GB21802 - Programming Challenges

Week 1 - Data Structures

Claus Aranha
caranha@cs.tsukuba.ac.jp

College of Information Science

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Results for the Previous Week

Results on Wednesday:

Week 0: Introduction and Problem Solving

Deadline: 4/18/2019, 11:59:59 PM (1 day, 07:07 hours from now)

Problems Solved -- 0P:16, 1P:5, 2P:2, 3P:2, 4P:13, 5P:2, 6P:3, 7P:1, 8P:4,

#	Name	Sol/Sub/Total	My Status
1	The 3n + 1 problem	27/31/48	
2	Cost Cutting	28/29/48	
3	Event Planning	21/22/48	
4	Horror Dash	26/26/48	
5	Y3K Problem	11/12/48	
6	Stack 'em Up	6/7/48	
7	Traffic Lights	7/7/48	
8	Jolly Jumpers	8/10/48	

click to show/hide

Hint: Take a quick look at all problems before solving!

Messages to Students:

1. Be careful with the input: Worst cases and TLE
2. Use **pipes** to avoid typing cases by hand!

```
$ java Main < input.in
1 10 20
10 1 20
10 10 7
```

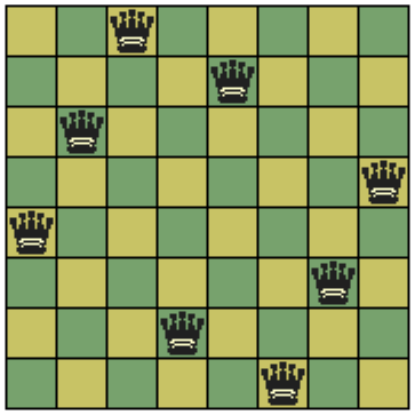
Data Structures
CP Book Chapter 2

Data Structures and Programming Challenges

- Using the correct data structure makes the program faster.
- Using the correct data structure makes the problem easier.
- Every program needs some data structure. Learn it!

In this lecture, we review some common data structures, and we also look a bit at common library functions

Example 0: 8 Queen Problem (UVA 750)



For a board of size $n \times n$, find how many safe configurations of n queens exist.

Because we need to find how many configurations exist, we need to test "all" configurations.

```
for i = 0 to #configurations do
  sum = testIfConfigurationIsSafe(i)
```

Image by Lee Daniel Crocker. CC-BY-SA 3.0

Example 0: 8 Queen Problem (UVA 750)

How can we represent a configuration?

(1) Position x, y of every queen (size: n^{n^2})

```
conf[0] = {{a,1}, {a,1}, {a,1}, ... {a,1}, {a,1}}
conf[1] = {{a,1}, {a,1}, {a,1}, ... {a,1}, {a,2}}
conf[2] = {{a,1}, {a,1}, {a,1}, ... {a,1}, {a,3}}
```

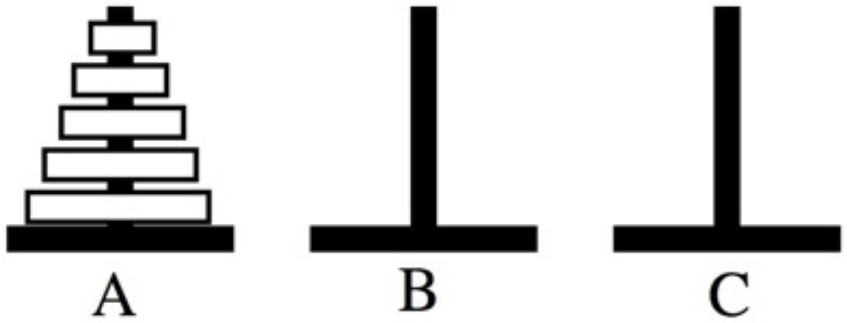
(2) Row r of every queen (size: n^n)

```
conf[0] = {0,0,0,0,0,0,0,0}
conf[1] = {0,0,0,0,0,0,0,1}
conf[2] = {0,0,0,0,0,0,0,2}
```

(3) Permutation of row positions (size: $n!$)

```
conf[0] = {0,1,2,3,4,5,6,7}
conf[1] = {0,1,2,3,4,5,7,6}
conf[2] = {0,1,2,3,4,6,5,7}
```

Example 1: The Towers of Hanoi



- You have N disks and K poles. Each disk has unique size s_i.
- A disk i can be moved from one pole to another.
- A move of disk i to pole k is only valid if k has no disks smaller than i
- Find the list of moves to move all disks from pole 1 to pole K.

