

Contents

| | | | | | |
|----------|--|-----------|-----------|---------------------------------|-----------|
| 1 | Data structures | 3 | 6 | Game Theory | 16 |
| 1.1 | Disjoint set with rollback | 3 | 6.1 | Grundy Numbers | 16 |
| 1.2 | Min-Max queue | 3 | 7 | Combinatorics | 17 |
| 1.3 | Sparse table | 3 | 7.1 | Factorial | 17 |
| 1.4 | Squirtle decomposition | 3 | 7.2 | Factorial mod <i>smallPrime</i> | 17 |
| 1.5 | In-Out trick | 3 | 7.3 | Lucas theorem | 17 |
| 1.6 | Parallel binary search | 3 | 7.4 | Stars and bars | 17 |
| 1.7 | Mo's algorithm | 4 | 7.5 | N choose K | 17 |
| 1.8 | Static to dynamic | 4 | 7.6 | Catalan | 17 |
| 1.9 | Disjoint intervals | 4 | 7.7 | Burnside's lemma | 17 |
| 1.10 | Ordered tree | 4 | 7.8 | Prime factors of N! | 17 |
| 1.11 | Unordered tree | 5 | 8 | Number Theory | 17 |
| 1.12 | D-dimensional Fenwick tree | 5 | 8.1 | Goldbach conjecture | 17 |
| 1.13 | Dynamic segment tree | 5 | 8.2 | Sieve of Eratosthenes | 17 |
| 1.14 | Persistent segment tree | 5 | 8.3 | Phi of euler | 18 |
| 1.15 | Wavelet tree | 5 | 8.4 | Miller-Rabin | 18 |
| 1.16 | Li Chao tree | 6 | 8.5 | Pollard-Rho | 18 |
| 1.17 | Explicit Treap | 6 | 8.6 | Amount of divisors | 18 |
| 1.18 | Implicit Treap | 7 | 8.7 | Bézout's identity | 18 |
| 1.19 | Splay tree | 7 | 8.8 | GCD | 18 |
| 2 | Graphs | 7 | 8.9 | LCM | 18 |
| 2.1 | Tarjan algorithm (SCC) | 7 | 8.10 | Euclid | 18 |
| 2.2 | Kosaraju algorithm (SCC) | 8 | 8.11 | Chinese remainder theorem | 18 |
| 2.3 | Two Sat | 8 | 9 | Math | 18 |
| 2.4 | Topological sort | 8 | 9.1 | Progressions | 18 |
| 2.5 | Cutpoints and Bridges | 8 | 9.2 | Mod multiplication | 19 |
| 2.6 | Detect a cycle | 8 | 9.3 | Fpow | 19 |
| 2.7 | Euler tour for Mo's in a tree | 8 | 9.4 | Fibonacci | 19 |
| 2.8 | Lowest common ancestor (LCA) | 8 | 10 | Bit tricks | 19 |
| 2.9 | Isomorphism | 9 | 10.1 | Bitset | 19 |
| 2.10 | Guni | 9 | | | |
| 2.11 | Centroid decomposition | 9 | | | |
| 2.12 | Heavy-light decomposition | 9 | | | |
| 2.13 | Link-Cut tree | 10 | | | |
| 3 | Flows | 10 | | | |
| 3.1 | Dinic $\mathcal{O}(\min(E \cdot flow, V^2 E))$ | 10 | | | |
| 3.2 | Min cost flow $\mathcal{O}(\min(E \cdot flow, V^2 E))$ | 11 | | | |
| 3.3 | Hopcroft-Karp $\mathcal{O}(E\sqrt{V})$ | 11 | | | |
| 3.4 | Hungarian $\mathcal{O}(N^3)$ | 11 | | | |
| 4 | Strings | 12 | | | |
| 4.1 | Hash | 12 | | | |
| 4.2 | KMP | 12 | | | |
| 4.3 | KMP automaton | 12 | | | |
| 4.4 | Z algorithm | 12 | | | |
| 4.5 | Manacher algorithm | 13 | | | |
| 4.6 | Suffix array | 13 | | | |
| 4.7 | Suffix automaton | 13 | | | |
| 4.8 | Aho corasick | 14 | | | |
| 4.9 | Eertree | 15 | | | |
| 5 | Dynamic Programming | 15 | | | |
| 5.1 | All submasks of a mask | 15 | | | |
| 5.2 | Matrix Chain Multiplication | 15 | | | |
| 5.3 | Digit DP | 15 | | | |
| 5.4 | Knapsack 0/1 | 15 | | | |
| 5.5 | Convex Hull Trick $\mathcal{O}(n^2) \Rightarrow \mathcal{O}(n)$ | 15 | | | |
| 5.6 | Divide and conquer $\mathcal{O}(kn^2) \Rightarrow \mathcal{O}(k \cdot n \log n)$ | 16 | | | |
| 5.7 | Knuth optimization $\mathcal{O}(n^3) \Rightarrow \mathcal{O}(n^2)$ | 16 | | | |

Think twice, code once

Template

tem.cpp

```
#pragma GCC optimize("Ofast,unroll-loops,no-stack-protector")
#include <bits/stdc++.h>
using namespace std;

#ifdef LOCAL
#include "debug.h"
#else
#define debug(...)
#endif

#define df(b, e) ((b) > (e))
#define fore(i, b, e) for (auto i = (b) - df(b, e); i != e - df(b, e); i += 1 - 2 * df(b, e))
#define sz(x) int(x.size())
#define all(x) begin(x), end(x)
#define f first
#define s second
#define pb push_back

using lli = long long;
using ld = long double;
using ii = pair<int, int>;
using vi = vector<int>;

int main() {
    cin.tie(0) -> sync_with_stdio(0), cout.tie(0);
    // solve the problem here D:
    return 0;
}

debug.h

template <class A, class B>
ostream & operator << (ostream &os, const pair<A, B> &p) {
    return os << "(" << p.first << ", " << p.second << "
        )";
}

template <class A, class B, class C>
basic_ostream<A, B> & operator << (basic_ostream<A, B>
    &os, const C &c) {
    os << "[";
    for (const auto &x : c)
        os << ", " + 2 * (&x == &begin(c)) << x;
    return os << "]";
}

void print(string s) { cout << endl; }

template <class H, class... T>
void print(string s, const H &h, const T&... t) {
    const static string reset = "\033[0m", blue = "\033[
        1;34m", purple = "\033[3;95m";
    bool ok = 1;
    do {
        if (s[0] == '\0') ok = 0;
        else cout << blue << s[0] << reset;
        s = s.substr(1);
    } while (s.size() && s[0] != ',');
    if (ok) cout << ": " << purple << h << reset;
    print(s, t...);
}
```

Randoms

```
mt19937 rng(chrono::steady_clock::now().
    time_since_epoch().count());
```

```
template <class T>
T ran(T l, T r) {
    return uniform_int_distribution<T>(l, r)(rng);
}
```

Fastio

```
char gc() { return getchar_unlocked(); }

void readInt() {}
template <class H, class... T>
void readInt(H &h, T&&... t) {
    char c, s = 1;
    while (isspace(c = gc()));
    if (c == '-') s = -1, c = gc();
    for (h = c - '0'; isdigit(c = gc()); h = h * 10 + c
        - '0');
    h *= s;
    readInt(t...);
}

void readFloat() {}
template <class H, class... T>
void readFloat(H &h, T&&... t) {
    int c, s = 1, fp = 0, fpl = 1;
    while (isspace(c = gc()));
    if (c == '-') s = -1, c = gc();
    for (h = c - '0'; isdigit(c = gc()); h = h * 10 + c
        - '0');
    h *= s;
    if (h == '.')
        for (; isdigit(c = gc()); fp = fp * 10 + c - '0',
            fpl *= 10);
    h += (double)fp / fpl;
    readFloat(t...);
}
```

Compilation (gedit ~/.zshenv)

```
touch a_in{1..9} // make files a_in1, a_in2,..., a_in9
tee {a..m}.cpp < tem.cpp // "" with tem.cpp like base
cat > a_in1 // write on file a_in1
gedit a_in1 // open file a_in1
rm -r a.cpp // deletes file a.cpp :(

red='\x1B[0;31m'
green='\x1B[0;32m'
noColor='\x1B[0m'
alias flags='-Wall -Wextra -Wshadow -
    D_GLIBCXX_ASSERTIONS -fmax-errors=3 -O2 -w'
go() { g++ --std=c++11 $2 ${flags} $1.cpp && ./a.out }
debug() { go $1 -DLOCAL < $2 }
run() { go $1 "" < $2 }

random() { // Make small test cases!!!
    g++ --std=c++11 $1.cpp -o prog
    g++ --std=c++11 gen.cpp -o gen
    g++ --std=c++11 brute.cpp -o brute
    for ((i = 1; i <= 200; i++)); do
        printf "Test case #${i}"
        ./gen > in
        diff -uwi <(. /prog < in) <(. /brute < in) > $1_diff
        if [[ ! $? -eq 0 ]]; then
            printf "${red} Wrong answer ${noColor}\n"
            break
        else
            printf "${green} Accepted ${noColor}\n"
        fi
    done
}

test() {
```

```

g++ --std=c++11 $1.cpp -o prog
for ((i = 1; i <= 50; i++)); do
[[ -f $1_in$i ]] || break
printf "Test case #i"
diff -uwi <(. /prog < $1_in$i) $1_out$i > $1_diff
if [[ ! $? -eq 0 ]]; then
    printf "${red} Wrong answer ${noColor}\n"
else
    printf "${green} Accepted ${noColor}\n"
fi
done
}

