

Algorithms Notes

Bliss Of Comprehension

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preface

This book is largely concerned with algorithms helpful for solving OJ problems.

An algorithmic way of approaching codeforces problems.

- Read and understand the problem statement.
- Read input format.
- Verify sample tests with brute force to check your understanding of problem statement.
- ReRead Bold words in the problem statement.
- Check the time limit.(may be you can use sqrt decomp etc)
- Come up with algorithm.
- Verify the sample tests with your algorithm.

Chapter 1

Stack

Stack is the suprising Data Structure that comes in handy in unexpected of times.

we can have a modified stack which gives minimum among the elements in $O(1)$ with rest other stack operations time remaining same.blog.

we can have a standard queue with same operations too blog.

1.1 Balanced Parantheses

A bracket sequence is balanced if either of the below are true. As all of them are equivalent.

- Every element of prefix sum array is ≥ 0 and last element is 0.
- When open bracket is encountered push it to the stack and pop the top open bracket otherwise. If there is no open bracket to pop or the stack is not empty at the end, the sequence is not balanced.
- Base Case : Empty sequence is balanced.
Constructor Case : If s,t (sequences) are balanced then s(t) is balanced.
Now check if our sequence can be produced this way using recursion.

Overlapping two balanced sequences produces a balanced sequence. Prove it using the 1st definition.

C_i (catalan number) counts the number of sequences containing n pairs of parentheses which are correctly matched. Using this we can calculate in $O(n)$

unlike other DP solutions.

Let $s[0..n-1]$ be a balanced sequence

- $s[0..i]$ is balanced iff $s[i+1..n-1]$ is balanced.

When sequence is balanced, we can pair up open and closed brackets. This is done during the 2nd definition. When we are popping out the open bracket from stack (when closed br is encountered) we pair those two.

The pairing can also be done like this. For open bracket at i , find the minimum index j S.t $sum[i..j]=0$. (i,j) are paired

Let i th and j th index ($i < j$) are paired.

- If $i < l < j$ then the partner of l (named as r), $i < r < j$.
Proof: We know $sum[i..l-1] > 0 \Rightarrow sum[l..j] < 0$ since $sum[l..l] = 1$ there exists $r < j$ S.t $sum[l..r] = 0$. We used the property that $sum[i..j]$ is continuous over j .

Chapter 2

XOR

Competitive problem setters love XOR (never understood the physical significance of it).

Different techniques to solve problems on XOR

- Bit Trie.
- Solving for each individual bit and combining them at the end.
- Using Lexicographic property. If the most significant bit in binary form a number is 1 and the other number has 0 then first number is greater (no matter what the other bits are).
- In problems concerning XOR over subarrays converting the array into prefix array can be useful.
- In tougher problems, divide and conquer is also used (i.e solve the problem for the numbers with 0 at considered bit, and solve for numbers with 1 at considered bit and combine them for the answer).
Problem link
- Gaussian elimination is used to find subset with maximum XOR.
- XOR of two numbers is just bitwise addition (mod 2).

Some tricks in solving XOR problems

- $4k \oplus (4k+1) \oplus (4k+2) \oplus (4k+3) = 0$ (used in finding XOR of numbers from $1..1e18$)
- If $a \oplus b = 0$ and $b \neq c \implies a \oplus c \neq 0$. This trick is mostly used in number theory to prove theorems on nim.

- If the array is sorted, all the elements with the same first x bits will be contiguous $\forall x$.
- $a + b = a \oplus b + 2 * (a \& b)$

2.1 Game Theory

There are different kinds of differentiation used in games.

- Simultaneous move game and extensive form game.
- Finite games and infinite games (both are extensive form games)
- perfect and imperfect information games.
- partial and impartial games. (In Extensive form games, if state of game is given but moves differ for two players then its partial game).
- zero sum and non zero sum

We deal with games which are two player, extensive, finite, perfect info, impartial and zero sum(not always) in nature(in OJ's).

Game Tree : A tree where nodes are all the states and edges are possible moves with root as starting state.

Strategy : For a player, A strategy is a complete algorithm for playing the game, telling a player what to do for every possible situation(state) throughout the game. (i.e for every state possible, a single move is associated with it).

payoff (reward) : In the game tree, we define payoff's for each players at every terminal node.(for example it may simply state who won i.e $payoff_a = inf, payoff_b = -inf$ if player a wins at that terminal node).