How do you represent the data in this problem?

Example 1: The Towers of Hanoi

A string with “n” disks, from smaller to larger.

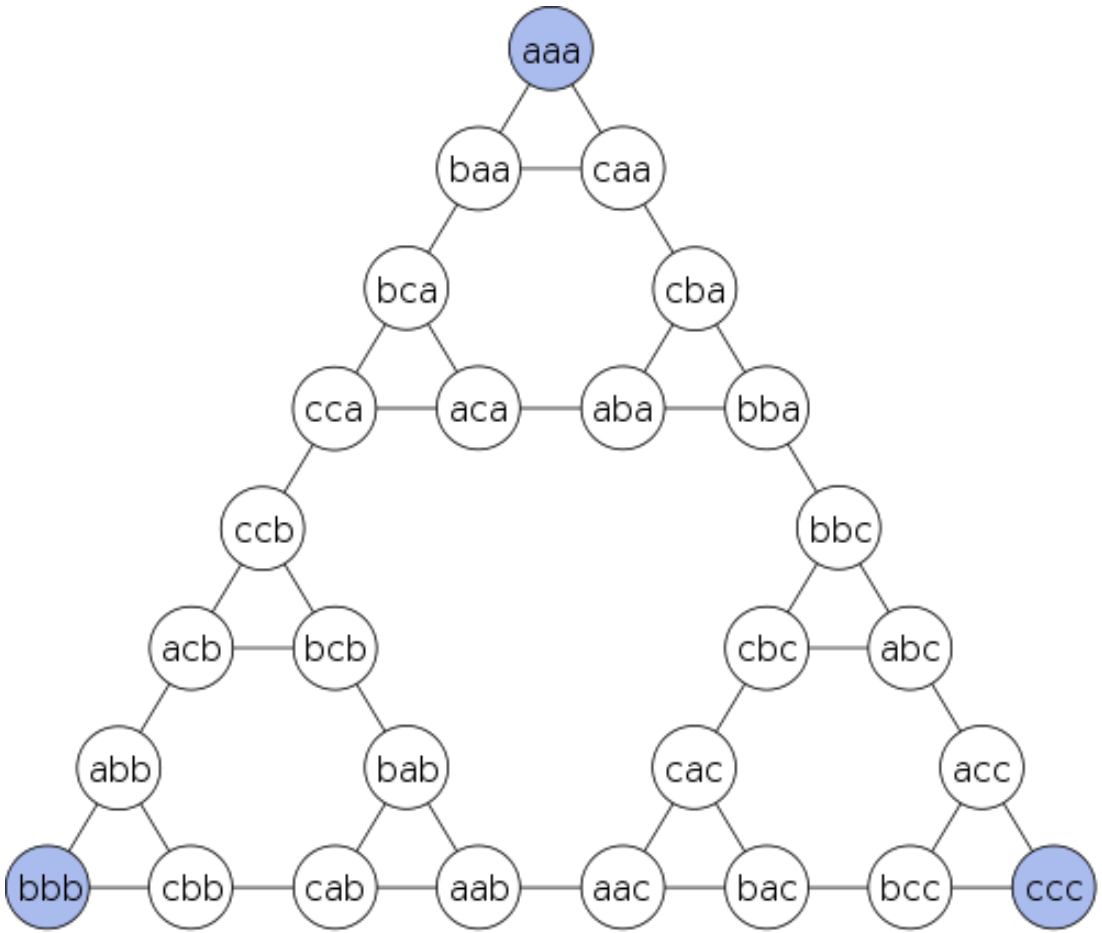


Image created by nonenmac

Example 2: Army Buddies (UVA 12356)

Problem Description

- There is a line of S soldiers: $0, 1, 2, 3, 4, ..., S$
- There are Q queries that remove soldiers from i to j:

```
Q1: 2,4          (removes soldiers 2, 3, 4)
Q2: 6,7          (removes soldiers 6, 7)
Q3: 1,1          (removes soldier 1)
```