```

Bump allocator

```

static char buf[450 << 20];
void* operator new(size_t s) {
    static size_t i = sizeof buf; assert(s < i);
    return (void *) &buf[i -= s];
}
void operator delete(void *) {}

```

1 Data structures

1.1 Disjoint set with rollback

```

struct Dsu {
    vi pr, tot;
    stack<ii> mem;

    Dsu(int n = 0) : pr(++n), tot(n, 1) {
        iota(all(pr), 0);
    }

    int find(int u) {
        return pr[u] == u ? u : find(pr[u]);
    }

    void unite(int u, int v) {
        u = find(u), v = find(v);
        if (u != v) {
            if (tot[u] < tot[v])
                swap(u, v);
            mem.emplace(u, v);
            tot[u] += tot[v];
            pr[v] = u;
        }
    }

    void rollback() {
        auto [u, v] = mem.top();
        mem.pop();
        if (u != -1) {
            tot[u] -= tot[v];
            pr[v] = v;
        }
    }
};

```

1.2 Min-Max queue

```

template <class T>
struct MinQueue : deque< pair<T, int> > {
    // add a element to the right {val, pos}
    void add(T val, int pos) {
        while (!empty() && back().f >= val)
            pop_back();
        emplace_back(val, pos);
    }
    // remove all less than pos
    void rem(int pos) {
        while (front().s < pos)
            pop_front();
    }
}

```

```

T qmin() { return front().f; }
};

```

1.3 Sparse table

```

template <class T, class F = function<T(const T&,
const T&)>>
struct Sparse {
    int n;
    vector<vector<T>> sp;
    F f;

    Sparse(vector<T> &a, const F &f) : n(sz(a)), sp(1 +
        __lg(n)), f(f) {
        sp[0] = a;
        for (int k = 1; (1 << k) <= n; k++) {
            sp[k].resize(n - (1 << k) + 1);
            fore (l, 0, sz(sp[k])) {
                int r = l + (1 << (k - 1));
                sp[k][l] = f(sp[k - 1][l], sp[k - 1][r]);
            }
        }
    }

    T query(int l, int r) {
        int k = __lg(r - l + 1);
        return f(sp[k][l], sp[k][r - (1 << k) + 1]);
    }
};

```

1.4 Sqrtle decomposition

The perfect block size is *squirtle* of N



```

int blo[N], cnt[N][B], a[N];

void update(int i, int x) {
    cnt[blo[i]][x]--;
    a[i] = x;
    cnt[blo[i]][x]++;
}

int query(int l, int r, int x) {
    int tot = 0;
    while (l <= r)
        if (l % B == 0 && l + B - 1 <= r) {
            tot += cnt[blo[l]][x];
            l += B;
        } else {
            tot += (a[l] == x);
            l++;
        }
    return tot;
}

```

1.5 In-Out trick

```

vector<int> in[N], out[N];
vector<Query> queries;

fore (x, 0, N) {
    for (int i : in[x])
        add(queries[i]);
    // solve
    for (int i : out[x])
        rem(queries[i]);
}

```

1.6 Parallel binary search

```

int lo[Q], hi[Q];
queue<int> solve[N];
vector<Query> queries;

```

```

fore (it, 0, 1 + __lg(N)) {
    fore (i, 0, sz(queries))
        if (lo[i] != hi[i]) {
            int mid = (lo[i] + hi[i]) / 2;
            solve[mid].emplace(i);
        }
    fore (x, 0, n) {
        // simulate
        while (!solve[x].empty()) {
            int i = solve[x].front();
            solve[x].pop();
            if (can(queries[i]))
                hi[i] = x;
            else
                lo[i] = x + 1;
        }
    }
}

```

1.7 Mo's algorithm

```

vector<Query> queries;
// N = 1e6, so aprox. sqrt(N) +/- C
uniform_int_distribution<int> dis(970, 1030);
const int blo = dis(rng);
sort(all(queries), [&](Query a, Query b) {
    const int ga = a.l / blo, gb = b.l / blo;
    if (ga == gb)
        return (ga & 1) ? a.r < b.r : a.r > b.r;
    return a.l < b.l;
});
int l = queries[0].l, r = l - 1;
for (Query &q : queries) {
    while (r < q.r)
        add(++r);
    while (r > q.r)
        rem(r--);
    while (l < q.l)
        rem(l--);
    while (l > q.l)
        add(--l);
    ans[q.i] = solve();
}

```

To make it faster, change the order to *hilbert(l, r)*

```

lli hilbert(int x, int y, int pw = 21, int rot = 0) {
    if (pw == 0)
        return 0;
    int hpw = 1 << (pw - 1);
    int k = ((x < hpw ? y < hpw ? 0 : 3 : y < hpw ? 1 :
        2) + rot) & 3;
    const int d[4] = {3, 0, 0, 1};
    lli a = 1LL << ((pw << 1) - 2);
    lli b = hilbert(x & (x ^ hpw), y & (y ^ hpw), pw - 1,
        (rot + d[k]) & 3);
    return k * a + (d[k] ? a - b - 1 : b);
}

```

Mo's algorithm with updates in $\mathcal{O}(n^{\frac{5}{3}})$

- Choose a *block* of size $n^{\frac{2}{3}}$
- Do a normal Mo's algorithm, in the *Query* definition add an extra variable for the *updatesSoFar*
- Sort the queries by the order $(l/block, r/block, updatesSoFar)$
- If the update lies inside the current query, update the data structure properly

```

struct Update {
    int pos, prv, nxt;
};

```

```

void undo(Update &u) {
    if (l <= u.pos && u.pos <= r) {
        rem(u.pos);
        a[u.pos] = u.prv;
        add(u.pos);
    } else {
        a[u.pos] = u.prv;
    }
}

```

- Solve the problem :D

```

l = queries[0].l, r = l - 1, upd = sz(updates) - 1;
for (Query &q : queries) {
    while (upd < q.upd)
        dodo(updates[++upd]);
    while (upd > q.upd)
        undo(updates[upd--]);
    // write down the normal Mo's algorithm
}

```

1.8 Static to dynamic

```

template <class Black, class T>
struct StaticDynamic {
    Black box[LogN];
    vector<T> st[LogN];

    void insert(T &x) {
        int p = 0;
        fore (i, 0, LogN)
            if (st[i].empty()) {
                p = i;
                break;
            }
        st[p].pb(x);
        fore (i, 0, p) {
            st[p].insert(st[p].end(), all(st[i]));
            box[i].clear(), st[i].clear();
        }
        for (auto y : st[p])
            box[p].insert(y);
        box[p].init();
    }
};

```

1.9 Disjoint intervals

```

struct Range {
    int l, r;
    bool operator < (const Range& rge) const {
        return l < rge.l;
    }
};

struct DisjointIntervals : set<Range> {
    void add(Range rge) {
        iterator p = lower_bound(rge), q = p;
        if (p != begin() && rge.l <= (--p)->r)
            rge.l = p->l, --q;
        for (; q != end() && q->l <= rge.r; erase(q++))
            rge.r = max(rge.r, q->r);
        insert(rge);
    }

    void add(int l, int r) {
        add(Range{l, r});
    }
};

```

1.10 Ordered tree

```

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace __gnu_pbds;

```

```

template <class K, class V = null_type>
using ordered_tree = tree<K, V, less<K>, rb_tree_tag,
    tree_order_statistics_node_update>;
// less_equal<K> for multiset, multimap (?)
#define rank order_of_key
#define kth find_by_order

```

1.11 Unordered tree

```

struct chash {
    const uint64_t C = uint64_t(2e18 * 3) + 71;
    const int R = rng();
    uint64_t operator()(uint64_t x) const {
        return __builtin_bswap64((x ^ R) * C);
    }
};

```

```

template <class K, class V = null_type>
using unordered_tree = gp_hash_table<K, V, chash>;

```

1.12 D-dimensional Fenwick tree

```

template <class T, int ...N>
struct Fenwick {
    T v = 0;
    void update(T v) { this->v += v; }
    T query() { return v; }
};

```

```

template <class T, int N, int ...M>
struct Fenwick<T, N, M...> {
    #define lsb(x) (x & -x)
    Fenwick<T, M...> fenw[N + 1];

```

```

    template <typename... Args>
    void update(int i, Args... args) {
        for (; i <= N; i += lsb(i))
            fenw[i].update(args...);
    }

```

```

    template <typename... Args>
    T query(int l, int r, Args... args) {
        T v = 0;
        for (; r > 0; r -= lsb(r))
            v += fenw[r].query(args...);
        for (--l; l > 0; l -= lsb(l))
            v -= fenw[l].query(args...);
        return v;
    }
};

```

1.13 Dynamic segment tree

```

struct Dyn {
    int l, r;
    lli sum = 0;
    Dyn *ls, *rs;

    Dyn(int l, int r) : l(l), r(r), ls(0), rs(0) {}

    void pull() {
        sum = (ls ? ls->sum : 0);
        sum += (rs ? rs->sum : 0);
    }

    void update(int p, lli v) {
        if (l == r) {
            sum += v;
            return;
        }
        int m = (l + r) >> 1;
        if (p <= m) {
            if (!ls) ls = new Dyn(l, m);
            ls->update(p, v);

