Team Note of 세상에 나쁜 알고리즘은 없다

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Contents

1 Data Structures For Range Query

1.1 Sparse Table

Usage: RMQ l r: `min(lift[l][len], lift[r-(1<<len)+1][len])`
Time Complexity: $\mathcal{O}(N) - \mathcal{O}(1)$

```
int k = ceil(log2(n));
vector<vector<int>> lift(n, vector<int>(k));
for (int i=0; i<n; ++i)
    lift[i][0] = lcp[i];
for (int i=1; i<k; ++i) {
    for (int j=0; j<=n-(1<<i); ++j)
        lift[j][i] = min(lift[j][i-1], lift[j+(1<<(i-1))][i-1]);
}
vector<int> bits(n+1);
for (int i=2; i<=n; ++i) {
    bits[i] = bits[i-1];
    while (1 << bits[i] < i)
        bits[i]++;
    bits[i]--;
}
```

1.2 Merge Sort Tree

Time Complexity: $\mathcal{O}(N \log N) - \mathcal{O}(\log^2 N)$

```
struct mst {
  int n;
  vector<vector<int>> tree;
  void init(vector<int> &arr) {
    n = 1 << (int)ceil(log2(arr.size()));
    tree.resize(n*2);
    for (int i=0; i<arr.size(); ++i)
      tree[n+i].push_back(arr[i]);
    for (int i=n-1; i>0; --i) {
      tree[i].resize(tree[i*2].size() + tree[i*2+1].size());
      merge(tree[i*2].begin(), tree[i*2].end(),
        tree[i*2+1].begin(), tree[i*2+1].end(), tree[i].begin());
    }
  }
  int sum(int l, int r, int k) {
    int ret = 0;
    for (l+=n, r+=n; l<=r; l/=2, r/=2) {
      if (l%2)
        ret += upper_bound(tree[l].begin(), tree[l].end(), k) -
        tree[l].begin(), l++;
      if (r%2 == 0)
        ret += upper_bound(tree[r].begin(), tree[r].end(), k) -
        tree[r].begin(), r--;
    }
    return ret;
  }
};
```

1.3 Persistence Segment Tree

Time Complexity: $\mathcal{O}(\log^2 N)$

```
struct pst {
  struct node {
    int cnt = 0;
    array<int, 2> go{};
  };
  vector<node> tree;
  vector<int> roots;
  pst() {
    roots.push_back(1);
    tree.resize(1 << 18);
    for (int i = 1; i < (1 << 17); ++i) {
```

```
      tree[i].go[0] = i * 2;
      tree[i].go[1] = i * 2 + 1;
    }
  }
  int insert(int x, int prev) {
    int curr = tree.size();
    roots.push_back(curr);
    tree.emplace_back();
    for (int i = 16; i >= 0; --i) {
      const int next = (x >> i) & 1;
      tree[curr].go[next] = tree.size();
      tree.emplace_back();
      tree[curr].go[!next] = tree[prev].go[!next];
      tree[curr].cnt = tree[prev].cnt + 1;
      curr = tree[curr].go[next];
      prev = tree[prev].go[next];
    }
    tree[curr].cnt = tree[prev].cnt + 1;
    return roots.back();
  }
  int query(int u, int v, int lca, int lca_par, int k) {
    int ret = 0;
    for (int i = 16; i >= 0; --i) {
      const int cnt = tree[tree[u].go[0]].cnt +
      tree[tree[v].go[0]].cnt -
                      tree[tree[lca].go[0]].cnt -
                      tree[tree[lca_par].go[0]].cnt;
      if (cnt >= k) {
        u = tree[u].go[0];
        v = tree[v].go[0];
        lca = tree[lca].go[0];
        lca_par = tree[lca_par].go[0];
      } else {
        k -= cnt;
        u = tree[u].go[1];
        v = tree[v].go[1];
        lca = tree[lca].go[1];
        lca_par = tree[lca_par].go[1];
        ret += 1 << i;
      }
    }
    return ret;
  }
};
```

1.4 Segment Tree Beats

Usage: Note the potential function
Time Complexity: $\mathcal{O}(\log^2 N)$

```
struct seg {
  vector<node> tree;
  void push(int x, int s, int e) {
    tree[x].x += tree[x].l;
    tree[x].o += tree[x].l;
    tree[x].a += tree[x].l;
    if (s != e) {
      tree[x*2].l += tree[x].l;
      tree[x*2+1].l += tree[x].l;
    }
    tree[x].l = 0;
  }
  void init(int x, int s, int e, const vector<int> &a) {
    if (s == e)
      tree[x].x = tree[x].o = tree[x].a = a[s];
    else {
      const int m = (s+e) / 2;
      init(x*2, s, m, a);
      init(x*2+1, m+1, e, a);
      tree[x] = tree[x*2] + tree[x*2+1];
    }
  }
  void off(int x, int s, int e, int l, int r, int v) {
    push(x, s, e);
    if (e < l || r < s || (tree[x].o & v) == 0)
      return;
    if (l <= s && e <= r && !(v & (tree[x].a^tree[x].o))) {
      tree[x].l -= v & tree[x].o;
      push(x, s, e);
    } else {
      const int m = (s+e) / 2;
```

```
      off(x*2, s, m, l, r, v);
      off(x*2+1, m+1, e, l, r, v);
      tree[x] = tree[x*2] + tree[x*2+1];
    }
  }
  void on(int x, int s, int e, int l, int r, int v) {
    push(x, s, e);
    if (e < l || r < s || (tree[x].a & v) == v)
      return;
    if (l <= s && e <= r && !(v & (tree[x].a^tree[x].o))) {
      tree[x].l += v & ~tree[x].o;
      push(x, s, e);
    } else {
      const int m = (s+e) / 2;
      on(x*2, s, m, l, r, v);
      on(x*2+1, m+1, e, l, r, v);
      tree[x] = tree[x*2] + tree[x*2+1];
    }
  }
  int sum(int x, int s, int e, int l, int r) {
    push(x, s, e);
    if (e < l || r < s)
      return 0;
    if (l <= s && e <= r)
      return tree[x].x;
    const int m = (s+e) / 2;
    return max(sum(x*2, s, m, l, r), sum(x*2+1, m+1, e, l, r));
  }
};
```

1.5 Fenwick RMQ

Time Complexity: Fast $\mathcal{O}(\log N)$

```
struct fenwick {
  static constexpr pii INF = {1e9 + 7, -(1e9 + 7)};
  vector<pii> tree1, tree2;
  const vector<int> &arr;
  static pii op(pii l, pii r) {
    return {min(l.first, r.first), max(l.second, r.second)};
  }
  fenwick(const vector<int> &a) : arr(a) {
    const int n = a.size();
    tree1.resize(n + 1, INF);
    tree2.resize(n + 1, INF);
    for (int i = 0; i < n; ++i)
      update(i, a[i]);
  }
  void update(int x, int v) {
    for (int i = x + 1; i < tree1.size(); i += i & -i)
      tree1[i] = op(tree1[i], {v, v});
    for (int i = x + 1; i > 0; i -= i & -i)
      tree2[i] = op(tree2[i], {v, v});
  }
  pii query(int l, int r) {
    pii ret = INF;
    l++, r++;
    int i;
    for (i = r; i - (i & -i) >= l; i -= i & -i)
      ret = op(tree1[i], ret);
    for (i = l; i + (i & -i) <= r; i += i & -i)
      ret = op(tree2[i], ret);
    ret = op({arr[i - 1], arr[i - 1]}, ret);
    return ret;
  }
};
```

