



University of Warsaw

UW3

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1 Contest

2 Mathematics

3 Data structures

4 Numerical

5 Number theory

6 Combinatorial

7 Graph

8 Geometry

9 Strings

10 Various

Contest (1)

sol.cpp 27 lines

```
#include <bits/stdc++.h>
using namespace std;
#define rep(i, a, b) for (int i = (a); i < (b); i++)
#define all(x) begin(x), end(x)
#define sz(x) int ((x).size())
using ll = long long;
using pii = pair<int, int>;
using vi = vector<int>;
#ifdef LOCAL
auto operator<<(auto& o, auto x) -> decltype(x.first, o)
{
    o << " ";
    for (int i = 0; auto y : x) o << " " + !i++ * 2 << y
        ;
    return o << " ";
}
auto operator<<(auto& o, auto x) -> decltype(x.first, o)
{
    return o << " (" << x.first << " " << x.second << ")"
        ;
}
void __print(auto... x) { ((cerr << x << " ", ...) << endl; }
#define debug(x...) __print("[ " #x " ]:", x)
#else
#define debug(...) 2137
#endif
int main() {
    cin.tie(0)->sync_with_stdio(0);
}
```

.bashrc 8 lines

```
c() {
    g++ -std=c++20 -fsanitize=address,undefined -g \
        -DLOCAL -Wall -Wextra -Wshadow $1.cpp -o $1;
}
nc() { g++ -std=c++20 -O2 $1.cpp -o $1; }
alias rm='trash'
alias mv='mv -i'
alias cp='cp -i'
```

.vimrc 8 lines

```
set nu et ts=2 sw=2
filetype indent on
syntax on
colorscheme habamax
hi MatchParen ctermfg=66 ctermbg=234 cterm=underline
nnoremap ; :
nnoremap ; :
innoremap {<cr> {<cr>}<esc>O <bs>
```

1 hash.sh 3 lines

```
# Hashes a file, ignoring all whitespace and comments.
Use for
# verifying that code was correctly typed.
cpp -dD -P -fpreprocessed | tr -d '[:space:]' | md5sum |
cut -c-6
```

test.sh 5 lines

```
for((i=1;i>0;i++)) do
    echo "$i"
    echo "$i" | ./gen > int
    diff -w <(. /sol < int) <(. /slow < int) || break
done
```

troubleshoot.txt 17 lines

Czy na wejściu pojawić się mogą long longi, np. m<=n^2?  
Czy treść jest w 100% jasna?  
Czy bardzo dokładnie przeczytana jest sekcja input?  
Daj komus innemu przeczytać treść niezależnie,  
zadaj pytanie.  
Czy działa dla brzegowych, np. n/m = 0/1,  
wszystkie a\_i = 0?  
Czy tablice za małe?  
Czy wszędzie modułujesz? Czy dobre modulo?  
Czy na wejściu mogą być liczby poza [0, mod)?  
Czy źle parsujesz wejście, np. zamiast wczytać double?  
WA z double nie oznacza błędu precyzji,  
tym bardziej z long double.  
Czy napisałeś cos, co mogłeś przepisać z biblioteczki?  
Czy interakcja jest poprawna, np. brak znaku zapytania?  
Czy format wyjścia jest poprawny, np. brak YES?  
Czy używasz double gdzieś, gdzie można tego uniknąć?

Mathematics (2)

2.1 Equations

$$ax^2 + bx + c = 0 \Rightarrow x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

The extremum is given by  $x = -b/2a$ .

$$\begin{aligned} ax + by &= e & x &= \frac{ed - bf}{ad - bc} \\ cx + dy &= f & y &= \frac{af - ec}{ad - bc} \end{aligned}$$

In general, given an equation  $Ax = b$ , the solution to a variable  $x_i$  is given by

$$x_i = \frac{\det A'_i}{\det A}$$

where  $A'_i$  is  $A$  with the  $i$ 'th column replaced by  $b$ .

2.2 Recurrences

If  $a_n = c_1 a_{n-1} + \dots + c_k a_{n-k}$ , and  $r_1, \dots, r_k$  are distinct roots of  $x^k - c_1 x^{k-1} - \dots - c_k$ , there are  $d_1, \dots, d_k$  s.t.

$$a_n = d_1 r_1^n + \dots + d_k r_k^n.$$

Non-distinct roots  $r$  become polynomial factors, e.g.  $a_n = (d_1 n + d_2) r^n$ .

2.3 Trigonometry

$$\sin(v + w) = \sin v \cos w + \cos v \sin w$$

$$\cos(v + w) = \cos v \cos w - \sin v \sin w$$

$$\tan(v + w) = \frac{\tan v + \tan w}{1 - \tan v \tan w}$$

$$\sin v + \sin w = 2 \sin \frac{v + w}{2} \cos \frac{v - w}{2}$$

$$\cos v + \cos w = 2 \cos \frac{v + w}{2} \cos \frac{v - w}{2}$$

$$(V + W) \tan(v - w)/2 = (V - W) \tan(v + w)/2$$

where  $V, W$  are lengths of sides opposite angles  $v, w$ .

$$a \cos x + b \sin x = r \cos(x - \phi)$$

$$a \sin x + b \cos x = r \sin(x + \phi)$$

where  $r = \sqrt{a^2 + b^2}, \phi = \text{atan2}(b, a)$ .

2.4 Geometry

2.4.1 Triangles

Side lengths:  $a, b, c$

Semiperimeter:  $p = \frac{a + b + c}{2}$

Area:  $A = \sqrt{p(p - a)(p - b)(p - c)}$

Circumradius:  $R = \frac{abc}{4A}$

Inradius:  $r = \frac{A}{p}$

Length of median (divides triangle into two equal-area triangles):

$$m_a = \frac{1}{2} \sqrt{2b^2 + 2c^2 - a^2}$$

Length of bisector (divides angles in two):

$$s_a = \sqrt{bc \left[ 1 - \left( \frac{a}{b + c} \right)^2 \right]}$$

Law of sines:  $\frac{\sin \alpha}{a} = \frac{\sin \beta}{b} = \frac{\sin \gamma}{c} = \frac{1}{2R}$

Law of cosines:  $a^2 = b^2 + c^2 - 2bc \cos \alpha$

Law of tangents:  $\frac{a + b}{a - b} = \frac{\tan \frac{\alpha + \beta}{2}}{\tan \frac{\alpha - \beta}{2}}$

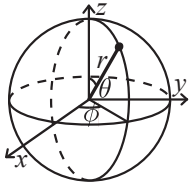
2.4.2 Quadrilaterals

With side lengths  $a, b, c, d$ , diagonals  $e, f$ , diagonals angle  $\theta$ , area  $A$  and magic flux  $F = b^2 + d^2 - a^2 - c^2$ :

$$4A = 2ef \cdot \sin \theta = F \tan \theta = \sqrt{4e^2 f^2 - F^2}$$

For cyclic quadrilaterals the sum of opposite angles is  $180^\circ$ ,  $ef = ac + bd$ , and  $A = \sqrt{(p - a)(p - b)(p - c)(p - d)}$ .

2.4.3 Spherical coordinates



$$\begin{aligned} x &= r \sin \theta \cos \phi & r &= \sqrt{x^2 + y^2 + z^2} \\ y &= r \sin \theta \sin \phi & \theta &= \arccos(z / \sqrt{x^2 + y^2 + z^2}) \\ z &= r \cos \theta & \phi &= \text{atan2}(y, x) \end{aligned}$$

2.5 Derivatives/Integrals

$$\frac{d}{dx} \arcsin x = \frac{1}{\sqrt{1 - x^2}} \quad \frac{d}{dx} \arccos x = -\frac{1}{\sqrt{1 - x^2}}$$

$$\frac{d}{dx} \tan x = 1 + \tan^2 x \quad \frac{d}{dx} \arctan x = \frac{1}{1 + x^2}$$

$$\int \tan ax = -\frac{\ln |\cos ax|}{a} \quad \int x \sin ax = \frac{\sin ax - ax \cos ax}{a^2}$$

$$\int e^{-x^2} = \frac{\sqrt{\pi}}{2} \text{erf}(x) \quad \int x e^{ax} dx = \frac{e^{ax}}{a^2} (ax - 1)$$

Integration by parts:

$$\int_a^b f(x)g(x)dx = [F(x)g(x)]_a^b - \int_a^b F(x)g'(x)dx$$

2.6 Sums

$$c^a + c^{a+1} + \dots + c^b = \frac{c^{b+1} - c^a}{c - 1}, c \neq 1$$

$$1 + 2 + 3 + \dots + n = \frac{n(n + 1)}{2}$$

$$1^2 + 2^2 + 3^2 + \dots + n^2 = \frac{n(2n + 1)(n + 1)}{6}$$

$$1^3 + 2^3 + 3^3 + \dots + n^3 = \frac{n^2(n + 1)^2}{4}$$

$$1^4 + 2^4 + 3^4 + \dots + n^4 = \frac{n(n + 1)(2n + 1)(3n^2 + 3n - 1)}{30}$$

2.7 Series

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots, (-\infty < x < \infty)$$

$$\ln(1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots, (-1 < x \leq 1)$$

$$\sqrt{1 + x} = 1 + \frac{x}{2} - \frac{x^2}{8} + \frac{2x^3}{32} - \frac{5x^4}{128} + \dots, (-1 \leq x \leq 1)$$

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \dots, (-\infty < x < \infty)$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots, (-\infty < x < \infty)$$

### 2.8 Probability theory

Let  $X$  be a discrete random variable with probability  $p_X(x)$  of assuming the value  $x$ . It will then have an expected value (mean)  $\mu = \mathbb{E}(X) = \sum_x x p_X(x)$  and variance  $\sigma^2 = V(X) = \mathbb{E}(X^2) - (\mathbb{E}(X))^2 = \sum_x (x - \mathbb{E}(X))^2 p_X(x)$  where  $\sigma$  is the standard deviation. If  $X$  is instead continuous it will have a probability density function  $f_X(x)$  and the sums above will instead be integrals with  $p_X(x)$  replaced by  $f_X(x)$ .

Expectation is linear:

$$\mathbb{E}(aX + bY) = a\mathbb{E}(X) + b\mathbb{E}(Y)$$

For independent  $X$  and  $Y$ ,

$$V(aX + bY) = a^2 V(X) + b^2 V(Y).$$

#### 2.8.1 Discrete distributions

##### Binomial distribution

The number of successes in  $n$  independent yes/no experiments, each which yields success with probability  $p$  is

$\text{Bin}(n, p)$ ,  $n = 1, 2, \dots$ ,  $0 \leq p \leq 1$ .

$$p(k) = \binom{n}{k} p^k (1-p)^{n-k}$$

$$\mu = np, \sigma^2 = np(1-p)$$

$\text{Bin}(n, p)$  is approximately  $\text{Po}(np)$  for small  $p$ .

##### First success distribution

The number of trials needed to get the first success in independent yes/no experiments, each which yields success with probability  $p$  is  $\text{Fs}(p)$ ,  $0 \leq p \leq 1$ .

$$p(k) = p(1-p)^{k-1}, k = 1, 2, \dots$$

$$\mu = \frac{1}{p}, \sigma^2 = \frac{1-p}{p^2}$$

##### Poisson distribution

The number of events occurring in a fixed period of time  $t$  if these events occur with a known average rate  $\kappa$  and independently of the time since the last event is  $\text{Po}(\lambda)$ ,  $\lambda = t\kappa$ .

$$p(k) = e^{-\lambda} \frac{\lambda^k}{k!}, k = 0, 1, 2, \dots$$

$$\mu = \lambda, \sigma^2 = \lambda$$

#### 2.8.2 Continuous distributions

##### Uniform distribution

If the probability density function is constant between  $a$  and  $b$  and 0 elsewhere it is  $\text{U}(a, b)$ ,  $a < b$ .

$$f(x) = \begin{cases} \frac{1}{b-a} & a < x < b \\ 0 & \text{otherwise} \end{cases}$$

$$\mu = \frac{a+b}{2}, \sigma^2 = \frac{(b-a)^2}{12}$$

### Exponential distribution

The time between events in a Poisson process is  $\text{Exp}(\lambda)$ ,  $\lambda > 0$ .

$$f(x) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & x < 0 \end{cases}$$

$$\mu = \frac{1}{\lambda}, \sigma^2 = \frac{1}{\lambda^2}$$

### Normal distribution

Most real random values with mean  $\mu$  and variance  $\sigma^2$  are well described by  $\mathcal{N}(\mu, \sigma^2)$ ,  $\sigma > 0$ .

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

If  $X_1 \sim \mathcal{N}(\mu_1, \sigma_1^2)$  and  $X_2 \sim \mathcal{N}(\mu_2, \sigma_2^2)$  then

$$aX_1 + bX_2 + c \sim \mathcal{N}(\mu_1 + \mu_2 + c, a^2\sigma_1^2 + b^2\sigma_2^2)$$

### 2.9 Markov chains

A *Markov chain* is a discrete random process with the property that the next state depends only on the current state. Let  $X_1, X_2, \dots$  be a sequence of random variables generated by the Markov process. Then there is a transition matrix  $\mathbf{P} = (p_{ij})$ , with  $p_{ij} = \Pr(X_n = i | X_{n-1} = j)$ , and  $\mathbf{p}^{(n)} = \mathbf{P}^n \mathbf{p}^{(0)}$  is the probability distribution for  $X_n$  (i.e.,  $p_i^{(n)} = \Pr(X_n = i)$ ), where  $\mathbf{p}^{(0)}$  is the initial distribution.

$\pi$  is a stationary distribution if  $\pi = \pi \mathbf{P}$ . If the Markov chain is *irreducible* (it is possible to get to any state from any state), then  $\pi_i = \frac{1}{\mathbb{E}(T_i)}$  where  $\mathbb{E}(T_i)$  is the expected time between two visits in state  $i$ .  $\pi_j / \pi_i$  is the expected number of visits in state  $j$  between two visits in state  $i$ .

For a connected, undirected and non-bipartite graph, where the transition probability is uniform among all neighbors,  $\pi_i$  is proportional to node  $i$ 's degree.

A Markov chain is *ergodic* if the asymptotic distribution is independent of the initial distribution. A finite Markov chain is ergodic iff it is irreducible and *aperiodic* (i.e., the gcd of cycle lengths is 1).  $\lim_{k \rightarrow \infty} \mathbf{P}^k = \mathbf{1P}$ .

A Markov chain is an A-chain if the states can be partitioned into two sets  $\mathbf{A}$  and  $\mathbf{G}$ , such that all states in  $\mathbf{A}$  are absorbing ( $p_{ii} = 1$ ), and all states in  $\mathbf{G}$  leads to an absorbing state in  $\mathbf{A}$ . The probability for absorption in state  $i \in \mathbf{A}$ , when the initial state is  $j$ , is  $a_{ij} = p_{ij} + \sum_{k \in \mathbf{G}} a_{ik} p_{kj}$ . The expected time until absorption, when the initial state is  $i$ , is  $t_i = 1 + \sum_{k \in \mathbf{G}} p_{ki} t_k$ .

### Data structures (3)

### OrderStatisticTree.h

**Description:** A set (not multiset!) with support for finding the  $n$ 'th element, and finding the index of an element. To get a map, change null.type.

**Time:**  $\mathcal{O}(\log N)$  b9b97b, 17 lines

```
#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace __gnu_pbds;
template<class T>
using Tree = tree<T, null_type, less<T>, rb_tree_tag,
tree_order_statistics_node_update>;
void example() {
    Tree<int> t, t2; t.insert(8);
    auto it = t.insert(10).first;
    assert(it == t.lower_bound(9));
    assert(t.order_of_key(10) == 1);
    assert(t.order_of_key(11) == 2);
    assert(*t.find_by_order(0) == 8);
    t.join(t2); // assuming T < T2 or T > T2, merge t2
                into t
}
```

### HashMap.h

**Description:** Hash map with mostly the same API as unordered\_map, but ~3x faster. Uses 1.5x memory. Initial capacity must be a power of 2 (if provided).

**Time:**  $\mathcal{O}(\log N)$  481ffe, 7 lines

```
#include <ext/pb_ds/assoc_container.hpp>
// To use most bits rather than just the lowest ones:
struct chash { // large odd number for C
    const uint64_t C = 11(4e18 * acos(0)) ^ 71;
    ll operator()(ll x) const { return __builtin_bswap64(
        x^C); }
};
__gnu_pbds::gp_hash_table<ll,ll,chash> h({}, {}, {}, {}, {
    1<<16});
```

### SegmentTree.h

**Description:** Zero-indexed max-tree. Bounds are inclusive to the left and exclusive to the right. Can be changed by modifying T, f and unit.

**Time:**  $\mathcal{O}(\log N)$  0f4bdb, 19 lines

```
struct Tree {
    typedef int T;
    static constexpr T unit = INT_MIN;
    T f(T a, T b) { return max(a, b); } // (any
    associative fn)
    vector<T> s; int n;
    Tree(int n = 0, T def = unit) : s(2*n, def), n(n) {}
    void update(int pos, T val) {
        for (s[pos] += n] = val; pos /= 2;)
            s[pos] = f(s[pos * 2], s[pos * 2 + 1]);
    }
    T query(int b, int e) { // query [b, e)
        T ra = unit, rb = unit;
        for (b += n, e += n; b < e; b /= 2, e /= 2) {
            if (b % 2) ra = f(ra, s[b++]);
            if (e % 2) rb = f(s[--e], rb);
            ra = f(ra, rb);
        }
        return f(ra, rb);
    }
};
```

### LazySegmentTree.h

**Description:** Segment tree with ability to add or set values of large intervals, and compute max of intervals. Can be changed to other things. Use with a bump allocator for better performance, and SmallPtr or implicit indices to save memory.

**Usage:** Node\* tr = new Node(v, 0, sz(v));

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

**Time:**  $\mathcal{O}(\log N)$  34ecf5, 50 lines

```
"/..various/BumpAllocator.h"
const int inf = 1e9;
struct Node {
    Node *l = 0, *r = 0;
    int lo, hi, mset = inf, madd = 0, val = -inf;
    Node(int lo, int hi):lo(lo), hi(hi){} // Large interval
    of -inf
    Node(vi& v, int lo, int hi) : lo(lo), hi(hi) {
        if (lo + 1 < hi) {
            int mid = lo + (hi - lo)/2;
            l = new Node(v, lo, mid); r = new Node(v, mid, hi
                );
            val = max(l->val, r->val);
        }
        else val = v[lo];
    }
};
```

```
int query(int L, int R) {
    if (R <= lo || hi <= L) return -inf;
    if (L <= lo && hi <= R) return val;
    push();
    return max(l->query(L, R), r->query(L, R));
}
void set(int L, int R, int x) {
    if (R <= lo || hi <= L) return;
    if (L <= lo && hi <= R) mset = val = x, madd = 0;
    else {
        push(), l->set(L, R, x), r->set(L, R, x);
        val = max(l->val, r->val);
    }
}
void add(int L, int R, int x) {
    if (R <= lo || hi <= L) return;
    if (L <= lo && hi <= R) {
        if (mset != inf) mset += x;
        else madd += x;
        val += x;
    }
    else {
        push(), l->add(L, R, x), r->add(L, R, x);
        val = max(l->val, r->val);
    }
}
void push() {
    if (!l) {
        int mid = lo + (hi - lo)/2;
        l = new Node(lo, mid); r = new Node(mid, hi);
    }
    if (mset != inf)
        l->set(lo, hi, mset), r->set(lo, hi, mset), mset =
            inf;
    else if (madd)
        l->add(lo, hi, madd), r->add(lo, hi, madd), madd = 0;
}
};
```

### UnionFind.h

**Description:** Disjoint-set data structure.

**Time:**  $\mathcal{O}(\alpha(N))$  7aa27c, 14 lines

```
struct UF {
    vi e;
    UF(int n) : e(n, -1) {}
    bool sameSet(int a, int b) { return find(a) == find(b)
        }; }
    int size(int x) { return -e[find(x)]; }
    int find(int x) { return e[x] < 0 ? x : e[x] = find(e
        [x]); }
    bool join(int a, int b) {
        a = find(a), b = find(b);
        if (a == b) return false;
        if (e[a] > e[b]) swap(a, b);
        e[a] += e[b]; e[b] = a;
        return true;
    }
};
```

### UnionFindRollback.h

**Description:** Disjoint-set data structure with undo. If undo is not needed, skip st, time() and rollback().

**Usage:** int t = uf.time(); ...; uf.rollback(t);

**Time:**  $\mathcal{O}(\log(N))$  de4ad0, 21 lines

```
struct RollbackUF {
    vi e; vector<pii> st;
    RollbackUF(int n) : e(n, -1) {}
    int size(int x) { return -e[find(x)]; }
    int find(int x) { return e[x] < 0 ? x : find(e[x]); }
    int time() { return sz(st); }
    void rollback(int t) {
        for (int i = time(); i --> t;)
            e[st[i].first] = st[i].second;
        st.resize(t);
    }
    bool join(int a, int b) {
        a = find(a), b = find(b);
        if (a == b) return false;
        if (e[a] > e[b]) swap(a, b);
        st.push_back({a, e[a]});
        st.push_back({b, e[b]});
        e[a] += e[b]; e[b] = a;
        return true;
    }
};
```