```

```

        } else {
            if (!rs) rs = new Dyn(m + 1, r);
            rs->update(p, v);
        }
        pull();
    }
};

```

```

lli qsum(int ll, int rr) {
    if (rr < l || r < ll || r < l)
        return 0;
    if (ll <= l && r <= rr)
        return sum;
    int m = (l + r) >> 1;
    return (ls ? ls->qsum(ll, rr) : 0) +
        (rs ? rs->qsum(ll, rr) : 0);
}
};

```

1.14 Persistent segment tree

```

struct Per {
    int l, r;
    lli sum = 0;
    Per *ls, *rs;

    Per(int l, int r) : l(l), r(r), ls(0), rs(0) {}

```

```

    Per* pull() {
        sum = ls->sum + rs->sum;
        return this;
    }

```

```

    void build() {
        if (l == r)
            return;
        int m = (l + r) >> 1;
        (ls = new Per(l, m))->build();
        (rs = new Per(m + 1, r))->build();
        pull();
    }

```

```

    Per* update(int p, lli v) {
        if (p < l || r < p)
            return this;
        Per* t = new Per(l, r);
        if (l == r) {
            t->sum = v;
            return t;
        }
        t->ls = ls->update(p, v);
        t->rs = rs->update(p, v);
        return t->pull();
    }

```

```

    lli qsum(int ll, int rr) {
        if (r < ll || rr < l)
            return 0;
        if (ll <= l && r <= rr)
            return sum;
        return ls->qsum(ll, rr) + rs->qsum(ll, rr);
    }
};

```

1.15 Wavelet tree

```

struct Wav {
    #define iter int* // vector<int>::iterator
    int lo, hi;
    Wav *ls, *rs;
    vi amt;

    Wav(int lo, int hi) : lo(lo), hi(hi), ls(0), rs(0)

```

```

{}

void build(iter b, iter e) { // array 1-indexed
    if (lo == hi || b == e)
        return;
    amt.reserve(e - b + 1);
    amt.pb(0);
    int m = (lo + hi) >> 1;
    for (auto it = b; it != e; it++)
        amt.pb(amt.back() + (*it <= m));
    auto p = stable_partition(b, e, [&](int x) {
        return x <= m;
    });
    (ls = new Wav(lo, m))->build(b, p);
    (rs = new Wav(m + 1, hi))->build(p, e);
}

int kth(int l, int r, int k) {
    if (r < l)
        return 0;
    if (lo == hi)
        return lo;
    if (k <= amt[r] - amt[l - 1])
        return ls->kth(amt[l - 1] + 1, amt[r], k);
    return rs->kth(l - amt[l - 1], r - amt[r], k - amt
        [r] + amt[l - 1]);
}

int leq(int l, int r, int mx) {
    if (r < l || mx < lo)
        return 0;
    if (hi <= mx)
        return r - l + 1;
    return ls->leq(amt[l - 1] + 1, amt[r], mx) +
        rs->leq(l - amt[l - 1], r - amt[r], mx);
}
};

```

1.16 Li Chao tree

```

struct Fun {
    lli m = 0, c = inf;
    lli operator()(lli x) const { return m * x + c; }
};

struct LiChao {
    Fun f;
    lli l, r;
    LiChao *ls, *rs;

    LiChao(lli l, lli r) : l(l), r(r), ls(0), rs(0) {}

    void add(Fun &g) {
        if (f(l) <= g(l) && f(r) <= g(r))
            return;
        if (g(l) < f(l) && g(r) < f(r)) {
            f = g;
            return;
        }
        lli m = (l + r) >> 1;
        if (g(m) < f(m))
            swap(f, g);
        if (g(l) <= f(l))
            ls = ls ? (ls->add(g), ls) : new LiChao(l, m, g);
        else
            rs = rs ? (rs->add(g), rs) : new LiChao(m + 1, r,
                g);
    }

    lli query(lli x) {
        if (l == r)

```

```

        return f(x);
        lli m = (l + r) >> 1;
        if (x <= m)
            return min(f(x), ls ? ls->query(x) : inf);
        return min(f(x), rs ? rs->query(x) : inf);
    }
};

```

1.17 Explicit Treap

```

typedef struct Node* Treap;
struct Node {
    Treap ch[2] = {0, 0}, p = 0;
    uint32_t pri = rng();
    int sz = 1, rev = 0;
    int val, sum = 0;

    void push() {
        if (rev) {
            swap(ch[0], ch[1]);
            for (auto ch : ch) if (ch != 0) {
                ch->rev ^= 1;
            }
            rev = 0;
        }
    }

    Treap pull() {
        #define gsz(t) (t ? t->sz : 0)
        #define gsum(t) (t ? t->sum : 0)
        sz = 1, sum = val;
        for (auto ch : ch) if (ch != 0) {
            ch->push();
            sz += ch->sz;
            sum += ch->sum;
            ch->p = this;
        }
        p = 0;
        return this;
    }

    Node(int val) : val(val) {}
};

pair<Treap, Treap> split(Treap t, int val) {
    // <= val goes to the left, > val to the right
    if (!t)
        return {t, t};
    t->push();
    if (val < t->val) {
        auto p = split(t->ch[0], val);
        t->ch[0] = p.s;
        return {p.f, t->pull()};
    } else {
        auto p = split(t->ch[1], val);
        t->ch[1] = p.f;
        return {t->pull(), p.s};
    }
}

Treap merge(Treap l, Treap r) {
    if (!l || !r)
        return l ? l : r;
    l->push(), r->push();
    if (l->pri > r->pri)
        return l->ch[1] = merge(l->ch[1], r), l->pull();
    else
        return r->ch[0] = merge(l, r->ch[0]), r->pull();
}

Treap qkth(Treap t, int k) { // 0-indexed

```

```

    if (!t)
        return t;
    t->push();
    int sz = gsz(t->ch[0]);
    if (sz == k)
        return t;
    return k < sz ? qkth(t->ch[0], k) : qkth(t->ch[1], k
        - sz - 1);
}

int qrank(Treap t, int val) { // 0-indexed
    if (!t)
        return -1;
    t->push();
    if (val < t->val)
        return qrank(t->ch[0], val);
    if (t->val == val)
        return gsz(t->ch[0]);
    return gsz(t->ch[0]) + qrank(t->ch[1], val) + 1;
}

Treap insert(Treap t, int val) {
    auto p1 = split(t, val);
    auto p2 = split(p1.f, val - 1);
    return merge(p2.f, merge(new Node(val), p1.s));
}

Treap erase(Treap t, int val) {
    auto p1 = split(t, val);
    auto p2 = split(p1.f, val - 1);
    return merge(p2.f, p1.s);
}

```

1.18 Implicit Treap

```

pair<Treap, Treap> splitsz(Treap t, int sz) {
    // <= sz goes to the left, > sz to the right
    if (!t)
        return {t, t};
    t->push();
    if (sz <= gsz(t->ch[0])) {
        auto p = splitsz(t->ch[0], sz);
        t->ch[0] = p.s;
        return {p.f, t->pull()};
    } else {
        auto p = splitsz(t->ch[1], sz - gsz(t->ch[0]) - 1);
        ;
        t->ch[1] = p.f;
        return {t->pull(), p.s};
    }
}

int pos(Treap t) {
    int sz = gsz(t->ch[0]);
    for (; t->p; t = t->p) {
        Treap p = t->p;
        if (p->ch[1] == t)
            sz += gsz(p->ch[0]) + 1;
    }
    return sz + 1;
}

```

1.19 Splay tree

```

typedef struct Node* Splay;
struct Node {
    Splay ch[2] = {0, 0}, p = 0;
    bool rev = 0;
    int sz = 1;

    int dir() {
        if (!p) return -2; // root of LCT component

```

```

        if (p->ch[0] == this) return 0; // left child
        if (p->ch[1] == this) return 1; // right child
        return -1; // root of current splay tree
    }

```

```

bool isRoot() { return dir() < 0; }

```

```

friend void add(Splay u, Splay v, int d) {
    if (v) v->p = u;
    if (d >= 0) u->ch[d] = v;
}

```

```

void rotate() {
    // assume p and p->p propagated
    assert(!isRoot());
    int x = dir();
    Splay g = p;
    add(g->p, this, g->dir());
    add(g, ch[x ^ 1], x);
    add(this, g, x ^ 1);
    g->pull(), pull();
}

```

```

void splay() {
    // bring this to top of splay tree
    while (!isRoot() && !p->isRoot()) {
        p->p->push(), p->push(), push();
        dir() == p->dir() ? p->rotate() : rotate();
        rotate();
    }
    if (!isRoot()) p->push(), push(), rotate();
    push(), pull();
}

```

```

void pull() {
    #define gsz(t) (t ? t->sz : 0)
    sz = 1 + gsz(ch[0]) + gsz(ch[1]);
}

```

```

void push() {
    if (rev) {
        swap(ch[0], ch[1]);
        for (auto ch : ch) if (ch) {
            ch->rev ^= 1;
        }
        rev = 0;
    }
}

```

```

void vsub(Splay t, bool add) {}
};