2 Graph & Flow

2.1 Hopcroft-Karp & Kőnig's

Usage: Dinic's variant. Maximum Matching = Minimum Vertex Cover = S - Maximum Independence Set
Time Complexity: $\mathcal{O}(\sqrt{V}E)$

```
while (true) {
  vector<int> level(sz, -1);
  queue<int> q;
  for (int x : l) {
    if (match[x] == -1) {
      level[x] = 0;
```

```
      q.push(x);
    }
  }
  while (!q.empty()) {
    const int x = q.front();
    q.pop();
    for (int next : e[x]) {
      if (match[next] != -1 && level[match[next]] == -1) {
        level[match[next]] = level[x] + 1;
        q.push(match[next]);
      }
    }
  }
  if (level.empty() || *max_element(level.begin(), level.end()) ==
  -1)
    break;
  function<bool(int)> dfs = [&](int x) {
    for (int next : e[x]) {
      if (match[next] == -1 ||
          (level[match[next]] == level[x] + 1 && dfs(match[next])))
          {
        match[next] = x;
        match[x] = next;
        return true;
      }
    }
    return false;
  };
  int total = 0;
  for (int x : l) if (level[x] == 0)  total += dfs(x);
  if (total == 0) break;
  flow += total;
}
set<int> alt; // Konig
function<void(int, bool)> dfs = [&](int x, bool left) {
  if (alt.contains(x)) return;
  alt.insert(x);
  for (int next : e[x]) {
    if ((next != match[x]) && left) dfs(next, false);
    if ((next == match[x]) && !left) dfs(next, true);
  }
};
for (int x : l) if (match[x] == -1) dfs(x, true);
int test = 0;
for (int i : l) {
  if (alt.contains(i)) {
    auto &[y, x] = pos[i];
    s[y][x] = 'C';
  }
}
for (int i : r) {
  if (!alt.contains(i)) {
    auto &[y, x] = pos[i];
    s[y][x] = 'C';
  }
}
```

2.2 Min Cost Max Flow

Time Complexity: $\mathcal{O}(VEf)$

```
void mcmf(){
  int cp = 0;
  while(cp<2){
    int prev[MN],dist[MN],inq[MN]={0};
    queue <int> Q;
    fill(prev, prev+MN, -1);
    fill(dist, dist+MN, INF);
    dist[S] = 0; inq[S] = 1;
    Q.push(S);
    while(!Q.empty()){
      int cur= Q.front();
      Q.pop();
      inq[cur] = 0;
      for(int nxt: adj[cur]){
        if(cap[cur][nxt] - flow[cur][nxt] > 0 &&
            dist[nxt] > dist[cur]+cst[cur][nxt]){
          dist[nxt] = dist[cur] + cst[cur][nxt];
          prev[nxt] = cur;
          if(!inq[nxt]){
            Q.push(nxt);
```

```
          inq[nxt] = 1;
        }
      }
    }
  }
  if(prev[E]==-1) break;
  int tmp = INF;
  for(int i=E;i!=S;i=prev[i])
    tmp = min(tmp, cap[prev[i]][i]-flow[prev[i]][i]);
  for(int i=E;i!=S;i=prev[i]){
    ans += tmp * cst[prev[i]][i];
    flow[prev[i]][i] += tmp;
    flow[i][prev[i]] -= tmp;
  }
  cp++;
 }
}
```

2.3 Dinic's

Time Complexity: $\mathcal{O}(V^2E)$, $\mathcal{O}(\min(V^{2/3}E, E^{3/2}))$ on unit capacity

```
while (true) {
  vector<int> level(n * 2 + 2, -1);
  queue<int> q;
  level[st] = 0;
  q.push(st);
  while (!q.empty()) {
    const int x = q.front();
    q.pop();
    for (int next : e[x]) {
      if (level[next] == -1 && cap[x][next] - flow[x][next] > 0) {
        level[next] = level[x] + 1;
        q.push(next);
      }
    }
  }
  if (level[dt] == -1)
    break;
  vector<int> vis(n * 2 + 1);
  function<int(int, int)> dfs = [&](int x, int total) {
    if (x == dt)
      return total;
    for (int &i = vis[x]; i < e[x].size(); ++i) {
      const int next = e[x][i];
      if (level[next] == level[x] + 1 && cap[x][next] -
      flow[x][next] > 0) {
        const int res = dfs(next, min(total, cap[x][next] -
        flow[x][next]));
        if (res > 0) {
          flow[x][next] += res;
          flow[next][x] -= res;
          return res;
        }
      }
    }
    return 0;
  };
  while (true) {
    const int res = dfs(st, 1e9 + 7);
    if (res == 0)
      break;
    ans += res;
  }
}
```

2.4 Strongly Connected Component

Time Complexity: $\mathcal{O}(N)$

```
int idx = 0, scnt = 0;
vector<int> scc(n, -1), vis(n, -1), st;
function<int (int)> dfs = [&] (int x) {
  int ret = vis[x] = idx++;
  st.push_back(x);
  for (int next : e[x]) {
    if (vis[next] == -1)
      ret = min(ret, dfs(next));
    else if (scc[next] == -1)
      ret = min(ret, vis[next]);
  }
  if (ret == vis[x]) {
```

```
    while (!st.empty()) {
      const int t = st.back();
      st.pop_back();
      scc[t] = scnt;
      if (t == x)
        break;
    }
    scnt++;
  }
  return ret;
};
```

2.5 Biconnected Component

Time Complexity: $\mathcal{O}(N)$

```
int idx = 0;
vector<int> vis(n, -1);
vector<pii> st;
vector<vector<pii>> bcc;
vector<bool> cut(n); // articulation point
function<int (int, int)> dfs = [&] (int x, int p) {
    int ret = vis[x] = idx++;
    int child = 0;
    for (int next : e[x]) {
        if (next == p)
            continue;
        if (vis[next] < vis[x])
            st.emplace_back(x, next);
        if (vis[next] != -1)
            ret = min(ret, vis[next]);
        else {
            int res = dfs(next, x);
            ret = min(ret, res);
            child++;
            if (vis[x] <= res) {
                if (p != -1)
                    cut[x] = true;
                bcc.emplace_back();
                while (st.back() != pii{x, next}) {
                    bcc.back().push_back(st.back());
                    st.pop_back();
                }
                bcc.back().push_back(st.back());
                st.pop_back();
            } // vis[x] < res to find bridges
        }
    }
    if (p == -1 && child > 1)
        cut[x] = true;
    return ret;
};
```

2.6 Lowest Common Ancestor

Usage: Query with the sparse table
Time Complexity: $\mathcal{O}(N \log N) - \mathcal{O}(\log N)$

```
for (int i=1; i<16; ++i) {
    for (int j=0; j<n; ++j)
        par[j][i] = par[par[j][i-1]][i-1];
}
```

2.7 Heavy-Light Decomposition

Usage: Query with the ETT number and it's root node
Time Complexity: $\mathcal{O}(N) - \mathcal{O}(\log N)$

```
vector<int> par(n), ett(n), rt(n), d(n), sz(n);
function<void (int)> dfs1 = [&] (int x) {
    sz[x] = 1;
    for (int &next : e[x]) {
        if (next == par[x]) continue;
        d[next] = d[x]+1;
        par[next] = x;
        dfs1(next);
        sz[x] += sz[next];
        if (e[x][0] == par[x] || sz[e[x][0]] < sz[next])
            swap(e[x][0], next);
    }
};
int idx = 1;
```

```
function<void (int)> dfs2 = [&] (int x) {
    ett[x] = idx++;
    for (int next : e[x]) {
        if (next == par[x]) continue;
        rt[next] = next == e[x][0] ? rt[x] : next;
        dfs2(next);
    }
};
```