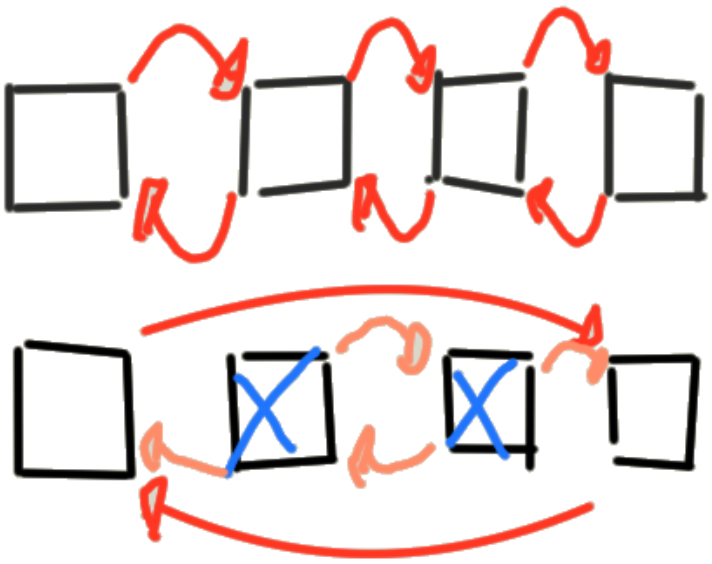
- For each query, list the soldier to the left and to the right

```
A1: 1,5          1 x x x 5 6 7
A2: 5,*          1 - - - 5 x x
A3: *,5          x - - - 5 - -
```

How do we solve this problem?

Example 2: Army Buddies (UVA 12356)

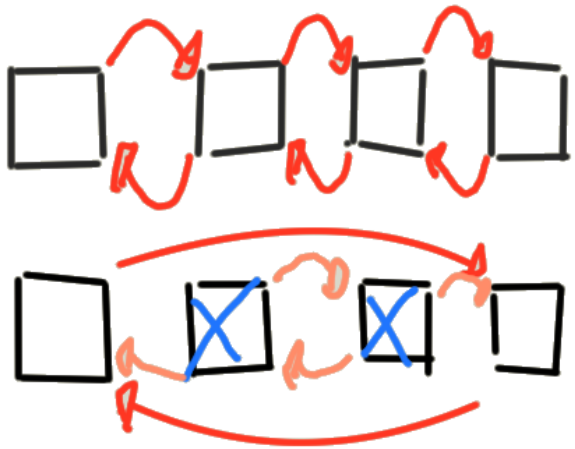
Idea 1: Linked Lists



- Represent the line as a linked list.
- Find the 1^{st} soldier (This is $O(n)$)
- Find the 2^{nd} soldier (This is $O(n)$)
- Update the list and print the neighbors. (This is $O(1)$)

Example 2: Army Buddies (UVA 12356)

A solution using linked lists



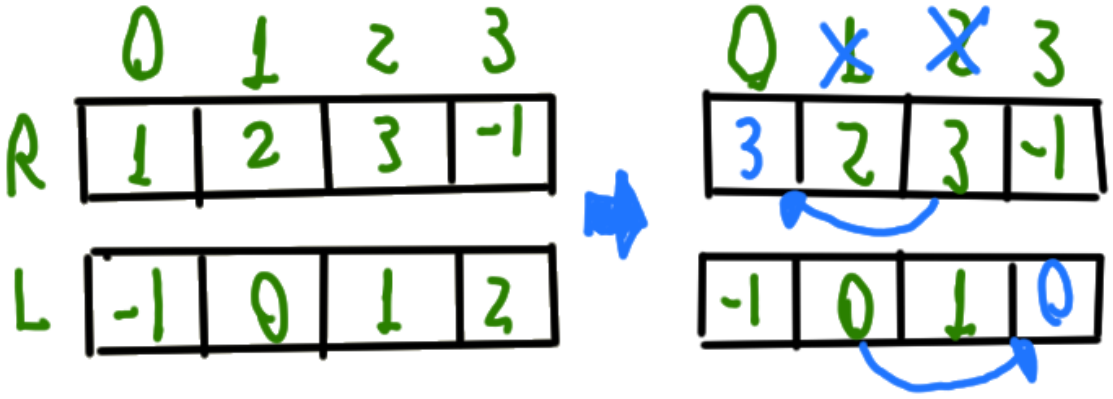
Problem! The input is too big, and O(n) takes too much time.

