Competitive Programming Reference

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Contents

1 Data Structures

Data Structure	Precomputation / Update	Query	Memory	Notes
Prefix Sum	O(N) / X	O(1)	O(N)	Associative Functions (+, XOR)
Sparse Table	O(N log N) / X	O(1)	O(N log N)	Non-Associative Functions (max, gcd)
Fenwick Tree	X / O(log N)	O(log N)	O(N)	Prefix Sum with Updates
Segment Tree	X / O(log N)	O(log N)	O(4N)	Allows more Information

Table 1: Quick Summary of Data Structures

1.1 Prefix Sums

1.1.1 1D

$O(N)$ precomputation, $O(1)$ query.

```
//Query - 1-Indexed
int query(int s, int e){
    return ps[e]-ps[s-1];
}

//Precomputation
ps[0] = 0;
for(int i = 1; i <= n; i++) ps[i] = ps[i-1]+a[i];
```

1.1.2 2D

$O(R \cdot C)$ precomputation, $O(1)$ query.

```
//Query - 1-Indexed
int query(int x1, int y1, int x2, int y2){
    return ps[x2][y2]-ps[x1-1][y2]-ps[x2][y1-1]+ps[x1-1][y1-1];
}

//Precomputation
for (int i = 0; i <= r; i++) ps[i][0] = 0;
for (int j = 0; j <= c; j++) ps[0][j] = 0;
for (int i = 1; i <= r; i++) {
    for (int j = 1; j <= c; j++) {
        ps[i][j] = ps[i-1][j]+ps[i][j-1]-ps[i-1][j-1]+a[i][j];
    }
}
```

1.2 Fenwick Trees

1.2.1 Point Update Range Query

$O(\log N)$ update and query.

```
inline int ls(int x){ return (x)&(-x); }

int fw[MAXN]; // 1-Indexed

void pu(int i, int v) {
    for(; i <= n; i += ls(i)) fw[i] += v;
}

int pq(int i) {
    int t = 0;
```

```
    for(; i; i -= ls(i)) t += fw[i];
    return t;
}

int rq(int s, int e) {
    return pq(e) - pq(s - 1);
}
```

1.2.2 Range Update Point Query

$O(\log N)$ update and query.

```
// Requires PURQ Code (PU, PQ)

void ru(int s, int e, int v) {
    pu(s, v);
    pu(e+1, -v);
}
```

1.2.3 Range Update Range Query

$O(\log N)$ update and query.

```
// Requires PURQ Code (PU, PQ)
// Functions need to be modified to take in array parameter
// e.g. int pu(*tree, int i, int v)

void ru(int s, int e, int v) {
    pu(fw1, s, v);
    pu(fw1, e+1, -v);
    pu(fw2, s, -v*(s-1));
    pu(fw2, e+1, v*e);
}

int ps(int i) {
    return pq(fw1, i)*i + pq(fw2, i);
}

int rq(int s, int e) {
    return ps(e) - ps(s - 1);
}
```

2 Graph Theory

2.1 Depth First Search

Runs in $O(V + E)$.

```
// For adjacency lists
void dfs(int x, int p) {
    for (int y : adj[x]) {
        if (y != p) {
            dist[y] = dist[x]+1;
            dfs(y, x);
        }
    }
}
```

2.2 Breadth First Search

Runs in $O(V + E)$.

```
// For adjacency lists
visited[s] = 1;
dist[s] = 0;
q.push(s);
while (!q.empty()) {
    int f = q.front(); q.pop();
    for (int i : adjlist[f]) {
        if (!visited[i]) {
            q.push(i);
            visited[i] = 1;
            dist[i] = dist[f] + 1;
        }
    }
}
```

2.3 0-1 BFS

Runs in $O(V + E)$.

```
// For adjacency lists
deque<int> dq;
dist[s] = 0;
dq.push(s);
while (!dq.empty()) {
    int u = dq.front(); dq.pop();
    for (int e : adjlist[u]) {
        int v = e.first, w = e.second;
        if (dist[v] > dist[u] + w) {
            dist[v] = dist[u] + w;
            if (w == 0) dq.push_front(v);
            else dq.push_back(v);
        }
    }
}
```

2.4 Floyd-Warshall

Runs in $O(N^3)$.

```
// Initialise adjacency matrix
for (int i = 0; i < n; i++) {
    for (int j = 0; j < n; j++) {
        if (i == j) adj[i][j] = 0;
        else adj[i][j] = INF;
    }
}
// Floyd-Warshall
for (int k = 0; k < n; k++) {
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < n; j++) {
            adj[i][j] = min(adj[i][j], adj[i][k]+adj[k][j]);
            if (adj[i][i] < 0) negCycle = true;
        }
    }
}
```