2.8 Centroid Decomposition

Usage: cent[x] is the parent in centroid tree
Time Complexity: $\mathcal{O}(N \log N)$

```
vector<int> sz(n);
vector<bool> fin(n);
function<int (int, int)> get_size = [&] (int x, int p) {
    sz[x] = 1;
    for (int next : e[x])
        if (!fin[next] && next != p) sz[x] += get_size(next, x);
    return sz[x];
};
function<int (int, int, int)> get_cent = [&] (int x, int p, int all)
{
    for (int next : e[x])
        if (!fin[next] && next != p && sz[next]*2 > all) return
        get_cent(next, x, all);
    return x;
};
vector<int> cent(n, -1);
function<void (int, int)> get_cent_tree = [&] (int x, int p) {
    get_size(x, p);
    x = get_cent(x, p, sz[x]);
    fin[x] = true;
    cent[x] = p;
    function<void (int, int, int, bool)> dfs = [&] (int x, int p,
    int d, bool test) {
        if (test) // update answer
        else // update state
        for (int next : e[x])
            if (!fin[next] && next != p) dfs(next, x, d, test);
    };
    for (int next : e[x]) {
        if (!fin[next]) {
            dfs(next, x, init, true);
            dfs(next, x, init+curr, false);
        }
    }
    for (int next : e[x])
        if (!fin[next] && next != p) get_cent_tree(next, x);
};
get_cent_tree(0, -1);
```

3 Geometry

3.1 Counter Clockwise

Usage: It returns $\{-1, 0, 1\}$ - the ccw of $b - a$ and $c - b$
Time Complexity: $\mathcal{O}(1)$

```
auto ccw = [] (const pii &a, const pii &b, const pii &c) {
    pii x = { b.first - a.first, b.second - a.second };
    pii y = { c.first - b.first, c.second - b.second };
    ll ret = 1LL * x.first * y.second - 1LL * x.second * y.first;
    return ret == 0 ? 0 : (ret > 0 ? 1 : -1);
};
```

3.2 Line intersection

Usage: Check the intersection of (x_1, x_2) and (y_1, y_2). It requires an additional condition when they are parallel
Time Complexity: $\mathcal{O}(1)$

```
ccw(x1, x2, y1) != ccw(x1, x1, y2) && ccw(y1, y2, x1) != ccw(y1, y2,
x2)
```

3.3 Graham Scan

Time Complexity: $\mathcal{O}(N \log N)$

```
struct point {
    int x, y, p, q;
```

```
    point() { x = y = p = q = 0; }
    bool operator < (const point& other) {
        if (1LL * other.p * q != 1LL * p * other.q)
            return 1LL * other.p * q < 1LL * p * other.q;
        else if (y != other.y)
            return y < other.y;
        else
            return x < other.x;
    }
};
swap(points[0], *min_element(points.begin(), points.end()));
for (int i=1; i<points.size(); ++i) {
    points[i].p = points[i].x - points[0].x;
    points[i].q = points[i].y - points[0].y;
}
sort(points.begin()+1, points.end());
vector<int> hull;
for (int i=0; i<points.size(); ++i) {
    while (hull.size() >= 2 && ccw(points[hull[hull.size()-2]],
    points[hull.back()], points[i]) < 1)
        hull.pop_back();
    hull.push_back(i);
}
```

3.4 Monotone Chain

Usage: Get the upper and lower hull of the convex hull
Time Complexity: $\mathcal{O}(N \log N)$

```
pair<vector<pii>, vector<pii>> getConvexHull(vector<pii> pt){
    sort(pt.begin(), pt.end());
    vector<pii> uh, dh;
    int un=0, dn=0; // for easy coding
    for (auto &tmp : pt) {
        while(un >= 2 && ccw(uh[un-2], uh[un-1], tmp))
            uh.pop_back(), --un;
        uh.push_back(tmp); ++un;
    }
    reverse(pt.begin(), pt.end());
    for (auto &tmp : pt) {
        while(dn >= 2 && ccw(dh[dn-2], dh[dn-1], tmp))
            dh.pop_back(), --dn;
        dh.push_back(tmp); ++dn;
    }
    return {uh, dh};
} // ref: https://namnamseo.tistory.com
```

3.5 Rotating Calipers

Usage: Get the maximum distance of the convex hull
Time Complexity: $\mathcal{O}(N)$

```
auto ccw4 = [&] (point& a1, point& a2, point& b1, point& b2) {
    return 1LL * (a2.x - a1.x) * (b2.y - b1.y) > 1LL * (a2.y - a1.y)
    * (b2.x - b1.x);
};
auto dist = [] (point& a, point& b) {
    return 1LL * (a.x - b.x) * (a.x - b.x) + 1LL * (a.y - b.y) *
    (a.y - b.y);
};
ll maxi = 0;
for (int i=0, j=1; i<hull.size();) {
    maxi = max(maxi, dist(hull[i], hull[j]));
    if (j < hull.size()-1 && ccw4(hull[i], hull[i+1], hull[j],
    hull[j+1]))
        j++;
    else
        i++;
}
```

4 Fast Fourier Transform

4.1 Fast Fourier Transform

Usage: FFT and multiply polynomials
Time Complexity: $\mathcal{O}(N \log N)$

```
using cd = complex<double>;
void fft(vector<cd> &f, cd w) {
  int n = f.size();
  if (n == 1)
```

```
    return;
  vector<cd> odd(n/2), even(n/2);
  for (int i=0; i<n; ++i)
    (i%2 ? odd : even)[i/2] = f[i];
  fft(odd, w*w);
  fft(even, w*w);
  cd x(1, 0);
  for (int i=0; i<n/2; ++i) {
    f[i] = even[i] + x * odd[i];
    f[i+n/2] = even[i] - x * odd[i];
    x *= w; // get through power to better accuracy
  }
}
vector<cd> mult(vector<cd> a, vector<cd> b) {
  int n;
  for (n=1; n<a.size() || n<b.size(); n*=2);
  n *= 2;
  vector<cd> ret(n);
  a.resize(n);
  b.resize(n);
  static constexpr double PI = 3.1415926535897932384;
  cd w(cos(PI*2/n), sin(PI*2/n));
  fft(a, w);
  fft(b, w);
  for (int i=0; i<n; ++i)
    ret[i] = a[i] * b[i];
  fft(ret, cd(1, 0)/w);
  for (int i=0; i<n; ++i) {
    ret[i] /= cd(n, 0);
    ret[i] = cd(round(ret[i].real()), round(ret[i].imag()));
  }
  return ret;
}
vector<cd> div(vector<cd> &f, int sz) {
  vector<cd> ret = {1 / f[0]};
  for (int i=1; i<sz; i*=2) {
    vector<cd> tmp(f.begin(), f.begin()+min((int)f.size(), i*2));
    tmp = mult(ret, tmp);
    tmp.resize(i * 2);
    for (cd &x : tmp) x = -x;
    tmp[0] += 2;
    ret = mult(ret, tmp);
    ret.resize(i * 2);
  }
  return ret;
}
```

4.2 Number Theoretic Transform

Usage: FFT with integer - to get better accuracy
Time Complexity: $\mathcal{O}(N \log N)$

```
// w is the root of mod e.g. 3/998244353 and 5/1012924417
void ntt(vector<ll> &f, const ll w, const ll mod) {
  const int n = f.size();
  if (n == 1)
    return;
  vector<ll> odd(n/2), even(n/2);
  for (int i=0; i<n; ++i)
    (i&1 ? odd : even)[i/2] = f[i];
  ntt(odd, w*w%mod, mod);
  ntt(even, w*w%mod, mod);
  ll x = 1;
  for (int i=0; i<n/2; ++i) {
    f[i] = (even[i] + x * odd[i] % mod) % mod;
    f[i+n/2] = (even[i] - x * odd[i] % mod + mod) % mod;
    x = x*w%mod;
  }
}
```

4.3 Fast Walsh Hadamard Transform

Usage: XOR convolution
Time Complexity: $\mathcal{O}(N \log N)$

```
void fwht(vector<ll> &f) {
  const int n = f.size();
  if (n == 1)
    return;
  vector<ll> odd(n/2), even(n/2);
  for (int i=0; i<n; ++i)
```

```
    (i&1 ? odd : even)[i/2] = f[i];
  fwht(odd);
  fwht(even);
  for (int i=0; i<n/2; ++i) {
    f[i*2] = even[i] + odd[i];
    f[i*2+1] = even[i] - odd[i];
  }
}
```