```

2 Graphs

2.1 Tarjan algorithm (SCC)

```

vector<vi> scc;
int tin[N], fup[N];
bitset<N> still;
stack<int> stk;
int timer = 0;

void tarjan(int u) {
    tin[u] = fup[u] = ++timer;
    still[u] = true;
    stk.push(u);
    for (int v : graph[u]) {
        if (!tin[v])
            tarjan(v);
        if (still[v])
            fup[u] = min(fup[u], fup[v]);
    }
}

```

```

if (fup[u] == tin[u]) {
    scc.pb({});
    int v;
    do {
        v = stk.top();
        stk.pop();
        still[v] = false;
        scc.back().pb(v);
    } while (v != u);
}
}

```

2.2 Kosaraju algorithm (SCC)

```

int scc[N], k = 0;
char vis[N];
vi order;

void dfs1(int u) {
    vis[u] = 1;
    for (int v : graph[u])
        if (vis[v] != 1)
            dfs1(v);
    order.pb(u);
}

void dfs2(int u, int k) {
    vis[u] = 2, scc[u] = k;
    for (int v : rgraph[u]) // reverse graph
        if (vis[v] != 2)
            dfs2(v, k);
}

void kosaraju() {
    fore (u, 1, n + 1)
        if (vis[u] != 1)
            dfs1(u);
    reverse(all(order));
    for (int u : order)
        if (vis[u] != 2)
            dfs2(u, ++k);
}

```

2.3 Two Sat

```

void add(int u, int v) {
    graph[u].pb(v);
    rgraph[v].pb(u);
}

void implication(int u, int v) {
    #define neg(u) ((n) + (u))
    add(u, v);
    add(neg(v), neg(u));
}

pair<bool, vi> satisfy(int n) {
    kosaraju(2 * n); // size of the two-sat is 2 * n
    vi ans(n + 1, 0);
    fore (u, 1, n + 1) {
        if (scc[u] == scc[neg(u)])
            return {0, ans};
        ans[u] = scc[u] > scc[neg(u)];
    }
    return {1, ans};
}

```

2.4 Topological sort

```

vi order;
int indeg[N];

void topsort() { // first fill the indeg[]
    queue<int> qu;

```

```

fore (u, 1, n + 1)
    if (indeg[u] == 0)
        qu.push(u);
while (!qu.empty()) {
    int u = qu.front();
    qu.pop();
    order.pb(u);
    for (int v : graph[u])
        if (--indeg[v] == 0)
            qu.push(v);
}
}

```

2.5 Cutpoints and Bridges

```

int tin[N], fup[N], timer = 0;

void findWeakness(int u, int p = 0) {
    tin[u] = fup[u] = ++timer;
    int children = 0;
    for (int v : graph[u]) if (v != p) {
        if (!tin[v]) {
            ++children;
            findWeakness(v, u);
            fup[u] = min(fup[u], fup[v]);
            if (fup[v] >= tin[u] && p) // u is a cutpoint
                if (fup[v] > tin[u]) // bridge u -> v
                    ;
        }
        fup[u] = min(fup[u], tin[v]);
    }
    if (!p && children > 1) // u is a cutpoint
        ;
}

```

2.6 Detect a cycle

```

bool cycle(int u) {
    vis[u] = 1;
    for (int v : graph[u]) {
        if (vis[v] == 1)
            return true;
        if (!vis[v] && cycle(v))
            return true;
    }
    vis[u] = 2;
    return false;
}

```

2.7 Euler tour for Mo's in a tree

Mo's in a tree, extended euler tour $tin[u] = ++timer$, $tout[u] = ++timer$

- $u = lca(u, v)$, $query(tin[u], tin[v])$
- $u \neq lca(u, v)$, $query(tout[u], tin[v]) + query(tin[lca], tin[lca])$

2.8 Lowest common ancestor (LCA)

```

const int LogN = 1 + __lg(N);
int pr[LogN][N], dep[N];

void dfs(int u, int pr[]) {
    for (int v : graph[u])
        if (v != pr[u]) {
            pr[v] = u;
            dep[v] = dep[u] + 1;
            dfs(v, pr);
        }
}

int lca(int u, int v) {
    if (dep[u] > dep[v])
        swap(u, v);
    fore (k, LogN, 0)
        if (dep[v] - dep[u] >= (1 << k))
            v = pr[k][v];
    if (u == v)

```



```

    return u;
    for (k, LogN, 0)
        if (pr[k][v] != pr[k][u])
            u = pr[k][u], v = pr[k][v];
    return pr[0][u];
}

int dist(int u, int v) {
    return dep[u] + dep[v] - 2 * dep[lca(u, v)];
}

void init(int r) {
    dfs(r, pr[0]);
    for (k, 1, LogN)
        for (u, 1, n + 1)
            pr[k][u] = pr[k - 1][pr[k - 1][u]];
}

```

2.9 Isomorphism

```

lli f(lli x) {
    // K * n <= 9e18
    static uniform_int_distribution<lli> uid(1, K);
    if (!mp.count(x))
        mp[x] = uid(rng);
    return mp[x];
}

lli hsh(int u, int p = 0) {
    dp[u] = h[u] = 0;
    for (int v : graph[u]) {
        if (v == p)
            continue;
        dp[u] += hsh(v, u);
    }
    return h[u] = f(dp[u]);
}

```

2.10 Guni

```

int tin[N], tout[N], who[N], sz[N], heavy[N], color[N];
int timer = 0;

int dfs(int u, int pr = 0) {
    sz[u] = 1, tin[u] = ++timer, who[timer] = u;
    for (int v : graph[u]) if (v != pr) {
        sz[u] += dfs(v, u);
        if (sz[v] > sz[heavy[u]])
            heavy[u] = v;
    }
    return tout[u] = timer, sz[u];
}

void guni(int u, int pr = 0, bool keep = 0) {
    for (int v : graph[u])
        if (v != pr && v != heavy[u])
            guni(v, u, 0);
    if (heavy[u])
        guni(heavy[u], u, 1);
    for (int v : graph[u])
        if (v != pr && v != heavy[u])
            for (i, tin[v], tout[v] + 1)
                add(color[who[i]]);
    add(color[u]);
    // Solve the subtree queries here
    if (keep == 0)
        for (i, tin[u], tout[u] + 1)
            rem(color[who[i]]);
}

```

2.11 Centroid decomposition

```

int cdp[N], sz[N];

```

```

bitset<N> rem;

int dfsz(int u, int p = 0) {
    sz[u] = 1;
    for (int v : graph[u])
        if (v != p && !rem[v])
            sz[u] += dfsz(v, u);
    return sz[u];
}

int centroid(int u, int n, int p = 0) {
    for (int v : graph[u])
        if (v != p && !rem[v] && 2 * sz[v] > n)
            return centroid(v, n, u);
    return u;
}

void solve(int u, int p = 0) {
    cdp[u = centroid(u, dfsz(u))] = p;
    rem[u] = true;
    for (int v : graph[u])
        if (!rem[v])
            solve(v, u);
}

```

2.12 Heavy-light decomposition

```

int pr[N], dep[N], sz[N], heavy[N], head[N], pos[N],
    who[N], timer = 0;
Lazy* tree; // generally a lazy segtree

int dfs(int u) {
    sz[u] = 1, heavy[u] = head[u] = 0;
    for (int v : graph[u]) if (v != pr[u]) {
        pr[v] = u;
        dep[v] = dep[u] + 1;
        sz[u] += dfs(v);
        if (sz[v] > sz[heavy[u]])
            heavy[u] = v;
    }
    return sz[u];
}

void hld(int u, int h) {
    head[u] = h, pos[u] = ++timer, who[timer] = u;
    if (heavy[u] != 0)
        hld(heavy[u], h);
    for (int v : graph[u])
        if (v != pr[u] && v != heavy[u])
            hld(v, v);
}

template <class F>
void processPath(int u, int v, F f) {
    for (; head[u] != head[v]; v = pr[head[v]]) {
        if (dep[head[u]] > dep[head[v]]) swap(u, v);
        f(pos[head[v]], pos[v]);
    }
    if (dep[u] > dep[v]) swap(u, v);
    if (u != v) f(pos[heavy[u]], pos[v]);
    f(pos[u], pos[u]); // process lca(u, v) too?
}

void updatePath(int u, int v, lli z) {
    processPath(u, v, [&](int l, int r) {
        tree->update(l, r, z);
    });
}

lli queryPath(int u, int v) {
    lli sum = 0;
}

```

```

processPath(u, v, [&](int l, int r) {
    sum += tree->qsum(l, r);
});
return sum;
}