## DequeRollback.h

**Description:** Deque-like undoing on data structures with amortized  $\mathcal{O}(\log n)$  overhead for operations. Maintains a deque of objects alongside a data structure that contains all of them. The data structure only needs to support insertions and undoing of last insertion using the following interface: - insert(...) - insert an object to DS - time() - returns current version number - rollback(t) - undo all operations after t Assumes time() == 0 for empty DS.

```
57bab5, 38 lines
struct DequeUndo {
    // Argument for insert(...) method of DS.
    using T = tuple<int, int>;
    DataStructure ds; // Configure DS type here.
    vector<T> elems[2];
    vector<pii> his = {{0,0}};
    // Push object to front or back of deque, depending
    // on side arg.
    void push(T val, bool side) {
        elems[side].push_back(val);
        doPush(0, side);
    }
    // Pop object from front or back of deque, depending
    // on side arg.
    void pop(int side) {
        auto &A = elems[side], &B = elems[!side];
        int cnt[2] = {};
        if (A.empty()) {
            assert(!B.empty());
            auto it = B.begin() + sz(B)/2 + 1;
            A.assign(B.begin(), it);
            B.erase(B.begin(), it);
            reverse(all(A)); his.resize(1);
            cnt[0] = sz(A); cnt[1] = sz(B);
        } else {
            do {
                cnt[his.back().y ^ side]++;
                his.pop_back();
            } while (cnt[0]*2 < cnt[1] && cnt[0] < sz(A));
        }
        cnt[0]--; A.pop_back();
        ds.rollback(his.back().x);
        for (int i : {1, 0})
            while (cnt[i]) doPush(--cnt[i], i^side);
    }
    void doPush(int i, bool s) {
        apply([&](auto... ret) { ds.insert(x...); }, elems[s].
            rbegin()[i]);
        his.push_back({ds.time(), s});
    }
};
```

## SubMatrix.h

**Description:** Calculate submatrix sums quickly, given upper-left and lower-right corners (half-open).

**Usage:** SubMatrix<int> m(matrix);

m.sum(0, 0, 2, 2); // top left 4 elements

**Time:**  $\mathcal{O}(N^2 + Q)$

```
c59ada, 13 lines
template<class T>
struct SubMatrix {
    vector<vector<T>>> p;
    SubMatrix(vector<vector<T>>> v) {
        int R = sz(v), C = sz(v[0]);
        p.assign(R+1, vector<T>(C+1));
        rep(r,0,R) rep(c,0,C)
            p[r+1][c+1] = v[r][c] + p[r][c+1] + p[r+1][c] - p[r+1][c];
    }
    T sum(int u, int l, int d, int r) {
        return p[d][r] - p[d][l] - p[u][r] + p[u][l];
    }
};
```

## Matrix.h

**Description:** Basic operations on square matrices.

**Usage:** Matrix<int, 3> A;

A.d = {{{{1,2,3}}, {{4,5,6}}, {{7,8,9}}}};

array<int, 3> vec = {1,2,3};

vec = (A^N) \* vec;

```
6ab5db, 26 lines
template<class T, int N> struct Matrix {
    typedef Matrix M;
    array<array<T, N>, N> d{};
    M operator*(const M& m) const {
        M a;
        rep(i,0,N) rep(j,0,N)
            rep(k,0,N) a.d[i][j] += d[i][k]*m.d[k][j];
    }
};
```

```
return a;
}
array<T, N> operator*(const array<T, N>& vec) const {
    array<T, N> ret{};
    rep(i,0,N) rep(j,0,N) ret[i] += d[i][j] * vec[j];
    return ret;
}
M operator^(ll p) const {
    assert(p >= 0);
    M a, b(*this);
    rep(i,0,N) a.d[i][i] = 1;
    while (p) {
        if (p&1) a = a*b;
        b = b*b;
        p >>= 1;
    }
    return a;
}
};
```

## LineContainer.h

**Description:** Container where you can add lines of the form  $kx+m$ , and query maximum values at points  $x$ . Useful for dynamic programming (“convex hull trick”).

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

```
8ec1c7, 30 lines
struct Line {
    mutable ll k, m, p;
    bool operator<(const Line& o) const { return k < o.k; }
}
bool operator<(ll x) const { return p < x; }
};
struct LineContainer : multiset<Line, less<>> {
    // (for doubles, use inf = 1/.0, div(a,b) = a/b)
    static const ll inf = LLONG_MAX;
    ll div(ll a, ll b) { // floored division
        return a / b - ((a ^ b) < 0 && a % b); }
    bool isect(iterator x, iterator y) {
        if (y == end()) return x->p = inf, 0;
        if (x->k == y->k) x->p = x->m > y->m ? inf : -inf;
        else x->p = div(y->m - x->m, x->k - y->k);
        return x->p >= y->p;
    }
    void add(ll k, ll m) {
        auto z = insert({k, m, 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));
    }
    ll query(ll x) {
        assert(!empty());
        auto l = *lower_bound(x);
        return l.k * x + l.m;
    }
};

ll query(ll x) {
    assert(!empty());
    auto l = *lower_bound(x);
    return l.k * x + l.m;
};
```

## Treap.h

**Description:** A short self-balancing tree. It acts as a sequential container with log-time splits/joins, and is easy to augment with additional data.

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

```
e8e28b, 77 lines
mt19937 rng(2137);
struct Node {
    Node *l = 0, *r = 0, *p = 0;
    int val, y, c = 1;
    Node(int val) : val(val), y(rng()) {}
    friend int cnt(Node* n) { return n ? n->c : 0; }
    void recalc() { c = cnt(l) + cnt(r) + 1; }
    void push() {}
};
void each(Node* n, auto f) {
    if (n) { each(n->l, f); f(n->val); each(n->r, f); }
}
pair<Node*, Node*> split(Node* n, int k) {
    if (!n) return {};
    n->push(); n->p = 0;
    if (cnt(n->l) >= k) { // "n->val >= k" for
        lower_bound(k)
        auto [L,R] = split(n->l, k);
        if (n->l = R) n->l->p = n;
        return n->recalc(), pair(L, n);
    } else {
        auto [L,R] = split(n->r, k - cnt(n->l) - 1); // and
        just "k"
        if (n->r = L) n->r->p = n;
        return n->recalc(), pair(n, R);
    }
};
```

```

}
Node* merge(Node* l, Node* r) {
    if (!l || !r) return l ? r :
    if (l->y > r->y) {
        l->push();
        if (l->r = merge(l->r, r)) l->r->p = l;
        return l->recalc(), l;
    } else {
        r->push();
        if (r->l = merge(l, r->l)) r->l->p = r;
        return r->recalc(), r;
    }
}
Node* ins(Node* t, Node* n, int pos) {
    auto [l,r] = split(t, pos);
    return merge(merge(l, n), r);
}
// Union of two sorted treaps,  $\mathcal{O}(m \log(n/m))$  where  $m < n$ 
// Makes small-to-large  $\mathcal{O}(n \log n)$  instead of  $\log^2$ .
// Requires lower_bound split (not the default one).
Node* unite(Node* a, Node* b) {
    if (!a || !b) return a ? b :
    if (a->y < b->y) swap(a, b);
    a->push(); a->p = 0;
    auto [l, r] = split(b, a->val); // lower_bound split
    if (a->l = unite(l, a->l)) a->l->p = a;
    if (a->r = unite(r, a->r)) a->r->p = a;
    return a->recalc(), a;
}
// Number of elements before n. If there are range
// reverse queries, recursively push the path to n.
int idx(Node* n) {
    int c = cnt(n->l);
    while (n->p) {
        if (n->p->l != n) c += cnt(n->p->l) + 1;
        n = n->p;
    }
    return c;
}
// Example application: move the range [l, r] to index
// k
void move(Node* &t, int l, int r, int k) {
    Node *a, *b, *c;
    tie(a,b) = split(t, l); tie(b,c) = split(b, r - 1);
    if (k <= l) t = merge(ins(a, b, k), c);
    else t = merge(a, ins(c, b, k - r));
}
};
```

## IntSet.h

**Description:** bitset with fast predecessor and successor queries. Assumes x86 shift overflows. Extremely fast (50-200mln operations in 1 second).

```
85cd6f, 32 lines
template<int N>
struct IntSet {
    static constexpr int B = 64;
    uint64_t V[N / B + 1] = {};
    IntSet(N < B + 1 ? 0 : N / B + 1) > up;
    bool has(int i) { return (V[i / B] >> i) & 1; }
    void add(int i) {
        if (!(V[i / B] & 1)) up.add(i / B);
        V[i / B] |= 1ull << i;
    }
    void del(int i) {
        if (!(V[i / B] & ~(1ull << i))) up.del(i / B);
        V[i / B] |= 1ull << i;
    }
    int next(int i) { // j > i such that j inside or -1
        auto x = V[i / B] >> i;
        if (x &= ~1) return i + __builtin_ctzll(x);
        return (i = up.next(i / B)) < 0 ? i :
            i * B + __builtin_ctzll(V[i]);
    }
    int prev(int i) { // j < i such that j inside or -1
        auto x = V[i / B] << (B - i - 1);
        if (x &= INT64_MAX)
            return i - __builtin_clzll(x);
        return (i = up.prev(i / B)) < 0 ? i :
            i * B + B - 1 - __builtin_clzll(V[i]);
    }
};
template<>
struct IntSet<0> {
    void add(int) {} void del(int) {}
    int next(int) { return -1; }
    int prev(int) { return -1; } };
};
```

## FenwickTree.h

**Description:** Computes partial sums  $a[0] + a[1] + \dots + a[\text{pos} - 1]$ , and updates single elements  $a[i]$ , taking the difference between the old and new value.

**Time:** Both operations are  $\mathcal{O}(\log N)$ .

e62fac, 22 lines

```
struct FT {
    vector<ll> s;
    FT(int n) : s(n) {}
    void update(int pos, ll dif) { // a[pos] += dif
        for (; pos < sz(s); pos |= pos + 1) s[pos] += dif;
    }
    ll query(int pos) { // sum of values in [0, pos]
        ll res = 0;
        for (; pos > 0; pos &= pos - 1) res += s[pos-1];
        return res;
    }
    int lower_bound(ll sum) { // min pos st sum of [0, pos]
        ] >= sum
        // Returns n if no sum is >= sum, or -1 if empty
        sum is.
        if (sum <= 0) return -1;
        int pos = 0;
        for (int pw = 1 << 25; pw; pw >>= 1) {
            if (pos + pw <= sz(s) && s[pos + pw-1] < sum)
                pos += pw, sum -= s[pos-1];
        }
        return pos;
    }
};
```

## FenwickTree2d.h

**Description:** Computes sums  $a[i,j]$  for all  $i < I, j < J$ , and increases single elements  $a[i,j]$ . Requires that the elements to be updated are known in advance (call fakeUpdate() before init()).

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

(Use persistent segment trees for

$\mathcal{O}(\log N)$ .)

\*FenwickTree.h" 157f07, 22 lines

```
struct FT2 {
    vector<vi> ys; vector<FT> ft;
    FT2(int limx) : ys(limx) {}
    void fakeUpdate(int x, int y) {
        for (; x < sz(ys); x |= x + 1) ys[x].push_back(y);
    }
    void init() {
        for (vi& v : ys) sort(all(v)), ft.emplace_back(sz(v)
            ));
    }
    int ind(int x, int y) {
        return (int)(lower_bound(all(ys[x]), y) - ys[x].
            begin()); }
    void update(int x, int y, ll dif) {
        for (; x < sz(ys); x |= x + 1)
            ft[x].update(ind(x, y), dif);
    }
    ll query(int x, int y) {
        ll sum = 0;
        for (; x; x &= x - 1)
            sum += ft[x-1].query(ind(x-1, y));
        return sum;
    }
};
```

## RMQ.h

**Description:** Range Minimum Queries on an array. Returns  $\min(V[a], V[a + 1], \dots, V[b - 1])$  in constant time.

**Usage:** RMQ rmq(values);

rmq.query(inclusive, exclusive);

**Time:**  $\mathcal{O}(|V| \log |V| + Q)$

510c32, 16 lines

```
template<class T>
struct RMQ {
    vector<vector<T>>> jmp;
    RMQ(const vector<T>& V) : jmp(1, V) {
        for (int pw = 1, k = 1; pw * 2 <= sz(V); pw *= 2,
            ++k) {
            jmp.emplace_back(sz(V) - pw * 2 + 1);
            rep(j,0,sz(jmp[k]))
                jmp[k][j] = min(jmp[k - 1][j], jmp[k - 1][j +
                    pw]);
        }
    }
    T query(int a, int b) {
        assert(a < b); // or return inf if a == b
        int dep = 31 - __builtin_clz(b - a);
        return min(jmp[dep][a], jmp[dep][b - (1 << dep)]);
    }
};
```

## MoQueries.h

**Description:** Answer interval or tree path queries by finding an approximate TSP through the queries, and moving from one query to the next by adding/removing points at the ends. If values are on tree edges, change step to add/remove the edge  $(a,c)$  and remove the initial add call (but keep in).

**Time:**  $\mathcal{O}(N\sqrt{Q})$  a12ef4, 49 lines

```
void add(int ind, int end) { ... } // add a[ind] (end = 0 or 1)

void del(int ind, int end) { ... } // remove a[ind]
int calc() { ... } // compute current answer
vi mo(vector<pii> Q) {
    int L = 0, R = 0, blk = 350; // ~N/sqrt(Q)
    vi s(sz(Q)), res = s;
    #define K(x) pii(x.first/blk, x.second ^ -(x.first/blk & 1))
    iota(all(s), 0);
    sort(all(s), [&](int s, int t){ return K(Q[s]) < K(Q[t]); });
    for (int qi : s) {
        pii q = Q[qi];
        while (L > q.first) add(--L, 0);
        while (R < q.second) add(R++, 1);
        while (L < q.first) del(L++, 0);
        while (R > q.second) del(--R, 1);
        res[qi] = calc();
    }
    return res;
}

vi moTree(vector<array<int, 2>> Q, vector<vi>& ed, int root=0){
    int N = sz(ed), pos[2] = {}, blk = 350; // ~N/sqrt(Q)
    vi s(sz(Q)), res = s, I(N), L(N), R(N), in(N), par(N)
    ;
    add(0, 0), in[0] = 1;
    auto dfs = [&](int x, int p, int dep, auto& f) ->
        void {
            par[x] = p;
            L[x] = N;
            if (dep) I[x] = N++;
            for (int y : ed[x]) if (y != p) f(y, x, !dep, f);
            if (!dep) I[x] = N++;
            R[x] = N;
        };
    dfs(root, -1, 0, dfs);
    #define K(x) pii(I[x][0] / blk, I[x][1] ^ -(I[x][0] / blk & 1))
    iota(all(s), 0);
    sort(all(s), [&](int s, int t){ return K(Q[s]) < K(Q[t]); });
    for (int qi : s) rep(end,0,2) {
        int &a = pos[end], b = Q[qi][end], i = 0;
        #define step(c) { if (in[c]) { del(a, end); in[a] = 0; } \
            else { add(c, end); in[c] = 1; } a = c; }
        while (!(L[bl] <= L[a] && R[a] <= R[bl]))
            I[i++] = b, b = par[b];
        while (a != b) step(par[a]);
        while (i-->) step(I[i]);
        if (end) res[qi] = calc();
    }
    return res;
}
```

## Numerical (4)

### 4.1 Polynomials and recurrences

#### Polynomial.h

c9b7b0, 17 lines

```
struct Poly {
    vector<double> a;
    double operator()(double x) const {
        double val = 0;
        for (int i = sz(a); i-->) (val += x) += a[i];
        return val;
    }
    void diff() {
        rep(i,1,sz(a)) a[i-1] = i*a[i];
        a.pop_back();
    }
    void divroot(double x0) {
        double b = a.back(), c; a.back() = 0;
        for(int i=sz(a)-1; i-->) c = a[i], a[i] = a[i+1]*x0
            +b, b=c;
        a.pop_back();
    }
};
```

## PolyRoots.h

**Description:** Finds the real roots to a polynomial.

**Usage:** polyRoots({{-2,-3,1}},-1e9,1e9) // solve  $x^2-3x+2 = 0$

**Time:**  $\mathcal{O}(n^2 \log(1/\epsilon))$

"Polynomial.h" b00bfe, 23 lines

```
vector<double> polyRoots(Poly p, double xmin, double
    xmax) {
    if (sz(p.a) == 2) { return {-p.a[0]/p.a[1]}; }
    vector<double> ret;
    Poly der = p;
    der.diff();
    auto dr = polyRoots(der, xmin, xmax);
    dr.push_back(xmin-1);
    dr.push_back(xmax+1);
    sort(all(dr));
    rep(i,0,sz(dr)-1) {
        double l = dr[i], h = dr[i+1];
        bool sign = p(l) > 0;
        if (sign ^ (p(h) > 0)) {
            rep(it,0,60) { // while (h - l > 1e-8)
                double m = (l + h) / 2, f = p(m);
                if ((f <= 0) ^ sign) l = m;
                else h = m;
            }
            ret.push_back((l + h) / 2);
        }
    }
    return ret;
}
```

## PolyInterpolate.h

**Description:** 1. Interpolate set of points  $(i, \text{vec}[i])$  and return it evaluated at  $x$ ; 2. Given  $n$  points  $(x, f(x))$  compute  $n-1$ -degree polynomial  $f$  that passes through them;

**Time:**  $\mathcal{O}(n)$  and  $\mathcal{O}(n^2)$

174038, 33 lines

```
template<class T>
T polyExtend(vector<T>& vec, T x) {
    int n = sz(vec);
    vector<T> fac(n, 1), suf(n, 1);
    rep(i, 1, n) fac[i] = fac[i-1] * i;
    for (int i=n; --i;) suf[i-1] = suf[i]*(x-i);
    T pref = 1, ret = 0;
    rep(i, 0, n) {
        T d = fac[i] * fac[n-i-1] * ((n-i)%2*2-1);
        ret += vec[i] * suf[i] * pref / d;
        pref *= x-i;
    }
    return ret;
}

template<class T>
vector<T> polyInterp(vector<pair<T, T>> P) {
    int n = sz(P);
    vector<T> ret(n), tmp(n);
    T last = 0;
    tmp[0] = 1;
    rep(k, 0, n-1) rep(i, k+1, n)
        P[i].second = (P[i].second-P[k].second) / (P[i].
            first-P[k].first);
    rep(k, 0, n) rep(i, 0, n) {
        ret[i] += P[k].second * tmp[i];
        swap(last, tmp[i]);
        tmp[i] -= last * P[k].first;
    }
    return ret;
}
```

## BerlekampMassey.h

**Description:** Recovers any  $n$ -order linear recurrence relation from the first  $2n$  terms of the recurrence. Useful for guessing linear recurrences after brute-forcing the first terms. Should work on any field, but numerical stability for floats is not guaranteed. Output will have size  $\leq n$ .

**Usage:** berlekampMassey({0, 1, 1, 3, 5, 11}) // {1, 2}

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

"../number-theory/ModPow.h" 96548b, 20 lines

```
vector<ll> berlekampMassey(vector<ll> s) {
    int n = sz(s), L = 0, m = 0;
    vector<ll> C(n), B(n), T;
    C[0] = B[0] = 1;
    ll b = 1;
    rep(i,0,n) { ++m;
        ll d = s[i] % mod;
        rep(j,1,L+1) d = (d + C[j] * s[i - j]) % mod;
        if (!d) continue;
```

```
        T = C; ll coef = d * modpow(b, mod-2) % mod;
        rep(j,m,n) C[j] = (C[j] - coef * B[j - m]) % mod;
        if (2 * L > i) continue;
        L = i + 1 - L; B = T; b = d; m = 0;
    }
    C.resize(L + 1); C.erase(C.begin());
    for (ll x : C) x = (mod - x) % mod;
    return C;
}
```

## LinearRecurrence.h

**Description:** Generates the  $k$ 'th term of an  $n$ -order linear recurrence  $S[i] = \sum_j S[i-j-1]tr[j]$ , given  $S[0 \dots \geq n-1]$  and  $tr[0 \dots n-1]$ . Faster than matrix multiplication. Useful together with Berlekamp-Massey.

**Usage:** linearRec({0, 1}, {1, 1}, k) //  $k$ 'th Fibonacci number

**Time:**  $\mathcal{O}(n^2 \log k)$

f4e444, 26 lines

```
typedef vector<ll> Poly;
ll linearRec(Poly S, Poly tr, ll k) {
    int n = sz(tr);
    auto combine = [&](Poly a, Poly b) {
        Poly res(n + 2 + 1);
        rep(i,0,n+1) rep(j,0,n+1)
            res[i + j] = (res[i + j] + a[i] * b[j]) % mod;
        for (int i = 2 * n; i > n; --i) rep(j,0,n)
            res[i - 1 - j] = (res[i - 1 - j] + res[i] * tr[j]
                ) % mod;
        res.resize(n + 1);
        return res;
    };
    Poly pol(n + 1), e(pol);
    pol[0] = e[1] = 1;
    for (++k; k; k /= 2) {
        if (k % 2) pol = combine(pol, e);
        e = combine(e, e);
    }
    ll res = 0;
    rep(i,0,n) res = (res + pol[i + 1] * S[i]) % mod;
    return res;
}
```

## FastMulDet.h

**Description:** Given a matrix  $M$ , s.t. we can quickly compute  $f(v) = Mv$  for any vector  $v$ , computes  $\det(M)$ . Single iteration fails on identity matrix with probability around  $n^2/\text{mod}$ . For small mod you can modify this to use a field extension.