- $1 \leq S \leq B \leq 10^5$; $(O(n^2)) = 10^{10}$
- Also multiple cases; $(O(n^2 k)) = 10^{10} k$

Think of a different solution! (Do not look at the next slide :-))

Example 2: Army Buddies (UVA 12356)

A solution using arrays



- Problem: Do not update ALL soldiers, just the edge.
- Idea: Neighbor Array
  - Let **R** be: **Int** Array of Right neighbors
  - Let **L** be: **Int** Array of Left neighbors
- Question: how do we update R and L after query (r, l)?

Data Structures and Programming Contests

- Choosing the right data structure makes the program easy and fast
- Always avoid pointers in programming contests
  - Too many bugs
  - Not enough gains
  - Better to use arrays!
- Remember the STL for common data structure!

The simple array!

Arrays are the simplest data structure, but also the most often used.

Merits

- Easy to implement! No worries about pointers;
- Can simulate pointers using index operations;
- Many library Functions;

Concerns

- Reordering many items can be expensive;

Implementing arrays/vectors (C++)

```
#include <vector>

int arr[5] = {7,7,7};          // arr = {7,7,7,0,0}
vector<int> v(5, 5);           // v = {5,5,5,5,5}

int x = arr[2] + v[2];         // x = 12

arr[5] = 5;                    // Runtime error
cout << v[7];                  // 0 !! Be careful.

v.push_back(6);                // v = {5,5,5,5,5,6}
```

Trying to access indexes outside of an array is a common source of Runtime Errors (RTE)

How do you reset an array?

Implementation matters

```
#include <vector>
#include <string.h>
vector<int> v(10000,7)

memset(v, 0, 10000*__SIZEOF_INT__);          // Method 1
fill(v.begin(), v.end(), 0);                 // Method 2
for (int i = 0; i < 10000; i++) v[i] = 0;    // Method 3
v.assign(v.size(), 0);                       // Method 4
```

Method	executable size		Time Taken (in sec)	
	-O0	-O3	-O0	-O3
1. memset	17 kB	8.6 kB	0.125	0.124
2. fill	19 kB	8.6 kB	13.4	0.124
3. manual	19 kB	8.6 kB	14.5	0.124
4. assign	24 kB	9.0 kB	1.9	0.591

Operations in Arrays

Example – Vito's Family (UVA 10041)

Input: A list of integers (street addresses):

10, 20, 10, 10, 40, 80, 30, 90, 20, 55, 20

Output: The address (integer) with minimal distance to all others.

- **10**: $0+10+0+0+30+70+20+80+10+45+10=275$
- **40**:
  $30+20+30+30+0+40+10+50+20+15+20=265$
- **20**: $10+0+10+10+20+60+10+70+0+35+0=225$

Result: 20!

How do we solve this problem?

Operations in Arrays

- Solution: Find the Median address.
- 1- sort the address array, 2- select the middle value.

```
#include<iostream>
#include<algorithm>
using namespace std;

int main() {
    int n; int add[100];
    cin >> n;
    for (int i=0; i<n; i++) { cin >> add[i]; }

    sort(add, add+n);

    cout << add[n/2] << endl;
}
```

Using Sorting

Sorting can be used for many, many things:

- Finding the Highest n values, Finding duplicate values;
- Binary Search ($O(\log n)$)
- Pre-processing data for other algorithms.