2.5 Bellman-Ford

Runs in $O(VE)$.

```
vector<int> dist(n, INF);
dist[s] = 0;
bool negCycle = false;
for (int i = 1; i <= n; i++) {
    bool update = false;
    for (Edge e : edges) {
        if (dist[e.u] < INF && dist[e.v] > dist[e.u] + e.w) {
            dist[e.v] = dist[e.u] + e.w;
            update = true;
        }
    }
    if (!update) break;
    if (update && i == n) negCycle = true;
}
```

2.6 Dijkstra's Algorithm

Runs in $O(E \log V)$.

```
priority_queue<pi, vector<pi>, greater<pi>> pq;
vector<int> dist(n, INF);
dist[s] = 0;
pq.push({0, s});
while (!pq.empty()) {
    pi f = pq.top(); pq.pop();
    int d = f.first, u = f.second;
    if (d != dist[u]) continue;
    for (pi x : adj[u]) {
        int v = x.first, w = x.second;
        if (dist[v] > d + w) {
            dist[v] = d + w;
            pq.push({ dist[v], v });
        }
    }
}
```

2.7 Shortest Path Faster Algorithm

Runs in $O(VE)$.

```
vector<int> dist(n, INF);
vector<int> inQueue(n, 0);
queue<int> q;
dist[s] = 0;
q.push(s);
inQueue[s]++;
bool negCycle = false;
while (!q.empty()) {
    int u = q.front(); q.pop();
    inQueue[u]--;
    for (Edge e : adj[u]) {
        if (dist[e.v] > dist[u] + e.w) {
            dist[e.v] = dist[u] + e.w;
            if (inQueue[e.v] == 0) {
                q.push(e.v);
```

```
                inQueue[e.v]++;
                if (inQueue[e.v] > n) {
                    negCycle = true;
                    break;
                }
            }
        }
    }
    if (negCycle) break;
}
```

2.8 Prim's Algorithm

Runs in $O(E \log V)$.

```
priority_queue<pi, vector<pi>, greater<pi>> pq;
vector<int> dist(n, INF);
vector<bool> vis(n, false);
dist[s] = 0;
pq.push({0, s});
while (!pq.empty()) {
    pi f = pq.top(); pq.pop();
    int d = f.first, u = f.second;
    if (vis[u]) continue;
    vis[u] = true;
    for (pi x : adj[u]) {
        int v = x.first, w = x.second;
        if (!vis[v] && dist[v] > w) {
            dist[v] = w;
            pq.push({ dist[v], v });
        }
    }
}
```

2.9 Union Find Disjoint Subset

With both path compression and union by rank, runs in $O(\alpha(n))$ (basically constant time).

```
int p[MAXN];
int sz[MAXN];

int root(int x) {
    if (p[x] == -1) return x;
    return p[x] = root(p[x]);
}

void connect(int x, int y) {
    x = root(x); y = root(y);
    if (x == y) return;
    if (sz[x] < sz[y]) swap(x, y);
    p[y] = x;
    sz[x] += sz[y];
}

fill(p, p+MAXN, -1);
fill(sz, sz+MAXN, 1);
```

2.10 Kruskal's Algorithm

Runs in $O(E \log E)$.

```
sort(edges.begin(), edges.end());
for (Edge e : edges) {
    if (root(e.u) != root(e.v)) {
        connect(e.u, e.v);
        cost += e.w;
    }
}
```

2.11 Topological Sort

Runs in $O(V + E)$.

```
void dfs(int x) {
    if (v[x]) return;
    v[x] = 1;
    for (int y : adj[x]) dfs(y);
    topo.push_back(x);
}
for (int i = 0; i < n; i++) dfs(i);
reverse(topo.begin(), topo.end());
```

2.12 Floyd's Cycle Finding Algorithm

For graphs with outdegree 1, runs in $O(V + E)$.

```
// detect cycle
int slow = s, fast = s;
do {
    slow = nxt[slow];
    fast = nxt[nxt[fast]];
} while (slow != fast);
// find start of cycle
slow = start;
while (slow != fast) {
    slow = nxt[slow];
    fast = nxt[fast];
}
// collect all nodes in cycle
vector<int> cycle;
int cur = slow;
do {
    cycle.push_back(cur);
    cur = nxt[cur];
} while (cur != slow);
```