```

2.13 Link-Cut tree

```

void access(Splay u) {
    // puts u on the preferred path, splay (right
    // subtree is empty)
    for (Splay v = u, pre = NULL; v; v = v->p) {
        v->splay(); // now pull virtual children
        if (pre) v->vsub(pre, false);
        if (v->ch[1]) v->vsub(v->ch[1], true);
        v->ch[1] = pre, v->pull(), pre = v;
    }
    u->splay();
}

void rootify(Splay u) {
    // make u root of LCT component
    access(u), u->rev ^= 1, access(u);
    assert(!u->ch[0] && !u->ch[1]);
}

Splay lca(Splay u, Splay v) {
    if (u == v) return u;
    access(u), access(v);
    if (!u->p) return NULL;
    return u->splay(), u->p ? u :
}

bool connected(Splay u, Splay v) {
    return lca(u, v) != NULL;
}

void link(Splay u, Splay v) { // make u parent of v
    if (!connected(u, v)) {
        rootify(v), access(u);
        add(v, u, 0), v->pull();
    }
}

void cut(Splay u) {
    // cut u from its parent
    access(u);
    u->ch[0]->p = u->ch[0] = NULL;
    u->pull();
}

void cut(Splay u, Splay v) { // if u, v are adjacent
    // in the tree
    cut(depth(u) > depth(v) ? u : v);
}

int depth(Splay u) {
    access(u);
    return gsz(u->ch[0]);
}

Splay getRoot(Splay u) { // get root of LCT component
    access(u);
    while (u->ch[0]) u = u->ch[0], u->push();
    return access(u), u;
}

Splay ancestor(Splay u, int k) {
    // get k-th parent on path to root
    k = depth(u) - k;
    assert(k >= 0);
}

```

```

for (; u->push()) {
    int sz = gsz(u->ch[0]);
    if (sz == k) return access(u), u;
    if (sz < k) k -= sz + 1, u = u->ch[1];
    else u = u->ch[0];
}
assert(0);
}

```

```

Splay query(Splay u, Splay v) {
    return rootify(u), access(v), v;
}

```

3 Flows

3.1 Dinic $\mathcal{O}(\min(E \cdot \text{flow}, V^2 E))$

If the network is massive, try to compress it by looking for patterns.

```

template <class F>
struct Dinic {
    struct Edge {
        int v, inv;
        F cap, flow;
        Edge(int v, F cap, int inv) : v(v), cap(cap), flow
            (0), inv(inv) {}
    };

    F eps = (F) 1e-9;
    int s, t, n, m = 0;
    vector< vector<Edge> > g;
    vi dist, ptr;

    Dinic(int n) : n(n), g(n), dist(n), ptr(n), s(n - 2)
        , t(n - 1) {}

    void add(int u, int v, F cap) {
        g[u].pb(Edge(v, cap, sz(g[v])));
        g[v].pb(Edge(u, 0, sz(g[u]) - 1));
        m += 2;
    }

    bool bfs() {
        fill(all(dist), -1);
        queue<int> qu({s});
        dist[s] = 0;
        while (sz(qu) && dist[t] == -1) {
            int u = qu.front();
            qu.pop();
            for (Edge &e : g[u]) if (dist[e.v] == -1)
                if (e.cap - e.flow > eps) {
                    dist[e.v] = dist[u] + 1;
                    qu.push(e.v);
                }
        }
        return dist[t] != -1;
    }

    F dfs(int u, F flow = numeric_limits<F>::max()) {
        if (flow <= eps || u == t)
            return max<F>(0, flow);
        for (int &i = ptr[u]; i < sz(g[u]); i++) {
            Edge &e = g[u][i];
            if (e.cap - e.flow > eps && dist[u] + 1 == dist[
                e.v]) {
                F pushed = dfs(e.v, min<F>(flow, e.cap - e.flow
                    ));
                if (pushed > eps) {
                    e.flow += pushed;
                    g[e.v][e.inv].flow -= pushed;
                    return pushed;
                }
            }
        }
    }
}

```

```

    }
}
return 0;
}

F maxFlow() {
    F flow = 0;
    while (bfs()) {
        fill(all(ptr), 0);
        while (F pushed = dfs(s))
            flow += pushed;
    }
    return flow;
}
};

3.2 Min cost flow  $\mathcal{O}(\min(E \cdot \text{flow}, V^2 E))$ 
If the network is massive, try to compress it by looking for patterns.

template <class C, class F>
struct MCMF {
    struct Edge {
        int u, v, inv;
        F cap, flow;
        C cost;
        Edge(int u, int v, C cost, F cap, int inv) : u(u),
            v(v), cost(cost), cap(cap), flow(0), inv(inv)
        {}
    };

    F eps = (F) 1e-9;
    int s, t, n, m = 0;
    vector< vector<Edge> > g;
    vector<Edge*> prev;
    vector<C> cost;
    vi state;

    MCMF(int n) : n(n), g(n), cost(n), state(n), prev(n),
        s(n - 2), t(n - 1) {}

    void add(int u, int v, C cost, F cap) {
        g[u].pb(Edge(u, v, cost, cap, sz(g[v])));
        g[v].pb(Edge(v, u, -cost, 0, sz(g[u]) - 1));
        m += 2;
    }

    bool bfs() {
        fill(all(state), 0);
        fill(all(cost), numeric_limits<C>::max());
        deque<int> qu;
        qu.push_back(s);
        state[s] = 1, cost[s] = 0;
        while (sz(qu)) {
            int u = qu.front(); qu.pop_front();
            state[u] = 2;
            for (Edge &e : g[u]) if (e.cap - e.flow > eps)
                if (cost[u] + e.cost < cost[e.v]) {
                    cost[e.v] = cost[u] + e.cost;
                    prev[e.v] = &e;
                    if (state[e.v] == 2 || (sz(qu) && cost[qu.
                        front()] > cost[e.v]))
                        qu.push_front(e.v);
                    else if (state[e.v] == 0)
                        qu.push_back(e.v);
                    state[e.v] = 1;
                }
        }
        return cost[t] != numeric_limits<C>::max();
    }

    pair<C, F> minCostFlow() {

```

```

        C cost = 0; F flow = 0;
        while (bfs()) {
            F pushed = numeric_limits<F>::max();
            for (Edge* e = prev[t]; e != nullptr; e = prev[e
                ->u])
                pushed = min(pushed, e->cap - e->flow);
            for (Edge* e = prev[t]; e != nullptr; e = prev[e
                ->u]) {
                e->flow += pushed;
                g[e->v][e->inv].flow -= pushed;
                cost += e->cost * pushed;
            }
            flow += pushed;
        }
        return make_pair(cost, flow);
    }
};

3.3 Hopcroft-Karp  $\mathcal{O}(E\sqrt{V})$ 
struct HopcroftKarp {
    int n, m = 0;
    vector<vi> g;
    vi dist, match;

    HopcroftKarp(int _n) : n(5 + _n), g(n + 5), dist(n +
        5), match(n + 5, 0) {}

    void add(int u, int v) {
        g[u].pb(v), g[v].pb(u);
        m += 2;
    }

    bool bfs() {
        queue<int> qu;
        fill(all(dist), -1);
        fore (u, 1, n + 1)
            if (!match[u])
                dist[u] = 0, qu.push(u);
        while (!qu.empty()) {
            int u = qu.front(); qu.pop();
            for (int v : g[u])
                if (dist[match[v]] == -1) {
                    dist[match[v]] = dist[u] + 1;
                    if (match[v])
                        qu.push(match[v]);
                }
        }
        return dist[0] != -1;
    }

    bool dfs(int u) {
        for (int v : g[u])
            if (!match[v] || (dist[u] + 1 == dist[match[v]]
                && dfs(match[v]))) {
                match[u] = v, match[v] = u;
                return 1;
            }
        dist[u] = 1 << 30;
        return 0;
    }

    int maxMatching() {
        int tot = 0;
        while (bfs())
            fore (u, 1, n + 1)
                tot += match[u] ? 0 : dfs(u);
        return tot;
    }
};

3.4 Hungarian  $\mathcal{O}(N^3)$ 
n jobs, m people

```

```

template <class C>
pair<C, vi> Hungarian(vector< vector<C> > &a) {
    int n = sz(a), m = sz(a[0]), p, q, j, k; // n <= m
    vector<C> fx(n, numeric_limits<C>::min()), fy(m, 0);
    vi x(n, -1), y(m, -1);
    fore (i, 0, n)
        fore (j, 0, m)
            fx[i] = max(fx[i], a[i][j]);
    fore (i, 0, n) {
        vi t(m, -1), s(n + 1, i);
        for (p = q = 0; p <= q && x[i] < 0; p++)
            for (k = s[p], j = 0; j < m && x[i] < 0; j++)
                if (abs(fx[k] + fy[j] - a[k][j]) < eps && t[j] < 0) {
                    s[+q] = y[j], t[j] = k;
                    if (s[q] < 0) for (p = j; p >= 0; j = p)
                        y[j] = k = t[j], p = x[k], x[k] = j;
                }
        if (x[i] < 0) {
            C d = numeric_limits<C>::max();
            fore (k, 0, q + 1)
                fore (j, 0, m) if (t[j] < 0)
                    d = min(d, fx[s[k]] + fy[j] - a[s[k]][j]);
            fore (j, 0, m)
                fy[j] += (t[j] < 0 ? 0 : d);
            fore (k, 0, q + 1)
                fx[s[k]] -= d;
            i--;
        }
    }
    C cost = 0;
    fore (i, 0, n) cost += a[i][x[i]];
    return make_pair(cost, x);
}

