Programming Challenges (GB21802)

Week 2 - Data Structures

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Lecture 02 – Data Structures
Part I – Introduction

Outline

When writing any program (and not just programming challenges!) the right data structure makes a great difference in how easy the program is to write and how time and memory efficient the algorithm is.

- In this lecture, we will review some data structures that commonly appear in programming challenges;
- This lecture covers Chapter 2 of the "Competitive Programming" book;
- In this lecture, we focus the **description and implementation** of data structures more than on their theoretical analysis.

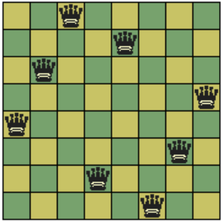
Comments on the last week:

- Numbers of Problems solved;
- Orders of Problems;
- Lecture Calendar for this week;

Motivating Problems

To introduce the topics of this class, let's show three problems where the choice of data structure can make a big difference;

Example 1: 8 Queen Problem (UVA 750)



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

Because you need to count how many configurations exist, it is necessary to test **all** valid configurations.

```
for (int i = 0; i < #configurations; i++)
  if configurationIsSafe(i) sum++
return(sum)
```

Example 1: 8 Queen Problem (UVA 750)

Last lecture we talked about how **pruning** can be used to reduce the problem size. This time we review this concept more concretely.

Consider how we store information about all the configurations. Imagine that we have an array, *conf*, which contains all configurations that we want to test.

Approach 1: For each queen, we store the pair (col, row).

```
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}}
  ...
conf[k]   = {{a,1}, {b,2}, {b,2}, ... {c,8}, {d,8}}
conf[k+1] = {{a,1}, {b,2}, {b,2}, ... {c,8}, {e,1}}
  ...
```

Looping through all options: n^{n^2} steps

Example 1: 8 Queen Problem (UVA 750)

Approach 2: We fix each queen on a column (a,b,c,d...). Our data structure only needs to represent the row of each queen.

We store an array of arrays, containing 8 integers representing the row:

```
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}
  ...
conf[k]   = {0,0,0,3,3,6,7,7}
conf[k+1] = {0,0,0,3,3,7,0,0}
  ...
```

Looping through all options: n^n steps

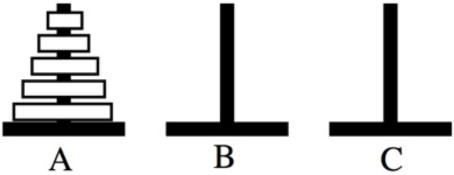
Example 1: 8 Queen Problem (UVA 750)

Approach 3: We fix each queen on a column (a,b,c,d...), and each configuration is a permutation of rows where we place the queens.

We store a string of rows, and each configuration is a permutation accessed using "next_permutation" function from C++ stl's "algorithm" header.

```
conf[0] = "01234567"
conf[1] = "01234576"
conf[2] = "01234657"
   ...
```

Example 2: The Towers of Hanoi

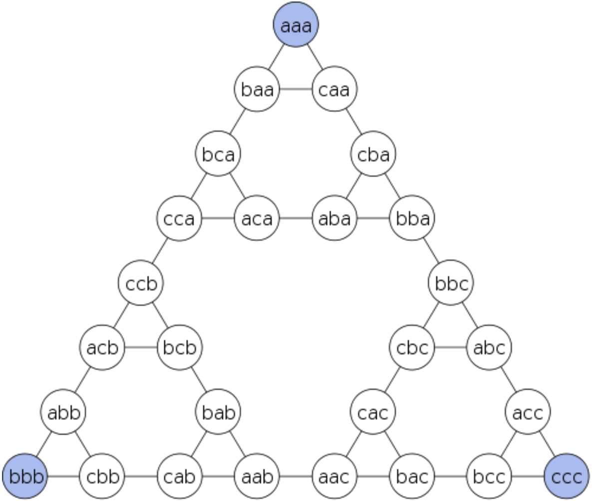


- You have N disks and K poles. Each disk has unique size s_i.
- A disk i can be moved from one pole to another.
- A move of disk i to pole k is only valid if k has no disks smaller than i
- Find the list of moves to move all disks from pole 1 to pole K.

How do you represent the data in this problem?