**Time:**  $4n$  calls to  $f$

"BerlekampMassey.h" 84262e, 30 lines

```
mt19937_64 rnd(2137);
vector<ll> rndVec(int n) {
    vector<ll> r(n);
    rep(i, 0, n) r[i] = rnd() % mod;
    return r;
}

ll dot(vector<ll> &a, vector<ll> &b) {
    ll r = 0;
    rep(i, 0, sz(a)) r += a[i] * b[i] % mod;
    return r % mod;
}

void pointwise(vector<ll> &a, vector<ll> &b) {
    rep(i, 0, sz(a)) a[i] = a[i] * b[i] % mod;
}

ll detOnce(int n, auto f) {
    auto v = rndVec(n), r = rndVec(n);
    vector<ll> vals;
    rep(_, 0, n*2) {
        pointwise(a, r);
        vals.push_back(dot(v, a = f(a)));
    }
    auto ber = berlekampMassey(vals);
    if (sz(ber) != n) return 0;
    ll prod = 1;
    for (ll x : r) prod = prod * x % mod;
    int sg = n % 2 ? 1 : -1;
    return (mod + ber[n-1] * sg) * modpow(prod, mod-2) % mod;
}

ll det(int n, auto f) {
    return detOnce(n, f) ?: detOnce(n, f); }
}
```

### 4.2 Optimization

#### GoldenSectionSearch.h

**Description:** Finds the argument minimizing the function  $f$  in the interval  $[a,b]$  assuming  $f$  is unimodal on the interval, i.e. has only one local minimum and no local maximum. The maximum error in the result is  $\text{eps}$ . Works equally well for maximization with a small change in the code. See TernarySearch.h in the Various chapter for a discrete version.

**Usage:** double func(double x) { return 4\*x+.3\*x\*x; }

double xmin = gss(-1000,1000,func);

**Time:**  $\mathcal{O}(\log((b-a)/\epsilon))$  31d45b, 14 lines

```
double gss(double a, double b, double (*f)(double)) {
    double r = (sqrt(5)-1)/2, eps = 1e-7;
    double x1 = b - r*(b-a), x2 = a + r*(b-a);
    double f1 = f(x1), f2 = f(x2);
    while (b-a > eps)
        if (f1 < f2) { //change to > to find maximum
            b = x2; x2 = x1; f2 = f1;
            x1 = b - r*(b-a); f1 = f(x1);
        } else {
            a = x1; x1 = x2; f1 = f2;
            x2 = a + r*(b-a); f2 = f(x2);
        }
    return a;
}
```

## HillClimbing.h

**Description:** Poor man's optimization for unimodal functions. Seeeaf, 14 lines

```
typedef array<double, 2> P;
template<class F> pair<double, P> hillClimb(P start, F
    f) {
    pair<double, P> cur(f(start), start);
    for (double jmp = 1e9; jmp > 1e-20; jmp /= 2) {
        rep(j,0,100) rep(dx,-1,2) rep(dy,-1,2) {
            P p = cur.second;
            p[0] += dx*jmp;
            p[1] += dy*jmp;
            cur = min(cur, make_pair(f(p), p));
        }
    }
    return cur;
}
```

## Integrate.h

**Description:** Simple integration of a function over an interval using Simpson's rule. The error should be proportional to  $h^4$ , although in practice you will want to verify that the result is stable to desired precision when epsilon changes.4756fc, 7 lines

```
template<class F>
double quad(double a, double b, F f, const int n =
    1000) {
    double h = (b - a) / 2 / n, v = f(a) + f(b);
    rep(i,1,n*2)
        v += f(a + i*h) * (i&1 ? 4 : 2);
    return v * h / 3;
}
```

## IntegrateAdaptive.h

**Description:** Fast integration using an adaptive Simpson's rule.

**Usage:** double sphereVolume = quad(-1, 1, [](double x) {
 return quad(-1, 1, [&](double z) {
 return quad(-1, 1, [&](double z) {
 return x\*x + y\*y + z\*z < 1; }));});}); 92dd79, 15 lines

```
typedef double d;
#define S(a,b) (f(a) + 4*f((a+b) / 2) + f(b)) * (b-a) / 6
template <class F>
d rec(F& f, d a, d b, d eps, d S) {
    d c = (a + b) / 2;
    d S1 = S(a, c), S2 = S(c, b), T = S1 + S2;
    if (abs(T - S) <= 15 * eps || b - a < 1e-10)
        return T + (T - S) / 15;
    return rec(f, a, c, eps / 2, S1) + rec(f, c, b, eps / 2, S2);
}

template<class F>
d quad(d a, d b, F f, d eps = 1e-8) {
    return rec(f, a, b, eps, S(a, b));
}
```

## Simplex.h

**Description:** Solves a general linear maximization problem: maximize  $c^T x$  subject to  $Ax \leq b$ ,  $x \geq 0$ . Returns -inf if there is no solution, inf if there are arbitrarily good solutions, or the maximum value of  $c^T x$  otherwise. The input vector is set to an optimal  $x$  (or in the unbounded case, an arbitrary solution fulfilling the constraints). Numerical stability is not guaranteed. For better performance, define variables such that  $x = 0$  is viable.

**Usage:** vvd A = {{1,-1}, {-1,1}, {-1,-2}};

vd b = {1,1,-4}, c = {-1,-1}, x;

T val = LPSolver(A, b, c).solve(x);

**Time:**  $\mathcal{O}(NM \times \#\text{pivots})$ , where a pivot may be e.g. an edge relaxation.  $\mathcal{O}(2^n)$  in the general case. aa8530, 68 lines

```
typedef double T; // long double, Rational, double +
modCP>...
typedef vector<T> vd;
typedef vector<vd> vvd;
const T eps = 1e-8, inf = 1/0.;
#define MP make_pair
#define ltj(X) if(s == -1 || MP(X[j],N[j]) < MP(X[s],N[s])) s=j
struct LPSolver {
    int m, n;
    vi N, B;
    vvd D;
    LPSolver(const vvd& A, const vd& b, const vd& c) :
        m(sz(b)), n(sz(c)), N(n+1), B(m), D(m+2, vd(n+2)) {
        rep(i,0,m) rep(j,0,n) D[i][j] = A[i][j];
        rep(i,0,m) { B[i] = n+i; D[i][n] = -1; D[i][n+1] = b[i];}
        rep(j,0,n) { N[j] = j; D[m][j] = -c[j]; }
        N[n] = -1; D[m+1][n] = 1;
    }
    void pivot(int r, int s) {
        T a = D[r].data(), inv = 1 / a[s];
        rep(i,0,m+2) if (i != r && abs(D[i][s]) > eps) {
            T *b = D[i].data(), inv2 = b[s] * inv;
            rep(j,0,n+2) b[j] -= a[j] * inv2;
            b[s] = a[s] * inv2;
        }
        rep(j,0,n+2) if (j != s) D[r][j] *= inv;
        rep(i,0,m+2) if (i != r) D[i][s] *= -inv;
        D[r][s] = inv;
        swap(B[r], N[s]);
    }
    bool simplex(int phase) {
        int x = m + phase - 1;
        for (;;) {
            int s = -1;
            rep(j,0,n+1) if (N[j] != -phase) ltj(D[x]);
            if (D[x][s] >= -eps) return true;
            int r = -1;
            rep(i,0,m) {
                if (D[i][s] <= eps) continue;
                if (r == -1 || MP(D[i][n+1] / D[i][s], B[i])
                    < MP(D[r][n+1] / D[r][s], B[r])) r = i;
            }
            if (r == -1) return false;
            pivot(r, s);
        }
    }
    T solve(vd &x) {
        int r = 0;
        rep(i,1,m) if (D[i][n+1] < D[r][n+1]) r = i;
        if (D[r][n+1] < -eps) {
            pivot(r, n);
            if (!simplex(2) || D[m+1][n+1] < -eps) return -inf;
            rep(i,0,m) if (B[i] == -1) {
                int s = 0;
                rep(j,1,n+1) ltj(D[i]);
                pivot(i, s);
            }
        }
        bool ok = simplex(1); x = vd(n);
        rep(i,0,m) if (B[i] < n) x[B[i]] = D[i][n+1];
        return ok ? D[m][n+1] : inf;
    }
};
```

## 4.3 Matrices

### Determinant.h

**Description:** Calculates determinant of a matrix. Destroys the matrix.

**Time:**  $\mathcal{O}(N^3)$

4583fb, 16 lines

```
template<class T>
T det(vector<vector<T>>& a) {
    int n = sz(a); T res = 1;
    rep(i,0,n) {
        int b = i;
        rep(j,i+1,n) if (abs(a[j][i]) > abs(a[b][i])) b = j;
        if (i != b) swap(a[i], a[b]), res *= -1;
        res *= a[i][i];
        if (res == 0) return 0;
        rep(j,i+1,n) {
            T v = a[j][i] / a[i][i];
            if (v != 0) rep(k,i+1,n) a[j][k] -= v * a[i][k];
        }
    }
    return res;
}
```

## IntDeterminant.h

**Description:** Calculates determinant using modular arithmetics. Modulos can also be removed to get a pure-integer version.

**Time:**  $\mathcal{O}(N^3)$

3313dc, 18 lines

```
const ll mod = 12345;
ll det(vector<vector<ll>>& a) {
    int n = sz(a); ll ans = 1;
    rep(i,0,n) {
        rep(j,i+1,n) {
            while (a[j][i] != 0) { // gcd step
                ll t = a[i][i] / a[j][i];
                if (t) rep(k,i,n)
                    a[i][k] = (a[i][k] - a[j][k] * t) % mod;
                swap(a[i], a[j]);
                ans *= -1;
            }
        }
        ans = ans * a[i][i] % mod;
        if (!ans) return 0;
    }
    return (ans + mod) % mod;
}
```

## SolveLinear.h

**Description:** Solves  $Ax = b$ . If no solutions exist, returns -1. Otherwise, returns the rank of A and transforms it s.t.  $\{A'_1, A'_2, \dots\}$  is a basis of the kernel of A.

**Time:**  $\mathcal{O}(n^2m)$

4f0aa8, 41 lines

```
const double eps = 1e-12;
template<class T>
int solveLinear(vector<vector<T>>& A, vector<T>& b,
    vector<T>& x) {
    int n = sz(A), m = sz(x), rank = 0, br, bc;
    if (n) assert(sz(A[0]) == m);
    vi col(m); iota(all(col), 0);
    rep(i,0,n) {
        T v, bv = 0;
        rep(r,i,n) rep(c,i,m)
            if ((v = abs(A[r][c])) > bv)
                br = r, bc = c, bv = v;
        if (bv <= eps) {
            rep(j,i,n) if (abs(b[j]) > eps) return -1;
            break;
        }
        swap(A[i], A[br]);
        swap(b[i], b[br]);
        swap(col[i], col[bc]);
        rep(j,0,n) swap(A[j][i], A[j][bc]);
        bv = 1/A[i][i];
        rep(j,0,n) if (j != i) {
            T fac = A[j][i] * bv;
            b[j] -= fac * b[i];
            rep(k,i+1,m) A[j][k] -= fac*A[i][k];
        }
        rank++;
    }
    x.assign(m, 0);
    for (int i = rank - 1; i >= 0; i--) {
        b[i] /= A[i][i];
        x[col[i]] = b[i];
    }
    vector<vector<T>> ker(m - rank, vector<T>(m));
    rep(i, rank, m) {
        ker[i - rank][col[i]] = 1;
        rep(j, 0, rank) ker[i - rank][col[j]] -= A[j][i] / A[i][j];
    }
}
```

```
    return A = ker, rank;
}
```

## SolveLinearBinary.h

**Description:** Solves  $Ax = b$  over  $\mathbb{F}_2$ . If there are multiple solutions, one is returned arbitrarily. Returns rank, or -1 if no solutions. Destroys A and b.

**Time:**  $\mathcal{O}(n^2m)$

fa2d7a, 34 lines

```
typedef bitset<1000> bs;
int solveLinear(vector<bs>& A, vi& b, bs& x, int m) {
    int n = sz(A), rank = 0, br;
    assert(m <= sz(x));
    vi col(m); iota(all(col), 0);
    rep(i,0,n) {
        for (br=i; br<n; ++br) if (A[br].any()) break;
        if (br == n) {
            rep(j,i,n) if (b[j]) return -1;
            break;
        }
        int bc = (int)A[br]._Find_next(i-1);
        swap(A[i], A[br]);
        swap(b[i], b[br]);
        swap(col[i], col[bc]);
        rep(j,0,n) if (A[j][i] != A[j][bc]) {
            A[j].flip(i); A[j].flip(bc);
        }
        rep(j,i+1,n) if (A[j][i]) {
            b[j] ^= b[i];
            A[j] ^= A[i];
        }
        rank++;
    }
    x = bs();
    for (int i = rank; i--;) {
        if (!b[i]) continue;
        x[col[i]] = 1;
        rep(j,0,i) b[j] ^= A[j][i];
    }
    return rank; // (multiple solutions if rank < m)
}
```

## MatrixInverse.h

**Description:** Invert matrix A. Returns rank; result is stored in A unless singular (rank < n). Can easily be extended to prime moduli; for prime powers, repeatedly set  $A^{-1} = A^{-1}(2I - AA^{-1}) \pmod{p^k}$  where  $A^{-1}$  starts as the inverse of A mod p, and k is doubled in each step.

**Time:**  $\mathcal{O}(n^3)$

d43579, 36 lines

```
template<class T>
int matInv(vector<vector<T>>& A) {
    int n = sz(A); vi col(n);
    vector<vector<T>> tmp(n, vector<T>(n));
    rep(i,0,n) tmp[i][i] = 1, col[i] = i;
    rep(i,0,n) {
        int r = i, c = i;
        rep(j,i,n) rep(k,i,n)
            if (abs(A[j][k]) > abs(A[r][c]))
                r = j, c = k;
        if (abs(A[r][c]) < 1e-12) return i;
        A[i].swap(A[r]); tmp[i].swap(tmp[r]);
        rep(j,0,n)
            swap(A[j][i], A[j][c]), swap(tmp[j][i], tmp[j][c]);
        swap(col[i], col[c]);
        T v = A[i][i];
        rep(j,i+1,n) {
            T f = A[j][i] / v;
            A[j][i] = 0;
            rep(k,i+1,n) A[j][k] -= f*A[i][k];
            rep(k,0,n) tmp[j][k] -= f*tmp[i][k];
        }
        rep(j,i+1,n) A[i][j] /= v;
        rep(j,0,n) tmp[i][j] /= v;
        A[i][i] = 1;
    }
    for (int i = n-1; i > 0; --i) rep(j,0,i) {
        T v = A[j][i];
        rep(k,0,n) tmp[j][k] -= v*tmp[i][k];
    }
    rep(i,0,n) rep(j,0,n) A[col[i]][col[j]] = tmp[i][j];
    return n;
}
```

## Tridiagonal.h

**Description:**  $x = \text{tridiagonal}(d,p,q,b)$  solves the equation system

$$\begin{pmatrix} b_0 & & & & & \\ b_1 & q_0 & p_0 & 0 & 0 & \cdots & 0 \\ b_2 & 0 & q_1 & d_2 & p_2 & \cdots & 0 \\ b_3 & & & \ddots & \ddots & \ddots & \vdots \\ \vdots & & 0 & 0 & \cdots & q_{n-3} & p_{n-2} \\ b_{n-1} & & 0 & 0 & \cdots & q_{n-2} & d_{n-1} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_{n-1} \end{pmatrix} = \begin{pmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_{n-1} \end{pmatrix}.$$

This is useful for solving problems on the type

$$a_i = b_i a_{i-1} + c_i a_{i+1} + d_i, 1 \leq i \leq n,$$

where  $a_0, a_{n+1}$ ,  $b_i$ ,  $c_i$  and  $d_i$  are known.  $a$  can then be obtained from

$$\{a_i\} = \text{tridiagonal}(\{1, -1, -1, \dots, -1, 1\}, \{0, c_1, c_2, \dots, c_n\}, \{b_1, b_2, \dots, b_n, 0\}, \{a_0, d_1, d_2, \dots, d_n, a_{n+1}\}).$$

Fails if the solution is not unique.

If  $|d_i| > |p_i| + |q_{i-1}|$  for all  $i$ , or  $|d_i| > |p_{i-1}| + |q_i|$ , or the matrix is positive definite, the algorithm is numerically stable and neither tr nor the check for diag[i] == 0 is needed.

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

8f9fa8, 26 lines

```
typedef double T;
vector<T> tridiagonal(vector<T> diag, const vector<T>&
    super,
    const vector<T>& sub, vector<T> b) {
    int n = sz(b); vi tr(n);
    rep(i,0,n-1) {
        if (abs(diag[i]) < 1e-9 * abs(super[i])) { // diag[
            i] == 0
            b[i+1] -= b[i] * diag[i+1] / super[i];
            if (i+2 < n) b[i+2] -= b[i] * sub[i+1] / super[i
                ];
            diag[i+1] = sub[i]; tr[++i] = 1;
        } else {
            diag[i+1] -= super[i]*sub[i]/diag[i];
            b[i+1] -= b[i]*sub[i]/diag[i];
        }
    }
    for (int i = n; i--;) {
        if (tr[i]) {
            swap(b[i], b[i-1]);
            diag[i-1] = diag[i];
            b[i] /= super[i-1];
        } else {
            b[i] /= diag[i];
            if (i) b[i-1] -= b[i]*super[i-1];
        }
    }
    return b;
}
```

## 4.4 Fourier transforms

### FastFourierTransform.h

**Description:** fft(a) computes  $f(k) = \sum_x a[x] \exp(2\pi i \cdot kx/N)$  for all  $k$ . N must be a power of 2. Useful for convolution: conv(a, b) = c, where  $c[x] = \sum a[i]b[x-i]$ . For convolution of complex numbers or more than two vectors: FFT, multiply pointwise, divide by n, reverse(start+1, end), FFT back. Rounding is safe if  $(\sum a_i^2 + \sum b_i^2) \log_2 N < 9 \cdot 10^{14}$  (in practice  $10^{16}$ ; higher for random inputs). Otherwise, use NTT/FFT-Mod.