2.13 Trees

2.13.1 Pre/Postorder Traversal

Runs in $O(V)$.

```
int prec = 0, postc = 0;
void dfs(int x, int p) {
    pre[x] = prec++;
    for(int y : adj[x]) {
```

```
        if (y != p) dfs(y, x);
    }
    post[x] = postc++;
}
```

2.13.2 Subtree to Range

Runs in $O(V)$.

```
int dfs(int x, int p) {
    pre[x] = c++;
    rig[pre[x]] = pre[x];
    for (int y : adj[x]) {
        if (y != p) {
            rig[pre[x]] = max(rig[pre[x]], dfs(y, x));
        }
    }
    return rig[pre[x]];
}
// Subtree -> pre[x], rig[pre[x]]
// Node Index -> pre[x]
// Range of Children -> pre[x]+1, rig[pre[x]]
```

2.13.3 Weighted Maximum Independent Set

Runs in $O(V)$.

```
int dp[MAXN][2];

int mis(int v, bool take, int p) {
    if (dp[v][take] != -1) return dp[v][take];
    int ans = take * c[v];
    for (int u : adj[v]) {
        if (u == p) continue;
        int temp = mis(u, 0, v);
        if (!take) temp = max(temp, mis(u, 1, v));
        ans += temp;
    }
    return dp[v][take] = ans;
}
void ans(int v, bool take, int p) {
    for (int u : adj[v]) {
        if (u == p) continue;
        int temp0 = dp[u][0], temp1 = (take ? -1 : dp[u][1]);
        if (temp0 > temp1) ans(u, 0, v);
        else { a.push_back(u); ans(u, 1, v); }
    }
}

memset(dp, -1, sizeof(dp));
mis(0, 0, -1); // don't take root
mis(0, 1, -1); // take root
if(dp[0][1] > dp[0][0]) { a.push_back(0); ans(0, 1, -1); }
else ans(0, 0, -1);
```

2.13.4 Diameter

Runs in $O(V)$.

```
pi dfs(int x, int p, int d) {
    pi b = {x, d};
    for (pi y : adj[x]) {
        if (y.first != p) {
            pi c = dfs(y.first, x, d + y.second);
            if (c.second > b.second) b = c;
        }
    }
    return b;
}
pi s = dfs(0, -1, 0);
pi e = dfs(s.first, -1, 0);
// e.second gives diameter
// For even diameter, centroid is at e.second / 2
// For odd diameter, centroid is at e.second / 2 and e.second / 2 + 1
```

2.13.5 2^K Decomposition

$O(N \log N)$ precomputation and memory, $O(\log N)$ query.

```
int par(int x, int k) {
    for(int i = MAXLOGN; i >= 0; i--) {
        if (k >= (1 << i)) {
            if(x == -1) return x;
            x = p[x][i];
            k -= (1 << i);
        }
    }
    return x;
}

int p[MAXN][MAXLOGN];
memset(p, -1, sizeof(p));
dfs(0); // compute initial parent p[i][0]
for (int k = 1; k <= MAXLOGN; k++) {
    for (int i = 0; i < n; i++) {
        if(p[i][k-1] != -1) p[i][k] = p[p[i][k-1]][k-1];
    }
}
```

2.13.6 Lowest Common Ancestor

Runs in $O(\log N)$.

```
int lca(int x, int y) {
    // make both nodes the same depth
    if (dep[x] < dep[y]) swap(x, y);
    for (int k = MAXLOGN; k >= 0; k--) {
        if (p[x][k] != -1 && dep[p[x][k]] >= dep[y]) x = p[x][k];
    }
    if (x == y) return x;
    // perform binary lifting while parents are different
    for (int k = MAXLOGN; k >= 0; k--) {
        if (p[x][k] != p[y][k]) {
            x = p[x][k];
            y = p[y][k];
        }
    }
```

```
    // find the next parent
    return p[x][0];
}
```

2.13.7 Shortest Path

Runs in $O(\log N)$.

```
int distance(int x, int y) {
    return dist[x] + dist[y] - 2 * dist[lca(x, y)];
}
```

3 Dynamic Programming

3.1 Maxsum

3.1.1 1D

Kadane's Algorithm. Runs in $O(N)$.

```
int ans = nums[0], cur = nums[0];
for (int i = 1; i < nums.size(); i++) {
    if (cur < 0) cur = 0;
    cur += nums[i];
    ans = max(ans, cur);
}
```