Let's do Sorting!

algorithm, sorting and binary search

```
#include <iostream>
#include <algorithm>
#include <vector>
using namespace std;

int main () {
  int n, t, search; vector<int> v;
  cin >> n >> search;
  for (int i=0; i<n; i++) { cin >> t; v.push_back(t); }

  sort (v.begin(), v.end());
  vector<int>::iterator low,up;
  low = lower_bound (v.begin(), v.end(), search);
  up  = upper_bound (v.begin(), v.end(), search);
  cout << (low-v.begin()) << " and " << (up-v.begin());
}
```

Sorting with specific sorting function

Imagine you need to sort by number of points (bigger is best), penalty (smaller is best), and name (alphabetical order)

```
#include <algorithm>
#include <vector>
#include <string>
struct team{ string name; int point; int penal;
             team(string _n, int _po, int _pe) :
               name(_n), point(_p), penal(_g){} };

bool cmp(team a, team b) {
  if (a.point != b.point) return a.point > b.point;
  if (a.penal != b.penal) return a.penal < b.penal;
  return strcmp(a.name,b.name); }

vector<team> v;
sort(v.begin(), v.end(), cmp); // sort using cmp
reverse(v.begin(), v.end()); // and reverse
```

A Permutation Problem

- Input: A set of item costs: $c_1, c_2, c_3, \ldots, c_n$, and your money m.
- Output: The list of indexes of items you can buy.
- how to do it?: Test all possible item permutations
- But how?

Looping Permutations

```
#include <iostream>
#include <vector>
using namespace std;

int main () {
  int n, t, m; vector<int> p;
  cin >> n >> m;
  for (int i=0; i<n; i++)
    { cin >> t; p.push_back(t); }

  for (int i = 0; i < (1 << n); i++) {
      t = 0;
      for (int j = 0; j < n; j++)
          t += (i & (1 << j) ? p[j] : 0);
      if (t == m)
          cout << "found!" << endl;
}}
```

Bitmasks

```
1 --> for (int i = 0; i < (1 << n); i++) {
2 --> t += (i & (1 << j) ? p[j] : 0);
```

- Bitmasks are sets of booleans using integers.
- They are very useful for representing sets
  - Set Looping;
  - Set Union (OR);
  - Set Intersection (AND);
- They are Very fast too

Binary Operatons on Bitmasks (2)

- Multiply/Divide an integer by two :: shift bits left, right

```
S                    = 34 =  100010
S = S << 1 = S*2 = 68 = 1000100
S = S >> 2 = S/4 = 17 =   10001
S = S >> 1 = S/2 =  8 =    1000
```

- Check if the i-th bit is turned on:

```
S           = 34        =  100010
j = 3, 1 << j           =  001000
i = 1, 1 << 1           =  000010
                           ------
Tj= S & ( 1 << j)       =  000000  = 0 # 3 is not set
Ti= S & ( 1 << i)       =  000010 != 0 # 1 is set
```

Binary Operations on Bitmasks (2)

- To set/turn on the jth item, use bitwise OR operation S |= (1 « j)

```
S              = 34          =  100010
j = 3, 1 << j                =  001000
                                ------ OR (S |= 1 << j)
S              = 42          =  101010
```

- To set/turn off the jth item, use bitwise AND operation S &= (1 « j)

```
S              = 50          =  110010
j = (1<<5)|(1<<3)            =  101000 # unset items 5,3
~j                           =  010111
                                ------
S &= ~(j)                    =  010010 # 18
```

- There is the bitset class, but it cannot be used as an array index.

Long Live the STL!

- The standard library implements many data structures that are useful for programming contests.
- Let's review a few of them here.
- The website `https://visualgo.net/` has good reviews of many data structures;

Deque, Queue, Stack

Sometimes you want special access to the start or end of a vector.

- stack: *pop* and *push* from the front;
- queue: *pop* from the back, *push* from the front;
- deque: *pop_front, push_front, pop_back, push_back*;

Behind C++

Actually, *Queue* and *Stack* are high level constructs, List or Deque are used to implement them.

Queue and Stacks

Queues and Stacks are useful to simplify common cases of vectors

Stack Example: Testing if a set of parenthesis is balanced.

```
#include <stack>
stack<char> s;
char c;

while(cin >> c) {
  if (c == '(') s.push(c);
  else {
    if (s.size() == 0) { s.push('*'); break; }
    s.pop();
  }
}
cout << (s.size() == 0 ? "balanced" : "unbalanced");
```

Problem Example: CD – 11849

Input:

- Jack CD collection: Up to 10^6 CDs, with ID up to 10^9
- Jill CD collection: Up to 10^6 CDs, with ID up to 10^9

Output:

- How Many CDs are in both Collections?