**Time:**  $\mathcal{O}(N \log N)$  with  $N = |A| + |B|$  ( $\sim 1s$  for  $N_{fft} = 2^{22}$ )

```
typedef complex<double> C;
typedef vector<double> vd;
void fft(vector<C>& a) {
    int n = sz(a), L = 31 - __builtin_clz(n);
    static vector<complex<long double>> R(2, 1);
    static vector<C> rt(2, 1); // (^ 10% faster if
        double)
    for (static int k = 2; k < n; k *= 2) {
        R.resize(n); rt.resize(n);
        auto x = polar(1.0/L, acos(-1.0/L) / k);
        rep(i,k,2*k) rt[i] = R[i] = i&1 ? R[i/2] * x : R[i
            /2];
    }
    vi rev(n);
    rep(i,0,n) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
    rep(i,0,n) if (i < rev[i]) swap(a[i], a[rev[i]]);
    for (int k = 1; k < n; k *= 2)
        for (int i = 0; i < n; i += 2 * k) rep(j,0,k) {
            C z = rt[j+k] * a[i+j+k]; // (25% faster if hand-
                rolled)
        }
    }
```

```
        a[i + j + k] = a[i + j] - z;
        a[i + j] += z;
    }
}

vd conv(const vd& a, const vd& b) {
    if (a.empty() || b.empty()) return {};
    vd res(sz(a) + sz(b) - 1);
    int L = 32 - __builtin_clz(sz(res)), n = 1 << L;
    vector<C> in(n), out(n);
    copy(all(a), begin(in));
    rep(i,0,sz(b)) in[i].imag(b[i]);
    fft(in);
    for (C& x : in) x *= x;
    rep(i,0,n) out[i] = in[-i & (n - 1)] - conj(in[i]);
    fft(out);
    rep(i,0,sz(res)) res[i] = imag(out[i]) / (4 * n);
    return res;
}
```

## FastFourierTransformMod.h

**Description:** Higher precision FFT, can be used for convolutions modulo arbitrary integers as long as  $N \log_2 N \cdot \text{mod} < 8.6 \cdot 10^{14}$  (in practice  $10^{16}$  or higher). Inputs must be in  $[0, \text{mod})$ .  
**Time:**  $\mathcal{O}(N \log N)$ , where  $N = |A| + |B|$  (twice as slow as NTT or FFT)

"FastFourierTransform.h"	b82773, 22 lines
<b>typedef</b> vector<ll> vl; <b>template</b> <int M> vl convMod(const vl &a, const vl &b) { if (a.empty()    b.empty()) <b>return</b> {}; vl res(sz(a) + sz(b) - 1); int B=32-__builtin_clz(sz(res)), n=1<<B, cut=int(sqrt(M)); vector<C> L(n), R(n), outs(n), outl(n); rep(i,0,sz(a)) L[i] = C((int)a[i] / cut, (int)a[i] % cut); rep(i,0,sz(b)) R[i] = C((int)b[i] / cut, (int)b[i] % cut); fft(L), fft(R); rep(i,0,n) { int j = -i & (n - 1); outl[j] = (L[i] + conj(L[j])) * R[i] / (2.0 * n); outs[j] = (L[i] - conj(L[j])) * R[i] / (2.0 * n) / 1i; } fft(outl), fft(outs); rep(i,0,sz(res)) { ll av = ll(real(outl[i])+.5), cv = ll(imag(outs[i])+.5); ll bv = ll(imag(outl[i])+.5) + ll(real(outs[i])+.5) ; res[i] = ((av % M * cut + bv) % M * cut + cv) % M; } <b>return</b> res; }	

## NumberTheoreticTransform.h

**Description:** ntt(a) computes  $\hat{f}(k) = \sum_x a[x]g^{xk}$  for all  $k$ , where  $g = \text{root}^{(\text{mod}-1)/N}$ . N must be a power of 2. Useful for convolution modulo specific nice primes of the form  $2^ab + 1$ , where the convolution result has size at most  $2^a$ . For arbitrary modulo, see FFTmod. conv(a, b) = c, where  $c[x] = \sum a[i]b[x - i]$ . For manual convolution: NTT the inputs, multiple pointwise, divide by n, reverse(start+1, end), NTT back. Inputs must be in  $[0, \text{mod})$ .  
**Time:**  $\mathcal{O}(N \log N)$

"../number-theory/ModPow.h"	ced03d, 35 lines
<b>const</b> ll mod = (119 << 23) + 1, root = 62; <b>//</b> = 998244353 <b>//</b> For p < 2^30 there is also e.g. 5 << 25, 7 << 26, 479 << 21 <b>//</b> and 483 << 21 (same root). The last two are > 10^9. <b>typedef</b> vector<ll> vl; <b>void</b> ntt(vl &a) { int n = sz(a), L = 31 - __builtin_clz(n); static vl rt(2, 1); for (static int k = 2, s = 2; k < n; k *= 2, s++) { rt.resize(n); ll z[] = {1, modpow(root, mod >> s)}; rep(i,k,2*k) rt[i] = rt[i / 2] * z[i & 1] % mod; } vi rev(n); rep(i,0,n) rev[i] = (rev[i / 2]   (i & 1) << L) / 2;	

```
rep(i,0,n) if (i < rev[i]) swap(a[i], a[rev[i]]);
for (int k = 1; k < n; k *= 2)
    for (int i = 0; i < n; i += 2 * k) rep(j,0,k) {
        ll z = rt[(j + k) * a[i + j + k] % mod, &ai = a[i + j]];
        a[i + j + k] = ai - z + (z > ai ? mod : 0);
        ai += (ai + z >= mod ? z - mod : z);
    }
}

vl conv(const vl &a, const vl &b) {
    if (a.empty() || b.empty()) return {};
    int s = sz(a) + sz(b) - 1, B = 32 - __builtin_clz(s), n = 1 << B;
    int inv = modpow(n, mod - 2);
    vl L(a), R(b), out(n);
    L.resize(n), R.resize(n);
    ntt(L), ntt(R);
    rep(i,0,n)
        out[-i & (n - 1)] = (ll)L[i] * R[i] % mod * inv % mod;
    ntt(out);
    return {out.begin(), out.begin() + s};
}
```

## FastSubsetTransform.h

**Description:** Transform to a basis with fast convolutions of the form  $c[z] = \sum_{x \oplus y = z} a[x] \cdot b[y]$ , where  $\oplus$  is one of AND, OR, XOR. The size of a must be a power of two.  
**Time:**  $\mathcal{O}(N \log N)$

```
void FST(vi& a, bool inv) {
    for (int n = sz(a), step = 1; step < n; step *= 2) {
        for (int i = 0; i < n; i += 2 * step) rep(j,i,i+step) {
            int &u = a[j], &v = a[j + step]; tie(u, v) =
            inv ? pii(v - u, u) : pii(v, u + v); // AND
            inv ? pii(v, u - v) : pii(u + v, u); // OR
            pii(u + v, v - u); // XOR
        }
        if (inv) for (int& x : a) x /= sz(a); // XOR only
    }
}

vi conv(vi a, vi b) {
    FST(a, 0); FST(b, 0);
    rep(i,0,sz(a)) a[i] *= b[i];
    FST(a, 1); return a;
}
```

## Number theory (5)

### 5.1 Modular arithmetic

#### ModInt.h

<b>Description:</b> Operators for modular arithmetic	
3f0e63, 29 lines	
<b>template</b> <int M, int R> <b>struct</b> Mod { static const int mod = M, rt = R; int x; Mod(ll y = 0) : x(y % M) { x += (x < 0) * M; } Mod& operator+=(Mod o) { if ((x += o.x) >= M) x -= M; <b>return</b> *this; } Mod& operator-=(Mod o) { if ((x -= o.x) < 0) x += M; <b>return</b> *this; } Mod& operator*=(Mod o) { x = 1ll * x * o.x % M; <b>return</b> *this; } Mod& operator/=(Mod o) { <b>return</b> *this *= o.inv(); } friend Mod operator+(Mod a, Mod b) { <b>return</b> a += b; } friend Mod operator-(Mod a, Mod b) { <b>return</b> a -= b; } friend Mod operator*(Mod a, Mod b) { <b>return</b> a *= b; } friend Mod operator/(Mod a, Mod b) { <b>return</b> a /= b; } auto operator<=> (const Mod&) const = default; Mod pow(ll n) const { Mod a = x, b = 1; for (; n; n /= 2, a *= a) if (n % 2) b *= a; <b>return</b> b; } Mod inv() const { assert(x); <b>return</b> pow(M - 2); } friend ostream& operator<<(ostream& os, Mod x) { <b>return</b> os << x.x; } }; <b>using</b> mint = Mod<998244353, 3>;	

#### ModInverse.h

**Description:** Pre-computation of modular inverses. Assumes  $\text{LIM} \leq \text{mod}$  and that mod is a prime.

```
const ll mod = 1000000007, LIM = 200000;  
ll* inv = new ll[LIM] - 1; inv[1] = 1;  
rep(i,2,LIM) inv[i] = mod - (mod / i) * inv[mod % i] % mod;
```

#### ModPow.h

b83e45, 8 lines
<b>const</b> ll mod = 1000000007; <b>//</b> faster if const ll modpow(ll b, ll e) { ll ans = 1; for (; e; b = b * b % mod, e /= 2) if (e & 1) ans = ans * b % mod; <b>return</b> ans; }

#### ModLog.h

**Description:** Returns the smallest  $x > 0$  s.t.  $a^x = b \pmod m$ , or  $-1$  if no such  $x$  exists. modLog(a,1,m) can be used to calculate the order of a.  
**Time:**  $\mathcal{O}(\sqrt{m})$

c040b8, 11 lines
ll modLog(ll a, ll b, ll m) { ll n = (ll) sqrt(m) + 1, e = 1, f = 1, j = 1; unordered_map<ll, ll> A; while (j <= n && (e = f = e * a % m) != b % m) A[e * b % m] = j++; if (e == b % m) <b>return</b> j; if (__gcd(m, e) == __gcd(m, b)) rep(i,2,n+2) if (A.count(e = e * f % m)) <b>return</b> n * i - A[e]; <b>return</b> -1; }

#### ModSum.h

**Description:** Sums of mod'd arithmetic progressions.  
modsum(to, c, k, m) =  $\sum_{i=0}^{to-1} (ki + c) \% m$ . divsum is similar but for floored division.  
**Time:** log(m), with a large constant.

5c5bc5, 16 lines
<b>typedef unsigned long long</b> ull; ull sumsq(ull to) { <b>return</b> to / 2 * ((to-1)   1); } ull divsum(ull to, ull c, ull k, ull m) { ull res = k / m * sumsq(to) + c / m * to; k %= m; c %= m; if (!k) <b>return</b> res; ull to2 = (to * k + c) / m; <b>return</b> res + (to - 1) * to2 - divsum(to2, m-1 - c, m, k); } ll modsum(ull to, ll c, ll k, ll m) { c = ((c % m) + m) % m; k = ((k % m) + m) % m; <b>return</b> to * c + k * sumsq(to) - m * divsum(to, c, k, m); }

#### ModLinear.h

**Description:** Statistics on a mod'ed arithmetic sequence.  
**Time:**  $\mathcal{O}(\log m)$

45f202, 34 lines
ll cdiv(ll x, ll y) { <b>return</b> x / y + ((x ^ y) > 0 && x % y); } <b>//</b> min (ax + b) % m for 0 <= x <= n ll minRemainder(ll a, ll b, ll m, ll n) { assert(a >= 0 && m > 0 && b >= 0 && n >= 0); a %= m, b %= m; n = min(n, m - 1); if (a == 0) <b>return</b> b; if (b >= a) { ll ad = cdiv(m - b, a); n -= ad; if (n < 0) <b>return</b> b; b += ad * a - m; } ll q = m / a, m2 = m % a; if (m2 == 0) <b>return</b> b; if (b / m2 > n / q) <b>return</b> b - n / q * m2; n -= b / m2 * q; b %= m2; ll y2 = (n * a + b) / m; ll x2 = cdiv(m2 * y2 - b, a); if (x2 * a - m2 * y2 + b >= m2) --x2; <b>return</b> minRemainder(a, b, m2, x2); } <b>//</b> min x >= 0 s.t. l <= (ax + b) % m <= r ll minBetween(ll a, ll b, ll m, ll l, ll r) { ll x, y, g = euclid(a, m, x, y); if (g > 1) <b>return</b> minBetween(a/g, b/g, m/g, 1/g+(l%g>b%g), r/g-(r%g<b%g)); if (l > r) <b>return</b> -1; <b>//</b> no solution

```
if ((x %= m) < 0) x += m;  
ll b2 = (l - b) * x % m;  
return minRemainder(x, b2 < 0 ? b2 + m : b2, m, r-1);  
}
```

#### ModMulLL.h

**Description:** Calculate  $a \cdot b \pmod c$  (or  $a^b \pmod c$ ) for  $0 \leq a, b \leq c \leq 7.2 \cdot 10^{18}$ .  
**Time:**  $\mathcal{O}(1)$  for modmul,  $\mathcal{O}(\log b)$  for modpow

bbbdf8f, 11 lines
<b>typedef unsigned long long</b> ull; ull modmul(ull a, ull b, ull M) { ll ret = a * b - M * ull(1.L / M * a * b); <b>return</b> ret + M * (ret < 0) - M * (ret >= (ll)M); } ull modpow(ull b, ull e, ull mod) { ull ans = 1; for (; e; b = modmul(b, b, mod), e /= 2) if (e & 1) ans = modmul(ans, b, mod); <b>return</b> ans; }

#### ModSqrt.h

**Description:** Tonelli-Shanks algorithm for modular square roots. Finds  $x$  s.t.  $x^2 = a \pmod p$  ( $-x$  gives the other solution) or  $-1$  if no such  $x$  exists.

**Time:**  $\mathcal{O}(\log^2 p)$  worst case,  $\mathcal{O}(\log p)$  for most p

b7cab4, 24 lines
ll sqrt(ll a, ll p) { a %= p; <b>if</b> (a < 0) a += p; <b>if</b> (a == 0) <b>return</b> 0; <b>if</b> (modpow(a, (p-1)/2, p) != 1) <b>return</b> -1; <b>if</b> (p % 4 == 3) <b>return</b> modpow(a, (p+1)/4, p); <b>//</b> a^(n+3)/8 or 2^(n+3)/8 * 2^(n-1)/4 works if p % 8 == 5 ll s = p - 1, n = 2; int r = 0, m; while (s % 2 == 0) ++r, s /= 2; while (modpow(n, (p - 1) / 2, p) != p - 1) ++n; ll x = modpow(a, (s + 1) / 2, p); ll b = modpow(a, s, p), g = modpow(n, s, p); for (; r = m) { ll t = b; for (m = 0; m < r && t != 1; ++m) t = t * t % p; <b>if</b> (m == 0) <b>return</b> x; ll gs = modpow(g, 1LL << (r - m - 1), p); g = gs * gs % p; x = x * gs % p; b = b * g % p; } }

#### PrimitiveRoot.h

**Description:** Finds a primitive root modulo p.  
"Factor.h", "ModMulLL.h"

d63925, 9 lines
mt19937_64 rng(2137); ll primitiveRoot(ll p) { auto f = factor(p - 1); sort(all(f)); f.resize(unique(all(f)) - f.begin()); rep: ll g = rng() % (p - 1) + 1; for (auto x : f) <b>if</b> (modpow(g, (p - 1) / x, p) == 1) goto rep; <b>return</b> g; }

### 5.2 Primality

#### FastEratosthenes.h

**Description:** Prime sieve for generating all primes smaller than LIM.  
**Time:** LIM=1e9  $\approx$  1.5s

6b2912, 20 lines
<b>const</b> int LIM = 1e6; bitset<LIM> isPrime; vi eratosthenes() { <b>const</b> int S = (int)round(sqrt(LIM)), R = LIM / 2; vi pr = {2}, sieve(S+1); pr.reserve(int(LIM/log(LIM)*1.1)); vector<pii> cp; for (int i = 3; i <= S; i += 2) <b>if</b> (!sieve[i]) { cp.push_back({i, i * i / 2}); for (int j = i * i; j <= S; j += 2 * i) sieve[j] = 1; } for (int L = 1; L <= R; L += S) {

```
array<bool, S> block{};
for (auto &[p, idx] : cp)
    for (int i=idx; i < S+L; idx = (i+=p)) block[i-L]
        = 1;
rep(i,0,min(S, R - L))
    if (!block[i]) pr.push_back((L + i) * 2 + 1);
}
for (int i : pr) isPrime[i] = 1;
return pr;
}
```

## MillerRabin.h

**Description:** Deterministic Miller-Rabin primality test. Guaranteed to work for numbers up to  $7\cdot 10^{18}$ ; for larger numbers, use Python and extend A randomly.

**Time:** 7 times the complexity of  $a^b \bmod c$ .

"ModMullL.h"	60dcd1, 12 lines
--------------	------------------

```
bool isPrime(ull n) {
    if (n < 2 || n % 6 % 4 != 1) return (n | 1) == 3;
    ull A[] = {2, 325, 9375, 28178, 450775, 9780504,
        1795265022},
        s = __builtin_ctzll(n-1), d = n >> s;
    for (ull a : A) { // ^ count trailing zeroes
        ull p = modpow(a%n, d, n), i = s;
        while (p != 1 && p != n - 1 && a % n && i--)
            p = modmul(p, p, n);
        if (p != n-1 && i != s) return 0;
    }
    return 1;
}
```

## Factor.h

**Description:** Pollard-rho randomized factorization algorithm. Returns prime factors of a number, in arbitrary order (e.g. 2299 -> {11, 19, 11}).

**Time:**  $\mathcal{O}(n^{1/4})$ , less for numbers with small factors.

"ModMullL.h", "MillerRabin.h"	d8d98d, 18 lines
-------------------------------	------------------

```
ull pollard(ull n) {
    ull x = 0, y = 0, t = 30, prd = 2, i = 1, q;
    auto f = [&](ull x) { return modmul(x, x, n) + i; };
    while (t++ % 40 || __gcd(prd, n) == 1) {
        if (x == y) x = ++i, y = f(x);
        if ((q = modmul(prd, max(x,y) - min(x,y), n))) prd
            = q;
        x = f(x), y = f(f(y));
    }
    return __gcd(prd, n);
}
vector<ull> factor(ull n) {
    if (n == 1) return {};
    if (isPrime(n)) return {n};
    ull x = pollard(n);
    auto l = factor(x), r = factor(n / x);
    l.insert(l.end(), all(r));
    return l;
}
```

## 5.3 Divisibility

### euclid.h

**Description:** Finds two integers  $x$  and  $y$ , such that  $ax+by = \gcd(a,b)$ . If you just need gcd, use the built in `_gcd` instead. If  $a$  and  $b$  are coprime, then  $x$  is the inverse of  $a$  modulo  $b$ .

```
ll euclid(ll a, ll b, ll &x, ll &y) {
    if (!b) return x = 1, y = 0, a;
    ll d = euclid(b, a % b, y, x);
    return y -= a/b * x, d;
}
```

## CRT.h

**Description:** Chinese Remainder Theorem.

`crt(a, m, b, n)` computes  $x$  such that  $x \equiv a \pmod m, x \equiv b \pmod n$ . If  $|a| < m$  and  $|b| < n$ ,  $x$  will obey  $0 \leq x < \operatorname{lcm}(m, n)$ . Assumes  $mn < 2^{62}$ .

"euclid.h"	04d93a, 7 lines
------------	-----------------

```
ll crt(ll a, ll m, ll b, ll n) {
    if (n > m) swap(a, b), swap(m, n);
    ll x, y, g = euclid(m, n, x, y);
    assert((a - b) % g == 0); // else no solution
    x = (b - a) % n * x % n / g * m + a;
    return x < 0 ? x + m*n/g : x;
}
```

### 5.3.1 Bézout's identity

For  $a \neq, b \neq 0$ , then  $d = \gcd(a, b)$  is the smallest positive integer for which there are integer solutions to

$$ax + by = d$$

If  $(x, y)$  is one solution, then all solutions are given by

$$\left(x + \frac{kb}{\gcd(a,b)}, y - \frac{ka}{\gcd(a,b)}\right), \quad k \in \mathbb{Z}$$

## phiFunction.h

**Description:** *Euler's*  $\phi$  function is defined as  $\phi(n) := \#$  of positive integers  $\leq n$  that are coprime with  $n$ .  $\phi(1) = 1$ ,  $p$  prime  $\Rightarrow \phi(p^k) = (p - 1)p^{k-1}$ ,  $m, n$  coprime  $\Rightarrow \phi(mn) = \phi(m)\phi(n)$ . If  $n = p_1^{k_1}p_2^{k_2}...p_r^{k_r}$  then  $\phi(n) = (p_1 - 1)p_1^{k_1-1}...(p_r - 1)p_r^{k_r-1}$ .  $\phi(n) = n \cdot \prod_{p|n}(1 - 1/p)$ .  $\sum_{d|n} \phi(d) = n$ ,  $\sum_{1 \leq k \leq n, \gcd(k,n)=1} k = n\phi(n)/2, n > 1$

**Euler's thm:**  $a, n$  coprime  $\Rightarrow a^{\phi(n)} \equiv 1 \pmod n$ .

**Fermat's little thm:**  $p$  prime  $\Rightarrow a^{p-1} \equiv 1 \pmod p, a \not\equiv 0$ .

const int LIM = 50000000;	
---------------------------	--

```
int phi[LIM];
void calculatePhi() {
    rep(i,0,LIM) phi[i] = i&1 ? i : i/2;
    for (int i = 3; i < LIM; i += 2) if (phi[i] == i)
        for (int j = i; j < LIM; j += i) phi[j] -= phi[j] / i;
}
```

## Min25.h

**Description:** Fast multiplicative function prefix sums. Requires `isPrime` calculated up to  $\sqrt{n}$ .

"FastEratosthenes.h"	4c2ea6, 47 lines
----------------------	------------------

```
template<class T>
struct Min25 {
    ll n, sq, s, hls; vi p;
    Min25(ll N) : n(N) {
        sq = sqrt(n) + 5;
        while (sq * sq > n) sq--;
        hls = quo(n, sq);
        if (hls != 1 && quo(n, hls - 1) == sq) hls--;
        s = hls + sq;
        rep(i, 2, sq + 1) if (isPrime[i]) p.push_back(i);
    }
    vector<T> sieve(auto f) {
        vector<T> h(s);
        rep(i, 1, hls) h[i] = f(quo(n, i)) - 1;
        rep(i, 1, sq + 1) h[s - i] = f(i) - 1;
        for (ll x : p) {
            T xt = f(x) - f(x - 1), pi = h[s - x + 1];
            ll x2=x*x, imax=min(hls, quo(n, x2) + 1), ix=x;
            for (int i = 1; i < imax; i++, ix += x)
                h[i] -= ((ix<hls?h[ix]:h[s-quo(n,ix)])-pi)*xt;
            for (int i = sq; i >= x2; i--)
                h[s - i] -= (h[s - quo(i, x)] - pi) * xt;
        }
        return h;
    }
    vector<T> unsieve(vector<T>& fp, auto f) {
        vector<ll> ns(s);
        rep(i, 1, hls) ns[i] = quo(n, i);
        rep(i, 1, sq + 1) ns[s - i] = i;
        auto F = fp, G = fp;
        for (ll P : p | views::reverse) {
            for (ll pk=P, k=1; quo(n,P)>=pk; k++, pk*=P) {
                T x=F[idx(P)], y=F(P,k,pk), z=F(P,k+1,pk*P);
                rep(i, 1, s) {
                    ll m = ns[i];
                    if (P * pk > m) break;
                    G[i] += y * (F[idx(quo(m, pk))] - x) + z;
                }
                copy_n(G.begin(), min(s, idx(P*P)+1), F.begin());
            }
            rep(i, 1, sz(ns)) F[i] += 1;
        }
        return F;
    }
}
```

```
    }
    ll quo(ll x, ll y) { return (double)x / y; }
    ll idx(ll x) { return x <= sq ? s - x : quo(n, x); }
};
```

## 5.4 Fractions

### ContinuedFractions.h

**Description:** Given  $N$  and a real number  $x \geq 0$ , finds the closest rational approximation  $p/q$  with  $p, q \leq N$ . It will obey  $|p/q - x| \leq 1/qN$ .