5 String

5.1 Knuth-Moris-Pratt

Time Complexity: $\mathcal{O}(N)$

```
vector<int> fail(m);
for (int i=1, j=0; i<m; ++i) {
    while (j > 0 && p[i] != p[j]) j = fail[j-1];
    if (p[i] == p[j]) fail[i] = ++j;
}
vector<int> ans;
for (int i=0, j=0; i<n; ++i) {
    while (j > 0 && t[i] != p[j]) j = fail[j-1];
    if (t[i] == p[j]) {
        if (j == m-1) {
            ans.push_back(i-j);
            j = fail[j];
        } else j++;
    }
}
```

5.2 Rabin-Karp

Usage: The Rabin fingerprint for const-length hashing
Time Complexity: $\mathcal{O}(N)$

```
ull hash, p;
vector<ull> ht;
for (int i=0; i<=l-mid; ++i) {
    if (i == 0) {
        hash = s[0];
        p = 1;
        for (int j=1; j<mid; ++j) {
            hash = hash * pi + s[j];
            p = p * pi; // pi is the prime e.g. 13
        }
    } else
        hash = (hash - p * s[i-1]) * pi + s[i+mid-1];
    ht.push_back(hash);
}
```

5.3 Manacher

Usage: Longest radius of palindrome substring
Time Complexity: $\mathcal{O}(N)$

```
vector<int> man(m);
int r = 0, p = 0;
for (int i=0; i<m; ++i) {
    if (i <= r)
        man[i] = min(man[p*2 - i], r - i);
    while (i-man[i] > 0 && i+man[i] < m-1 && v[i-man[i]-1] ==
    v[i+man[i]+1])
        man[i]++;
    if (r < i + man[i]) {
        r = i + man[i];
        p = i;
    }
}
```

5.4 Suffix Array and LCP Array

Time Complexity: $\mathcal{O}(N \log N) - \mathcal{O}(N)$

```
const int m = max(255, n)+1;
vector<int> sa(n), ord(n*2), nord(n*2);
for (int i=0; i<n; ++i) {
    sa[i] = i;
    ord[i] = s[i];
}
for (int d=1; d<n; d*=2) {
```

```
    auto cmp = [&] (int i, int j) {
        if (ord[i] == ord[j])
            return ord[i+d] < ord[j+d];
        return ord[i] < ord[j];
    };
    vector<int> cnt(m), tmp(n);
    for (int i=0; i<n; ++i)
        cnt[ord[i+d]]++;
    for (int i=0; i+1<m; ++i)
        cnt[i+1] += cnt[i];
    for (int i=n-1; i>=0; --i)
        tmp[--cnt[ord[i+d]]] = i;
    fill(cnt.begin(), cnt.end(), 0);
    for (int i=0; i<n; ++i)
        cnt[ord[i]]++;
    for (int i=0; i+1<m; ++i)
        cnt[i+1] += cnt[i];
    for (int i=n-1; i>=0; --i)
        sa[--cnt[ord[tmp[i]]]] = tmp[i];
    nord[sa[0]] = 1;
    for (int i=1; i<n; ++i)
        nord[sa[i]] = nord[sa[i-1]] + cmp(sa[i-1], sa[i]);
    swap(ord, nord);
}
vector<int> inv(n), lcp(n);
for (int i=0; i<n; ++i)
    inv[sa[i]] = i;
for (int i=0, k=0; i<n; ++i) {
    if (inv[i] == 0)
        continue;
    for (int j=sa[inv[i]-1]; s[i+k]==s[j+k]; ++k);
    lcp[inv[i]] = k ? k-- : 0;
}
```

5.5 Aho-Corasick

Time Complexity: $\mathcal{O}(N + \sum M)$

```
struct trie {
  array<trie *, 3> go;
  trie *fail;
  int output, idx;
  trie() {
    fill(go.begin(), go.end(), nullptr);
    fail = nullptr;
    output = idx = 0;
  }
  ~trie() {
    for (auto &x : go)
      delete x;
  }
  void insert(const string &input, int i) {
    if (i == input.size())
      output++;
    else {
      const int x = input[i] - 'A';
      if (!go[x])
        go[x] = new trie();
      go[x]->insert(input, i+1);
    }
  }
};
queue<trie*> q; // make fail links; requires root->insert before
root->fail = root;
q.push(root);
while (!q.empty()) {
    trie *curr = q.front();
    q.pop();
    for (int i=0; i<26; ++i) {
        trie *next = curr->go[i];
        if (!next)
            continue;
        if (curr == root)
            next->fail = root;
        else {
            trie *dest = curr->fail;
            while (dest != root && !dest->go[i])
                dest = dest->fail;
            if (dest->go[i])
                dest = dest->go[i];
            next->fail = dest;
```

```
        }
        if (next->fail->output)
            next->output = true;
        q.push(next);
    }
}
trie *curr = root; // start query
bool found = false;
for (char c : s) {
    c -= 'a';
    while (curr != root && !curr->go[c])
        curr = curr->fail;
    if (curr->go[c])
        curr = curr->go[c];
    if (curr->output) {
        found = true;
        break;
    }
}
```

6 Offline Query

6.1 Mo's

Usage: sort by $(L\sqrt{L}, R)$
Time Complexity: $\mathcal{O}(Q\log Q + N\sqrt{N})$

```
sort(q.begin(), q.end(), [&] (const auto &a, const auto &b) {
    if (get<0>(a)/rt != get<0>(b)/rt)
        return get<0>(a)/rt < get<0>(b)/rt;
    return get<1>(a) < get<1>(b);
});
int res = 0, s = get<0>(q[0]), e = get<1>(q[0]);
vector<int> count(1e6), result(m);
for (int i=s; i<=e; ++i)
    res += count[a[i]]++ == 0;
result[get<2>(q[0])] = res;
for (int i=1; i<m; ++i) {
    while (get<0>(q[i]) < s)
        res += count[a[--s]]++ == 0;
    while (get<1>(q[i]) > e)
        res += count[a[++e]]++ == 0;
    while (get<0>(q[i]) > s)
        res -= --count[a[s++]] == 0;
    while (get<1>(q[i]) < e)
        res -= --count[a[e--]] == 0;
    result[get<2>(q[i])] = res;
}
```

6.2 Parallel Binary Search

Time Complexity: $\mathcal{O}(N\log N)$

```
vector<int> lo(q, -1), hi(q, m), answer(q);
while (true) {
    int fin = 0;
    vector<vector<int>> mids(m);
    for (int i=0; i<q; ++i) {
        if (lo[i] + 1 < hi[i]) mids[(lo[i] + hi[i])/2].push_back(i);
        else fin++;
    }
    if (fin == q) break;
    ufind uf;
    uf.init(n+1);
    for (int i=0; i<m; ++i) {
        const auto &[eig, a, b] = edges[i];
        uf.merge(a, b);
        for (int x : mids[i]) {
            if (uf.find(qs[x].first) == uf.find(qs[x].second)) {
                hi[x] = i;
                answer[x] = -uf.par[uf.find(qs[x].first)];
            } else lo[x] = i;
        }
    }
}
```