Problem Example: CD – 11849

Naive Solution:

1. Store all IDs in collection 1 in a Vector (n)
2. Sort the Vector (nlogn)
3. For each ID in collection 2, test if it exists in Vector with Binary Search (nlogn)

Total Cost: $n + n\log n + n\log n$

Let's use a MAP for $O(\log N)$ search using a balanced search tree

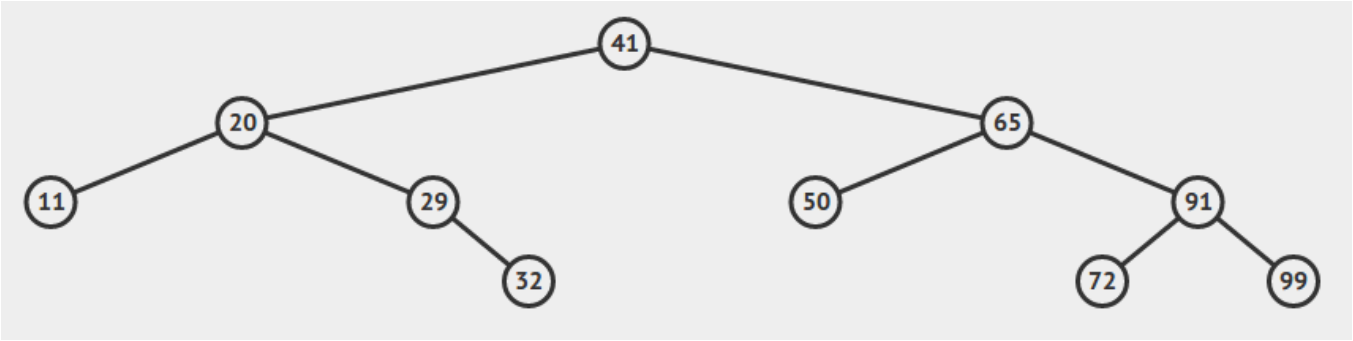
Solving CD with a MAP (Approximate Solution)

```
#include <iostream>
#include <set>
using namespace std;

int main() {
    int N, M, num;
    cin >> N >> M;

    set<int> first, second;
    while (N--) { cin >> num; first.insert(num); }
    while (M--) { cin >> num; second.insert(num); }
    int count = 0;
    for (set<int>::iterator iter = first.begin();
         iter != first.end(); ++iter)
      if (second.find(*iter) != second.end())
        ++count;
      cout << count << '\n';
}
```

Balanced Search Trees



- *Search Trees* Keep items in an ordered relationship.
- For example: Left children always have smaller values, Right children always have larger values;
- Insertion/Search/Deletion in a tree costs $O(h)$, where h is the height of the tree;
- For a tree with n elements, the minimum height is $\log n$
- For a balanced tree, the maximum height is also $\log n$
- How to keep the tree balanced?

Balanced Search Trees

How to keep the tree balanced?

There are many Tree implementations/algorithms for keeping an BST balanced, and minimizing the tree height efficiently:

- AVL Tree (Adelson-Velskii-Landis);
- Red-Black Tree;
- B-Tree;
- Splay Tree;

However, in a programming context (or even day to day life), implementing these trees from scratch is Dangerous.

Luckly, most standard libraries include some implementation of BST.

ABLs in C++: Map and Set

- In C++, the *Map* and *Set* classes are implemented using BSTs
- *Map* Accept Key-value pairs;
- *Set* Accepts only Keys;

Using Map in C++

```
#include <map>
map<string, int> ages;    ages.clear();

ages["john"] = 40;
ages["billy"] = 39;
ages["andy"] = 29;
ages["steven"] = 42;
ages["felix"] = 33;

// What is the age of andy?
map<string, int>::iterator it = ages.find("andy");
cout << it->second << endl;

// Which names are between "f" and "m" ??
for (map<string, int>::iterator it =
     age.lower_bound("f");                    // finds felix
     it != age.upper_bound("m"); it++)   // finds johm
        cout << " " << ((string)it->first).c_str();
```