3.2 Longest Increasing Subsequence

3.2.1 N^2 DP

```
int ans = 0, dp[n];
memset(dp, 0, sizeof(dp));
for (int i = 0; i < n; i++) {
    for (int j = 0; j < i; j++) {
        if (a[j] < a[i]) {
            dp[i] = max(dp[i], dp[j]);
        }
    }
    dp[i]++;
    ans = max(ans, dp[i]);
}
```

3.3 Coin Combinations

Runs in $O(N \cdot V)$.

```
int ways[v+1];
memset(ways, 0, sizeof(ways));
ways[0] = 1;
for (int i = 0; i < n; i++) {
    int c = coins[i];
    for (int sum = c; sum <= v; sum++) {
        ways[sum] = (ways[sum] + ways[sum - c]) % MOD;
    }
}
cout << ways[v];
```

3.4 Coin Change

Runs in $O(N \cdot V)$.

```
const int INF = 1e9;
vector<int> dp(v + 1, INF);
dp[0] = 0;
for (int i = 1; i <= v; i++) {
    for (int j = 0; j < n; j++) {
        if (i >= c[j] && dp[i - c[j]] != INF) {
            dp[i] = min(dp[i], dp[i - c[j]] + 1);
        }
    }
}
cout << dp[v];
```

3.5 Knapsack

3.5.1 0-1

Runs in $O(N \cdot S)$.

```
for (int i = 0; i < n; i++) {
    for (int j = s; j >= w[i]; j--) {
        dp[j] = max(dp[j], dp[j - w[i]] +v[i]);
    }
}
cout << dp[s];
```

3.6 Digit DP

Runs in $O(D)$.

```
// Example - Numbers
// Compute the number of palindrome free numbers in a given range

vector<int> num;
ll dp[20][11][11][2][2]; // idx, last1, last2, tight, hasStarted

ll derp(int pos, int last1, int last2, bool tight, bool hasStarted) {
    if(pos == num.size()) return 1; // successfully populated whole number

    if(dp[pos][last1][last2][tight][hasStarted] != -1) {
        // state already visited
        return dp[pos][last1][last2][tight][hasStarted];
    }

    ll res = 0;
    int limit = tight ? num[pos] : 9; // do we need to keep to the range
    for(int d = 0; d <= limit; d++) { // try all next digits
        bool newHasStarted = hasStarted || (d != 0);
        bool newTight = tight && (d == limit);
        // skip palindromes only if the number has started
        if(newHasStarted) {
            if(d == last1) continue; // palindrome length 2
            if(d == last2) continue; // palindrome length 3
        }
        int newLast1 = newHasStarted ? d : 10;
        int newLast2 = hasStarted ? last1 : 10;
```

```
        res += derp(pos+1, newLast1, newLast2, newTight, newHasStarted);
    }
    return dp[pos][last1][last2][tight][hasStarted] = res;
}

// convert number to digits
void dcmp(ll x){
    num.clear();
    if(x == 0) num.push_back(0);
    while(x > 0) {
        num.push_back(x % 10);
        x /= 10;
    }
    reverse(num.begin(), num.end());
}


// Total Valid with value <= x
// Use PIE to get number within [a, b]
ll solve(ll x){
    dcmp(x);
    memset(dp, -1, sizeof(dp));
    return derp(0, 10, 10, true, false);
}

// To compute the kth string satisfying
// Either binary search or build character by character:
int count = 0;
vector<int> ans;
for (int i = 0; i < n; i++) {
    int x = 0;
    for (int j = 1; j < 10; j++) { // adjust to size of alphabet
        if (count + dp(i, j) > k) {
            break;
        }
        x = j;
    }
    count += dp(i, x); // position i is bounded by x
    ans.push_back(x);
}
```

4 Math

4.1 Fast Exponentiation

Runs in $O(\log b)$.

```
int powmod(int a, int b, int m) {
    int res = 1;
    while (b > 0) {
        if (b & 1) res = (res * a) % m;
        a = (a * a) % m;
        b >>= 1;
    }
    return res % m;
}
```

4.2 Prime Factorisation

Runs in $O(\sqrt{x})$.

```
map<int, int> cnt;
while (x % 2 == 0) {
    cnt[2]++;
    x /= 2;
}
for (int i = 3; i * i <= x; i++) {
    while (x % i == 0) {
        cnt[i]++;
        x /= i;
    }
}
if (x > 1) {
    cnt[x]++;
}
```

4.3 Sieve of Eratosthenes

Runs in $O(n \log \log n)$ with high constant.

```
bitset<MAXN> prime;
prime.set();
prime[0] = prime[1] = 0;
for (int i = 2; i < MAXN; i++) {
    if (prime[i]) {
        for (int j = i*i; j < MAXN; j += i) {
            prime[j] = 0;
        }
    }
}
```