In zerosum games $payoff_b = -payoff_a$ at every terminal node.

Payoff function: It takes strategies of players as input and outputs payoff's for both the players. It just outputs the payoffs of the terminal node at which game ends when actually played.(Since strategies are known we know how game will play out).

When optimal play is stated in the problem. They imply what's the payoff when backward induction strategy profile is used?

When player tries to maximize some quantity is given in the problem. Then that quantity is payoff.

Backward induction strategy profile is a Nash equilibrium strategy profile(proven theorem).

There are two type of operations involved in game theory of impartial extensive(second player plays after first player finishes the move) games.

- MEX
- XOR

Sprague-Grundy Theorem :

If we know the MEX function of different games (G_1, G_2, \dots) then the MEX function of combined games is XOR of all the functions.

- In a nim game with custom moves (examp. we can remove 1,2,5 stones at once) there will always be a periodicity of mexes with number of stones.

Chapter 3

Counting

- Given a binary string, find number of 3-tuple (indices $i, j, k \ni i < j < k$) and exactly one of $s[i], s[j], s[k]$ is 1.
- There are r boxes in a row and n identical balls. Find number of different ways we can distribute balls among boxes.
 ${}^{n+r-1}C_{r-1}$
- In problems, to convert A to B using minimum operations. Looking at the final operation may help.
- When trying to solve non-linear recurrences using matrix expo. $f_i = f_{i-1} + 2i^2 + 5$. The left column vectors should be $\begin{pmatrix} f_i \\ i^2 \\ i \\ 1 \end{pmatrix}$ and $\begin{pmatrix} f_{i-1} \\ (i-1)^2 \\ i-1 \\ 1 \end{pmatrix}$ otherwise the matrices wouldn't be same and we cannot combine the equations.

3.1 Probability

3.1.1 Randomized algorithms

Before we use randomized algorithm, we already know answer for the given input (we can find that out using brute force if we have a really fast computer for bruteforcing).

So to find out what the answer really is we take help of probabilities.

Since our classical computer cannot generate ideal randomness. Our algorithm cannot give a random answer (we can determine even before we run

it).But it gives answer with bruteforce almost all the time (we can find test cases that doesn't though).

Chapter 4

Graphs

In OJ's most of the problems concerning MST's can be solved with Kruskal's algorithm.(others are Prim's and Boruvka's).

There are certain kind of problems where number of edges are huge. They are not given in the input but told to us using certain properties of vertices. (Example. There are n nodes and each has a value a_i . There is an edge between i and j iff $a[i] \oplus a[j] == k$).

A graph is bipartite \iff there is no odd cycle in the graph.

- Sometimes these problems can be solved by adding some more nodes to the graph and connecting the real vertices with new vertices. The property for the graph(ex.number of components) asked in the question may remain same for the new graph and now edges may be less.

Given a graph with both directed and undirected edges. If there are no cycles using only directed edges, we can always direct all undirected edges without forming a cycle.proof.

Normally problems like above involve eulerian cycle and direct edges according to that.

There are only tree edges and back edges in dfs-tree of undirected graph. Unlike in dag's can have cross edges extra.

In an undirected graph an edge($v \rightarrow to$ where (v,to) is tree edge in dfs-tree) is a bridge \iff there is no backedges from one of to 's descendants to any v 's ancestor node. This can be checked by having a value $high_u$ at every node, corresponding to highest node which is adjacent to u in original graph. And by checking if the minimum among descendant nodes is higher than our

bridge. Or we can use intime of dfs traversal to check instead of depth as criteria.

4.1 Trees

These are the different ways we approach problems based on trees.

- Tree dp.
- Normal dfs (greedy version of dp approach).
- Process nodes from lowest level to top.(leaves to root).

```

void dfs(int u, int par){
    for(auto v:g[u]){
        if(v!=par){
            dfs(v,u);    //recursively solve for all the
                           subtrees
        }
    }
    //When the function reaches this step all the children
      will be processed.Now use the children's
      information to solve for u.
    /*
        actual code.
    */
    return;
}

```

- start time, end time on nodes.
- binary lifting.
- Using Lowest common ancestor (this can be done using binary lifting).
- sqrt decomposition on trees.