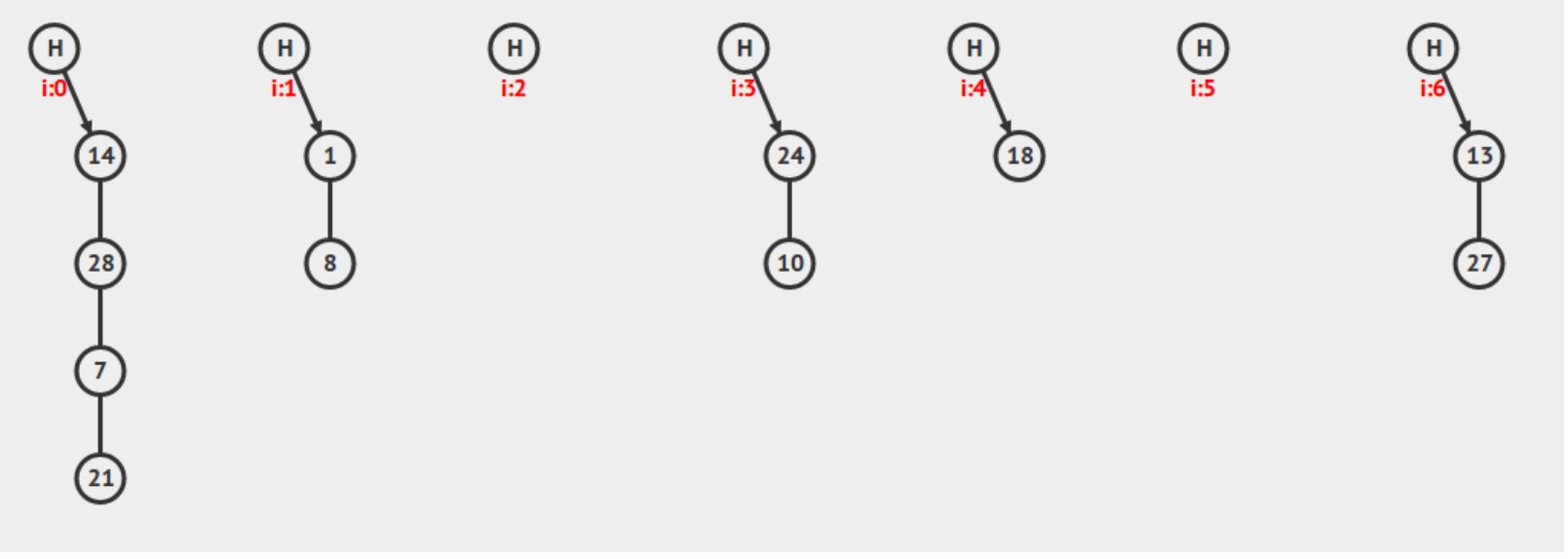
Using Set in C++

```
#include <set>
set<int> CDs;
CDs.clear();

// Adding some values
CDs.insert(1000); CDs.insert(999); CDs.insert(1337);
CDs.insert(1313); CDs.insert(100020);

// Testing if a particular value exists (O(logn))
set<int>::iterator f = used_values.find(79);
if (f == used_values.end())
  cout << "not found!\n";
else
  cout << *f;     // Index!
```

Hash Tables



- Very fast insertion and Search – Slow iteration;
- Simple implementation using *unordered_map*;
- Important: Policies about collisions;
- Learn more about hash tables here:
  `https://visualgo.net/ja/hashtable`

Hand-making Data Structures

- Sometimes, it is necessary to extend the standard data structures (arrays, maps, etc)
- Other times, it is necessary to implement data structures not included in the standard libraries (graphs, UFDS, etc)
- Let's see a few examples.

Union-Find Disjoint Set (UFDS)

Motivating Problem

Network Connections – UVA793

In a network with *n* computers, some are connected to others.

Input: A series of "commands"

- c i j – Means computer *i* is connected to computer *j*
- q i j – Question: is computer *i* connected to computer *j*?

Output: The number of "q" with answer yes, and the number of "q" with answer no.