For consecutive convergents,  $p_{k+1}q_k - q_{k+1}p_k = (-1)^k$ . ( $p_k/q_k$  alternates between  $> x$  and  $< x$ .) If  $x$  is rational,  $y$  eventually becomes  $\infty$ ; if  $x$  is the root of a degree 2 polynomial the  $a$ 's eventually become cyclic.

Time: $\mathcal{O}(\log N)$	dd6c5e, 21 lines
-----------------------------	------------------

```
typedef double d; // for N ~ 1e7; long double for N ~ 1e9
pair<ll, ll> approximate(d x, ll N) {
    ll LP = 0, LQ = 1, P = 1, Q = 0, inf = LLONG_MAX; d y = x;
    for (;) {
        ll lim = min(P ? (N-LP) / P : inf, Q ? (N-LQ) / Q : inf),
            a = (ll)floor(y), b = min(a, lim),
            NP = b*P + LP, NQ = b*Q + LQ;
        if (a > b) {
            // If b > a/2, we have a semi-convergent that gives us a
            // better approximation; if b = a/2, we *may* have one.
            // Return {P, Q} here for a more canonical approximation.
            return (abs(x - (d)NP / (d)NQ) < abs(x - (d)P / (d)Q)) ?
                make_pair(NP, NQ) : make_pair(P, Q);
        }
        if (abs(y = 1/(y - (d)a)) > 3*N) {
            return {NP, NQ};
        }
        LP = P; P = NP;
        LQ = Q; Q = NQ;
    }
}
```

## FracBinarySearch.h

**Description:** Given  $f$  and  $N$ , finds the smallest fraction  $p/q \in [0, 1]$  such that  $f(p/q)$  is true, and  $p, q \leq N$ . You may want to throw an exception from `f` if it finds an exact solution, in which case  $N$  can be removed.

**Usage:** `fracBS({}(Frac f) { return f.p>=3*f.q; }, 10);` // {1,3}

Time: $\mathcal{O}(\log(N))$	27ab3e, 25 lines
------------------------------	------------------

```
struct Frac { ll p, q; };
template<class F>
Frac fracBS(F f, ll N) {
    bool dir = 1, A = 1, B = 1;
    Frac lo{0, 1}, hi{1, 1}; // Set hi to 1/0 to search (0, N)
    if (f(lo)) return lo;
    assert(f(hi));
    while (A || B) {
        ll adv = 0, step = 1; // move hi if dir, else lo
        for (int si = 0; step; (step *= 2) >= si) {
            adv += step;
            Frac mid{lo.p * adv + hi.p, lo.q * adv + hi.q};
            if (abs(mid.p) > N || mid.q > N || dir == !f(mid))
                adv -= step; si = 2;
        }
        hi.p += lo.p * adv;
        hi.q += lo.q * adv;
        dir = !dir;
        swap(lo, hi);
        A = B; B = !!adv;
    }
    return dir ? hi : lo;
}
```

## 5.5 Pythagorean Triples

The Pythagorean triples are uniquely generated by

$$a = k \cdot (m^2 - n^2), \quad b = k \cdot (2mn), \quad c = k \cdot (m^2 + n^2),$$

with  $m > n > 0, k > 0, m \perp n$ , and either  $m$  or  $n$  even.

## 5.6 Primes

$p = 962592769$  is such that  $2^{21} \mid p - 1$ , which may be useful. For hashing use 970592641 (31-bit number), 31443539979727 (45-bit), 3006703054056749 (52-bit). There are 78498 primes less than 1 000 000.

Primitive roots exist modulo any prime power  $p^a$ , except for  $p = 2, a > 2$ , and there are  $\phi(\phi(p^a))$  many. For  $p = 2, a > 2$ , the group  $\mathbb{Z}_{2^a}^\times$  is instead isomorphic to  $\mathbb{Z}_2 \times \mathbb{Z}_{2^{a-2}}$ .

## 5.7 Estimates

$$\sum_{d|n} d = O(n \log \log n).$$

The number of divisors of  $n$  is at most around 100 for  $n < 5e4$ , 500 for  $n < 1e7$ , 2000 for  $n < 1e10$ , 200 000 for  $n < 1e19$ .

## 5.8 Mobius Function

$$\mu(n) = \begin{cases} 0 & n \text{ is not square free} \\ 1 & n \text{ has even number of prime factors} \\ -1 & n \text{ has odd number of prime factors} \end{cases}$$

Mobius Inversion:

$$g(n) = \sum_{d|n} f(d) \Leftrightarrow f(n) = \sum_{d|n} \mu(d)g(n/d)$$

Other useful formulas/forms:

$$\sum_{d|n} \mu(d) = [n = 1] \text{ (very useful)}$$

$$g(n) = \sum_{n|d} f(d) \Leftrightarrow f(n) = \sum_{n|d} \mu(d/n)g(d)$$

$$g(n) = \sum_{1 \leq m \leq n} f(\lfloor \frac{n}{m} \rfloor) \Leftrightarrow f(n) = \sum_{1 \leq m \leq n} \mu(m)g(\lfloor \frac{n}{m} \rfloor)$$

## Combinatorial (6)

### 6.1 Permutations

#### 6.1.1 Factorial

$n$	1	2	3	4	5	6	7	8	9	10
$n!$	1	2	6	24	120	720	5040	40320	362880	3628800
$n$	11	12	13	14	15	16	17			
$n$	4.0e7	4.8e8	6.2e9	8.7e10	1.3e12	2.1e13	3.6e14			
$n$	20	25	30	40	50	100	150	171		
$n!$	2e18	2e25	3e32	8e47	3e64	9e157	6e262	>DBL_MAX		

## IntPerm.h

**Description:** Permutation -> integer conversion. (Not order preserving.) Integer -> permutation can use a lookup table.

Time: $\mathcal{O}(n)$	044568, 6 lines
------------------------	-----------------

```
int permToInt(vi& v) {
    int use = 0, i = 0, r = 0;
    for (int x:v) r = r * ++i + __builtin_popcount(use &
        -(1<<x)),
        use |= 1 << x; // (note: minus, not ~!)
    return r;
}
```



6.1.2 Cycles

Let  $g_S(n)$  be the number of  $n$ -permutations whose cycle lengths all belong to the set  $S$ . Then

$$\sum_{n=0}^\infty g_S(n) \frac{x^n}{n!} = \exp \left( \sum_{n \in S} \frac{x^n}{n} \right)$$

6.1.3 Derangements

Permutations of a set such that none of the elements appear in their original position.

$$D(n) = (n-1)(D(n-1)+D(n-2)) = nD(n-1)+(-1)^n$$

6.1.4 Burnside’s lemma

Given a group  $G$  of symmetries and a set  $X$ , the number of elements of  $X$  up to symmetry equals

$$\frac{1}{|G|} \sum_{g \in G} |X^g|,$$

where  $X^g$  are the elements fixed by  $g$  ( $g.x = x$ ).

If  $f(n)$  counts “configurations” (of some sort) of length  $n$ , we can ignore rotational symmetry using  $G = \mathbb{Z}_n$  to get

$$g(n) = \frac{1}{n} \sum_{k=0}^{n-1} f(\gcd(n, k)) = \frac{1}{n} \sum_{k|n} f(k) \phi(n/k).$$

6.2 Partitions and subsets

6.2.1 Partition function

Number of ways of writing  $n$  as a sum of positive integers, disregarding the order of the summands.

$$p(0) = 1, \quad p(n) = \sum_{k \in \mathbb{Z} \setminus \{0\}} (-1)^{k+1} p(n - k(3k - 1)/2)$$

$$p(n) \sim 0.145 n \cdot \exp(2.56\sqrt{n})$$

$n$	0	1	2	3	4	5	6	7	8	9	20	50	100
$p(n)$	1	1	2	3	5	7	11	15	22	30	627	~2e5	~2e8

6.2.2 Lucas’ Theorem

Let  $n, m$  be non-negative integers and  $p$  a prime. Write  $n = n_k p^k + \dots + n_1 p + n_0$  and  $m = m_k p^k + \dots + m_1 p + m_0$ . Then  $\binom{n}{m} \equiv \prod_{i=0}^k \binom{n_i}{m_i} \pmod{p}$ .

6.2.3 Binomials multinomial.h

**Description:** Computes  $\binom{k_1 + \dots + k_n}{k_1, k_2, \dots, k_n} = \frac{(\sum k_i)!}{k_1! k_2! \dots k_n!}$ .

```
ll multinomial(vi& v) {
    ll c = 1, m = v.empty() ? 1 : v[0];
    rep(i,1,sz(v)) rep(j,0,v[i]) c = c * ++m / (j+1);
    return c;
}
```

6.3 General purpose numbers

6.3.1 Bernoulli numbers

EGF of Bernoulli numbers is  $B(t) = \frac{t}{e^t-1}$  (FFT-able).  
 $B[0, \dots] = [1, -\frac{1}{2}, \frac{1}{6}, 0, -\frac{1}{30}, 0, \frac{1}{42}, \dots]$

Sums of powers:

$$\sum_{i=1}^n n^m = \frac{1}{m+1} \sum_{k=0}^m \binom{m+1}{k} B_k \cdot (n+1)^{m+1-k}$$

Euler-Maclaurin formula for infinite sums:

$$\begin{aligned} &= \left\lfloor \frac{n!}{e} \sum_{i=m}^\infty f(i) \right\rfloor = \int_m^\infty f(x) dx - \sum_{k=1}^\infty \frac{B_k}{k!} f^{(k-1)}(m) \\ &\approx \int_m^\infty f(x) dx + \frac{f(m)}{2} - \frac{f'(m)}{12} + \frac{f'''(m)}{720} + O(f^{(5)}(m)) \end{aligned}$$

6.3.2 Stirling numbers of the first kind

Number of permutations on  $n$  items with  $k$  cycles.

$$c(n, k) = c(n-1, k-1) + (n-1)c(n-1, k), \quad c(0, 0) = 1$$
$$\sum_{k=0}^n c(n, k) x^k = x(x+1) \dots (x+n-1)$$

$$\begin{aligned} c(8, k) &= 8, 0, 5040, 13068, 13132, 6769, 1960, 322, 28, 1 \\ c(n, 2) &= 0, 0, 1, 3, 11, 50, 274, 1764, 13068, 109584, \dots \end{aligned}$$

6.3.3 Eulerian numbers

Number of permutations  $\pi \in S_n$  in which exactly  $k$  elements are greater than the previous element.  $k, j$ : s.t.  $\pi(j) > \pi(j+1)$ ,  $k+1, j$ : s.t.  $\pi(j) \geq j$ ,  $k, j$ : s.t.  $\pi(j) > j$ .

$$E(n, k) = (n-k)E(n-1, k-1) + (k+1)E(n-1, k)$$

$$E(n, 0) = E(n, n-1) = 1$$

$$E(n, k) = \sum_{j=0}^k (-1)^j \binom{n+1}{j} (k+1-j)^n$$

6.3.4 Stirling numbers of the second kind

Partitions of  $n$  distinct elements into exactly  $k$  groups.

$$S(n, k) = S(n-1, k-1) + kS(n-1, k)$$

$$S(n, 1) = S(n, n) = 1$$

$$S(n, k) = \frac{1}{k!} \sum_{j=0}^k (-1)^{k-j} \binom{k}{j} j^n$$

6.3.5 Bell numbers

Total number of partitions of  $n$  distinct elements.  $B(n) = 1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, \dots$ . For  $p$  prime,

$$B(p^m + n) \equiv mB(n) + B(n+1) \pmod{p}$$

6.3.6 Labeled unrooted trees

# on  $n$  vertices:  $n^{n-2}$   
# on  $k$  existing trees of size  $n_i$ :  
 $n_1 n_2 \dots n_k n^{k-2}$   
# with degrees  $d_i$ :  
 $(n-2)! / ((d_1-1)! \dots (d_n-1)!)$

6.3.7 Catalan numbers

$$C_n = \frac{1}{n+1} \binom{2n}{n} = \binom{2n}{n} - \binom{2n}{n+1} = \frac{(2n)!}{(n+1)!n!}$$

$$C_0 = 1, \quad C_{n+1} = \frac{2(2n+1)}{n+2} C_n, \quad C_{n+1} = \sum C_i C_{n-i}$$

$$C_n = 1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786, \dots$$

- sub-diagonal monotone paths in an  $n \times n$  grid.
- strings with  $n$  pairs of parenthesis, correctly nested.
- binary trees with with  $n+1$  leaves (0 or 2 children).
- ordered trees with  $n+1$  vertices.
- ways a convex polygon with  $n+2$  sides can be cut into triangles by connecting vertices with straight lines.
- permutations of  $[n]$  with no 3-term increasing subseq.

6.4 Other

DeBruijn.h

**Description:** Recursive FKM, given alphabet  $[0, k)$  constructs cyclic string of length  $k^n$  that contains every length  $n$  string as substr. a7faa5, 13 lines

```
vi dseq(int k, int n) {
    if (k == 1) return {0};
    vi res, aux(n+1);
    function<void(int,int)> gen = [&](int t, int p) {
        if (t > n) { // consider lyndon word of len p
            if (n%p == 0) FOR(i,1,p+1) res.pb(aux[i]);
        } else {
            aux[t] = aux[t-p]; gen(t+1,p);
            FOR(i,aux[t-p]+1,k) aux[t] = i, gen(t+1,t);
        }
    };
    gen(1,1); return res;
}
```

PermGroup.h

**Description:** Schreier-Sims lets you add a permutation to a group, count number of permutations in a group, test whether a permutation is a member of a group. Works well for  $n \leq 15$ , maybe for larger too. Construct PermGroup() and run order() to get order of the group.

**Time:**  $O(n^6)$  d6edf4, 54 lines

```
vi inv(vi v) { vi V(sz(v)); rep(i,sz(v)) V[v[i]]=i; return V; }
vi id(int n) { vi v(n); iota(all(v),0); return v; }
vi operator*(const vi& a, const vi& b) {
    vi c(sz(a)); rep(i,sz(a)) c[i] = a[b[i]];
    return c;
}
struct PermGroup {
    struct Group {
        vi flag;
        vector<vi> gen, sigma;
        Group(int n, int p) : flag(n), sigma(n) {
            flag[p] = 1; sigma[p] = id(n);
        }
    };
    int n = 0; vector<Group> g;
    PermGroup() {}
    bool check(const vi& cur, int k) {
```

```
if (!k) return 1;
int t = cur[k];
return g[k].flag[t] ? check(inv(g[k].sigma[t])*cur,
    k-1) : 0;
}
void updateX(const vi& cur, int k) {
    int t = cur[k]; // if flag, fixes k -> k
    if (g[k].flag[t]) ins(inv(g[k].sigma[t])*cur,k-1);
    else {
        g[k].flag[t] = 1, g[k].sigma[t] = cur;
        for(auto x: g[k].gen)
            updateX(x*cur,k);
    }
}
void ins(const vi& cur, int k) {
    if (check(cur,k)) return;
    g[k].gen.pb(cur);
    rep(i,n) if (g[k].flag[i]) updateX(cur*g[k].sigma[i],k);
}
ll order(vector<vi> gen) {
    if(sz(gen) == 0) return 1;
    n = sz(gen[0]);
    rep(i,n) g.pb(Group(n,i));
    for(auto a: gen)
        ins(a, n-1); // insert perms into group one by one
    ll tot = 1; // watch out for overflows, can be up to n!
    rep(i,n) {
        int cnt = 0;
        rep(j,i+1) cnt += g[i].flag[j];
        tot *= cnt;
    }
    return tot;
}
};
```

GrayCode.h

**Description:** Gray code: gray(0), ..., gray( $2^n-1$ ) - permutation in which each two consecutive (cyclically) numbers. differ in exactly one bit. b4cc82, 6 lines

```
using ull = unsigned long long;
ull gray(ull i) { return i^i>>1; }
ull invg(ull i) { // i=invg(gray(i))=gray(inv(i))
    i^=i>>1; i^=i>>2; i^=i>>4;
    i^=i>>8; i^=i>>16; i^=i>>32; return i;
}
```

Graph (7)

7.1 Fundamentals

BellmanFord.h

**Description:** Calculates shortest paths from  $s$  in a graph that might have negative edge weights. Unreachable nodes get dist = inf; nodes reachable through negative-weight cycles get dist = -inf. Assumes  $V^2 \max |w_i| < \sim 2^{63}$ .

**Time:**  $O(VE)$  830a8f, 23 lines

```
const ll inf = LLONG_MAX;
struct Ed { int a, b, w, s() { return a < b ? a : -a; } };
struct Node { ll dist = inf; int prev = -1; };
void bellmanFord(vector<Node>& nodes, vector<Ed>& eds, int s) {
    nodes[s].dist = 0;
    sort(all(eds), [](Ed a, Ed b) { return a.s() < b.s(); });
    int lim = sz(nodes) / 2 + 2; // /3+100 with shuffled vertices
    rep(i,0,lim) for (Ed ed : eds) {
        Node cur = nodes[ed.a], &dest = nodes[ed.b];
        if (abs(cur.dist) == inf) continue;
        ll d = cur.dist + ed.w;
        if (d < dest.dist) {
            dest.prev = ed.a;
            dest.dist = (i < lim-1 ? d : -inf);
        }
    }
    rep(i,0,lim) for (Ed e : eds) {
        if (nodes[e.a].dist == -inf)
            nodes[e.b].dist = -inf;
    }
}
```

## FloydWarshall.h

**Description:** Calculates all-pairs shortest path in a directed graph that might have negative edge weights. Input is an distance matrix  $m$ , where  $m[i][j] = \text{inf}$  if  $i$  and  $j$  are not adjacent. As output,  $m[i][j]$  is set to the shortest distance between  $i$  and  $j$ ,  $\text{inf}$  if no path, or  $-\text{inf}$  if the path goes through a negative-weight cycle.

**Time:**  $\mathcal{O}(N^3)$

531245, 12 lines

```
const ll inf = 1LL << 62;
void floydWarshall(vector<vector<ll>>& m) {
    int n = sz(m);
    rep(i,0,n) m[i][i] = min(m[i][i], 0LL);
    rep(k,0,n) rep(i,0,n) rep(j,0,n)
        if (m[i][k] != inf && m[k][j] != inf) {
            auto newDist = max(m[i][k] + m[k][j], -inf);
            m[i][j] = min(m[i][j], newDist);
        }
    rep(k,0,n) if (m[k][k] < 0) rep(i,0,n) rep(j,0,n)
        if (m[i][k] != inf && m[k][j] != inf) m[i][j] = -
            inf;
}
```

## TopoSort.h

**Description:** Topological sorting. Given is an oriented graph. Output is an ordering of vertices, such that there are edges only from left to right. If there are cycles, the returned list will have size smaller than  $n$  – nodes reachable from cycles will not be returned.

**Time:**  $\mathcal{O}(|V| + |E|)$

d678d8, 8 lines

```
vi topoSort(const vector<vi>& gr) {
    vi indeg(sz(gr)), q;
    for (auto& li : gr) for (int x : li) indeg[x]++;
    rep(i,0,sz(gr)) if (indeg[i] == 0) q.push_back(i);
    rep(j,0,sz(q)) for (int x : gr[q[j]])
        if (--indeg[x] == 0) q.push_back(x);
    return q;
}
```

## SPFA.h

**Description:** SPFA with subtree erasure heuristic. Returns array of distances or empty array if negative cycle is reachable from source.  $\text{par}[v]$  = parent in shortest path tree

**Time:**  $\mathcal{O}(VE)$  but fast on random

bf4a3f, 33 lines

```
using Edge = pair<int, ll>;
vector<ll> spfa(vector<vector<Edge>>& G,
               vi& par, int src) {
    int n = sz(G); vi que, prv(n+1);
    iota(all(prv), 0); vi nxt = prv;
    vector<ll> dist(n, INT64_MAX);
    par.assign(n, -1);
    auto add = [&](int v, int p, ll d) {
        par[v] = p; dist[v] = d;
        prv[n] = nxt[prv[v] = prv[nxt[v] = n]] = v;
    };
    auto del = [&](int v) {
        nxt[prv[nxt[v]]] = prv[v] = nxt[v];
        prv[v] = nxt[v] = v;
    };
    for (add(src, -2, 0); nxt[n] != n;) {
        int v = nxt[n]; del(v);
        for (auto e : G[v]) {
            ll alt = dist[v] + e.y;
            if (alt < dist[e.x]) {
                que = {e.x};
                rep(i, sz(que)) {
                    int w = que[i]; par[w] = -1;
                    del(w);
                    for (auto f : G[w])
                        if (par[f.x] == w) que.pb(f.x);
                }
                if (par[v] == -1) return {};
                add(e.x, v, alt);
            }
        }
    }
    return dist;
}
```

### 7.2 Network flow

#### PushRelabel.h

**Description:** Push-relabel using the highest label selection rule and the gap heuristic. Quite fast in practice. To obtain the actual flow, look at positive values only.