While performing tree dp we can keep a map (of values in the subtree) at each node. This is a very generic trick and seems to have high potential. we will traverse the tree from the down most level (level wise).

- Have maps at each of the lowest level nodes.(each map has only one entry)
- Now when we go up to produce map of node 'u' in this level.
Take the largest map among children of u and add remaining children maps in to this big map. Now add the value corresponding to 'u' to the map. Now this map is the final map for 'u'.
- Since when each node moves from one map m1 to other m2, $sizeof(m2) \geq sizeof(m1)$. Final size of m2 after addition will be $\geq 2 * sizeof(m1)$. So any node will change maps only $lg(n)$ times. So the time complexity is $O(nlg(n))$.
- The memory is $O(n)$ throught out the procedure. Since we are inserting smaller maps in to the big map(which is already present).
- This can be implemented using dfs.

In DSU, while performing dsu one of the three types of techniques is used.

- Path Compression

```
Find(x)
    if x.parent != x
        x.parent := Find(x.parent)
    return x.parent
```

- Path Halving

```
Find(x)
    while x.parent != x
        x.parent := x.parent.parent
        x := x.parent
    return x
```

- Path Splitting.

In the problems where we need a pointer to an ancestor in a tree (or similarly in the array) and update operations makes you add more links then Path compression is useful. Example

Given a tree with each node having a value a_i . There are two kind of operations

Update : update a_i with c where $c < a_i$.

Query : Given u . Find the deepest node with value $\geq k$ which is ancestor of u .

In similar problems (having pointer in tree or array) we can use binary lifting on pointer's sometimes.

Chapter 5

C++ tricks

- In a normal set finding the *ith* element is not possible in $O(\lg n)$ and it is also not possible to know number of elements less than a given value.
- As the above operations are theoretically possible for a balanced BST, we use policy data structure to support those two additional operations along with normal set operations. [Blog link](#)
- But for using the above structure as a multiset, there is no easy way to do it. We will use a shortcut by inserting pair (value, time of insertion) to distinguish equal elements. And do operations around that.
- `_gcd(x,0)` doesn't work in g++, even though its mathematically defined.
- While using two pointers having the second pointer ('j') pointing to the minimum index such that `[i,j]` subarray satisfies the condition eases the code most of the times. (instead of `[i,j]`).
- Use `mt19937` instead of `rand()`. (due to low max value, and periodicity).

```
mt19937 rng(chrono::steady_clock::now().
            time_since_epoch().count());
int RandomOutput = rng(); \\ generate a random number.
shuffle(a.begin(), a.end(), rng); \\ shuffle array a.
```

- when generating random trees to test your solution. Donot generate bigger size trees because edge cases will be missed (Probability that the tree will be a line is almost zero for bigger size). Similarly for the arrays too.

Chapter 6

Arrays

- When we are asked to count number of pairs that satisfy a specific condition in an array. You should first try to rearrange the equation to get all the i^{th} index terms to left side and j^{th} index terms to right side. This will help us reduce $O(n^2)$ to $O(n)$.
- Let p be an array of distinct elements and $next_i$ be the smallest $j > i$ s.t $p[j] > p[i]$. Then when we draw edges(curves) from $i \rightarrow next_i$ on top of the array then no two edges intersect. (i.e the condition $i < j < next_i < next_j$ is never satisfied for any pair of indices i, j).
- **Langford pairing** : It is possible $\iff n \equiv 0 \text{ or } 3 \pmod{4}$.
- If we are asked to find $\sum_1^{n-k} |f(i, i+k)|$. We can partition the array in to chains, each chain has indices which are pairwise congruent modulo k and in the same order as in array. Now we can solve separately for each chain and combine them to produce overall answer. The above is generalized version of separating even and odd indices and solving them separately(example in the transforming array problems(ex. Xoring adjacent elements)).
- There are 3 types(tentative) of sqrt decomp I know.
 - MO's algorithm(offline algo) : When there is no query of update form then we can take all the queries and sort them in a certain way to make naive computation faster.
 - (online algo) Divide the array in to blocks each of size (\sqrt{n}) and process both kind of queries in $O(\sqrt{n})$ each.
When there are updates with addition or deletion of elements. Simply add the element in to the corresponding block, which increases it's

size by 1. After each \sqrt{q} updates, preprocess the array again (As the new blocks doesn't maintain the \sqrt{n} size anymore).