```

4 Strings

4.1 Hash

```

vi mod = {999727999, 999992867, 1000000123, 1000002193,
          1000003211, 1000008223, 1000009999, 1000027163,
          1070777777};

struct H : array<lli, 2> {
    #define oper(op) friend H operator op (H a, H b) { \
        fore (i, 0, sz(a)) a[i] = (a[i] op b[i] + mod[i]) % \
            mod[i]; \
        return a; }
    oper(+) oper(-) oper(*)
} pw[N], ipw[N];

struct Hash {
    vector<H> h;

    Hash(string &s) : h(sz(s) + 1) {
        fore (i, 0, sz(s)) {
            int x = s[i] - 'a' + 1;
            h[i + 1] = h[i] + pw[i] * H{x, x};
        }
    }

    H cut(int l, int r) {
        return (h[r + 1] - h[l]) * ipw[l];
    }
};

const int P = uniform_int_distribution<int>(27, min(
    mod[0], mod[1]) - 1)(rng);
pw[0] = ipw[0] = {1, 1};
H Q = {inv(P, mod[0]), inv(P, mod[1])};
fore (i, 1, N) {
    pw[i] = pw[i - 1] * H{P, P};
}

```

```

ipw[i] = ipw[i - 1] * Q;
}

// Save {l, r} in the struct and when you do a cut
H merge(vector<H> &cuts) {
    F f = {0, 0};
    fore (i, sz(cuts), 0) {
        F g = cuts[i];
        f = g + f * pw[g.r - g.l + 1];
    }
    return f;
}

```

4.2 KMP

period = $n - p[n - 1]$, period(abcabc) = 3, $n \bmod \text{period} \equiv 0$

```

vi lps(string &s) {
    vi p(sz(s), 0);
    int j = 0;
    fore (i, 1, sz(s)) {
        while (j && s[i] != s[j])
            j = p[j - 1];
        if (s[i] == s[j])
            j++;
        p[i] = j;
    }
    return p;
}

// how many times t occurs in s
int kmp(string &s, string &t) {
    vi p = lps(t);
    int j = 0, tot = 0;
    fore (i, 0, sz(s)) {
        while (j && s[i] != t[j])
            j = p[j - 1];
        if (s[i] == t[j])
            j++;
        if (j == sz(t))
            tot++; // pos: i - sz(t) + 1;
    }
    return tot;
}

```

4.3 KMP automaton

```

int go[N][A];

void kmpAutomaton(string &s) {
    s += "$";
    vi p = lps(s);
    fore (i, 0, sz(s))
        fore (c, 0, A) {
            if (i && s[i] != 'a' + c)
                go[i][c] = go[p[i - 1]][c];
            else
                go[i][c] = i + ('a' + c == s[i]);
        }
    s.pop_back();
}

```

4.4 Z algorithm

```

vi zf(string &s) {
    vi z(sz(s), 0);
    for (int i = 1, l = 0, r = 0; i < sz(s); i++) {
        if (i <= r)
            z[i] = min(r - i + 1, z[i - l]);
        while (i + z[i] < sz(s) && s[i + z[i]] == s[z[i]])
            ++z[i];
        if (i + z[i] - 1 > r)
            l = i, r = i + z[i] - 1;
    }
    return z;
}

```

4.5 Manacher algorithm

```
vector<vi> manacher(string &s) {
    vector<vi> pal(2, vi(sz(s), 0));
    for (k, 0, 2) {
        int l = 0, r = 0;
        for (i, 0, sz(s)) {
            int t = r - i + !k;
            if (i < r)
                pal[k][i] = min(t, pal[k][l + t]);
            int p = i - pal[k][i], q = i + pal[k][i] - !k;
            while (p >= 1 && q + 1 < sz(s) && s[p - 1] == s[q + 1])
                ++pal[k][i], --p, ++q;
            if (q > r)
                l = p, r = q;
        }
    }
    return pal;
}
```

4.6 Suffix array

- Duplicates $\sum_{i=1}^n lcp[i]$
- Longest Common Substring of various strings
Add *notUsed* characters between strings, i.e. $a+\$+b+\#+c$
Use two-pointers to find a range $[l, r]$ such that all *notUsed* characters are present, then *query*($lcp[l + 1], \dots, lcp[r]$) for that window is the common length.

```
struct SuffixArray {
    int n;
    string s;
    vi sa, lcp;

    SuffixArray(string &s) : n(sz(s) + 1), s(s), sa(n),
        lcp(n) {
        vi top(max(256, n)), rk(n);
        for (i, 0, n)
            top[rk[i] = s[i] & 255]++;
        partial_sum(all(top), top.begin());
        for (i, 0, n)
            sa[--top[rk[i]]] = i;
        vi sb(n);
        for (int len = 1, j; len < n; len <= 1) {
            for (i, 0, n) {
                j = (sa[i] - len + n) % n;
                sb[top[rk[j]]++] = j;
            }
            sa[sb[top[0] = 0]] = j = 0;
            for (i, 1, n) {
                if (rk[sb[i]] != rk[sb[i - 1]] || rk[sb[i] + len] != rk[sb[i - 1] + len])
                    top[++j] = i;
                sa[sb[i]] = j;
            }
            copy(all(sa), rk.begin());
            copy(all(sb), sa.begin());
            if (j >= n - 1)
                break;
        }
        for (int i = 0, j = rk[lcp[0] = 0], k = 0; i < n - 1; i++, k++)
            while (k >= 0 && s[i] != s[sa[j - 1] + k])
                lcp[j] = k--, j = rk[sa[j] + 1];
    }

    char at(int i, int j) {
        int k = sa[i] + j;
        return k < n ? s[k] : 'z' + 1;
    }

    int count(string &t) {
```

```
        ii lo(0, n - 1), hi(0, n - 1);
        for (i, 0, sz(t)) {
            while (lo.f + 1 < lo.s) {
                int mid = (lo.f + lo.s) / 2;
                (at(mid, i) < t[i] ? lo.f : lo.s) = mid;
            }
            while (hi.f + 1 < hi.s) {
                int mid = (hi.f + hi.s) / 2;
                (t[i] < at(mid, i) ? hi.s : hi.f) = mid;
            }
            int p1 = (at(lo.f, i) == t[i] ? lo.f : lo.s);
            int p2 = (at(hi.s, i) == t[i] ? hi.s : hi.f);
            if (at(p1, i) != t[i] || at(p2, i) != t[i] || p1 > p2)
                return 0;
            lo = hi = ii(p1, p2);
        }
        return lo.s - lo.f + 1;
    }
};
```

4.7 Suffix automaton

- $sam[u].len - sam[sam[u].link].len = \text{distinct strings}$
- Number of different substrings (dp)

$$diff(u) = 1 + \sum_{v \in trie[u]} diff(v)$$

- Total length of all different substrings (2 x dp)

$$totLen(u) = \sum_{v \in trie[u]} diff(v) + totLen(v)$$

- Leftmost occurrence $trie[u].pos = trie[u].len - 1$
if it is **clone** then $trie[clone].pos = trie[q].pos$
- All occurrence positions
- Smallest cyclic shift
Construct sam of $s + s$, find the lexicographically smallest path of $sz(s)$
- Shortest non-appearing string

$$nonAppearing(u) = \min_{v \in trie[u]} nonAppearing(v) + 1$$

```
struct SuffixAutomaton {
    struct Node : map<char, int> {
        int link = -1, len = 0;
    };

    vector<Node> trie;
    int last;

    SuffixAutomaton() { last = newNode(); }

    int newNode() {
        trie.pb({});
        return sz(trie) - 1;
    }

    void extend(char c) {
        int u = newNode();
        trie[u].len = trie[last].len + 1;
        int p = last;
        while (p != -1 && !trie[p].count(c)) {
            trie[p][c] = u;
            p = trie[p].link;
        }
        if (p == -1)
            trie[u].link = 0;
        else {
            int q = trie[p][c];
            if (trie[p].len + 1 == trie[q].len)
                trie[u].link = q;
```

```

else {
    int clone = newNode();
    trie[clone] = trie[q];
    trie[clone].len = trie[p].len + 1;
    while (p != -1 && trie[p][c] == q) {
        trie[p][c] = clone;
        p = trie[p].link;
    }
    trie[q].link = trie[u].link = clone;
}
}
last = u;
}

string kthSubstring(lli kth, int u = 0) {
    // number of different substrings (dp)
    string s = "";
    while (kth > 0)
        for (auto &[c, v] : trie[u]) {
            if (kth <= diff(v)) {
                s.pb(c), kth--, u = v;
                break;
            }
            kth -= diff(v);
        }
    return s;
}

void occurs() {
    // trie[u].occ = 1, trie[clone].occ = 0
    vi who;
    fore (u, 1, sz(trie))
        who.pb(u);
    sort(all(who), [&](int u, int v) {
        return trie[u].len > trie[v].len;
    });
    for (int u : who) {
        int l = trie[u].link;
        trie[l].occ += trie[u].occ;
    }
}

lli queryOccurrences(string &s, int u = 0) {
    for (char c : s) {
        if (!trie[u].count(c))
            return 0;
        u = trie[u][c];
    }
    return trie[u].occ;
}

int longestCommonSubstring(string &s, int u = 0) {
    int mx = 0, clen = 0;
    for (char c : s) {
        while (u && !trie[u].count(c)) {
            u = trie[u].link;
            clen = trie[u].len;
        }
        if (trie[u].count(c))
            u = trie[u][c], clen++;
        mx = max(mx, clen);
    }
    return mx;
}

string smallestCyclicShift(int n, int u = 0) {
    string s = "";
    fore (i, 0, n) {
        char c = trie[u].begin()->f;
        s += c;

```

```

        u = trie[u][c];
    }
    return s;
}

int leftmost(string &s, int u = 0) {
    for (char c : s) {
        if (!trie[u].count(c))
            return -1;
        u = trie[u][c];
    }
    return trie[u].pos - sz(s) + 1;
}