**Time:**  $\mathcal{O}(V^2\sqrt{E})$

0ae1d4, 48 lines

```
struct PushRelabel {
    struct Edge {
        int dest, back;
        ll f, c;
    };
    vector<vector<Edge>> g;
    vector<ll> ec;
    vector<Edge*> cur;
    vector<vi> hs; vi H;
    PushRelabel(int n) : g(n), ec(n), cur(n), hs(2*n), H(
        n) {}
    void addEdge(int s, int t, ll cap, ll rcap=0) {
        if (s == t) return;
        g[s].push_back({t, sz(g[t]), 0, cap});
        g[t].push_back({s, sz(g[s])-1, 0, rcap});
    }
    void addFlow(Edge& e, ll f) {
        Edge &back = g[e.dest][e.back];
        if (!ec[e.dest] && f) hs[H[e.dest]].push_back(e.
            dest);
        e.f += f; e.c -= f; ec[e.dest] += f;
        back.f -= f; back.c += f; ec[back.dest] -= f;
    }
    ll calc(int s, int t) {
        int v = sz(g); H[s] = v; ec[t] = 1;
        vi co(2*v); co[0] = v-1;
        rep(i,0,v) cur[i] = g[i].data();
        for (Edge& e : g[s]) addFlow(e, e.c);
        for (int hi = 0;;) {
            while (hs[hi].empty()) if (!hi--) return -ec[s];
            int u = hs[hi].back(); hs[hi].pop_back();
            while (ec[u] > 0) // discharge u
                if (cur[u] == g[u].data() + sz(g[u])) {
                    H[u] = 1e9;
                    for (Edge& e : g[u]) if (e.c && H[u] > H[e.
                        dest]+1)
                        H[u] = H[e.dest]+1, cur[u] = &e;
                    if (++co[H[u]], !--co[hi] && hi < v)
                        rep(i,0,v) if (hi < H[i] && H[i] < v)
                            --co[H[i]], H[i] = v + 1;
                    hi = H[u];
                } else if (cur[u]->c && H[u] == H[cur[u]->dest
                        ]+1)
                    addFlow(*cur[u], min(ec[u], cur[u]->c));
                else ++cur[u];
            }
        }
    }
    bool leftOfMinCut(int a) { return H[a] >= sz(g); }
};
```

## MinCostMaxFlow.h

**Description:** Min-cost max-flow. If costs can be negative, call setpi before maxflow, but note that negative cost cycles are not supported. To obtain the actual flow, look at positive values only.

**Time:**  $\mathcal{O}(FE \log(V))$  where F is max flow.  $\mathcal{O}(KE)$  for setpi.

```
#include <ext/pb_ds/priority_queue.hpp>
const ll INF = numeric_limits<ll>::max() / 4;
struct MCMF {
    struct edge {
        int from, to, rev;
        ll cap, cost, flow;
    };
    int N;
    vector<vector<edge>> ed;
    vi seen;
    vector<ll> dist, pi;
    vector<edge*> par;
    MCMF(int N) : N(N), ed(N), seen(N), dist(N), pi(N),
        par(N) {}
    void addEdge(int from, int to, ll cap, ll cost) {
        if (from == to) return;
        ed[from].push_back(edge{ from,to,sz(ed[to]),cap,
            cost,0 });
        ed[to].push_back(edge{ to,from,sz(ed[from])-1,0,-
            cost,0 });
    }
    void path(int s) {
        fill(all(seen), 0);
        fill(all(dist), INF);
        dist[s] = 0; ll di;
        __gnu_pbds::priority_queue<pair<ll, int>> q;
        vector<decltype(q)::point_iterator> its(N);
        q.push({ 0, s });
        while (!q.empty()) {
            s = q.top().second; q.pop();
            seen[s] = 1; di = dist[s] + pi[s];
            for (edge& e : ed[s]) if (!seen[e.to]) {
                ll val = di - pi[e.to] + e.cost;
```

```
            if (e.cap - e.flow > 0 && val < dist[e.to]) {
                dist[e.to] = val;
                par[e.to] = &e;
                if (its[e.to] == q.end())
                    its[e.to] = q.push({ -dist[e.to], e.to });
                else
                    q.modify(its[e.to], { -dist[e.to], e.to });
            }
        }
        rep(i,0,N) pi[i] = min(pi[i] + dist[i], INF);
    }
    pair<ll, ll> maxflow(int s, int t) {
        ll totflow = 0, totcost = 0;
        while (path(s), seen[t]) {
            ll fl = INF;
            for (edge* x = par[t]; x; x = par[x->from])
                fl = min(fl, x->cap - x->flow);
            totflow += fl;
            for (edge* x = par[t]; x; x = par[x->from]) {
                x->flow += fl;
                ed[x->to][x->rev].flow -= fl;
            }
        }
        rep(i,0,N) for(edge& e : ed[i]) totcost += e.cost *
            e.flow;
        return {totflow, totcost/2};
    }
    // If some costs can be negative, call this before
    // maxflow:
    void setpi(int s) { // (otherwise, leave this out)
        fill(all(pi), INF); pi[s] = 0;
        int it = N, ch = 1; ll v;
        while (ch-- && it--)
            rep(i,0,N) if (pi[i] != INF)
                for (edge& e : ed[i]) if (e.cap)
                    if ((v = pi[i] + e.cost) < pi[e.to])
                        pi[e.to] = v, ch = 1;
        assert(it >= 0); // negative cost cycle
    }
};
```

## EdmondsKarp.h

**Description:** Flow algorithm with guaranteed complexity  $\mathcal{O}(VE^2)$ . To get edge flow values, compare capacities before and after, and take the positive values only.

482fe0, 36 lines

```
template<class T> T edmondsKarp(vector<unordered_map<
    int, T>&g
    graph, int source, int sink) {
    assert(source != sink);
    T flow = 0;
    vi par(sz(graph)), q = par;
    for (;;) {
        fill(all(par), -1);
        par[source] = 0;
        int ptr = 1;
        q[0] = source;
        rep(i,0,ptr) {
            int x = q[i];
            for (auto e : graph[x]) {
                if (par[e.first] == -1 && e.second > 0) {
                    par[e.first] = x;
                    q[ptr++] = e.first;
                    if (e.first == sink) goto out;
                }
            }
        }
        return flow;
    }
    T inc = numeric_limits<T>::max();
    for (int y = sink; y != source; y = par[y])
        inc = min(inc, graph[par[y]][y]);
    flow += inc;
    for (int y = sink; y != source; y = par[y]) {
        int p = par[y];
        if ((graph[p][y] -- inc) <= 0) graph[p].erase(y);
        graph[y][p] += inc;
    }
}

out:
};
```

## Dinic.h

**Description:** Flow algorithm with complexity  $\mathcal{O}(VE \log U)$  where  $U = \max|cap|$ .  $\mathcal{O}(\min(E^{1/2}, V^{2/3})E)$  if  $U = 1$ ;  $\mathcal{O}(\sqrt{VE})$  for bipartite matching.

d7f0f1, 42 lines

```
struct Dinic {
    struct Edge {
        int to, rev;
```

```
        ll c, oc;
        ll flow(t) { return max(oc - c, 0LL); } // if you
            need flows
    };
    vi lvl, ptr, q;
    vector<vector<Edge>> adj;
    Dinic(int n) : lvl(n), ptr(n), q(n), adj(n) {}
    void addEdge(int a, int b, ll c, ll rcap = 0) {
        adj[a].push_back({b, sz(adj[b]), c, c});
        adj[b].push_back({a, sz(adj[a]) - 1, rcap, rcap});
    }
    ll dfs(int v, int t, ll f) {
        if (v == t || !f) return f;
        for (int& i = ptr[v]; i < sz(adj[v]); i++) {
            Edge& e = adj[v][i];
            if (lvl[e.to] == lvl[v] + 1)
                if (ll p = dfs(e.to, t, min(f, e.c))) {
                    e.c -= p; adj[e.to][e.rev].c += p;
                    return p;
                }
        }
        return 0;
    }
    ll calc(int s, int t) {
        ll flow = 0; q[0] = s;
        rep(L,0,31) do { // 'int L=30' maybe faster for
            random data
            lvl = ptr = vi(sz(q));
            int qi = 0, ge = lvl[s] = 1;
            while (qi < ge && !lvl[t]) {
                int v = q[qi++];
                for (Edge& e : adj[v])
                    if (!lvl[e.to] && e.c >> (30 - L))
                        q[ge++] = e.to, lvl[e.to] = lvl[v] + 1;
            }
            while (ll p = dfs(s, t, LLONG_MAX)) flow += p;
        } while (lvl[t]);
        return flow;
    }
    bool leftOfMinCut(int a) { return lvl[a] != 0; }
};
```

## MinCut.h

**Description:** After running max-flow, the left side of a min-cut from  $s$  to  $t$  is given by all vertices reachable from  $s$ , only traversing edges with positive residual capacity.

## GlobalMinCut.h

**Description:** Find a global minimum cut in an undirected graph, as represented by an adjacency matrix.

**Time:**  $\mathcal{O}(V^3)$

8b0e19, 21 lines

```
pair<int, vi> globalMinCut(vector<vi> mat) {
    pair<int, vi> best = {INT_MAX, {}};
    int n = sz(mat);
    vector<vi> co(n);
    rep(i,0,n) mat[s][i] += mat[t][i];
    rep(ph,1,n) {
        rep(ph,1,n) {
            vi w = mat[0];
            size_t s = 0, t = 0;
            rep(it,0,n-ph) { //  $\mathcal{O}(V^2)$  ->  $\mathcal{O}(E \log V)$  with prio.
                queue
                w[t] = INT_MIN;
                s = t, t = max_element(all(w)) - w.begin();
                rep(i,0,n) w[i] += mat[t][i];
            }
            best = min(best, {w[t] - mat[t][t], co[t]});
            co[s].insert(co[s].end(), all(co[t]));
            rep(i,0,n) mat[s][i] += mat[t][i];
            rep(i,0,n) mat[i][s] = mat[s][i];
            mat[0][t] = INT_MIN;
        }
    }
    return best;
}
```

## GomoryHu.h

**Description:** Given a list of edges representing an undirected flow graph, returns edges of the Gomory-Hu tree. The max flow between any pair of vertices is given by minimum edge weight along the Gomory-Hu tree path.

**Time:**  $\mathcal{O}(V)$  Flow Computations

\*PushRelabel.h

0418b3, 13 lines

```
typedef array<ll, 3> Edge;
vector<Edge> gomoryHu(int N, vector<Edge> ed) {
    vector<Edge> tree;
    vi par(N);
```



```

int d = INT_MAX;
rep(b, n+1, nx+1)
    if (st[b] == b && S[b] == 1)
        d = min(d, lab[b]/2);
rep(x, 1, nx+1)
    if (st[x] == x && slack[x]) {
        if (S[x] == -1)
            d = min(d, delta(g[slack[x]][x]));
        else if (!S[x])
            d = min(d, delta(g[slack[x]][x])/2);
    }
rep(u, 1, n+1) {
    if (!S[st[u]]) {
        if (lab[u] <= d) return 0;
        lab[u] -= d;
    } else if (S[st[u]] == 1) lab[u] += d;
}
rep(b, n+1, nx+1) if (st[b] == b) {
    if (!S[st[b]]) lab[b] += d*2;
    else if (S[st[b]] == 1) lab[b] -= d*2;
}
q = {};
rep(x, 1, nx+1)
    if (st[x] == x && slack[x] &&
        st[slack[x]] != x &&
        !delta(g[slack[x]][x]) &&
        found(g[slack[x]][x])) return 1;
rep(b, n+1, nx+1)
    if (st[b] == b && S[b] == 1 && !lab[b])
        blossom(b);
}
return 0;
}
}

```

## 7.4 DFS algorithms

### SCC.h

**Description:** Finds strongly connected components in a directed graph. If vertices  $u, v$  belong to the same component, we can reach  $u$  from  $v$  and vice versa.

**Usage:** `scc(graph, [&](vi& v) { ... })` visits all components in reverse topological order. `comp[i]` holds the component index of a node (a component only has edges to components with lower index). `ncmps` will contain the number of components.

**Time:**  $\mathcal{O}(E + V)$  76b5c9, 24 lines

```

vi val, comp, z, cont;
int Time, ncmps;
template<class G, class F> int dfs(int j, G& g, F& f) {
    int low = val[j] = ++Time, x; z.push_back(j);
    for (auto e : g[j]) if (comp[e] < 0)
        low = min(low, val[e] ? : dfs(e, g, f));
    if (low == val[j]) {
        do {
            x = z.back(); z.pop_back();
            comp[x] = ncmps;
            cont.push_back(x);
        } while (x != j);
        f(cont); cont.clear();
        ncmps++;
    }
    return val[j] = low;
}
template<class G, class F> void scc(G& g, F f) {
    int n = sz(g);
    val.assign(n, 0); comp.assign(n, -1);
    Time = ncmps = 0;
    rep(i, 0, n) if (comp[i] < 0) dfs(i, g, f);
}

```

## BiconnectedComponents.h

**Description:** Finds all biconnected components in an undirected graph, and runs a callback for the edges in each. In a biconnected component there are at least two distinct paths between any two nodes. Note that a node can be in several components. An edge which is not in a component is a bridge, i.e., not part of any cycle.

**Usage:** `int eid = 0; ed.resize(N);`  
for each edge (a,b) {  
ed[a].emplace\_back(b, eid);  
ed[b].emplace\_back(a, eid++); }  
**bicomps** [&](const vi& edgelist) {...};  
**Time:**  $\mathcal{O}(E + V)$  c6b7c7, 32 lines

```

vi num, st;
vector<vector<pii>> ed;
int Time;
template<class F>
int dfs(int at, int par, F& f) {
    int me = num[at] = ++Time, top = me;
    for (auto [y, e] : ed[at]) if (e != par) {
        if (num[y]) {
            top = min(top, num[y]);
            if (num[y] < me)
                st.push_back(e);
        } else {
            int si = sz(st);
            int up = dfs(y, e, f);
            top = min(top, up);
            if (up == me) {
                st.push_back(e);
                f(vi(st.begin() + si, st.end()));
                st.resize(si);
            }
            else if (up < me) st.push_back(e);
            else { /* e is a bridge */ }
        }
    }
    return top;
}
template<class F>
void bicomps(F f) {
    num.assign(sz(ed), 0);
    rep(i, 0, sz(ed)) if (!num[i]) dfs(i, -1, f);
}

```

### 2sat.h

**Description:** Calculates a valid assignment to boolean variables  $a, b, c, \dots$  to a 2-SAT problem, so that an expression of the type  $(a||b)\&\&(!a||c)\&\&(d||!b)\&\&\dots$  becomes true, or reports that it is unsatisfiable. Negated variables are represented by bit-inversions ( $\sim x$ ).

**Usage:** `TwoSat ts` (number of boolean variables);  
`ts.either(0, ~3);` // Var 0 is true or var 3 is false  
`ts.setValue(2);` // Var 2 is true  
`ts.atMostOne({0, ~1, 2});` //  $\leq 1$  of vars 0, ~1 and 2 are true  
`ts.solve();` // Returns true iff it is solvable  
`ts.values[0..N-1]` holds the assigned values to the vars  
**Time:**  $\mathcal{O}(N + E)$ , where  $N$  is the number of boolean variables, and  $E$  is the number of clauses. 5f9706, 56 lines

```

struct TwoSat {
    int N;
    vector<vi> gr;
    vi values; // 0 = false, 1 = true
    TwoSat(int n = 0) : N(n), gr(2*n) {}
    int addVar() { // (optional)
        gr.emplace_back();
        gr.emplace_back();
        return N++;
    }
    void either(int f, int j) {
        f = max(2*f, -1-2*f);
        j = max(2*j, -1-2*j);
        gr[f].push_back(j^1);
        gr[j].push_back(f^1);
    }
    void setValue(int x) { either(x, x); }
    void atMostOne(const vi& li) { // (optional)
        if (sz(li) <= 1) return;
        int cur = ~li[0];
        rep(i, 2, sz(li)) {
            int next = addVar();
            either(cur, ~li[i]);
            either(cur, next);
            either(~li[i], next);
            cur = ~next;
        }
        either(cur, ~li[1]);
    }
    vi val, comp, z; int time = 0;
    int dfs(int i) {
        int low = val[i] = ++time, x; z.push_back(i);
        for(int e : gr[i]) if (!comp[e])
            low = min(low, val[e] ? : dfs(e));
    }
}

```

```

if (low == val[i]) do {
    x = z.back(); z.pop_back();
    comp[x] = low;
    if (values[x]>1) == -1)
        values[x]>1 = x&1;
    } while (x != i);
    return val[i] = low;
}
bool solve() {
    values.assign(N, -1);
    val.assign(2*N, 0); comp = val;
    rep(i, 0, 2*N) if (!comp[i]) dfs(i);
    rep(i, 0, N) if (comp[2*i] == comp[2*i+1]) return 0;
    return 1;
}
}
}

```

## EulerWalk.h

**Description:** Eulerian undirected/directed path/cycle algorithm. Input should be a vector of (dest, global edge index), where for undirected graphs, forward/backward edges have the same index. Returns a list of pairs (node, incoming edge) in the Eulerian path/cycle with `src` at both start and end, or empty list if no cycle/path exists.

**Time:**  $\mathcal{O}(V + E)$  c62d93, 16 lines

```

vector<pii> eulerWalk(vector<vector<pii>>& gr, int
    nedges, int src=0) {
    int n = sz(gr);
    vi D(n), its(n), eu(nedges); vector<pii> ret, s = {{
        src, -1}};
    D[src]++; // to allow Euler paths, not just cycles
    while (!s.empty()) {
        int x = s.back().first, y, e, &it = its[x], end =
            sz(gr[x]);
        if (it == end) {
            ret.push_back(s.back()); s.pop_back(); continue;
        }
        tie(y, e) = gr[x][it++];
        if (!eu[e]) {
            D[x]--, D[y]++;
            eu[e] = 1; s.push_back({y, e});
        }
    }
    for (int x : D) if (x < 0 || sz(ret) != nedges+1)
        return {};
    return {ret.rbegin(), ret.rend()};
}

```

## Dominators.h

**Description:** Tarjan's dominators in directed graph. Returns tree (as array of parents) of immediate dominators `idom`. `idom[root] = root`, `idom[v] = -1` if  $v$  is unreachable from root.  
**Time:**  $\mathcal{O}(|E|\log|V|)$  50d914, 32 lines

```

vi dominators(vector<vi>& G, int root) {
    int n = sz(G); vector<vi> in(n), bucket(n);
    vi pre(n, -1), anc(n, -1), par(n), best(n);
    vi ord, idom(n, -1), sdom(n, n), rdom(n);
    auto dfs = [&](auto f, int v, int p) -> void {
        if (pre[v] == -1) {
            par[v] = p; pre[v] = sz(ord);
            ord.push_back(v);
            for auto e : G[v]
                in[e].push_back(v), f(f, e, v);
        }
        auto find = [&](auto f, int v) -> pii {
            if (anc[v] == -1) return {best[v], v};
            int b; tie(b, anc[v]) = f(f, anc[v]);
            if (sdom[b] < sdom[best[v]]) best[v] = b;
            return {best[v], anc[v]};
        };
        rdom[root] = idom[root] = root;
        iota(all(best), 0); dfs(dfs, root, -1);
        rep(i, 0, sz(ord)) {
            int v = ord[sz(ord)-i-1], b = pre[v];
            f(f, auto e : in[v])
                b = min(b, pre[e] < pre[v] ? pre[e] :
                    sdom[find(find, e).first]);
            for (auto u : bucket[v]) rdom[u] = find(find, u).first;
            sdom[v] = b; anc[v] = par[v];
            bucket[ord[sdom[v]]].push_back(v);
        }
        for (auto v : ord) idom[v] = (rdom[v] == v ?
            ord[sdom[v]] : idom[rdom[v]]);
        return idom;
    }
}

```

## KthShortest.h

**Description:** Given directed weighted graph with non-negative edge weights gets  $K$ -th shortest walk (not necessarily simple) or  $-1$  if no next path (can only happen in DAG).

