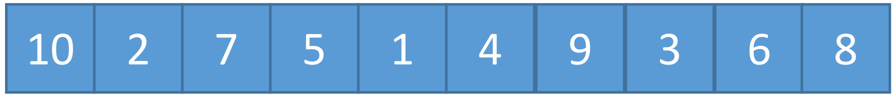
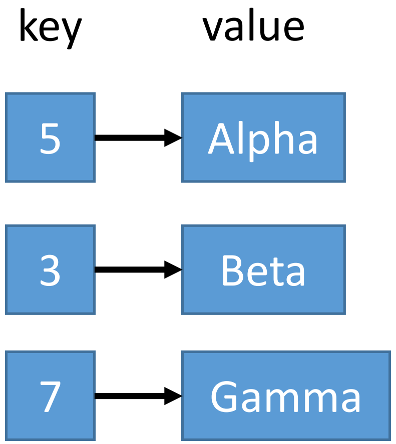
Data Structures



10	2	7	5	1	4	9	3	6	8

Sequence

e.g., C-Arrays, std::vector, std::deque, std::list



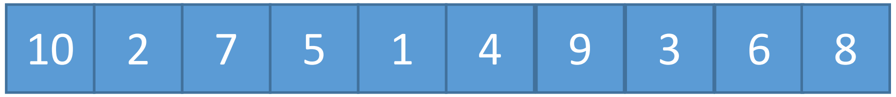
key	value
5	Alpha
3	Beta
7	Gamma

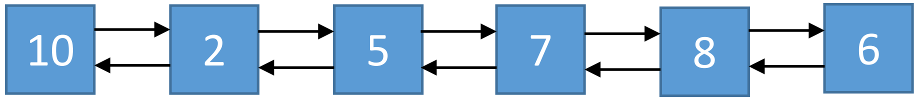
Associative

e.g., C-Arrays, std::map, std::set, std::unordered_map

Data Structures

- Operations:
  - Insertion
  - Searching
  - Deletion
- Variants:
  - Ordered
  - Unordered





Sequential Containers

Arrays, Lists, Queues, Stacks

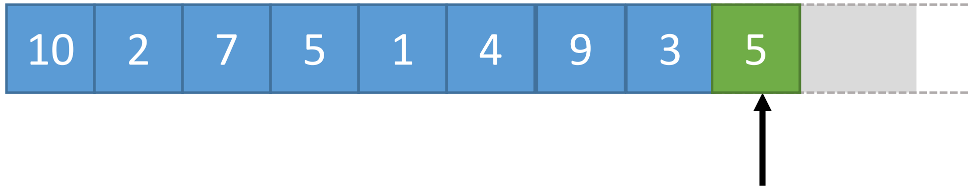
STL Containers

- Sequence Containers
    - vector (flexible sequence)
    - deque (double-ended queue)
    - list (double linked list)
    - array (fixed sequence, C++11)
    - forward_list (single linked list, C++11)

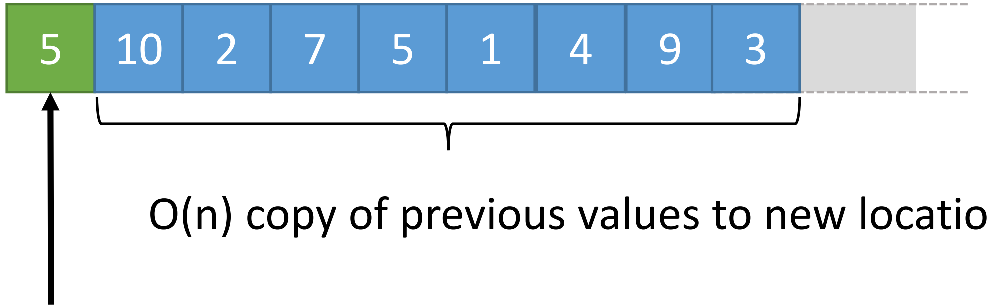
C-Arrays

- Simplest Sequence Data Structure
- Data stored in range [0, numElements)
- Fixed Size, Wasteful
- Consecutive Memory (efficient access)

```
int a[10000];
int numElements = 0;

// insertion at end O(1)
a[numElements++] = new_value;

// insertion at beginning O(n)
for(int i = numElements; i > 0; i--) a[i] = a[i-1];
a[0] = new_value;
numElements++;
```