Union-Find Disjoint Set (UFDS)

Motivating Problem – Naive answer

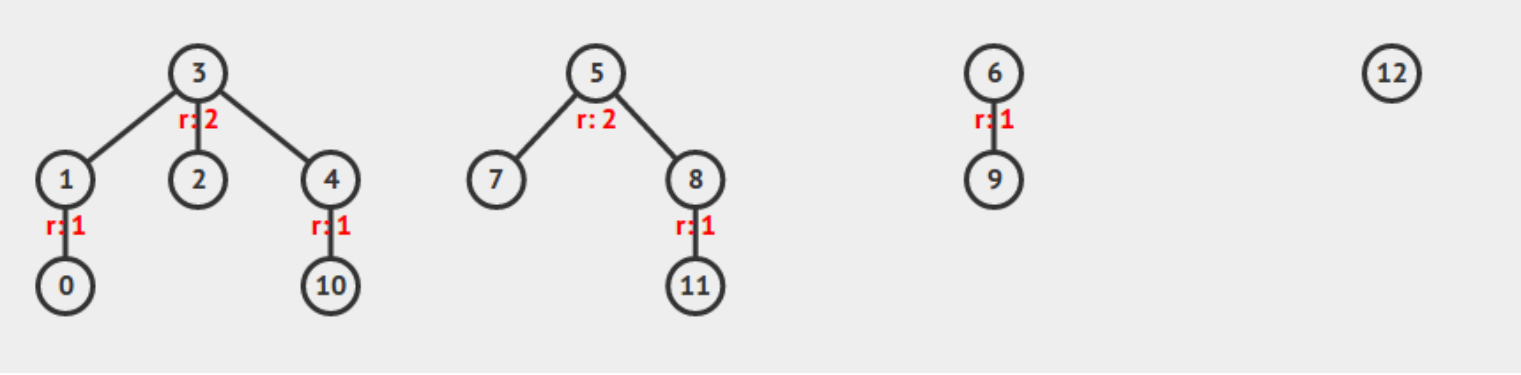
- One idea: Use a Neighborhood Matrix ($n \times n$) initalized with zeros.
- For every “c i j”, $N_{i,j}$, $N_{j,i}$ becomes 1.
- We can follow the graph to answer “q i j”.

How good is this solution?

- Cost to insert a new connection: O(1)
- Cost to check if “q i j”: O(n) (worst case)

We can do better!

Union-Find Disjoint Set



- The UFDS keeps sets of items, each is represented by a parent;
- When you join two sets You join their parents;
- When you test the parent of an item You flatten the tree;
- Test_item and Join_item are both O(1);
- More Information `https://visualgo.net/ja/ufds`;

UFDS Implementation using Arrays

```
int p[MAX], r[MAX];
int find(int x) {
    return x == p[x] ? x : p[x]=find(p[x]);
}
int join(int x, int y) {
    x = find(x), y = find(y);
    if(x != y) {
        if(r[x] < r[y])
            p[x] = y, r[y] += r[x];
        else
            p[y] = x, r[x] += r[y];
        return 1;
    }
    return 0;
}
void init() {
    for(int i = 0; i < MAX; i++)
        p[i] = i, r[i] = 1; }
```

Union Find Disjoint Set

Problem II – War

From a set of 10k people, some are friends, other are enemies.

- If A,B are friends, and B,C are friends, then A,C are friends
- If A,B are friends, and B,C are enemies, then A,C are enemies
- If A,B are enemies, and B,C are enemies, then A,C are friends

Input: A series of commands from the set below:

- SetFriends(i,j)
- SetEnemies(i,j)
- TestFriends(i,j)
- TestEnemies(i,j)

Output:

- If a “SetFriends” or “SetEnemies” is impossible, output “-1”
- For a “TestFriends”, “TestEnemies”, output 0 - false, 1 - true

Union Find Disjoint Set

Problem II – War

This problem is similar to “Networking”, but now you need to keep track of **TWO** relations.

Some ideas:

- Keep UFDS for friends, and UFDS for enemies?
- Keep an “enemy” flag for each person?
- Add “negative people” to friend-set on UFDS?

Which idea is easier to implement?

Segment Tree and Fenwick Tree (Self Study)

There are many more specific data structures which are common in programming contests.

Two suggestions for you to study by yourself:

- Segment Tree (section 2.4.3): Finds and update the largest values in intervals in an unordered set.
- Fenwick Tree (section 2.4.4): Finds and update the sum of values in intervals in an unordered set.

End of the Class!

- Questions about the problems?
- Other questions?