**Memory:**  $\mathcal{O}(m \log m + k \log m)$  (uses persistent heaps)  
**Time:**  $\mathcal{O}(m \log m + k \log m)$  e29f5a, 57 lines

```

constexpr ll INF = 1e18;
struct Eppstein {
    using T = ll; using Edge = pair<int, T>;
    struct Node { int E[2] = {}, s = 0; Edge x; };
    T shortest; // Shortest path length
    priority_queue<pair<T, int>> Q;
    vector<Node> P[1]; vi h;
    Eppstein(vector<vector<Edge>>& G, int s, int t) {
        int n = sz(G); vector<vector<Edge>> H(n);
        rep(i, 0, n) for(auto &[j, w] : G[i])
            H[j].push_back({i, w});
        vi ord, par(n, -1); vector<T> d(n, -INF);
        Q.push({d[t] = 0, t});
        while (!Q.empty()) {
            auto [dd, v] = Q.top(); Q.pop();
            if (d[v] == dd) {
                ord.push_back(v);
                for(auto &[u, w] : H[v])
                    if (dd-w > d[u]) {
                        Q.push({d[u] = dd-w, u});
                        par[u] = v;
                    }
            }
        }
        if ((shortest = -d[s]) >= INF) return;
        h.resize(n);
        for(auto &v : ord) {
            int p = par[v]; if (p+1) h[v] = h[p];
            for(auto &[u, w] : G[v]) if (d[u] > -INF) {
                T k = w - d[u] + d[v];
                if (k || u != p)
                    h[v] = push(h[v], {u, k});
                else p = -1;
            }
        }
        P[0].x.first = s; Q.push({0, 0});
    }
    int push(int t, Edge x) {
        P.push_back(P[t]);
        if (!P[t = sz(P)-1].s || P[t].x.second >= x.second)
            swap(x, P[t].x);
        if (P[t].s) {
            int i = P[t].E[0], j = P[t].E[1];
            int d = P[i].s > P[j].s;
            int k = push(d ? j : i, x);
            P[t].E[d] = k; // Don't inline k!
        }
        P[t].s++; return t;
    }
    ll nextPath() { // next length, -1 if no next path
        if (Q.empty()) return -1;
        auto [d, v] = Q.top(); Q.pop();
        for (int i : P[v].E) if (i)
            Q.push({ d-P[i].x.second+P[v].x.second, i });
        int t = h[P[v].x.first];
        if (t) Q.push({d - P[t].x.second, t });
        return shortest - d; }
};

```

## DenseDFS.h

**Description:** DFS over dense graph. Suddenly DFS over  $N \leq 1000$  graph many times becomes feasible 6e9645, 68 lines

```

// DFS over bit-packed adjacency matrix
// G = NxN adjacency matrix of graph
// G(i, j) <=> (i, j) is edge
// V = 1xN matrix containing unvisited vertices
// V(0, i) <=> i-th vertex is not visited
// Total DFS time:  $\mathcal{O}(n^2/64)$ 
using ull = uint64_t;
// Matrix over  $\mathbb{Z}_2$  (bits and xor)
// TODO: arithmetic operations //HIDE
struct BitMatrix {
    vector<ull> M;
    int rows, cols, stride;
    // Create matrix with n rows and m columns
    BitMatrix(int n = 0, int m = 0) {
        rows = n; cols = m;
        stride = (m+63)/64;
        M.resize(n*stride);
    }
    // Get pointer to bit-packed data of i-th row
    ull* row(int i) { return &M[i*stride]; }
    // Get value in i-th row and j-th column
    bool operator()(int i, int j) {

```

```

    return (row[i][j/64] >> (j%64)) & 1;
}
// Set value in i-th row and j-th column
void set(int i, int j, bool val) {
    ull &w = row[i][j/64], m = 1ull << (j%64);
    if (val) w |= m;
    else w &= ~m;
}
}
struct DenseDFS {
    BitMatrix G, V; // space: O(n^2/64)
    // Initialize structure for n vertices
    DenseDFS(int n = 0) : G(n, n), V(1, n) {
        reset();
    }
    // Mark all vertices as unvisited
    void reset() { for(auto &x : V.M) x = -1; }
    // Get/set visited flag for i-th vertex
    void setVisited(int i) { V.set(0, i, 0); }
    bool isVisited(int i) { return !V(0, i); }
    // DFS step: func is called on each unvisited
    // neighbour of i. You need to manually call
    // setVisited(child) to mark it visited
    // or this function will call the callback
    // with the same vertex again.
    void step(int i, auto func) {
        ull* E = G.row(i);
        for (int w = 0; w < G.stride; w++) {
            ull x = E[w] & V.row(0)[w];
            if (x) func((w<<6) | __builtin_ctzll(x));
            else w++;
        }
    }
}
};

```

## PlanarFaces.h

**Description:** Finds the faces of a simple planar graph and returns the vertex indices for each face in either clockwise (inner) or counterclockwise (outer) order. Disconnected graphs may have multiple outer faces and require careful handling.  
**Time:**  $\mathcal{O}(n \log n)$

```

"./geometry/Point.h", "./geometry/AngleCmp.h" 2c9685, 24 lines
template<class P>
vector<vi> planarFaces(vector<vi>& g, vector<P>& p) {
    int n = sz(g); P o;
    auto cmp = [&](int x,int y) {
        return angleCmp(p[X] - o, p[Y] - o); };
    vector<vi> vis(n);
    rep(i, 0, n) {
        o = p[i], sort(all(g[i]), cmp);
        vis[i].resize(sz(g[i]));
    }
    vector<vi> f;
    rep(i, 0, n) rep(j, 0, sz(adj[i])) {
        if (vis[i][j]) continue;
        vi s; int u = i, k = j;
        while (!vis[u][k]) {
            vis[u][k] = 1; s.push_back(u);
            int v = adj[u][k]; o = p[v];
            int kk=lower_bound(all(g[v]), u, cmp)-g[v].begin();
            u = v, k = (kk + 1) % sz(adj[u]);
        }
        f.push_back(s);
    }
    return f;
}
}

```

## 7.5 Coloring

### EdgeColoring.h

**Description:** Given a simple, undirected graph with max degree  $D$ , computes a  $(D + 1)$ -coloring of the edges such that no neighboring edges share a color. ( $D$ -coloring is NP-hard, but can be done for bipartite graphs by repeated matchings of max-degree nodes.)  
**Time:**  $\mathcal{O}(NM)$

```

vi edgeColoring(int N, vector<pii> eds) {
    vi cc(N + 1), ret(sz(eds)), fan(N), free(N), loc;
    for (pii e : eds) ++cc[e.first], ++cc[e.second];
    int u, v, ncols = *max_element(all(cc)) + 1;
    vector<vi> adj(N, vi(ncols, -1));
    for (pii e : eds) {
        tie(u, v) = e;
        fan[0] = v;
        loc.assign(ncols, 0);
        int at = u, end = u, d, c = free[u], ind = 0, i = 0;
    }
}

```

```

while (d = free[v], !loc[d] && (v = adj[u][d]) != -1)
    loc[d] = ++ind, cc[ind] = d, fan[ind] = v;
cc[loc[d]] = c;
for (int cd = d; at != -1; cd ^= c ^ d, at = adj[at][cd])
    swap(adj[at][cd], adj[end = at][cd ^ c ^ d]);
while (adj[fan[i]][d] != -1) {
    int left = fan[i], right = fan[++i], e = cc[i];
    adj[u][e] = left;
    adj[left][e] = u;
    adj[right][e] = -1;
    free[right] = e;
}
adj[u][d] = fan[i];
adj[fan[i]][d] = u;
for (int y : {fan[0], u, end})
    for (int& z = free[y] = 0; adj[y][z] != -1; z++);
}
rep(i, 0, sz(eds))
    for (tie(u, v) = eds[i]; adj[u][ret[i]] != v; ++ret[i]);
return ret;
}

```

## ChromaticNumber.h

**Description:** Calculates chromatic number of a graph represented by a vector of bitmasks. Self loops are not allowed.  
**Usage:** chromaticNumber{6, 5, 3} // 3-clique  
**Time:**  $\mathcal{O}(2^n n)$

```

const int MOD = 1000500103; // big prime
int chromaticNumber(vi g) {
    int n = sz(g);
    if (!n) return 0;
    vi ind(1 << n, 1), s(1 << n);
    rep(i, 0, 1 << n) s[i] = __popcount(i) & 1 ? -1 : 1;
    rep(i, 1, 1 << n) {
        int ctz = __builtin_ctz(i);
        ind[i] = ind[i - (1 << ctz)] + ind[(i - (1 << ctz)) & ~g[ctz]];
        if (ind[i] % MOD) ind[i] -= MOD;
    }
    rep(k, 1, n) {
        ll sum = 0;
        rep(i, 0, 1 << n) {
            s[i] = int((ll)s[i] * ind[i] % MOD);
            sum += s[i];
        }
        if (sum % MOD) return k;
    }
    return n;
}

```

## 7.6 Heuristics

### MaximalCliques.h

**Description:** Runs a callback for all maximal cliques in a graph (given as a symmetric bitset matrix; self-edges not allowed). Callback is given a bitset representing the maximal clique.

**Time:**  $\mathcal{O}(3^{n/3})$ , much faster for sparse graphs.

```

typedef bitset<128> B;
template<class F>
void cliques(vector<B>& eds, F f, B P = ~B(), B X={}, B R={}) {
    if (!P.any()) { if (!X.any()) f(R); return; }
    auto q = (P | X)._Find_first();
    auto cands = P & ~eds[q];
    rep(i, 0, sz(eds)) if (cands[i]) {
        R[i] = 1;
        cliques(eds, f, P & eds[i], X & eds[i], R);
        R[i] = P[i] = 0; X[i] = 1;
    }
}
}

```

## MaximumClique.h

**Description:** Quickly finds a maximum clique of a graph (given as symmetric bitset matrix; self-edges not allowed). Can be used to find a maximum independent set by finding a clique of the complement graph.

**Time:** Runs in about 1s for  $n=155$  and worst case random graphs ( $p=.90$ ). Runs faster for sparse graphs.

```

typedef vector<bitset<200>> vb;
struct Maxclique {
    double limit=0.025, pk=0;
    struct Vertex { int i, d=0; };
    typedef vector<Vertex> vv;
}

```

```

vb e;
vv V;
vector<vi> C;
vi qmax, q, S, old;
void init(vv& r) {
    for (auto& v : r) v.d = 0;
    for (auto& v : r) for (auto j : r) v.d += e[v.i][j].i;
    sort(all(r), [](auto a, auto b) { return a.d > b.d; });
}
int mxD = r[0].d;
rep(i, 0, sz(r)) r[i].d = min(i, mxD) + 1;
}
void expand(vv& R, int lev = 1) {
    S[lev] += S[lev - 1] - old[lev];
    old[lev] = S[lev - 1];
    while (sz(R)) {
        if (sz(q) + R.back().d <= sz(qmax)) return;
        q.push_back(R.back().i);
        vv T;
        for(auto v:R) if (e[R.back().i][v.i]) T.push_back((v.v));
        if (sz(T))
            if (S[lev]++ / ++pk < limit) init(T);
            int j = 0, mxk = 1, mnk = max(sz(qmax) - sz(q) + 1, 1);
            C[1].clear(), C[2].clear();
            for (auto v : T) {
                int k = 1;
                auto f = [&](int i) { return e[v.i][i]; };
                while (any_of(all(C[k]), f)) k++;
                if (k > mxk) mxk = k, C[mxk + 1].clear();
                if (k < mnk) T[j++] .i = v.i;
                C[k].push_back(v.i);
            }
            if (j > 0) T[j - 1].d = 0;
            rep(k, mnk, mxk + 1) for (int i : C[k])
                T[j].i = i, T[j++].d = k;
            expand(T, lev + 1);
        } else if (sz(q) > sz(qmax)) qmax = q;
        q.pop_back(), R.pop_back();
    }
}
vi maxClique() { init(V), expand(V); return qmax; }
Maxclique(vb conn) : e(conn), C(sz(e)+1), S(sz(C)), old(S) {
    rep(i, 0, sz(e)) V.push_back({i});
}
}

```

## MaximumIndependentSet.h

**Description:** To obtain a maximum independent set of a graph, find a max clique of the complement. If the graph is bipartite, see MinimumVertexCover.

## 7.7 Trees

### BinaryLifting.h

**Description:** Calculate power of two jumps in a tree, to support fast upward jumps and LCAs. Assumes the root node points to itself.

**Time:** construction  $\mathcal{O}(N \log N)$ , queries  $\mathcal{O}(\log N)$ .

```

vector<vi> treeJump(vi& P) {
    int on = 1, d = 1;
    while (on < sz(P)) on *= 2, d++;
    vector<vi> jmp(d, P);
    rep(i, 1, d) rep(j, 0, sz(P))
        jmp[i][j] = jmp[i-1][jmp[i-1][j]];
    return jmp;
}
int jmp(vector<vi>& tbl, int nod, int steps) {
    rep(i, 0, sz(tbl))
        if (steps < (1<<i)) nod = tbl[i][nod];
    return nod;
}
int lca(vector<vi>& tbl, vi& depth, int a, int b) {
    if (depth[a] < depth[b]) swap(a, b);
    a = jmp(tbl, a, depth[a] - depth[b]);
    if (a == b) return a;
    for (int i = sz(tbl); i--;) {
        int c = tbl[i][a], d = tbl[i][b];
        if (c != d) a = c, b = d;
    }
    return tbl[0][a];
}
}

```

## LCA.h

**Description:** Data structure for computing lowest common ancestors in a tree (with 0 as root). C should be an adjacency list of the tree, either directed or undirected.

**Time:**  $\mathcal{O}(N \log N + Q)$

```

"./data-structures/RMQ.h" 0f62fb, 21 lines
struct LCA {
    int T = 0;
    vi time, path, ret;
    RMQ<int> rmq;
    LCA(vector<vi>& C) : time(sz(C)), rmq((dfs(C, 0, -1), ret), {});
    void dfs(vector<vi>& C, int v, int par) {
        time[v] = T++;
        for (int y : C[v]) if (y != par) {
            path.push_back(v), ret.push_back(time[v]);
            dfs(C, y, v);
        }
    }
    int lca(int a, int b) {
        if (a == b) return a;
        tie(a, b) = minmax(time[a], time[b]);
        return path[rmq.query(a, b)];
    }
    //dist(a,b){return depth[a] + depth[b] - 2*depth[lca(a,b)];}
};

```

## CompressTree.h

**Description:** Given a rooted tree and a subset S of nodes, compute the minimal subtree that contains all the nodes by adding all (at most  $|S| - 1$ ) pairwise LCAs and compressing edges. Returns a list of (par, orig.index) representing a tree rooted at 0. The root points to itself.  
**Time:**  $\mathcal{O}(|S| \log |S|)$

```

"LCA.h" 9775a0, 21 lines
typedef vector<pair<int, int>> vpi;
vpi compressTree(LCA& lca, const vi& subset) {
    static vi rev; rev.resize(sz(lca.time));
    vi li = subset, &T = lca.time;
    auto cmp = [&](int a, int b) { return T[a] < T[b]; };
    sort(all(li), cmp);
    int m = sz(li)-1;
    rep(i, 0, m) {
        int a = li[i], b = li[i+1];
        li.push_back(lca.lca(a, b));
    }
    sort(all(li), cmp);
    li.erase(unique(all(li)), li.end());
    rep(i, 0, sz(li)) rev[li[i]] = i;
    vpi ret = {pii(0, li[0])};
    rep(i, 0, sz(li)-1) {
        int a = li[i], b = li[i+1];
        ret.emplace_back(rev[lca.lca(a, b)], b);
    }
    return ret;
}
}

```

## HLD.h

**Description:** Decomposes a tree into vertex disjoint heavy paths and light edges such that the path from any leaf to the root contains at most  $\log(n)$  light edges. Code does additive modifications and max queries, but can support commutative segtree modifications/queries on paths and subtrees. Takes as input the full adjacency list. VALS.EDGES being true means that values are stored in the edges, as opposed to the nodes. All values initialized to the segtree default. Root must be 0.

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

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

```

"./data-structures/LazySegmentTree.h" 9547af, 46 lines
template<bool VALS_EDGES> struct HLD {
    int N, tim = 0;
    vector<vi> adj;
    vi par, siz, rt, pos;
    Node *tree;
    HLD(vector<vi> adj_)
        : N(sz(adj_)), adj(adj_), par(N, -1), siz(N, 1),
          rt(N), pos(N), tree(new Node(0, N)) {}
    void dfsHld(0);
    void dfsSz(int v) {
        for (int& u : adj[v]) {
            adj[u].erase(find(all(adj[u]), v));
            par[u] = v;
            dfsSz(u);
            siz[v] += siz[u];
            if (siz[u] > siz[adj[v][0]]) swap(u, adj[v][0]);
        }
    }
}

```

```

    }
}
void dfsHld(int v) {
    pos[v] = tim++;
    for (int u : adj[v]) {
        rt[u] = (u == adj[v][0] ? rt[v] : u);
        dfsHld(u);
    }
}
template <class B> void process(int u, int v, B op) {
    for (; v = par[rt[v]] ) {
        if (pos[u] > pos[v]) swap(u, v);
        if (rt[u] == rt[v]) break;
        op(pos[rt[v]], pos[v] + 1);
    }
    op(pos[u] + VALS_EDGES, pos[v] + 1);
}
void modifyPath(int u, int v, int val) {
    process(u, v, [&](int l, int r) { tree->add(l, r, val); });
}
int queryPath(int u, int v) { // Modify depending on problem
    int res = -1e9;
    process(u, v, [&](int l, int r) {
        res = max(res, tree->query(l, r));
    });
    return res;
}
int querySubtree(int v) { // modifySubtree is similar
    return tree->query(pos[v] + VALS_EDGES, pos[v] + siz[v]);
}
};

```

## LCT.h

**Description:** Link-cut tree with path and subtree queries. Path operations can be arbitrary, but subtree operations need to be reversible. Current implementation supports subtree addition and sum.

**Time:**  $\mathcal{O}(\log n)$  6758b4, 104 lines

```

struct Node {
    Node *p, *c[2];
    Node() { p = c[0] = c[1] = 0; }
    bool rev = 0;
    ll v, s, vs = 0;
    int sz, vsz = 0;
    ll d = 0, vd = 0, cc = 0;
    void add(ll x) {
        d += x, vd += x;
        v += x, s += sz * x, vs += vsz * x;
    }
    void flip() { swap(c[0], c[1]), rev ^= 1; }
    void push() {
        if (rev) {
            rep(i, 0, 2) if (c[i]) c[i]->flip();
            rev = 0;
        }
        if (d) {
            rep(i, 0, 2) if (c[i]) c[i]->add(d);
            d = 0;
        }
    }
    void pull() {
        s = v + vs;
        sz = 1 + vsz;
        if (c[0]) s += c[0]->s, sz += c[0]->sz;
        if (c[1]) s += c[1]->s, sz += c[1]->sz;
    }
    // Add a virtual edge, cancel current virtual delta
    void vadd(Node* x) {
        vs += x->s;
        vsz += x->sz;
        x->cc = vd;
    }
    // Delete a virutal edge, push the virtual delta
    void vdel(Node* x) {
        x->add(vd - x->cc);
        vs -= x->s;
        vsz -= x->sz;
        x->cc = 0;
    }
    // Swap the cancels because of a splay rotation
    void vswap(Node* x, Node* y) {
        swap(x->cc, y->cc);
    }
    int up() {
        if (!p) return -2;
        rep(i, 0, 2) if (p->c[i] == this) return i;
        return -1;
    }
}

```

```

    }
    bool isRoot() { return up() < 0; }
    friend void setLink(Node* x, Node* y, int d) {
        if (y) y->p = x;
        if (d >= 0) x->c[d] = y;
    }
    void rot() {
        int x = up(); Node* pp = p;
        setLink(pp->p, this, pp->up());
        setLink(pp, c[x ^ 1], x); setLink(this, pp, x ^ 1);
        if (pp->p) pp->p->vswap(pp, this);
        pp->pull();
    }
    void fix() { if (!isRoot()) p->fix(); push(); }
    void splay() {
        for (fix(); !isRoot(); ) {
            if (p->isRoot()) rot();
            else if (up() == p->up()) p->rot(), rot();
            else rot(), rot();
        }
        pull();
    }
};
struct LinkCut {
    vector<Node> t;
    LinkCut(int n) : t(n) {}
    void link(int u, int v) {
        makeRoot(&t[v]); access(&t[u]);
        setLink(&t[v], &t[u], 0); t[v].pull();
    }
    void cut(int u, int v) {
        makeRoot(&t[u]); access(&t[v]);
        t[v].c[0] = t[u].p = 0; t[v].pull();
    }
    bool connected(int u, int v) {
        return lca(&t[u], &t[v]);
    }
    Node* lca(Node* u, Node* v) {
        if (u == v) return u;
        access(u); access(v); if (!u->p) return 0;
        u->splay(); if (u->p) return u;
    }
    void access(Node* u) {
        for (Node* x = u, *y = 0; x; x = x->p) {
            x->splay();
            if (y) x->vdel(y);
            if (x->c[1]) x->vadd(x->c[1]);
            x->c[1] = y; x->pull(); y = x;
        }
        u->splay();
    }
    void makeRoot(Node* u) {
        access(u), u->flip(), u->push();
    }
};

```

## DirectedMST.h

**Description:** Finds a minimum spanning tree/arborescence of a directed graph, given a root node. If no MST exists, returns -1.