7 DP Optimization

7.1 Convex Hull Trick w/ Stack

Usage: `dp[i] = min(dp[j] + b[j] * a[i]), b[j] >= b[j+1]`

Time Complexity: $\mathcal{O}(N \log N) - \mathcal{O}(N)$ where `a[i] <= a[i+1]`

```
struct lin {
  ll a, b;
  double s;
  ll f(ll x) { return a*x + b; }
};
inline double cross(const lin &x, const lin &y) {
  return 1.0 * (x.b - y.b) / (y.a - x.a);
}
vector<ll> dp(n);
vector<lin> st;
for (int i=1; i<n; ++i) {
    lin curr = { b[i-1], dp[i-1], 0 };
    while (!st.empty()) {
        curr.s = cross(st.back(), curr);
        if (st.back().s < curr.s)
            break;
        st.pop_back();
    }
    st.push_back(curr);
    int x = -1;
    for (int y = st.size(); y > 0; y /= 2) {
        while (x+y < st.size() && st[x+y].s < a[i])
            x += y;
    }
    dp[i] = s[x].f(a[i]);
}
while (x+1 < st.size() && st[x+1].s < a[i]) ++x; // O(N) case
```

7.2 Convex Hull Trick w/ Li-Chao Tree

Usage: `update(l, r, 0, { a, b })`
Time Complexity: $\mathcal{O}(N \log N)$

```
static constexpr ll INF = 2e18;
struct lin {
  ll a, b;
  ll f(ll x) { return a*x + b; }
};
struct lichao {
struct node {
  int l, r;
  lin line;
};
vector<node> tree;
void init() { tree.push_back({-1, -1, { 0, -INF }}); }
void update(ll s, ll e, int n, const lin &line) {
  lin hi = tree[n].line;
  lin lo = line;
  if (hi.f(s) < lo.f(s))
    swap(lo, hi);
  if (hi.f(e) >= lo.f(e)) {
    tree[n].line = hi;
    return;
  }
  const ll m = s + e >> 1;
  if (hi.f(m) > lo.f(m)) {
    tree[n].line = hi;
    if (tree[n].r == -1) {
      tree[n].r = tree.size();
      tree.push_back({-1, -1, { 0, -INF }});
    }
    update(m+1, e, tree[n].r, lo);
  } else {
    tree[n].line = lo;
    if (tree[n].l == -1) {
      tree[n].l = tree.size();
      tree.push_back({-1, -1, { 0, -INF }});
    }
    update(s, m, tree[n].l, hi);
  }
}
ll query(ll s, ll e, int n, ll x) {
  if (n == -1)
    return -INF;
  const ll m = s + e >> 1;
  if (x <= m)
    return max(tree[n].line.f(x), query(s, m, tree[n].l, x));
  else
    return max(tree[n].line.f(x), query(m+1, e, tree[n].r, x));
```

```
  }
};
```

7.3 Divide and Conquer Optimization

Usage: `dp[t][i] = min(dp[t-1][j] + c[j][i]), c is Monge`
Time Complexity: $\mathcal{O}(KN \log N)$

```
vector<vector<ll>> dp(n, vector<ll>(t));
function<void (int, int, int, int, int)> dnc = [&] (int l, int r,
int s, int e, int u) {
    if (l > r)
        return;
    const int mid = (l + r) / 2;
    int opt;
    for (int i=s; i<=min(e, mid); ++i) {
        ll x = sum[i][mid] + C;
        if (i && u)
            x += dp[i-1][u-1];
        if (x >= dp[mid][u]) {
            dp[mid][u] = x;
            opt = i;
        }
    }
    dnc(l, mid-1, s, opt, u);
    dnc(mid+1, r, opt, e, u);
};
for (int i=0; i<t; ++i)
    dnc(0, n-1, 0, n-1, i);
```

7.4 Monotone Queue Optimization

Usage: `dp[i] = min(dp[j] + c[j][i]), c is Monge, find cross`
Time Complexity: $\mathcal{O}(N \log N)$

```
auto cross = [&](ll p, ll q) {
  ll lo = min(p, q) - 1, hi = n + 1;
  while (lo + 1 < hi) {
    const ll mid = (lo + hi) / 2;
    if (f(p, mid) < f(q, mid)) lo = mid;
    else hi = mid;
  }
  return hi;
};
deque<pll> st;
for (int i = 1; i <= n; ++i) {
  pll curr{i - 1, 0};
  while (!st.empty() &&
          (curr.second = cross(st.back().first, i - 1)) <=
          st.back().second)
    st.pop_back();
  st.push_back(curr);
  while (st.size() > 1 && st[1].second <= i) st.pop_front();
  dp[i] = f(st[0].first, i);
}
```

7.5 Aliens Trick

Usage: `dp[t][i] = min(dp[t-1][j] + c[j+1][i]), c is Monge, find lambda w/ half bs`
Time Complexity: $\mathcal{O}(N \log N)$

```
  ll lo = 0, hi = 1e15;
  while (lo + 1 < hi) {
    const ll mid = (lo + hi) / 2;
    auto [dp, cnt] = dec(mid); // the best DP[N][K] and its K value
    if (cnt < k) hi = mid;
    else lo = mid;
  }
  cout << (dec(lo).first - lo * k) / 2;
```

7.6 Knuth Optimization

Usage: `dp[i] = min(dp[i][k] + dp[k][j]) + c[i][j]`, Monge, Monotonic
Time Complexity: $\mathcal{O}(N^2)$

```
vector<vector<int>> dp(n, vector<int>(n)), opt(n, vector<int>(n));
for (int i=0; i<n; ++i)
    opt[i][i] = i;
for (int j=1; j<n; ++j) {
    for (int s=0; s<n-j; ++s) {
        int e = s+j;
```

```
        dp[s][e] = 1e9+7;
        for (int o=opt[s][e-1]; o<min(opt[s+1][e]+1, e); ++o) {
            if (dp[s][e] > dp[s][o] + dp[o+1][e]) {
                dp[s][e] = dp[s][o] + dp[o+1][e];
                opt[s][e] = o;
            }
        }
        dp[s][e] += sum[e+1] - sum[s];
    }
}
```

7.7 Slope Trick

Usage: Use priority queue, convex condition
Time Complexity: $\mathcal{O}(N \log N)$

```
pq.push(A[0]);
for (int i=1; i<N; ++i) {
    pq.push(A[i] - i);
    pq.push(A[i] - i);
    pq.pop();
    A[i] = pq.top();
}
```

7.8 Sum Over Subsets

Usage: `dp[mask] = sum(A[i]), i is in mask`
Time Complexity: $\mathcal{O}(N2^N)$

```
for (int i=0; i<(1<<n); i++)
    f[i] = a[i];
for (int j=0; j<n; j++)
    for(int i=0; i<(1<<n); i++)
      if (i & (1<<j)) f[i] += f[i ^ (1<<j)];
```

8 Number Theory

8.1 Modular Operator

Usage: For Fermat's little theorem and Pollard rho
Time Complexity: $\mathcal{O}(\log N)$

```
using ull = unsigned long long;
ull modmul(ull a, ull b, ull n) { return ((unsigned __int128)a * b)
% n; }
ull modmul(ull a, ull b, ull n) { // if __int128 isn't available
   if (b == 0) return 0;
   if (b == 1) return a;
   ull t = modmul(a, b/2, n);
   t = (t+t)%n;
   if (b % 2) t = (t+a)%n;
   return t;
}
ull modpow(ull a, ull d, ull n) {
    if (d == 0) return 1;
    ull r = modpow(a, d/2, n);
    r = modmul(r, r, n);
    if (d % 2) r = modmul(r, a, n);
    return r;
}
ull gcd(ull a, ull b) { return b ? gcd(b, a%b) : a; }
```

8.2 Modular Inverse in $\mathcal{O}(N)$

Usage: Get inverse of factorial
Time Complexity: $\mathcal{O}(N) - \mathcal{O}(1)$

```
const int mod = 1e9+7;
vector<int> fact(n+1), inv(n+1), factinv(n+1);
fact[0] = fact[1] = inv[1] = factinv[0] = factinv[1] = 1;
for (int i=2; i<=n; ++i) {
    fact[i] = 1LL * fact[i-1] * i % mod;
    inv[i] = mod - 1LL * mod/i * inv[mod%i] % mod;
    factinv[i] = 1LL * factinv[i-1] * inv[i] % mod;
}
```