Example 2: The Towers of Hanoi

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



Example 3: 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 - -
```

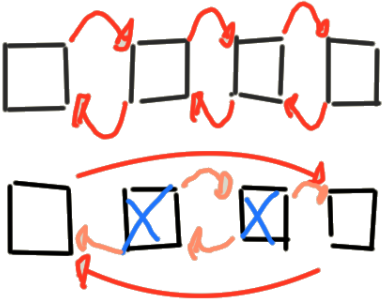
How do we solve this problem?

Example 2: Army Buddies (UVA 12356)

Idea 1: Linked Lists

For each query, we find the first soldier, and we remove each soldier until we find the second soldier.

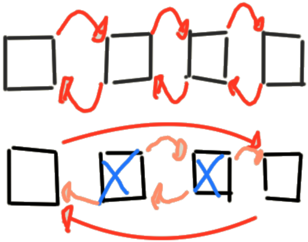
We use the linked list to reduce the size of the list after each query.



- Represent the line as a linked list.
- Find the 1st soldier and 2nd soldiers ($O(n)$ steps)
- Repeat the operation above for each query. ($O(nm)$ steps)

Example 2: Army Buddies (UVA 12356)

A solution using linked lists



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

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

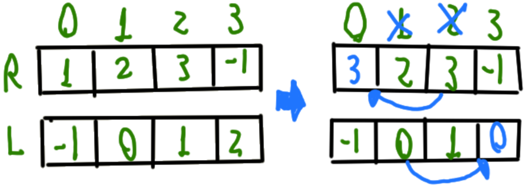
Let's think of a different solution! (Before looking at the next slide)

Example 2: Army Buddies (UVA 12356)

A solution using arrays

The problem with last solution is that it costs n to search the soldiers. We need to access the sodier position in $O(1)$ using an **index**. We also need to keep track of neighbors when removing soldiers.

- Idea: To use **two** Neighbor Arrays
  - 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)?

Motivating Data Structure

As you can see, the choice of data structure and problem representation is very important.

- Choosing the right data structure:
  - Changes the time or memory complexity of the implementation;
  - Makes the programming task simpler or more complex;
- Hints for programming contests;
  - Avoid using pointers (source of bugs, programming overhead);
  - Prefer multiple variables, instead of complex structs;
  - In larger programs (not challenges) you want more complex structures;
- Learn the library tools of your language (STL, java.utils, etc);

End of part I

Lecture 02 – Data Structures
Part II – Linear Data Structures

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
```

Lecture 02 – Data Structures
Part III – Data Structures from Libraries

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

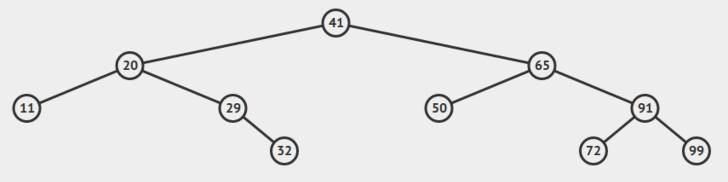
Solving CD with a MAP (Approximate Solution)

```
#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();
```

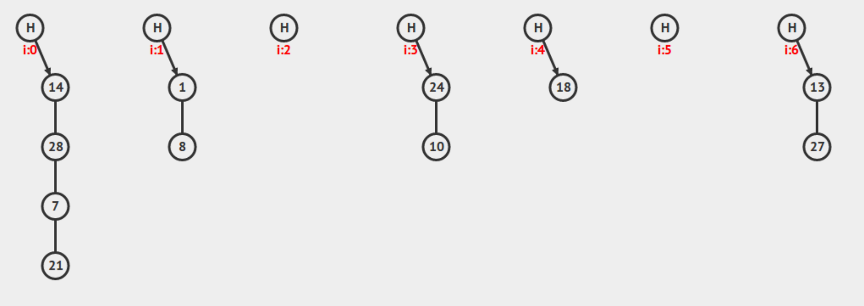
Using Set in C++

```
#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



- Insertion and Search: O(1) – Slow iteration;
- C++ library: *std::unordered_map*;
- Hash parameter – Defines Collision results.
- Learn more about hash tables here:
  `https://visualgo.net/ja/hashtable`

Lecture 02 – Data Structures
Part IV – Hand-made Data Structures

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

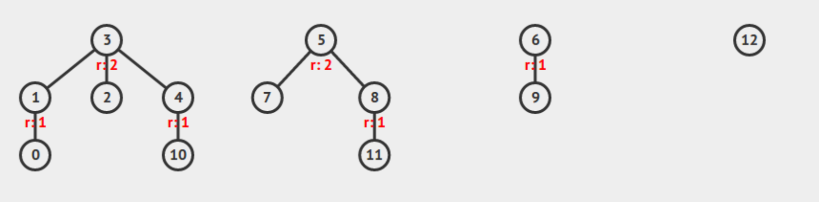
- One idea: Use a Neighborhood Matrix ($n \times n$) initalized with zeros.
- For every "c i j", $N_{i,j}$, $N_{j,i}$ becomes 1.
- We can follow the graph to answer "q i j".

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”

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?

Range Maximum Query – RMQ

Suppose you have an array of values:

```
Value: 18 17 13 19 15 11 20
Index:  0  1  2  3  4  5  6
```

The Range Maximum Query problem asks you to find the index with the maximum value between two indexes:

- RMQ(0,0) = 0
- RMQ(0,6) = 6
- RMQ(1,4) = 3

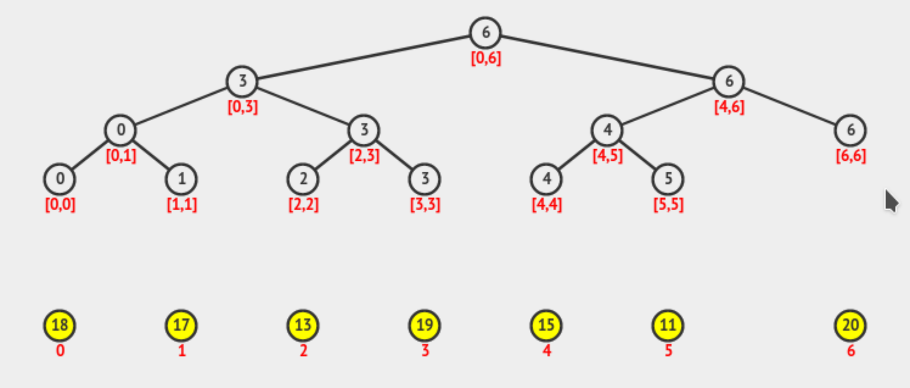
Naive Method: loop from i to j, find maximum value. ($O(nk)$)

But what is the number of **Values** or **Queries** is too big?

Segment Tree

- Basic idea: index the array data in a binary tree
- Creation of the tree: $O(n)$
- Query of a segment: $O(\log n)$
- Update of the tree: $O(\log n)$ Important Part
- Many Implementations
  (this implementation: vector based heap)

Segment Tree



Let's see the segment tree animation at VISUALGO.

Coding the Segment Tree

Creating the Tree

```
typedef vector<int> vi; // We always use this!

class SegmentTree { // OOP implementation,
private: vi st, A;  // vi: typedef vector<int> vi;
  int n;
  int left (int p) { return  p<<1; }  // heap-like index;
  int right(int p) { return (p<<1) + 1; }

  void build(int p, int L, int R) {   // O(n log n)
    if (L == R)
      st[p] = L;                      // store the index
    else {                            // recursive build
      build(left(p) , L          , (L+R)/2);
      build(right(p), (L+R)/2 + 1, R      );
      int p1 = st[left(p)], p2 = st[right(p)];
      st[p] = (A[p1] <= A[p2]) ? p1 : p2;
  } }
```

Code from https://github.com/stevenhalim/cpbook-code

Coding the Segment Tree

Query the Tree

rmq(1, 0, n-1, i, j) – Query from i to j.

```
int rmq(int p, int L, int R, int i, int j) // O(log n)
{
  if (i >  R || j <  L)
    return -1;    // outside query range
  if (L >= i && R <= j)
    return st[p]; // inside query range

  // compute the min position in the left and right part
  int p1 = rmq(left(p) , L         , (L+R)/2, i, j);
  int p2 = rmq(right(p), (L+R)/2+1, R       , i, j);

  if (p1 == -1) return p2;   // segment outside query
  if (p2 == -1) return p1;   // segment outside query
  return (A[p1] <= A[p2]) ? p1 : p2;
}
```

Code from `https://github.com/stevenhalim/cpbook-code`

Coding the Segment Tree

Update the Tree

update(1, 0, n-1, i, v) – update index i to value v

```
int update(int p, int L, int R, int idx, int new_value) {
  int i = idx, j = idx;    //for point update i = j = idx
  // if the curr interval does not intersect the update,
  if (i > R || j < L) return st[p];  //return node value!
  // if the current interval is in the update range,
  if (L == i && R == j) {
    A[i] = new_value;     // update the underlying array
    return st[p] = L;     // this index
  }
  // compute the min pos in L/R part of the interval
  int p1, p2;
  p1=update(left(p) , L        , (L+R)/2, idx, new_value);
  p2=update(right(p), (L+R)/2+1, R      , idx, new_value);
  // return the position where the overall minimum is
  return st[p] = (A[p1] <= A[p2]) ? p1 : p2;
}
```

Code from https://github.com/stevenhalim/cpbook-code

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