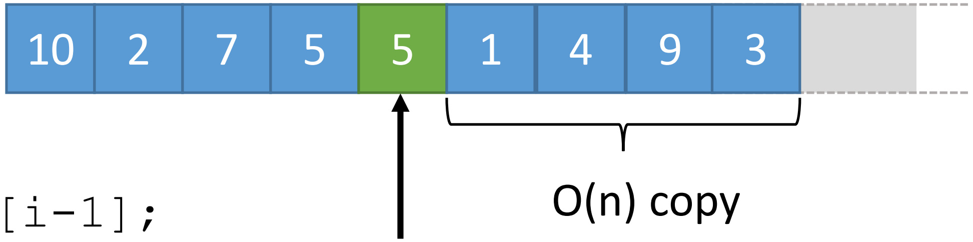


Inserting at end is O(1)



O(n) copy of previous values to new location

Therefore inserting at beginning is O(n)



O(n) copy

inserting in the middle is O(n)

std::vector

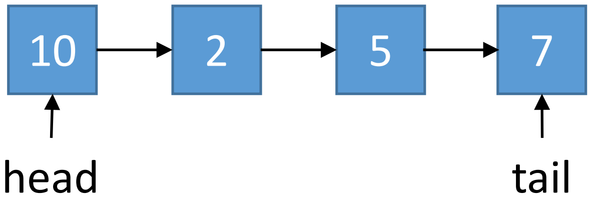
```
#include <iostream>
#include <vector>

using namespace std;

// empty construction
vector<int> a;
// sized construction
vector<int> a(10);
// sized construction with initial value
vector<int> a(100, -1);
// C++ 11 initializer lists
vector<int> a { 3, 5, 7, 9, 11 };

// insertion at end
a.push_back(3);
a.push_back(5);
a.push_back(7);

// delete at end
a.pop_back();

// insertion at beginning
a.insert(a.begin(), new_value);
```

```
// accessing elements just like arrays
for(int i = 0; i < a.size(); i++) {
   cout << a[i] << endl;
}

// using iterators
for(auto i = a.begin(); i != a.end(); ++i) {
   cout << *i << endl;
}

// C++11 for each
for(auto element : a) {
   cout << element << endl;
}
```

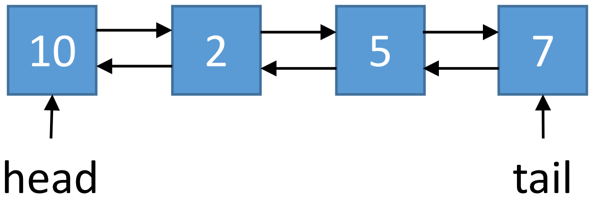
Linked-List

- List Elements connected through pointers
- First Element (head) and last element (tail) are always known
- Insertion/Deletion at **both** ends in O(1)
- Insertion in the middle is also cheaper
  - Finding insertion location is O(n) compared to O(1) with C-Arrays
  - But insertion itself happens in O(1) instead of O(n) copies
- Dynamic Size
- Distributed in memory

Single Linked-List:
only pointer of next element



Double Linked-List:
pointer of previous and next element



```
struct Node {
     Node * prev;
     Node * next;
     int data;
}
```