- (online algo) Consider \sqrt{q} operations at a time. Since there can be atmost $O(\sqrt{q})$ update operations. The array will be changed at atmost \sqrt{q} indices hence if we find a way to answer the query operations (in this \sqrt{q} block) with some preprocessing each in $O(\sqrt{q})$.

(Example. Find answer for this query without considering any updates in $O(1 \text{ or } \lg n)$ and update this answer according to changed indices in this range (which are only \sqrt{q} in number). The time complexity of each block will be $O(q)$ hence total complexity will be $O(q\sqrt{q})$. (PreProcessing is done for each block seperately just before considering the block). Example Problem Link.

- Some problems involving subarrays, we can approach this problem through prefix sums, (donot forget that dp also works, even in max subarray sum).
- Finding min element in subarray can be done using sparse table ($O(n \lg n)$ preprocess and $O(1)$ query). For 2d array ($O(nm \lg n \lg m)$ preprocess and $O(1)$ query). Where Seg tree takes $O(nm)$ preprocess and $O(\lg n \lg m)$ for query. (queries can be up to $n^2 m^2$ in number).
- Queries of rectangles with fixed sizes can be done in $O(mn)$ pre and $O(1)$ query.

We can have pointers to the nearest equal, less or greater elements (either to left or right). This can help in certain problems

- Find number of unique elements in range. More generally count number of elements in range, but if freq of an element is greater than 'k' take it only k.
We can do it by having pointer to kth equal element to left. Then in range [l,r] find number of elements with $ptr[i] < l$, which is the answer.
- Number of distinct subsequences in an array. For 'i' have the nearest left equal element 'j'. Then $dp[i] = 2 * dp[i - 1] - dp[j]$ (where $dp[i]$ = number of distinct subsequences in $[0 \dots i]$)

Consider a divide and conquer algorithm with time complexity recurrence.

$$T(n) = T(e_1) + T(e_2) + e_1 (e_1 \leq e_2 \wedge e_1 + e_2 = n).$$

The closed form is $T(n) = O(n \lg n)$.

This can be proved using induction or realising the fact the every element is

included in the e_1 term atmost lgn times.

6.1 Segment Tree

You are given an array of elements(may be null initially) and queries over subarrays.

There are two properties for a segment tree.

- SegProp : required property from a segment.
- update type.

For the Segment tree to be valid it needs to satisfy

- req 1 : We need to be able to find segprop from segprop's of any contiguous partition subsegments of segment.

For the lazy segment tree to be valid it needs to satisfy this below additional properties.

- req 2 : If there are two or more updates on the same segment, we need to be able to combine them in to a single update.
- req 3 : If there is an update for a segment(whole segment). We need to be able to update segprop for the segment in $O(1)$.

Lazy segment tree update template

```
void update(int si ,int ss , int se , int l , int r , int val){
    If there is lazy update pending:
        update seg prop for this node with lazy update; \\req 3
        make lazy update for this node null;
        combine the lazy updates of children with this update;
        \\req 2

    If current node segment is out of update range return;

    If the current node segment is completely in update range:
        update segprop of this node; \\req 3
        combine the lazy updates of children with this update;
        \\req 2
        return;
    recursively call update for both children;
    update this node segprop with childrens seg prop. \\req 1
}
```

Store the segprop's and lazy updates in $4*N$ sized array.

We can even store entire subsegment's in each node. The memory is only $O(n \lg n)$.

If there are updates of type "change an element to x". Then to find that element now, we only need to consider last update(of above type).

6.2 Permutation

- If we have a directed graph of n nodes, and connect i th to j th iff $p[i] = j$; then we get a bunch of disjoint cycles.
- You can find number of inversions in an array using policy data structure (balance BST). Infact we can do many variations of inversion problem. (Example. Find number of inversions when equal elements are present, Which is not possible using merge sort.)
- **Factorial number system** is used to number permutations. Finding the k^{th} lexicographic permutation, will be easy if k is represented in this number system. And given a permutation finding its lexicographic order in this number system is straight forward. (After that we may need to convert this in to decimal).