8.3 Extended Euclidean

Usage: get a and b as arguments and return the solution (x, y) of equation $ax + by = \gcd(a, b)$.
Time Complexity: $\mathcal{O}(\log a + \log b)$

```
pair<ll, ll> extGCD(ll a,ll b){
    if (b != 0) {
```

```
        auto tmp = extGCD(b, a % b);
        return {tmp.second, tmp.first - (a / b) * tmp.second};
    } else return {1ll, 0ll};
}
```

8.4 Miller-Rabin

Usage: Fast prime test for big integers
Time Complexity: $\mathcal{O}(k \log N)$

```
bool is_prime(ull n) {
    const ull as[7] = {2, 325, 9375, 28178, 450775, 9780504,
    1795265022};
    // const ull as[12] = {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31,
    37}; // easier to remember
    auto miller_rabin = [] (ull n, ull a) {
        ull d = n-1, temp;
        while (d % 2 == 0) {
            d /= 2;
            temp = modpow(a, d, n);
            if (temp == n-1)
                return true;
        }
        return temp == 1;
    };
    for (ull a : as) {
        if (a >= n)
            break;
        if (!miller_rabin(n, a))
            return false;
    }
    return true;
}
```

8.5 Chinese Remainder Theorem

Usage: Solution for the system of linear congruence
Time Complexity: $\mathcal{O}(\log N)$

```
w1 = modpow(mod2, mod1-2, mod1);
w2 = modpow(mod1, mod2-2, mod2);
ll ans = ((__int128)mod2 * w1 * f1[i] + (__int128)mod1 * w2 * f2[i])
% (mod1*mod2);
```

8.6 Pollard Rho

Usage: Factoring large numbers fast
Time Complexity: $\mathcal{O}(N^{1/4})$

```
void pollard_rho(ull n, vector<ull> &factors) {
    if (n == 1)
        return;
    if (n % 2 == 0) {
        factors.push_back(2);
        pollard_rho(n/2, factors);
        return;
    }
    if (is_prime(n)) {
        factors.push_back(n);
        return;
    }
    ull x, y, c = 1, g = 1;
    auto f = [&] (ull x) { return (modmul(x, x, n) + c) % n; };
    y = x = 2;
    while (g == 1 || g == n) {
        if (g == n) {
            c = rand() % 123;
            y = x = rand() % (n-2) + 2;
        }
        x = f(x);
        y = f(f(y));
        g = gcd(n, y>x ? y-x : x-y);
    }
    pollard_rho(g, factors);
    pollard_rho(n / g, factors);
}
```

9 ETC

9.1 Gaussian Elimination

Time Complexity: $\mathcal{O}(\log N)$

```
struct basis {
  const static int n = 30; // log2(1e9)
  array<int, n> data{};
  void insert(int x) {
    for (int i=0; i<n; ++i)
      if (data[i] && (x >> (n-1-i) & 1)) x ^= data[i];
    int y;
    for (y=0; y<n; ++y)
      if (!data[y] && (x >> (n-1-y) & 1)) break;
    if (y < n) {
      for (int i=0; i<n; ++i)
        if (data[i] >> (n-1-y) & 1) data[i] ^= x;
      data[y] = x;
    }
  }
  basis operator+(const basis &other) {
    basis ret{};
    for (int x : data) ret.insert(x);
    for (int x : other.data) ret.insert(x);
    return ret;
  }
};
```

9.2 Randomized Meldable Heap

Usage: Min-heap `H` is declared as `Heap<T> H`. You can use `push`, `size`, `empty`, `top`, `pop` as `std::priority_queue`. Use `H.meld(G)` to meld contents from `G` to `H`.
Time Complexity: $\mathcal{O}(logn)$

```
namespace Meldable {
mt19937 gen(0x94949);
template<typename T>
struct Node {
  Node *l, *r;
  T v;
  Node(T x): l(0), r(0), v(x){}
};
template<typename T>
Node<T>* Meld(Node<T>* A, Node<T>* B) {
  if(!A) return B; if(!B) return A;
  if(B->v < A->v) swap(A, B);
  if(gen()&1) A->l = Meld(A->l, B);
  else A->r = Meld(A->r, B);
  return A;
}
template<typename T>
struct Heap {
  Node<T> *r; int s;
  Heap(): r(0), s(0){}
  void push(T x) {
    r = Meld(new Node<T>(x), r);
    ++s;
  }
  int size(){ return s; }
  bool empty(){ return s == 0;}
  T top(){ return r->v; }
  void pop() {
    Node<T>* p = r;
    r = Meld(r->l, r->r);
    delete p;
    --s;
  }
  void Meld(Heap x) {
    s += x->s;
    r = Meld(r, x->r);
  }
};
}
```

9.3 Berlekamp-Massey

Usage: `get_nth({1, 1, 2, 3, 5}, n)`

```
const int mod = 998244353;
using lint = long long;
lint ipow(lint x, lint p){
  lint ret = 1, piv = x;
  while(p){
    if(p & 1) ret = ret * piv % mod;
    piv = piv * piv % mod;
    p >>= 1;
  }
```

```
  return ret;
}
vector<int> berlekamp_massey(vector<int> x){
  vector<int> ls, cur;
  int lf, ld;
  for(int i=0; i<x.size(); i++){
    lint t = 0;
    for(int j=0; j<cur.size(); j++){
      t = (t + 1ll * x[i-j-1] * cur[j]) % mod;
    }
    if((t - x[i]) % mod == 0) continue;
    if(cur.empty()){
      cur.resize(i+1);
      lf = i;
      ld = (t - x[i]) % mod;
      continue;
    }
    lint k = -(x[i] - t) * ipow(ld, mod - 2) % mod;
    vector<int> c(i-lf-1);
    c.push_back(k);
    for(auto &j : ls) c.push_back(-j * k % mod);
    if(c.size() < cur.size()) c.resize(cur.size());
    for(int j=0; j<cur.size(); j++){
      c[j] = (c[j] + cur[j]) % mod;
    }
    if(i-lf+(int)ls.size()>=(int)cur.size()){
      tie(ls, lf, ld) = make_tuple(cur, i, (t - x[i]) % mod);
    }
    cur = c;
  }
  for(auto &i : cur) i = (i % mod + mod) % mod;
  return cur;
}
int get_nth(vector<int> rec, vector<int> dp, lint n){
  int m = rec.size();
  vector<int> s(m), t(m);
  s[0] = 1;
  if(m != 1) t[1] = 1;
  else t[0] = rec[0];
  auto mul = [&rec](vector<int> v, vector<int> w){
    int m = v.size();
    vector<int> t(2 * m);
    for(int j=0; j<m; j++){
      for(int k=0; k<m; k++){
        t[j+k] += 1ll * v[j] * w[k] % mod;
        if(t[j+k] >= mod) t[j+k] -= mod;
      }
    }
    for(int j=2*m-1; j>=m; j--){
      for(int k=1; k<=m; k++){
        t[j-k] += 1ll * t[j] * rec[k-1] % mod;
        if(t[j-k] >= mod) t[j-k] -= mod;
      }
    }
    t.resize(m);
    return t;
  };
  while(n){
    if(n & 1) s = mul(s, t);
    t = mul(t, t);
    n >>= 1;
  }
  lint ret = 0;
  for(int i=0; i<m; i++) ret += 1ll * s[i] * dp[i] % mod;
  return ret % mod;
}
int guess_nth_term(vector<int> x, lint n){
  if(n < x.size()) return x[n];
  vector<int> v = berlekamp_massey(x);
  if(v.empty()) return 0;
  return get_nth(v, x, n);
}
struct elem{int x, y, v;}; // A_(x, y) <- v, 0-based. no duplicate
please..
vector<int> get_min_poly(int n, vector<elem> M){
  // smallest poly P such that A^i = sum_{j < i} {A^j \times P_j}
  vector<int> rnd1, rnd2;
  mt19937 rng(0x14004);
  auto randint = [&rng](int lb, int ub){
    return uniform_int_distribution<int>(lb, ub)(rng);
```

```
  };
  for(int i=0; i<n; i++){
    rnd1.push_back(randint(1, mod - 1));
    rnd2.push_back(randint(1, mod - 1));
  }
  vector<int> gobs;
  for(int i=0; i<2*n+2; i++){
    int tmp = 0;
    for(int j=0; j<n; j++){
      tmp += 1ll * rnd2[j] * rnd1[j] % mod;
      if(tmp >= mod) tmp -= mod;
    }
    gobs.push_back(tmp);
    vector<int> nxt(n);
    for(auto &i : M){
      nxt[i.x] += 1ll * i.v * rnd1[i.y] % mod;
      if(nxt[i.x] >= mod) nxt[i.x] -= mod;
    }
    rnd1 = nxt;
  }
  auto sol = berlekamp_massey(gobs);
  reverse(sol.begin(), sol.end());
  return sol;
}
lint det(int n, vector<elem> M){
  vector<int> rnd;
  mt19937 rng(0x14004);
  auto randint = [&rng](int lb, int ub){
    return uniform_int_distribution<int>(lb, ub)(rng);
  };
  for(int i=0; i<n; i++) rnd.push_back(randint(1, mod - 1));
  for(auto &i : M){
    i.v = 1ll * i.v * rnd[i.y] % mod;
  }
  auto sol = get_min_poly(n, M)[0];
  if(n % 2 == 0) sol = mod - sol;
  for(auto &i : rnd) sol = 1ll * sol * ipow(i, mod - 2) % mod;
  return sol;
}
```