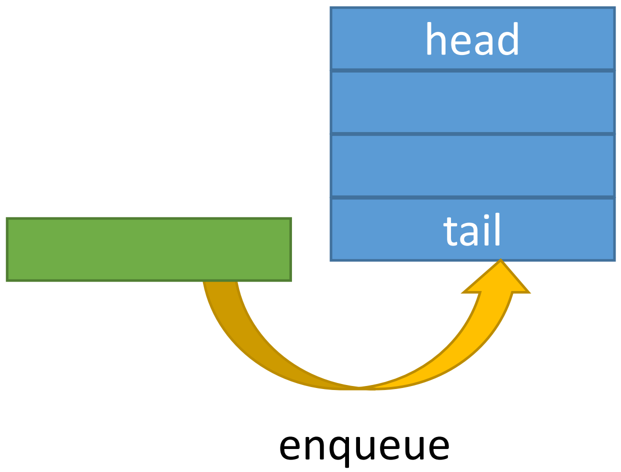
std::list

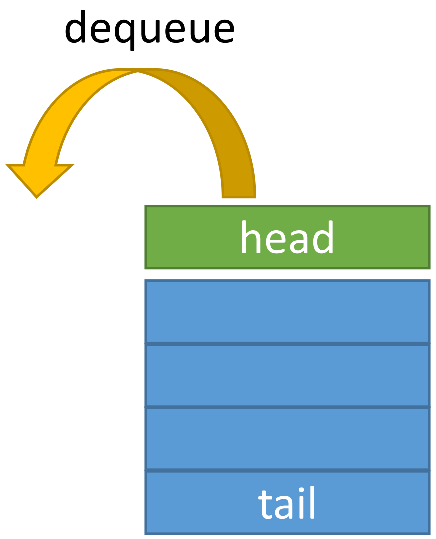
```
#include <iostream>
#include <list>

using namespace std;

// empty construction
list<int> a;
// sized construction
list<int> a(10);
// sized construction with initial value
list<int> a(100, -1);
// C++ 11 initializer lists
list<int> a { 3, 5, 7, 9, 11 };

// insertion at beginning
a.push_front(3);

// insertion at end
a.push_back(3);

// delete at beginning
a.pop_front();

// delete at end
a.pop_back();
```

```
// access front element
int first = a.front();

// access last element
int last = a.back();

// using iterators
for(auto i = a.begin(); i != a.end(); ++i) {
   cout << *i << endl;
}

// C++11 for each
for(auto element : a) {
   cout << element << endl;
}
```

Queue

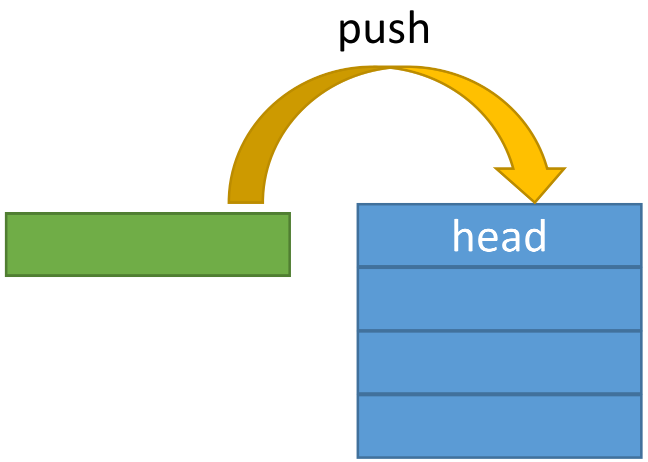
- First-In-First-Out (FIFO) data structure
- Implementations:
  - Double-Linked-List
- Operations:
  - **enqueue**: put element in queue (insert at tail)
  - **dequeue**: get first element in queue (remove head)

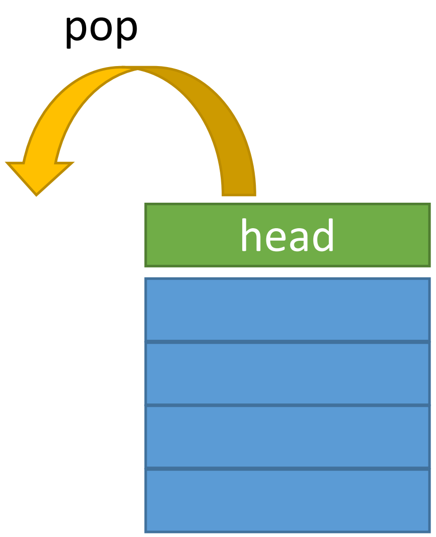


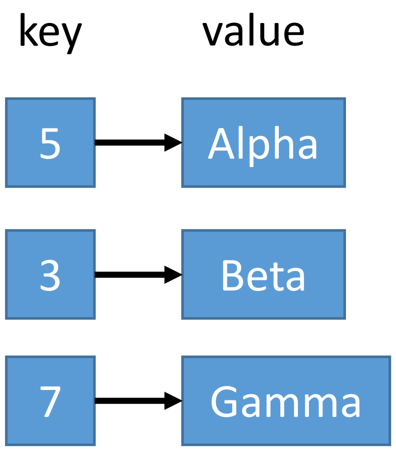


Stack

- Last-In-First-Out (LIFO) data structure
- Implementations:
  - C-Array
  - Single-Linked-List
- Operations:
  - **push**: put element on stack (insert as first element)
  - **pop**: get first element on stack (remove head)







key	value
5	Alpha
3	Beta
7	Gamma

Associative Containers

Dictionaries, Maps, Sets

Associative Containers

- Map a key to a value
- Searching for a specific element in unsorted sequential containers takes **linear** time O(n)
- Getting a specific element from an associative container can be as fast as **constant** time O(1)

STL Containers

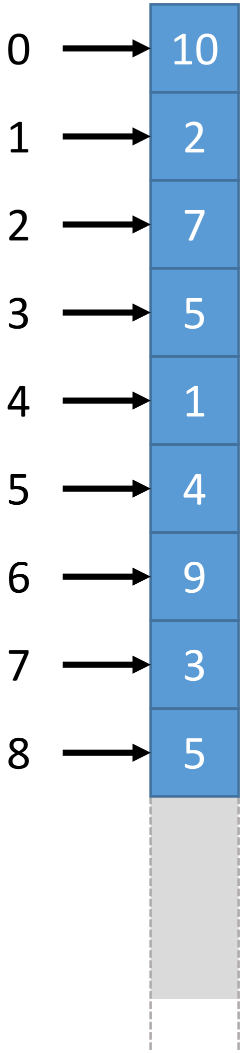
- Associative Containers
    - map
    - set
    - multimap
    - multiset