4.4 Greatest Common Divisor

Runs in $O(\log \min(a, b))$.

```
int gcd(int a, int b) {
    if (a > b) swap(a, b);
    while (a != 0) {
        b %= a;
        swap(a, b);
    }
    return b;
}
```

4.5 Lowest Common Multiple

```
int lcm(int a, int b) {
    return a / gcd(a, b) * b;
}
```

4.6 Modular Inverse

```
ll modinv(ll a){
    return powmod(a, MOD-2, MOD);
}
```

4.7 $\binom{n}{k}$

Precomputation takes $O(MAXN)$ time, queries answered in $O(1)$.

```
ll fac[MAXN+1], modinv[MAXN+1];

ll nck(ll n, ll k) {
    if (n < k) return 0;
    ll res = fac[n];
    res = (res * modinv[k]) % MOD;
    res = (res * modinv[n-k]) % MOD;
    return res;
}

fac[0] = 1;
for(int i = 1; i <= MAXN; i++) {
    fac[i] = fac[i-1] * i % MOD;
}
modinv[MAXN] = powmod(fac[MAXN], MOD-2, MOD);
for(int i = MAXN; i > 0; i--) {
    modinv[i-1] = modinv[i] * i % MOD;
}
```

4.8 Fibonacci

Runs in $O(\log N)$ time.

```
struct Mat {
    ll a, b, c, d; // 2x2 Matrix: [a b; c d]
};

Mat mul(Mat x, Mat y) {
    return {
        x.a*y.a + x.b*y.c,
        x.a*y.b + x.b*y.d,
        x.c*y.a + x.d*y.c,
        x.c*y.b + x.d*y.d
    };
}

Mat mpow(Mat base, long long exp) {
    Mat res = {1, 0, 0, 1}; // Identity Matrix
    while (exp) {
        if (exp & 1) res = mul(res, base);
        base = mul(base, base);
        exp >>= 1;
    }
    return res;
}

ll fib(long long n) {
    if (n == 0) return 0;
    Mat m = {1, 1, 1, 0}; // Fibonacci Seed Matrix
```

```
    return mpow(m, n-1).a;
}
```

5 Algorithms

5.1 Binary Search

Find the cuberoot of n. Runs in $O(\log N)$.

```
long long n; cin >> n;
long long mini = 0, maxi = 1e6, medi;
while (mini < maxi) {
    medi = mini+(maxi-mini)/2;
    if (medi * medi * medi >= n) maxi = medi;
    else mini = medi+1;
}
cout << mini << "\n";
```

5.2 Binary Search using Lifting

Find the cuberoot of n. Runs in $O(\log N)$.

```
long long n; cin >> n;
long long cur = 0, gap = 1e6, next;
while (gap > 0) {
    while (next = cur + gap, next * next * next < n) {
        cur = next;
    }
    gap >>= 1;
}
cout << cur+1 << "\n";
```

5.3 Sliding Set

Speeds up DP from $O(N^2)$ to $O(N \log N)$.

```
// Example - Candymountain
// Jump across with minimax candies
// Populate with initial window
for(int i = 0; i < k; i++) {
    dp[i] = candies[i];
    s.insert(candies[i]);
}
// Sliding Set
for(int i = k; i < n; i++){
    dp[i] = max(candies[i], *s.begin());
    s.erase(s.find(dp[i-k]));
    s.insert(dp[i]);
}
```

5.4 Set Merging

Reduces complexity from $O(Q \cdot N \log N)$ to $O(N \log^2 N)$.

```
for (int i = 0; i < q; i++) {
    cin >> a >> b;
    // small to large merging
```

```
    if (s[a].size() > s[b].size()) swap(s[a], s[b]);
    for (int x : s[a]) s[b].insert(x);
    s[a].clear();
    cout << s[b].size() << "\n";
}
```

6 Miscellaneous

6.1 Fast I/O

Cannot use with `scanf`, `printf`.

```
ios_base::sync_with_stdio(false);
cin.tie(0);
```

6.2 Superfast I/O

Only for non-negative integer input.

```
inline ll ri () {
    ll x = 0;
    char ch = getchar_unlocked();
    while (ch < '0' || ch > '9') ch = getchar_unlocked();
    while (ch >= '0' && ch <= '9') {
        x = (x << 3) + (x << 1) + ch - '0';
        ch = getchar_unlocked();
    }
    return x;
}
```