implemented as a `std::deque`
````

Example Code ```c++ std::queue q;

//-------------------------------- // General Operations //--------------------------------

// Insert q.push(value);

// Access head, tail int head = q.front(); // head int tail = q.back(); // tail

// Size unsigned int size = q.size();

// Remove q.pop();

````
-------------------------------------------------------
### 1.9 Priority Queue `std::priority_queue`
**Use for**
* First-In First-Out operations where **priority** overrides arrival time
* Ex: CPU scheduling (smallest job first, system/user priority)
* Ex: Medical emergencies (gunshot wound vs. broken arm)

**Notes**
* Often implemented as a `std::vector`

**Example Code**
```c++
std::priority_queue<int> p;

//---------------------------------
// General Operations
//---------------------------------

// Insert
p.push(value);

// Access
int top = p.top();  // 'Top' element

// Size
unsigned int size = p.size();

// Remove
p.pop();
````

1.10 Heap `std::priority_queue`

Notes * A heap is essentially an instance of a priority queue * A **min** heap is structured with the root node as the smallest and each child subsequently larger than its parent * A **max** heap is structured with the root node as the largest and each child subsequently smaller than its parent * A min heap could be used for *Smallest Job First* CPU Scheduling * A max heap could be used for *Priority* CPU Scheduling

Max Heap Example (using a binary tree)

2.0 Trees

2.1 Binary Tree

* A binary tree is a tree with at most two (2) child nodes per parent
* Binary trees are commonly used for implementing `O(log(n))` operations for ordered maps, sets, heaps, and binary search trees
* Binary trees are **sorted** in that nodes with values greater than their parents are inserted to the **right**, while nodes with values less than their parents are inserted to the **left**

Binary Search Tree

2.2 Balanced Trees
````

- Balanced trees are a special type of tree which maintains its balance to ensure `O(log(n))` operations
- When trees are not balanced the benefit of `log(n)` operations is lost due to the highly vertical structure
- Examples of balanced trees:
    - AVL Trees
    - Red-Black Trees

2.3 Binary Search

Idea: 1. If current element, return 2. If less than current element, look left 3. If more than current element, look right 4. Repeat

Data Structures: * Tree * Sorted array

Space: * `O(1)`

Best Case: * `O(1)`

Worst Case: * `O(log n)`

Average: * `O(log n)`

Visualization:

2.4 Depth-First Search

Idea: 1. Start at root node 2. Recursively search all adjacent nodes and mark them as searched 3. Repeat

Data Structures: * Tree * Graph

Space: * `O(V)`, `V = number of verticies`

Performance: * `O(E)`, `E = number of edges`

Visualization:

2.5 Breadth-First Search

Idea: 1. Start at root node 2. Search neighboring nodes first before moving on to next level

Data Structures: * Tree * Graph

Space: * `O(V)`, `V = number of verticies`

Performance: * `O(E)`, `E = number of edges`

Visualization:

3.0 NP Complete Problems

3.1 NP Complete

- **NP Complete** means that a problem is unable to be solved in **polynomial time**
- NP Complete problems can be *verified* in polynomial time, but not *solved*

3.2 Traveling Salesman Problem

3.3 Knapsack Problem

Implementation

4.0 Algorithms

4.1 Insertion Sort

Idea

1. Iterate over all elements
2. For each element:
    - Check if element is larger than largest value in sorted array
3. If larger: Move on
4. If smaller: Move item to correct position in sorted array

Details

- **Data structure:** Array
- **Space:** `O(1)`
- **Best Case:** Already sorted, `O(n)`
- **Worst Case:** Reverse sorted, `O(n^2)`
- **Average:** `O(n^2)`

Advantages

- Easy to code
- Intuitive
- Better than selection sort and bubble sort for small data sets
- Can sort in-place

Disadvantages

- Very inefficient for large datasets

Visualization

4.2 Selection Sort

Idea

1. Iterate over all elements
2. For each element:
    - If smallest element of unsorted sublist, swap with left-most unsorted element

Details

- **Data structure:** Array
- **Space:** `O(1)`
- **Best Case:** Already sorted, `O(n^2)`
- **Worst Case:** Reverse sorted, `O(n^2)`
- **Average:** `O(n^2)`

Advantages

- Simple
- Can sort in-place
- Low memory usage for small datasets

Disadvantages

- Very inefficient for large datasets

Visualization

SelectionSort

4.3 Bubble Sort

Idea

1. Iterate over all elements
2. For each element:

    - Swap with next element if out of order
3. Repeat until no swaps needed

Details

- **Data structure:** Array
- **Space:** `O(1)`
- **Best Case:** Already sorted `O(n)`
- **Worst Case:** Reverse sorted, `O(n^2)`
- **Average:** `O(n^2)`

Advantages

- Easy to detect if list is sorted

Disadvantages

- Very inefficient for large datasets
- Much worse than even insertion sort

Visualization

4.4 Merge Sort

Idea

1. Divide list into smallest unit (1 element)
2. Compare each element with the adjacent list
3. Merge the two adjacent lists
4. Repeat

Details

- **Data structure:** Array
- **Space:** `O(n) auxiliary`
- **Best Case:** `O(nlog(n))`
- **Worst Case:** Reverse sorted, `O(nlog(n))`
- **Average:** `O(nlog(n))`

Advantages

- High efficiency on large datasets
- Nearly always O(nlog(n))
- Can be parallelized
- Better space complexity than standard Quicksort

Disadvantages

- Still requires O(n) extra space
- Slightly worse than Quicksort in some instances

Visualization

MergeSort

4.5 Quicksort

Idea

1. Choose a **pivot** from the array
2. Partition: Reorder the array so that all elements with values *less* than the pivot come before the pivot, and all values *greater* than the pivot come after
3. Recursively apply the above steps to the sub-arrays

Details

- **Data structure:** Array
- **Space:** `O(n)`

- **Best Case:** `O(nlog(n))`
- **Worst Case:** All elements equal, `O(n^2)`
- **Average:** `O(nlog(n))`

Advantages

- Can be modified to use O(log(n)) space
- Very quick and efficient with large datasets
- Can be parallelized
- Divide and conquer algorithm

Disadvantages

- Not stable (could swap equal elements)
- Worst case is worse than Merge Sort

Optimizations

- Choice of pivot:
  - Choose median of the first, middle, and last elements as pivot
  - Counters worst-case complexity for already-sorted and reverse-sorted

Visualization

QuickSort