9.4 Splay Tree w/ Lazy

```
struct splay_tree {
  struct node {
    node *l, *r, *p;
    ll key, sum, lazy, cnt;
    bool inv;
    node(ll value) {
      l = r = p = nullptr;
      cnt = 1;
      key = value;
      sum = value;
      lazy = 0;
      inv = false;
    }
  } *tree;
  void push(node *x) {
    x->key += x->lazy;
    if (x->inv) swap(x->l, x->r);
    if (x->l) {
      x->l->lazy += x->lazy;
      x->l->sum += x->lazy * x->l->cnt;
      x->l->inv ^= x->inv;
    }
    if (x->r) {
      x->r->lazy += x->lazy;
      x->r->sum += x->lazy * x->r->cnt;
      x->r->inv ^= x->inv;
    }
    x->lazy = 0;
    x->inv = false;
  }
  void rotate(node *x) {
    auto p = x->p;
    node *tmp;
    push(p), push(x);
    if (x == p->l) {
      p->l = tmp = x->r;
      x->r = p;
    } else {
```

```
      p->r = tmp = x->l;
      x->l = p;
    }
    x->p = p->p;
    p->p = x;
    if (tmp) tmp->p = p;
    (x->p ? (x->p->l == p ? x->p->l : x->p->r) : tree) = x;
    update(p), update(x);
  }
  void splay(node *x) {
    while (x->p) {
      auto p = x->p;
      auto g = p->p;
      if (g) rotate((x == p->l) == (p == g->l) ? p : x);
      rotate(x);
    }
  }
  void update(node *x) {
    x->cnt = 1;
    x->sum = x->key;
    if (x->l) {
      x->cnt += x->l->cnt;
      x->sum += x->l->sum;
    }
    if (x->r) {
      x->cnt += x->r->cnt;
      x->sum += x->r->sum;
    }
  }
  void init(int n) {
    node *x;
    tree = x = new node(0);
    tree->cnt = n;
    for (int i = 1; i < n; ++i) {
      x->r = new node(0);
      x->r->p = x;
      x = x->r;
      x->cnt = n - i;
    }
  }
  void add(int i, ll v) {
    find_kth(i);
    tree->sum += v;
    tree->key += v;
  }
  void add(int l, int r, ll v) {
    interval(l, r);
    auto x = tree->r->l;
    x->sum += v * x->cnt;
    x->lazy += v;
  }
  void interval(int l, int r) {
    find_kth(l - 1);
    auto x = tree;
    tree = x->r;
    tree->p = nullptr;
    find_kth(r - l + 1);
    x->r = tree;
    tree->p = x;
    tree = x;
  }
  ll sum(int l, int r) {
    interval(l, r);
    return tree->r->l->sum;
  }
  void reverse(int l, int r) {
    interval(l, r);
    tree->r->l->inv ^= true;
  }
  void insert(ll key) {
    auto x = new node(key);
    if (!tree) {
      tree = x;
      return;
    }
    auto p = tree;
    node **t;
    while (true) {
      if (key == p->key) return;
      if (key < p->key) {
```

```
        if (!p->l) {
          t = &p->l;
          break;
        }
        p = p->l;
      } else {
        if (!p->r) {
          t = &p->r;
          break;
        }
        p = p->r;
      }
    }
    *t = x;
    x->p = p;
    splay(x);
  }
  bool find(int key) {
    if (!tree) return false;
    auto p = tree;
    while (p) {
      push(p);
      if (key == p->key) break;
      if (key < p->key) {
        if (!p->l) break;
        p = p->l;
      } else {
        if (!p->r) break;
        p = p->r;
      }
    }
    splay(p);
    return key == p->key;
  }
  void erase(ll key) {
    if (!find(key)) return;
    auto p = tree;
    if (p->l) {
      if (p->r) {
        tree = p->l;
        tree->p = nullptr;
        auto x = tree;
        while (x->r)
          x = x->r;
        x->r = p->r;
        p->r->p = x;
        splay(x);
        delete p;
        return;
      }
      tree = p->l;
      tree->p = nullptr;
      delete p;
      return;
    }
    if (p->r) {
      tree = p->r;
      tree->p = nullptr;
      delete p;
      return;
    }
    delete p;
    tree = nullptr;
  }
  void find_kth(int k) {
    auto x = tree;
    while (x) {
      push(x);
      while (x->l && x->l->cnt > k) {
        x = x->l;
        push(x);
      }
      if (x->l) k -= x->l->cnt;
      if (!k--) break;
      x = x->r;
    }
    splay(x);
  }
};
```

9.5 Useful Stuff

- Catalan Number
  1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786, 208012,742900
  $C_n = binomial(n * 2, n)/(n + 1);$
  - 길이가 2n인 올바른 괄호 수식의 수
  - n + 1개의 리프를 가진 풀 바이너리 트리의 수
  - n + 2각형을 n개의 삼각형으로 나누는 방법의 수

- Burnside's Lemma
  경우의 수를 세는데, 특정 transform operation(회전, 반사, ..) 해서 같은 경우들은 하나로 친다. 전체 경우의 수는? 각 operation마다 이 operation을 했을 때 변하지 않는 경우의 수를 센다 (단, "아무것도 하지 않는다" 라는 operation도 있어야 함!) 전체 경우의 수를 더한 후, operation의 수로 나눈다. (답이 맞다면 항상 나누어 떨어져야 한다)

- 알고리즘 게임
  - Nim Game의 해법 : 각 더미의 돌의 개수를 모두 XOR했을 때 0 이 아니면 첫번째, 0 이면 두번째 플레이어가 승리.
  - Grundy Number : 어떤 상황의 Grundy Number는, 가능한 다음 상황들의 Grundy Number를 모두 모은 다음, 그 집합에 포함 되지 않는 가장 작은 수가 현재 state의 Grundy Number가 된다. 만약 다음 state가 독립된 여러개의 state 들로 나뉠 경우, 각각의 state의 Grundy Number의 XOR 합을 생각한다.
  - Subtraction Game : 한 번에 k 개까지의 돌만 가져갈 수 있는 경우, 각 더미의 돌의 개수를 k + 1로 나눈 나머지를 XOR 합하여 판단한다.
  - Index-k Nim : 한 번에 최대 k개의 더미를 골라 각각의 더미에서 아무렇게나 돌을 제거할 수 있을 때, 각 binary digit에 대하여 합을 k + 1로 나눈 나머지를 계산한다. 만약 이 나머지가 모든 digit에 대하여 0이라면 두번째, 하나라도 0이 아니라면 첫번째 플레이어가 승리.