```

```

Node& operator [](int u) {
    return trie[u];
}
};

```

4.8 Aho corasick

```

struct AhoCorasick {
    struct Node : map<char, int> {
        int link = 0, cnt = 0;
    };

    vector<Node> trie;

    AhoCorasick() { newNode(); }

    int newNode() {
        trie.pb({});
        return sz(trie) - 1;
    }

    void insert(string &s, int u = 0) {
        for (char c : s) {
            if (!trie[u][c])
                trie[u][c] = newNode();
            u = trie[u][c];
        }
        trie[u].cnt++;
    }

    int go(int u, char c) {
        while (u && !trie[u].count(c))
            u = trie[u].link;
        return trie[u][c];
    }

    void pushLinks() {
        queue<int> qu;
        qu.push(0);
        while (!qu.empty()) {
            int u = qu.front();
            qu.pop();
            for (auto &[c, v] : trie[u]) {
                int l = (trie[v].link = u ? go(trie[u].link, c) : 0);
                trie[v].cnt += trie[l].cnt;
                qu.push(v);
            }
        }
    }

    int match(string &s, int u = 0) {
        int ans = 0;
        for (char c : s)
            u = go(u, c), ans += trie[u].cnt;
        return ans;
    }
}

```

```

Node& operator [] (int u) {
    return trie[u];
}
};

4.9 Eertree
struct Eertree {
    struct Node : map<char, int> {
        int link = 0, len = 0;
    };

    vector<Node> trie;
    string s = "$";
    int last;

    Eertree() {
        last = newNode(), newNode();
        trie[0].link = 1, trie[1].len = -1;
    }

    int newNode() {
        trie.pb({});
        return sz(trie) - 1;
    }

    int go(int u) {
        while (s[sz(s) - trie[u].len - 2] != s.back())
            u = trie[u].link;
        return u;
    }

    void extend(char c) {
        s += c;
        int u = go(last);
        if (!trie[u][c]) {
            int v = newNode();
            trie[v].len = trie[u].len + 2;
            trie[v].link = trie[go(trie[u].link)][c];
            trie[u][c] = v;
        }
        last = trie[u][c];
    }

    Node& operator [] (int u) {
        return trie[u];
    }
};

```

5 Dynamic Programming

5.1 All submasks of a mask

```
for (int B = A; B > 0; B = (B - 1) & A)
```

5.2 Matrix Chain Multiplication

```

int dp(int l, int r) {
    if (l > r)
        return 0LL;
    int &ans = mem[l][r];
    if (!done[l][r]) {
        done[l][r] = true, ans = inf;
        for (k, l, r + 1) // split in [l, k] [k + 1, r]
            ans = min(ans, dp(l, k) + dp(k + 1, r) + add);
    }
    return ans;
}

```

5.3 Digit DP

Counts the amount of numbers in $[l, r]$ such are divisible by k .
(flag *nonzero* is for different lengths)
It can be reduced to $dp(i, x, small)$, and has to be solve like $f(r) - f(l - 1)$

```

#define state [i][x][small][big][nonzero]
int dp(int i, int x, bool small, bool big, bool nonzero) {
    if (i == sz(r))
        return x % k == 0 && nonzero;
    int &ans = mem[state];
    if (done[state] != timer) {
        done[state] = timer;
        ans = 0;
        int lo = small ? 0 : l[i] - '0';
        int hi = big ? 9 : r[i] - '0';
        for (y, lo, max(lo, hi) + 1) {
            bool small2 = small | (y > lo);
            bool big2 = big | (y < hi);
            bool nonzero2 = nonzero | (x > 0);
            ans += dp(i + 1, (x * 10 + y) % k, small2, big2, nonzero2);
        }
    }
    return ans;
}

```

5.4 Knapsack 0/1

```

for (auto &cur : items)
    fore (w, W + 1, cur.w) // [cur.w, W]
        umax(dp[w], dp[w - cur.w] + cur.cost);

```

5.5 Convex Hull Trick $\mathcal{O}(n^2) \Rightarrow \mathcal{O}(n)$

$dp[i] = \min_{j < i} (dp[j] + b[j] * a[i])$
 $dp[i][j] = \min_{k < j} (dp[i - 1][k] + b[k] * a[j])$
 $b[j] \geq b[j + 1]$ optionally $a[i] \leq a[i + 1]$

```

// for doubles, use inf = 1/.0, div(a,b) = a / b
struct Line {
    mutable lli m, c, p;
    bool operator < (const Line &l) const { return m < l.m; }
    bool operator < (lli x) const { return p < x; }
    lli operator () (lli x) const { return m * x + c; }
};

```

```

struct DynamicHull : multiset<Line, less<>> {
    lli div(lli a, lli b) {
        return a / b - ((a ^ b) < 0 && a % b);
    }
}

```

```

bool isect(iterator x, iterator y) {
    if (y == end())
        return x->p = inf, 0;
    if (x->m == y->m)
        x->p = (x->c > y->c ? inf : -inf);
    else
        x->p = div(x->c - y->c, y->m - x->m);
    return x->p >= y->p;
}

```

```

void add(lli m, lli c) {
    auto z = insert({m, c, 0}), y = z++, x = y;
    while (isect(y, z)) z = erase(z);
    if (x != begin() && isect(--x, y))
        isect(x, y = erase(y));
    while ((y = x) != begin() && (--x)->p >= y->p)
        isect(x, erase(y));
}

```

```

lli query(lli x) {
    if (empty()) return 0LL;
    auto f = *lower_bound(x);
    return f(x);
}

```

5.6 Divide and conquer $\mathcal{O}(kn^2) \Rightarrow \mathcal{O}(k \cdot n \log n)$

Split the array of size n into k continuous groups. $k \leq n$
 $cost(a, c) + cost(b, d) \leq cost(a, d) + cost(b, c)$ with $a \leq b \leq c \leq d$

```
void dc(int cut, int l, int r, int optl, int optr) {
    if (r < l)
        return;
    int mid = (l + r) / 2;
    pair<lli, int> best = {inf, -1};
    for (p, optl, min(mid, optr) + 1) {
        lli nxt = dp[~cut & 1][p - 1] + cost(p, mid);
        if (nxt < best.f)
            best = {nxt, p};
    }
    dp[cut & 1][mid] = best.f;
    int opt = best.s;
    dc(cut, l, mid - 1, optl, opt);
    dc(cut, mid + 1, r, opt, optr);
}

for (i, 1, n + 1)
    dp[1][i] = cost(1, i);
for (cut, 2, k + 1)
    dc(cut, cut, n, cut, n);
```

5.7 Knuth optimization $\mathcal{O}(n^3) \Rightarrow \mathcal{O}(n^2)$

$dp[l][r] = \min_{l \leq k \leq r} \{dp[l][k] + dp[k][r]\} + cost(l, r)$

```
for (len, 1, n + 1)
    for (l, 0, n) {
        int r = l + len - 1;
        if (r > n - 1)
            break;
        if (len <= 2) {
            dp[l][r] = 0;
            opt[l][r] = l;
            continue;
        }
        dp[l][r] = inf;
        for (k, opt[l][r - 1], opt[l + 1][r] + 1) {
            lli cur = dp[l][k] + dp[k][r] + cost(l, r);
            if (cur < dp[l][r]) {
                dp[l][r] = cur;
                opt[l][r] = k;
            }
        }
    }
}
```

6 Game Theory

6.1 Grundy Numbers

If the moves are consecutive $S = \{1, 2, 3, \dots, x\}$ the game can be solved like $stackSize \pmod{x+1} \neq 0$

```
int mem[N];

int mex(set<int> &st) {
    int x = 0;
    while (st.count(x))
        x++;
    return x;
}

int grundy(int n) {
    if (n < 0)
        return inf;
    if (n == 0)
        return 0;
    int &g = mem[n];
    if (g == -1) {
```

```
set<int> st;
for (int x : {a, b})
    st.insert(grundy(n - x));
g = mex(st);
}
return g;
}
```


7 Combinatorics

| Combinatorics table | | |
|---------------------|---------------|---------|
| Number | Factorial | Catalan |
| 0 | 1 | 1 |
| 1 | 1 | 1 |
| 2 | 2 | 2 |
| 3 | 6 | 5 |
| 4 | 24 | 14 |
| 5 | 120 | 42 |
| 6 | 720 | 132 |
| 7 | 5,040 | 429 |
| 8 | 40,320 | 1,430 |
| 9 | 362,880 | 4,862 |
| 10 | 3,628,800 | 16,796 |
| 11 | 39,916,800 | 58,786 |
| 12 | 479,001,600 | 208,012 |
| 13 | 6,227,020,800 | 742,900 |

7.1 Factorial

```

fac[0] = 1LL;
for (i, 1, N)
    fac[i] = lli(i) * fac[i - 1] % mod;
ifac[N - 1] = fpow(fac[N - 1], mod - 2);
for (i, N - 1, 0)
    ifac[i] = lli(i + 1) * ifac[i + 1] % mod;

```

7.2 Factorial mod *smallPrime*

```

lli facMod(lli n, int p) {
    lli r = 1LL;
    for (; n > 1; n /= p) {
        r = (r * ((n / p) % 2 ? p - 1 : 1)) % p;
        for (i, 2, n % p + 1)
            r = r * i % p;
    }
    return r % p;
}