Chapter 7

Numbers

- $\lfloor a/(bc) \rfloor = \lfloor \lfloor a/b \rfloor / c \rfloor$
- Number of perfect squares in $[l, r], l \leq r$ is $\lfloor \sqrt{r} \rfloor - \lceil \sqrt{l} \rceil + 1$
- $\frac{1}{1} + \frac{1}{2} + \frac{1}{3} + \dots$ is divergent. Sum of first n elements
 $\ln(n+1) \leq \sum_{i=1}^n \frac{1}{i} \leq \ln(n) + 1$ Proof link
- the factors of any number are quite smaller compared to the number. There doesn't exist a pair of distinct factors whose sum is \geq the actual number.
- 'a' is multiple of n_1 and 'a' is multiple of n_2 iff 'a' is multiple of $LCM(n_1, n_2)$.
- similarly 'd' is divisor of n_1 and 'd' is divisor of n_2 iff 'd' is divisor of $GCD(n_1, n_2)$.
- The set of all integer combinations of a and b is precisely the set of all integer multiples of the GCD of a and b. proof
- The above statement is generalized version of Bezout's identity.
- $dp[i][j]$, number of subsets of length i whose gcd is j, then
 $dp[i][j] = \binom{cnt_j}{i} - \sum_{k=2}^{\infty} dp[i][k * j]$, where cnt_j is number of elements divisible by j. This is a generalized version of simply finding number of subsets of gcd exactly == j (which is solved similarly but with 1-dim dp).
- $GCD(a_l, a_{l+1}, ..a_r) = GCD(a_l, a_{l+1} - a_l, a_{l+2} - a_{l+1}, .., a_r - a_{r-1})$

- Range queries for GCD with a single update is straight forward. But for range update, we keep two segment trees, one to find a single element with the range update, one over difference between adjacent elements to get GCD over range of difference array. As for difference array only two elements change with range update(update is addition). We answer in $O(\lg n)$ using above formula.
- if d is gcd of a list of numbers. Then d divides their sum.
- In gcd problems, iterating over the prime divisors (and enumerating all the elements which are multiples of this) almost always works, Instead of iteration over all divisors. The first method has less complexity as every element has at most $\lg n$ prime divisors but $n^{\frac{1}{3}}$ factors hence getting enumerated only $\lg n$ times.
- $n!(\text{mod } m)$ is zero when $n \geq m$.
- $$\sum_{i=0}^n i.i! = (n+1)! - 1$$
- There is a number system called **Factorial number system**. From the above fact any number can be uniquely represented in this system.
- For $m, n \geq 1$ $\gcd(f_m, f_n) = f_{\gcd(m,n)}$. Where f is fibonacci. proof

7.1 Modulo

- If you want to calculate a^b modulo p (prime) where b is very large ($b = 100000^{100000}$) we can use Fermat's **little** theorem. As $a^{p-1} \equiv 1(\text{mod } p)$, $a^b \equiv a^{b \text{mod } (p-1)}(\text{mod } p)$.
- For prime p , and any number a relatively prime to p , $a, 2a, 3a, \dots, p*a$ are all distinct modulo p .
- But a^1, a^2, \dots, a^{p-1} are not distinct modulo p . ($a=6, p=5$)
- $ab \text{ mod } ac = a(b \text{ mod } c)$.
- Consider a number n , if you keep on modulo it by different numbers x_i , it only changes $\lg n$ times. Since every time it changes it becomes $\leq \frac{n}{2}$.

7.2 CRT

Find the solution set of $x \equiv a_1 \pmod{n_1}$ and $x \equiv a_2 \pmod{n_2}$.

Let $\gcd(n_1, n_2) = d$ and find x' and y' s.t $n_1x' + n_2y' = d$. (this is bezout's identity. Find it using Extended euclidean algorithm).

Note: d should divide $a_2 - a_1$, otherwise there is no solution for the given two equations.

One of our solution is $x_o = a_1 + x' \frac{a_2 - a_1}{d} n_1$. And our solution set is $x_o + u * \text{lcm}(n_1, n_2), u \in \mathbb{Z}$. This obtained solution set is equal to solution set of $x \equiv x_o \pmod{\text{lcm}(n_1, n_2)}$.