- Pick's Theorem
  격자점으로 구성된 simple polygon이 주어짐. I 는 polygon 내부의 격자점 수, B 는 polygon 선분 위 격자점 수, A는 polygon의 넓이라고 할 때, 다음과 같은 식이 성립한다. $A = I + B/2 - 1$

- 가장 가까운 두 점 : 분할정복으로 가까운 6개의 점만 확인

- 홀의 결혼 정리 : 이분그래프(L-R)에서, 모든 L을 매칭하는 필요충분 조건 = L 에서 임의의 부분집합 S를 골랐을 때, 반드시 (S의 크기) <= (S와 연결되어있는 모든 R의 크기)이다.

- 오일러 정리 : V - E + f(면)가 일정

- 소수 : 10 007 , 10 009 , 10 111 , 31 567 , 70 001 , 1 000 003 , 1 000 033 , 4 000 037 , 99 999 989 , 999 999 937 , 1 000 000 007 , 1 000 000 009 , 9 999 999 967 , 99 999 999 977

- 소수 개수 : (1e5 이하 : 9592), (1e7 이하 : 664 579) , (1e9 이하 : 50 847 534)

- 10^{15} 이하의 정수 범위의 나눗셈 한번은 오차가 없다.

- N의 약수의 개수 = $O(N^{1/3})$, N의 약수의 합 = $O(NloglogN)$

- $\phi(mn) = \phi(m)\phi(n), \phi(pr^n) = pr^n - pr^{n-1}, a^{\phi(n)} \equiv 1 \pmod n$ if coprime

- Euler's phi $\phi(n) = n \prod_{p|n} \left(1 - \frac{1}{p}\right)$

- Lucas' Theorem $\binom{m}{n} = \prod \binom{m_i}{n_i} \pmod p$ m_i, n_i는 p^i의 계수

- 스케줄링에서 데드라인이 빠른 걸 쓰는게 이득. 늦은 스케줄이 안들어갈 때 가장 시간 소모가 큰 스케줄 1개를 제거하면 이득.

9.6 Template

```cpp
// precision
cout.precision(16);
cout << fixed;
// gcc bit operator
__builtin_popcount(bits); // popcountll for ll
__builtin_clz(bits);      // left
__builtin_ctz(bits);      // right
// random number generator
random_device rd;
mt19937 mt(rd());
uniform_int_distribution<> half(0, 1);
cout << half(mt);
// 128MB = int * 33,554,432
struct custom_hash {
  static uint64_t splitmix64(uint64_t x) {
    // http://xorshift.di.unimi.it/splitmix64.c
    x += 0x9e3779b97f4a7c15;
    x = (x ^ (x >> 30)) * 0xbf58476d1ce4e5b9;
    x = (x ^ (x >> 27)) * 0x94d049bb133111eb;
    return x ^ (x >> 31);
  }
```

```
  size_t operator()(uint64_t x) const {
    static const uint64_t FIXED_RANDOM =
        chrono::steady_clock::now().time_since_epoch().count();
    return splitmix64(x + FIXED_RANDOM);
  }
};
#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace __gnu_pbds;
template <typename K, typename V, typename Comp = less<K>>
using ordered_map =
    tree<K, V, Comp, rb_tree_tag,
    tree_order_statistics_node_update>;
template <typename K, typename Comp = less<K>>
using ordered_set = ordered_map<K, null_type, Comp>;
```

9.7 자주 쓰이는 문제 접근법

- 비슷한 문제를 풀어본 적이 있던가?
- 단순한 방법에서 시작할 수 있을까? (brute force)
- 내가 문제를 푸는 과정을 수식화할 수 있을까? (예제를 직접 해결해보면서)
- 문제를 단순화할 수 없을까?
- 그림으로 그려볼 수 있을까?
- 수식으로 표현할 수 있을까?
- 문제를 분해할 수 있을까?
- 뒤에서부터 생각해서 문제를 풀 수 있을까?
- 순서를 강제할 수 있을까?
- 특정 형태의 답만을 고려할 수 있을까? (정규화)
- 특수 조건을 꼭 활용
- 여사건으로 생각하기
- 게임이론 - 거울 전략 혹은 DP 연계
- 겁먹지 말고 경우 나누어 생각
- 해법에서 역순으로 가능한가?
- 딱 맞는 시간복잡도에 집착하지 말자
- 문제에 의미있는 작은 상수 이용
- 스몰투라지나 트라이 같은 트릭 생각
- 잘못된 방법으로 파고들지 말고 버리자

9.8 DP 최적화 접근

- C[i, j] = A[i] * B[j]이고 A, B가 단조증가, 단조감소이면 Monge
- l..r의 값들의 sum이나 min은 Monge
- 식 정리해서 일차(CHT) 혹은 비슷한(MQ) 함수를 발견, 구현 힘들면 Li-Chao
- $a <= b <= c <= d$에서 $A[a, c] + A[b, d] <= A[a, d] + A[b, c]$
- Monge 성질을 보이기 어려우면 N^2 나이브 짜서 opt의 단조성을 확인하고 찍맞
- 식이 간단하거나 변수가 독립적이면 DP 테이블을 세그 위에 올려서 해결
- 침착하게 점화식부터 세우고 Monge인지 판별
- Monge에 집착하지 말고 단조성이나 볼록성만 보여도 됨

9.9 Fast I/O

```
#pragma GCC optimize("O3")
#pragma GCC optimize("Ofast")
#pragma GCC optimize("unroll-loops")

inline int readChar();
template<class T = int> inline T readInt();
template<class T> inline void writeInt(T x, char end = 0);
inline void writeChar(int x);
inline void writeWord(const char *s);
static const int buf_size = 1 << 18;
inline int getChar(){
    #ifndef LOCAL
    static char buf[buf_size];
    static int len = 0, pos = 0;
```

```
    if(pos == len) pos = 0, len = fread(buf, 1, buf_size, stdin);
    if(pos == len) return -1;
    return buf[pos++];
    #endif
}
inline int readChar(){
    #ifndef LOCAL
    int c = getChar();
    while(c <= 32) c = getChar();
    return c;
    #else
    char c; cin >> c; return c;
    #endif
}
template <class T>
inline T readInt(){
    #ifndef LOCAL
    int s = 1, c = readChar();
    T x = 0;
    if(c == '-') s = -1, c = getChar();
    while('0' <= c && c <= '9') x = x * 10 + c - '0', c = getChar();
    return s == 1 ? x : -x;
    #else
    T x; cin >> x; return x;
    #endif
}
static int write_pos = 0;
static char write_buf[buf_size];
inline void writeChar(int x){
    if(write_pos == buf_size) fwrite(write_buf, 1, buf_size,
    stdout), write_pos = 0;
    write_buf[write_pos++] = x;
}
template <class T>
inline void writeInt(T x, char end){
    if(x < 0) writeChar('-'), x = -x;
    char s[24]; int n = 0;
    while(x || !n) s[n++] = '0' + x % 10, x /= 10;
    while(n--) writeChar(s[n]);
    if(end) writeChar(end);
}
inline void writeWord(const char *s){
    while(*s) writeChar(*s++);
}
struct Flusher{
    ~Flusher(){ if(write_pos) fwrite(write_buf, 1, write_pos,
    stdout), write_pos = 0; }
}flusher;
```