```

7.3 Lucas theorem

Changes $\binom{n}{k} \bmod p$, with $n \geq 2e6, k \geq 2e6$ and $p \leq 1e7$

$$\binom{n}{k} \equiv \prod_{i=0}^n \binom{n_i}{k_i} \bmod p$$

```

lli lucas(lli n, lli k) {
    if (k == 0)
        return 1LL;
    return lucas(n / mod, k / mod) * choose(n % mod, k % mod) % mod;
}

```

7.4 Stars and bars

Enclosing n objects in k boxes

$$\binom{n+k-1}{k-1} = \binom{n+k-1}{n}$$

7.5 N choose K

$$\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$$

$$\binom{n}{k_1, k_2, \dots, k_m} = \frac{n!}{k_1! * k_2! * \dots * k_m!}$$

```

lli choose(int n, int k) {
    if (n < 0 || k < 0 || n < k)
        return 0LL;
    return fac[n] * ifac[k] % mod * ifac[n - k] % mod;
}

lli choose(int n, int k) {

```

```

double r = 1;
for (i, 1, k + 1)
    r = r * (n - k + i) / i;
return lli(r + 0.01);
}

```

7.6 Catalan

```

catalan[0] = 1LL;
for (i, 0, N) {
    catalan[i + 1] = catalan[i] * lli(4 * i + 2) % mod *
        fpow(i + 2, mod - 2) % mod;
}

```

7.7 Burnside's lemma

$$|classes| = \frac{1}{|G|} \cdot \sum_{x \in G} f(x)$$

7.8 Prime factors of N!

```

vector< pair<lli, int> > factorialFactors(lli n) {
    vector< pair<lli, int> > fac;
    for (lli p : primes) {
        if (n < p)
            break;
        lli mul = 1LL, k = 0;
        while (mul <= n / p) {
            mul *= p;
            k += n / mul;
        }
        fac.emplace_back(p, k);
    }
    return fac;
}

```

8 Number Theory

8.1 Goldbach conjecture

- All number ≥ 6 can be written as sum of 3 *primes*
- All even number > 2 can be written as sum of 2 *primes*

8.2 Sieve of Eratosthenes

Numbers up to $2e8$

```

int erat[N >> 6];
#define bit(i) ((i >> 1) & 31)
#define prime(i) !(erat[i >> 6] >> bit(i) & 1)

void bitSieve() {
    for (int i = 3; i * i < N; i += 2) if (prime(i))
        for (int j = i * i; j < N; j += (i << 1))
            erat[j >> 6] |= 1 << bit(j);
}

```

To factorize divide x by $factor[x]$ until is equal to 1

```

void factorizeSieve() {
    iota(factor, factor + N, 0);
    for (int i = 2; i * i < N; i++) if (factor[i] == i)
        for (int j = i * i; j < N; j += i)
            factor[j] = i;
}

```

Use it if you need a huge amount of $\phi[x]$ up to some N

```

void phiSieve() {
    isp.set(); // bitset<N> is faster
    iota(phi, phi + N, 0);
    for (i, 2, N) if (isp[i])
        for (int j = i; j < N; j += i) {
            isp[j] = (i == j);
            phi[j] /= i;
            phi[j] *= i - 1;
        }
}

```

8.3 Phi of euler

```
lli phi(lli n) {
    if (n == 1)
        return 0;
    lli r = n;
    for (lli i = 2; i * i <= n; i++)
        if (n % i == 0) {
            while (n % i == 0)
                n /= i;
            r -= r / i;
        }
    if (n > 1)
        r -= r / n;
    return r;
}
```

8.4 Miller-Rabin

```
bool compo(lli p, lli d, lli n, lli k) {
    lli x = fpow(p % n, d, n), i = k;
    while (x != 1 && x != n - 1 && p % n && i--)
        x = mul(x, x, n);
    return x != n - 1 && i != k;
}

bool miller(lli n) {
    if (n < 2 || n % 6 % 4 != 1)
        return (n | 1) == 3;
    int k = __builtin_ctzll(n - 1);
    lli d = n >> k;
    for (lli p : {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37}) {
        if (compo(p, d, n, k))
            return 0;
        if (compo(2 + rng() % (n - 3), d, n, k))
            return 0;
    }
    return 1;
}
```

8.5 Pollard-Rho

```
lli f(lli x, lli c, lli mod) {
    return (mul(x, x, mod) + c) % mod;
}

lli rho(lli n) {
    while (1) {
        lli x = 2 + rng() % (n - 3), c = 1 + rng() % 20, y
            = f(x, c, n), g;
        while ((g = __gcd(n + y - x, n)) == 1)
            x = f(x, c, n), y = f(f(y, c, n), c, n);
        if (g != n) return g;
    }
    return -1;
}

void pollard(lli n, map<lli, int> &fac) {
    if (n == 1) return;
    if (n % 2 == 0) {
        fac[2]++;
        pollard(n / 2, fac);
        return;
    }
    if (miller(n)) {
        fac[n]++;
        return;
    }
    lli x = rho(n);
    pollard(x, fac);
    pollard(n / x, fac);
}
```

8.6 Amount of divisors

```
lli divs(lli n) {
    lli cnt = 1LL;
    for (lli p : primes) {
        if (p * p * p > n)
            break;
        if (n % p == 0) {
            lli k = 0;
            while (n > 1 && n % p == 0)
                n /= p, ++k;
            cnt *= (k + 1);
        }
    }
    lli sq = mysqrt(n); // A binary search, the last x *
        x <= n
    if (miller(n))
        cnt *= 2;
    else if (sq * sq == n && miller(sq))
        cnt *= 3;
    else if (n > 1)
        cnt *= 4;
    return cnt;
}
```

8.7 Bézout's identity

$a_1 * x_1 + a_2 * x_2 + \dots + a_n * x_n = g$
 $g = \gcd(a_1, a_2, \dots, a_n)$

8.8 GCD

$a \leq b; \gcd(a + k, b + k) = \gcd(b - a, a + k)$

8.9 LCM

$x = p * lcm(a_1, a_2, \dots, a_k) + q, 0 \leq q < lcm(a_1, a_2, \dots, a_k)$
 $x \pmod{a_i} \equiv q \pmod{a_i}$ as $a_i \mid lcm(a_1, a_2, \dots, a_k)$

8.10 Euclid

```
pair<lli, lli> euclid(lli a, lli b) {
    if (b == 0)
        return {1, 0};
    auto p = euclid(b, a % b);
    return {p.s, p.f - a / b * p.s};
}
```

8.11 Chinese remainder theorem

```
pair<lli, lli> crt(pair<lli, lli> a, pair<lli, lli> b)
{
    if (a.s < b.s)
        swap(a, b);
    auto p = euclid(a.s, b.s);
    lli g = a.s * p.f + b.s * p.s, l = a.s / g * b.s;
    if ((b.f - a.f) % g != 0)
        return {-1, -1}; // no solution
    p.f = a.f + (b.f - a.f) % b.s * p.f % b.s / g * a.s;
    return {p.f + (p.f < 0) * l, l};
}
```

9 Math

9.1 Progressions

Arithmetic progressions

$$a_n = a_1 + (n - 1) * diff$$

$$\sum_{i=1}^n a_i = n * \frac{a_1 + a_n}{2}$$

Geometric progressions

$$a_n = a_1 * r^{n-1}$$

$$\sum_{k=1}^n a_1 * r^k = a_1 * \left(\frac{r^{n+1} - 1}{r - 1} \right) : r \neq 1$$

9.2 Mod multiplication

```
lli mul(lli x, lli y, lli mod) {
    lli r = 0LL;
    for (x %= mod; y > 0; y >>= 1) {
        if (y & 1) r = (r + x) % mod;
        x = (x + x) % mod;
    }
    return r;
}
```

9.3 Fpow

```
lli fpow(lli x, lli y, lli mod) {
    lli r = 1;
    for (; y > 0; y >>= 1) {
        if (y & 1) r = mul(r, x, mod);
        x = mul(x, x, mod);
    }
    return r;
}
```

9.4 Fibonacci

$$\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}^n = \begin{bmatrix} fib_{n+1} & fib_n \\ fib_n & fib_{n-1} \end{bmatrix}$$

10 Bit tricks

| Bits++ | |
|--|--|
| Operations on <i>int</i> | Function |
| $x \& -x$ | Least significant bit in x |
| $_lg(x)$ | Most significant bit in x |
| $c = x\&-x, r = x+c;$ $((r\^x) \gg 2)/c \mid r$ | Next number after x with same number of bits set |
| <code>__builtin__</code> | Function |
| <code>popcount(x)</code> | Amount of 1's in x |
| <code>clz(x)</code> | 0's to the left of biggest bit |
| <code>ctz(x)</code> | 0's to the right of smallest bit |

10.1 Bitset

| Bitset<Size> | |
|---|----------------------------------|
| Operation | Function |
| <code>_Find_first()</code> | Least significant bit |
| <code>_Find_next(idx)</code> | First set bit after index idx |
| <code>any()</code> , <code>none()</code> , <code>all()</code> | Just what the expression says |
| <code>set()</code> , <code>reset()</code> , <code>flip()</code> | Just what the expression says x2 |
| <code>to_string('.', 'A')</code> | Print 011010 like .AA.A. |