For solving multiple equations combine first two equations in to one using above technique. Then again combine the newly obtained equation with the 3rd one and so on.

7.3 Euler's phi function

- Euler's phi function is multiplicative. proof.
- using above we can calculate $\varphi(n) = n \cdot \prod_{p|n} \left(1 - \frac{1}{p}\right)$. where p 's are primes.
- Let any number k coprime to n then $(k \bmod n) \in \varphi(n)$.
- A more generalized form $\varphi(mn) = \varphi(m)\varphi(n) \cdot \frac{d}{\varphi(d)}$. This is when m and n aren't necessarily co-prime.
- if $d|n$, the number of integers $k \leq n$ and $\text{GCD}(k, n) = d$ are $\varphi(n/d)$.
- a more general euler's theorem (which is inturn more general fermat's little theorem) $x^n \equiv x^{\phi(m) + [n \bmod \phi(m)]} \pmod{m}$. This is when x and m aren't necessarily coprime.

Chapter 8

DP

Write recurrence relation for a problem. When we draw a directed graph from the recurrence(i.e draw edge from state s_i to all the subproblems it requires to find $dp[s_i]$ (i.e the right side of recurrence states)). Then in order to solve the problem using dp the graph should be acyclic. (If not we cannot come to the answer with this dp alone, even though the recurrences are correct. You can even check if recurrences are correct between states after finding out answers with some other algorithm).

On the above graph there are three ways to solve.

- Topdown dp.
- bottom up dp.
- forward dp.

Some Points to note

- Counting problems either involves combinatorics or dp and nothing else.
- There are counting DP problem's where we need to find no of ways to pair or group elements. We can have dp with one dimension representing no of groups which are not closed yet. This can be used both in arrays, trees etc.
- we prove most optimization dp's using this kind of proving techniques. proof.

- while solving optimization dp(topdown,bottomup,forward), Keep another array 'prev' which stores the state from which this state's answer is calculated.(among all the searched subproblem states). Which makes it easy to recover the complete solution instead of only value. This can be done just by having a while loop starting at final state and iterating through prev states.

8.1 arrayDP

- Consider an array 'A' of length 2^n . Then we need to calculate

$$F[mask] = \sum_{i \subseteq mask} A[i]$$

. This can be naively be calculated in $O(3^n)$. Let

$$S(mask, i) = \{x | x \subseteq mask \wedge mask \oplus x < 2^{i+1}\}$$

. Then

$$S(mask, i) = \begin{cases} S(mask, i-1) & i^{th} \text{ bit OFF in mask} \\ S(mask, i-1) \cup S(mask \oplus 2^i, i-1) & i^{th} \text{ bit ON in mask} \end{cases}$$

(We can similarly do it for other operation than sigma).

8.2 treeDP

- In some problems we root the tree at random node(r). Initially we calculate a certain property $SubProp_u$ for a subtree rooted at node u $\forall u \in V(vertexSet)$ in $O(n)$ using dfs. Now we can reroot the tree to one of the children of r and recompute all the $Subprop_u$ in $O(1)$ as only two $SubProp_u$'s changes(one is r and the other is the new root(selected child of r)). Template is below
precalculate SubProp's for random node initially. Then call the below dfs from that node.

```
void dfs(int u, int par){
    // Now all the SubProp array is correctly
    // calculated when u is the root. Use it.
    for(auto v:g[u]){
        if(v!=par){
            //reroot the tree to v and adjust SubProp
            // array correctly.
```



```
        dfs(v,u);
        \\reroot the tree to u and adjust SubProp
           array correctly.
    }
}
return;
}
```

Chapter 9

Ad-hoc

Any kind of observations, tricks etc are just used to decrease the time complexity and or memory complexity of the problem compared to brute force.(Similar to any standard algo or ds you studied).

Ways to approach adhoc problem.

- For the optimization problems or counting problems(count objects of some type), put multiple **EXAMPLES** on the paper and find the pattern.
- Similarly for the problems that require some quantity (nth element in array, sum of nth row in a matrix), when given relation between elements or rows to calculate them. But cannot do it due to time constraint. There may be a pattern present, write down **EXAMPLES** or write a brute force code for smaller n and output it to visualize the pattern.