    - unordered_map (C++11)
    - unordered_set (C++11)
    - unordered_multimap (C++11)
    - unordered_multiset (C++11)

C-Array as Associative Container

- Simplest associative data structure
- maps **integer number** to data
  - 0 -> a[0]
  - 1 -> a[1]
  - …
- **efficient access in O(1)**
- **inefficient storage**
- **limited to positive integer numbers as keys**

```
int a[10000];
```



Ordered maps

- Maps **arbitrary keys** (objects, basic types) to **arbitrary values** (objects, basic types)
- Basic idea: if keys are sortable, we can store nodes in a data structure sorted by its keys. Sorted data structures can be searched more quickly, e.g. with binary search in O(log(n))
- Elements ordered by key
- **Worst case lookup time is O(log(n))**

std::map

```
#include <iostream>
#include <map>
#include <string>

using namespace std;

map<string, string> capitals;

// setting value for key
capitals["Austria"] = "Vienna";
capitals["France"] = "Paris";
capitals["Italy"] = "Rome";

// getting value from key
cout << "Capital of Austria: " << capitals["Austria"] << endl;
string & capital_of_france = capitals["France"];
cout << "Capital of France: " << capitals << endl;


// check if key is set
if (capitals.find("Spain") != capitals.end()) {
    cout << "Capital of Spain is " << capitals["Spain"]  << endl;
else {
    cout << "Capital of Spain not found!" << endl;
}
```

std::map

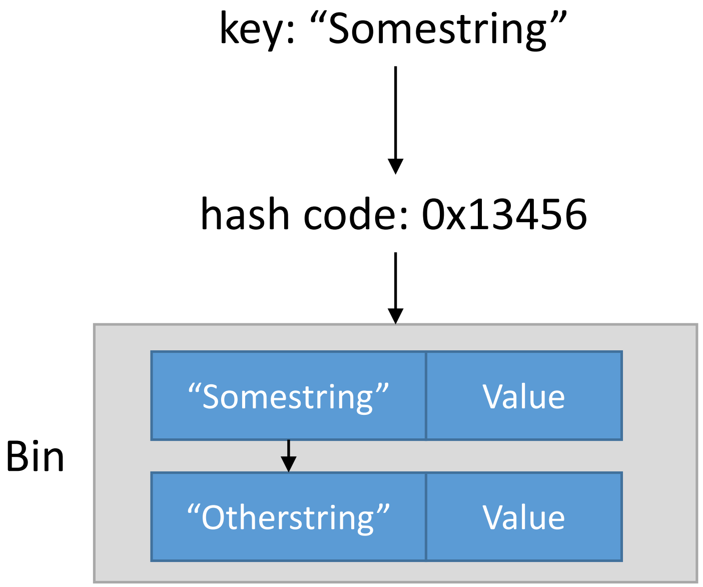
```
// iterate over all elements
for (map<string, string>::iterator it = capitals.begin(); it != capitals.end(); ++it) {
    string & key = it->first;
    string & value = it->second;
    cout << "The capitol of " << key << " is " << value << endl;
}

// C++11: iterate over all elements
for (auto it = capitals.begin(); it != capitals.end(); ++it) {
    string & key = it->first;
    string & value = it->second;
    cout << "The capitol of " << key << " is " << value << endl;
}

// C++11: iterate over all elements
for (auto & kv : capitals) {
    string & key = kv.first;
    string & value = kv.second;
    cout << "The capitol of " << key << " is " << value << endl;
}
```

Unordered maps / Hash maps

On average lookup times are O(1). But this is only true if there are only few hash collisions.

Hash maps require **a good hashing function**, which reduces the amount of hash collisions.

- Maps **arbitrary keys** (objects, basic types) to **arbitrary values** (objects, basic types)
- **On average accessing a hash map through keys takes O(1)**
- In general unordered structure - you can't get out objects in the same order you inserted them.
- a number, called a **hash code**, is generated using a **hash function** based on key in O(1)
- Each hash code can be mapped to a location called a bin
- A bin stores nodes with keys which map to the same hash code
- Lookup therefore consists of:
  - Determining the hash code of the key O(1)
  - Selecting the correct node inside the bin is in the worst case O(n)


key: "Somestring"
hash code: 0x13456
Bin
"Somestring"
Value
"Otherstring"
Value