**Time:**  $\mathcal{O}(E \log V)$  39e620, 60 lines

```

.../data-structures/UnionFindRollback.h"
struct Edge { int a, b; ll w; };
struct Node {
    Edge key;
    Node *l, *r;
    ll delta;
    void prop() {
        key.w += delta;
        if (l) l->delta += delta;
        if (r) r->delta += delta;
        delta = 0;
    }
    Edge top() { prop(); return key; }
};
Node *merge(Node *a, Node *b) {
    if (!a || !b) return a ? b;
    a->prop(), b->prop();
    if (a->key.w > b->key.w) swap(a, b);
    swap(a->l, (a->r = merge(b, a->r)));
    return a;
}
void pop(Node* &a) { a->prop(); a = merge(a->l, a->r); }
pair<ll, vi> dmst(int n, int r, vector<Edge> &g) {
    RollbackUF uf(n);
    vector<Node*> heap(n);
    for (Edge e : g) heap[e.b] = merge(heap[e.b], new Node(e));
    ll res = 0;
}

```

```

vi seen(n, -1), path(n), par(n);
seen[r] = r;
vector<Edge> Q(n), in(n, {-1,-1}), comp;
deque<tuple<int, int, vector<Edge>>> cyscs;
rep(s,0,n) {
    int u = s, qi = 0, w;
    while (seen[u] < 0) {
        if (!heap[u]) return {-1,{} };
        Edge e = heap[u]->top();
        heap[u]->delta -= e.w, pop(heap[u]);
        Q[qi] = e, path[qi++] = u, seen[u] = s;
        res += e.w, u = uf.find(e.a);
        if (seen[u] == s) {
            Node* cyc = 0;
            int end = qi, time = uf.time();
            do cyc = merge(cyc, heap[w = path[--qi]]);
            while (uf.join(u, w));
            u = uf.find(u), heap[u] = cyc, seen[u] = -1;
            cyscs.push_front({u, time, {&Q[qi], &Q[end]}});
        }
    }
    rep(i,0,qi) in[uf.find(Q[i].b)] = Q[i];
}
for (auto& [u,t,comp] : cyscs) { // restore sol ( optional)
    uf.rollback(t);
    Edge inEdge = in[u];
    for (auto& e : comp) in[uf.find(e.b)] = e;
    in[uf.find(inEdge.b)] = inEdge;
}
rep(i,0,n) par[i] = in[i].a;
return {res, par};
}

```

## CentroidTree.h

**Description:** Centroid decomposition tree. Example usage can be extended for weighted trees with a BST.

**Time:**  $\mathcal{O}(n \log n + q \log^2 n)$

fd433b, 60 lines

```

.../data-structures/FenwickTree.h"
struct CT {
    vi sub, cp, d; // centroid subtree, parent, depth
    vector<vi> g, dst; // dst[depth][descendant]
    CT(vector<vi> &g) : sub(sz(G)), cp(sz(G), -2),
        d(sz(G)), g(G), dst(_lg(sz(G)) + 1, vi(sz(G))) {
        rec(0, 0);
    }
    void dfs(int u, int p) {
        sub[u] = 1;
        for (int v : g[u]) if (v != p && cp[v] == -2)
            dfs(v, u), sub[u] += sub[v];
    }
    void gen(int u, int p, int lev) {
        dst[lev][u] = dst[lev][p] + 1;
        for (int v : g[u]) if (v != p && cp[v] == -2)
            gen(v, u, lev);
    }
    int rec(int u, int dd) {
        dfs(u, -1);
        int p = -1, s = sub[u]; rep:
        for (int v : g[u])
            if (v != p && cp[v] == -2 && sub[v] > s / 2) {
                p = u, u = v; goto rep;
            }
        sub[u] = s, d[u] = dd, cp[u] = -1;
        for (int v : g[u]) if (cp[v] == -2)
            gen(v, u, d[u]), cp[rec(v, dd + 1)] = u;
        return u;
    }
    void path(int u, auto f) { // f(centroid, son, dist)
        for (int x = u, y = -1; x != -1; y = x, x = cp[x])
            f(x, y, dst[d[x]][u]);
    }
};
struct ContourAdd : CT {
    vector<FT> d, c;
    ContourAdd(vector<vi> &G) : CT(G), d(sz(g), FT(0)), c(d){
        rep(i, 0, sz(g)) d[i] = c[i] = FT(sub[i] + 1);
    }
    // Add x to verts whose distance from p is in [l, r)
    void add(int p, int l, int r, int x) {
        path(p, [&](int u, int v, int dd) {
            d[u].update(max(0, l - dd), x);
            if (r - dd < sub[u])
                d[u].update(max(0, r - dd), -x);
            if (v != -1) {
                c[v].update(max(0, l - dd), x);
                if (r - dd < sub[u])
                    c[v].update(max(0, r - dd), -x);
            }
        });
    }
};

```

```

ll get(int p) {
    ll ans = 0;
    path(p, [&](int u, int v, int dd) {
        ans += d[u].query(dd + 1);
        if (v != -1) ans -= c[v].query(dd + 1);
    });
    return ans;
}
};

```

## RerootDP.h

**Description:** Calculates a DP from every root in a tree. Use dp, rdp and p for edge dp.

**Time:**  $\mathcal{O}(\sum d \log d)$  c0a8b6, 40 lines

```

struct S {
    void init(int u) {}
    void join(int u, int i, const S& c) {}
    void push(int u, int i) {} // i = -1 if root
};
vector<S> reroot(vector<vi> &g) {
    int n = sz(g), t = 1;
    vi q(n), p(n);
    for (int u : q) for (int v : g[u]) if (p[u] != v) {
        p[v] = u, q[t++] = v;
    }
    vector<S> dp(n), rdp(n), ans(n);
    for (int i = n - 1; i >= 0; i--) {
        int u = q[i], k = -1;
        dp[u].init(u);
        rep(j, 0, sz(g[u])) {
            if (g[u][j] != p[u]) dp[u].join(u, j, dp[g[u][j]]);
            else k = j;
        }
        ans[u] = dp[u], dp[u].push(u, k);
    }
    if (n == 1) return dp;
    for (int u : q) {
        int d = sz(g[u]); vector<S> e(d);
        rep(i, 0, d) e[i].init(u);
        for (int b = _lg(d); b >= 0; b--) {
            for (int i = d - 1; i >= 0; i--) e[i] = e[i / 2];
            rep(i, 0, d - (d & !b)) {
                S& s = g[u][i] != p[u] ? dp[g[u][i]] : rdp[u];
                e[(i >> b) ^ 1].join(u, i, s);
            }
        }
        rep(i, 0, sz(g[u])) {
            if (p[u] != g[u][i]) (rdp[g[u][i]] = e[i]).push(u, i);
            else ans[u].join(u, i, rdp[u]);
        }
        ans[u].push(u, -1);
    }
    return ans;
}
}

```

## 7.8 Math

### 7.8.1 Number of Spanning Trees

Create an  $N \times N$  matrix mat, and for each edge  $a \rightarrow b \in G$ , do  $\text{mat}[a][b]--$ ,  $\text{mat}[b][b]++$  (and  $\text{mat}[b][a]--$ ,  $\text{mat}[a][a]++$  if  $G$  is undirected).

Remove the  $i$ th row and column and take the determinant; this yields the number of directed spanning trees rooted at  $i$  (if  $G$  is undirected, remove  $i$ th row and column).

### 7.8.2 Pólya's enumeration theorem

A simple graph with node degrees  $d_1 \geq \dots \geq d_n$  exists iff  $d_1 + \dots + d_n$  is even and for every  $k = 1 \dots n$ ,

$$\sum_{i=1}^k d_i \leq k(k-1) + \sum_{i=k+1}^n \min(d_i, k).$$

## Geometry (8)

### 8.1 Geometric primitives

#### Point.h

**Description:** Class to handle points in the plane. T can be e.g. double or long long. (Avoid int.)

```
template <class T> int sgn(T x) { return (x > 0) - (x < 0); }
template<class T>
struct Point {
    typedef Point P;
    T x, y;
    auto operator<=>(const P&) const = default;
    P operator+(P p) const { return P(x+p.x, y+p.y); }
    P operator-(P p) const { return P(x-p.x, y-p.y); }
    P operator*(T d) const { return P(x*d, y*d); }
    P operator/(T d) const { return P(x/d, y/d); }
    T dot(P p) const { return x*p.x + y*p.y; }
    T cross(P p) const { return x*p.y - y*p.x; }
    T cross(P a, P b) const { return (a->this).cross(b->this); }
    T dist2() const { return x*x + y*y; }
    double dist() const { return sqrt((double)dist2()); }
    // angle to x-axis in interval [-pi, pi]
    double angle() const { return atan2(y, x); }
    P unit() const { return this/dist(); } // makes dist 1
    P perp() const { return P(-y, x); } // rotates +90 degrees
    P normal() const { return perp().unit(); }
    // returns point rotated 'a' radians ccw around the origin
    P rotate(double a) const {
        return P(x*cos(a)-y*sin(a),x*sin(a)+y*cos(a)); }
    friend ostream& operator<<(ostream& os, P p) {
        return os << "(" << p.x << ", " << p.y << ")"; }
};
```

#### lineDistance.h

**Description:** Returns the signed distance between point p and the line containing points a and b. Positive value on left side and negative on right as seen from a towards b. a==b gives nan. P is supposed to be Point<T> or Point3D<T> where T is e.g. double or long long. It uses products in intermediate steps so watch out for overflow if using int or long long. Using Point3D will always give a non-negative distance. For Point3D, call .dist on the result of the cross product.

```
"Point.h" f6bf6b, 4 lines
template<class P>
double lineDist(const P& a, const P& b, const P& p) {
    return (double) (b-a).cross(p-a)/(b-a).dist();
}
```

#### SegmentDistance.h

**Description:** Returns the shortest distance between point p and the line segment from point s to e.

**Usage:** Point<double> a, b(2,2), p(1,1);  
bool onSegment = segDist(a,b,p) < 1e-10;

```
"Point.h" 5c88f4, 6 lines
typedef Point<double> P;
double segDist(P& s, P& e, P& p) {
    if (s==e) return (p-s).dist();
    auto d = (e-s).dist2(), t = min(d,max(.0, (p-s).dot(e-s)));
    return ((p-s)*d-(e-s)*t).dist()/d;
}
```

#### SegmentIntersection.h

**Description:** If a unique intersection point between the line segments going from s1 to e1 and from s2 to e2 exists then it is returned. If no intersection point exists an empty vector is returned. If infinitely many exist a vector with 2 elements is returned, containing the endpoints of the common line segment. The wrong position will be returned if P is Point<ll> and the intersection point does not have integer coordinates. Products of three coordinates are used in intermediate steps so watch out for overflow if using int or long long.

**Usage:** vector<P> inter = segInter(s1,e1,s2,e2);  
if (sz(inter)==1)  
cout << "segments intersect at " << inter[0] << endl;

```
"Point.h", "OnSegment.h" 9d57f2, 13 lines
```

```
template<class P> vector<P> segInter(P a, P b, P c, P d) {
    {
        auto oa = c.cross(d, a), ob = c.cross(d, b),
        oc = a.cross(b, c), od = a.cross(b, d);
        // Checks if intersection is single non-endpoint point.
        if (sgn(oa) * sgn(ob) < 0 && sgn(oc) * sgn(od) < 0)
            return {(a * ob - b * oa) / (ob - oa)};
        set<P> s;
        if (onSegment(c, d, a)) s.insert(a);
        if (onSegment(c, d, b)) s.insert(b);
        if (onSegment(a, b, c)) s.insert(c);
        if (onSegment(a, b, d)) s.insert(d);
        return {all(s)};
    }
}
```

#### lineIntersection.h

**Description:** If a unique intersection point of the lines going through s1,e1 and s2,e2 exists {1, point} is returned. If no intersection point exists {0, (0,0)} is returned and if infinitely many exists {-1, (0,0)} is returned. The wrong position will be returned if P is Point<ll> and the intersection point does not have integer coordinates. Products of three coordinates are used in intermediate steps so watch out for overflow if using int or ll.

**Usage:** auto res = lineInter(s1,e1,s2,e2);  
if (res.first == 1)  
cout << "intersection point at " << res.second << endl;

```
"Point.h" a01f81, 8 lines
template<class P>
pair<int, P> lineInter(P s1, P e1, P s2, P e2) {
    auto d = (e1 - s1).cross(e2 - s2);
    if (d == 0) // if parallel
        return {(s1.cross(e1, s2) == 0), P(0, 0)};
    auto p = s2.cross(e1, e2), q = s2.cross(e2, s1);
    return {1, (s1 * p + e1 * q) / d};
}
```

#### sideOf.h

**Description:** Returns where p is as seen from s towards e. 1/0/-1 ⇔ left/on line/right. If the optional argument eps is given 0 is returned if p is within distance eps from the line. P is supposed to be Point<T> where T is e.g. double or long long. It uses products in intermediate steps so watch out for overflow if using int or long long.

**Usage:** bool left = sideOf(p1,p2,q)==1;

```
"Point.h" 3af81c, 9 lines
template<class P>
int sideOf(P s, P e, P p) { return sgn(s.cross(e, p)); }

template<class P>
int sideOf(const P& s, const P& e, const P& p, double eps) {
    auto a = (e-s).cross(p-s);
    double l = (e-s).dist()*eps;
    return (a > l) - (a < -l);
}
```

#### OnSegment.h

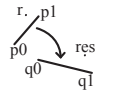
**Description:** Returns true iff p lies on the line segment from s to e. Use (segDist(s,e,p)<=epsilon) instead when using Point<double>.

```
"Point.h" c597e8, 3 lines
template<class P> bool onSegment(P s, P e, P p) {
    return p.cross(s, e) == 0 && (s - p).dot(e - p) <= 0;
}
```

#### linearTransformation.h

**Description:**  
Apply the linear transformation (translation, rotation and scaling) which takes line p0-p1 to line q0-q1 to point r.

```
"Point.h" 03a306, 6 lines
typedef Point<double> P;
P linearTransformation(const P& p0, const P& p1,
    const P& q0, const P& q1, const P& r) {
    P dp = p1-p0, dq = q1-q0, num(dp.cross(dq), dp.dot(dq));
    return q0 + P((r-p0).cross(num), (r-p0).dot(num))/dp.dist2();
}
```



#### LineProjectionReflection.h

**Description:** Projects point p onto line ab. Set refl=true to get reflection of point p across line ab instead. The wrong point will be returned if P is an integer point and the desired point doesn't have integer coordinates. Products of three coordinates are used in intermediate steps so watch out for overflow.

```
"Point.h" b5562d, 5 lines
template<class P>
P lineProj(P a, P b, P p, bool refl=false) {
    P v = b - a;
    return p - v.perp()*(1+refl)*v.cross(p-a)/v.dist2();
}
```

#### Angle.h

**Description:** A class for ordering angles (as represented by int points and a number of rotations around the origin). Useful for rotational sweeping. Sometimes also represents points or vectors.

**Usage:** vector<Angle> v = {w[0], w[0].t360() ...};  
sorted  
int j = 0; rep(i,0,n) { while (v[j] < v[i].t180())  
++j; }  
// sweeps j such that (j-i) represents the number of positively oriented triangles with vertices p[i], p[j], p[i+1]

```
"Point.h" 9f6602, 85 lines
struct Angle {
    int x, y;
    int t;
    Angle(int x, int y, int t=0) : x(x), y(y), t(t) {}
    Angle operator-(Angle b) const { return {x-b.x, y-b.y, t}; }

    int half() const {
        assert(x || y);
        return x < 0 || (y == 0 && x < 0);
    }

    Angle t90() const { return {-y, x, t + (half() && x >= 0)}; }
    Angle t180() const { return {-x, -y, t + half()}; }
    Angle t360() const { return {x, y, t + 1}; }
};

bool operator<(Angle a, Angle b) {
    // add a.dist2() and b.dist2() to also compare distances
    return make_tuple(a.t, a.half(), a.y * (ll)b.x) <
        make_tuple(b.t, b.half(), a.x * (ll)b.y);
}
```

```
// Given two points, this calculates the smallest angle between them, i.e., the angle that covers the defined line segment.
pair<Angle, Angle> segmentAngles(Angle a, Angle b) {
    if (b < a) swap(a, b);
    return (b < a.t180() ?
        make_pair(a, b) : make_pair(b, a.t360()));
}

Angle operator+(Angle a, Angle b) { // point a + vector b
    Angle r(a.x + b.x, a.y + b.y, a.t);
    if (a.t180() < r.t) r.t--;
    return r.t180() < a ? r.t360() : r;
}

Angle angleDiff(Angle a, Angle b) { // angle b - angle a
    int tu = b.t - a.t; a.t = b.t;
    return {a.x*b.x + a.y*b.y, a.x*b.y - a.y*b.x, tu - (b < a)};
}
```

#### AngleCmp.h

**Description:** Sorts points in ascending order by angle within the interval  $(-\pi, \pi]$ . The point (0,0) has an angle of 0. Equivalent to sorting by atan2(y, x).

```
"Point.h" 496e9b, 6 lines
template<class P>
bool angleCmp(P a, P b) {
    auto half = [](P p){ return sgn(p.y) ? -sgn(p.x); };
    int A = half(a), B = half(b);
    return A == B ? a.cross(b) > 0 : A < B;
}
```

#### directedSegment.h

**Description:** Segment representation usefull for sweeping. Compares two disjoint (can touch) segments on the sweep line (OY projection). Transitivity breaks if three segments touch in one point and are on different side of the sweep line. Can be easily fixed by comparing mean X coordinates.

```
"Point.h" d144f8, 15 lines
template<class P>
struct dirSeg {
    P s, e; int rev;
    dirSeg(P _s, P _e) : s(_s), e(_e), rev(0) {
        if(e < s) swap(s, e), rev = 1;
    }
    P getY(P X) { // takes x * 2, returns y * 2 as a fraction
        P d = (e - s);
        return !sgn(d.x) ? P(s.y+e.y, 1) : P(d.cross(s*2-X), d.x);
    }
    int cmp(dirSeg b) { // needs ~64 * M^3 !
        P X(max(s.x, b.s.x) + min(e.x, b.e.x), 0);
        return sgn(getY(X).cross(b.getY(X)));
    }
};
```

### 8.2 Circles

#### CircleIntersection.h

**Description:** Computes the pair of points at which two circles intersect. Returns false in case of no intersection.

```
"Point.h" 84d6d3, 11 lines
typedef Point<double> P;
bool circleInter(P a,P b,double r1,double r2,pair<P, P> &x) out {
    if (a == b) { assert(r1 != r2); return false; }
    P vec = b - a;
    double d2 = vec.dist2(), sum = r1+r2, dif = r1-r2,
        p = (d2 + r1*r1 - r2*r2)/(d2*2), h2 = r1*r1 - p*p*d2;
    if (sum*sum < d2 || dif*dif > d2) return false;
    P mid = a + vec*p, per = vec.perp() * sqrt(fmax(0, h2) / d2);
    *out = {mid + per, mid - per};
    return true;
}
```

#### CircleTangents.h

**Description:** Finds the external tangents of two circles, or internal if r2 is negated. Can return 0, 1, or 2 tangents – 0 if one circle contains the other (or overlaps it, in the internal case, or if the circles are the same); 1 if the circles are tangent to each other (in which case .first = .second and the tangent line is perpendicular to the line between the centers). .first and .second give the tangency points at circle 1 and 2 respectively. To find the tangents of a circle with a point set r2 to 0.

```
"Point.h" b0153d, 13 lines
template<class P>
vector<pair<P, P>> tangents(P c1, double r1, P c2, double r2) {
    P d = c2 - c1;
    double dr = r1 - r2, d2 = d.dist2(), h2 = d2 - dr * dr;
    if (d2 == 0 || h2 < 0) return {};
    vector<pair<P, P>> out;
    for (double sign : {-1, 1}) {
        P v = (d * dr + d.perp() * sqrt(h2) * sign) / d2;
        out.push_back({c1 + v * r1, c2 + v * r2});
    }
    if (h2 == 0) out.pop_back();
    return out;
}
```

#### CircleLine.h

**Description:** Finds the intersection between a circle and a line. Returns a vector of either 0, 1, or 2 intersection points. P is intended to be Point<double>.

```
"Point.h" e0cfba, 9 lines
template<class P>
vector<P> circleLine(P a, double r, P a, P b) {
    P ab = b - a, p = a + ab * (-a).dot(ab) / ab.dist2();
    double s = a.cross(b, c), h2 = r*r - s*s / ab.dist2();
    if (h2 < 0) return {};
    if (h2 == 0) return {p};
    P h = ab.unit() * sqrt(h2);
    return {p - h, p + h};
}
```



# CirclePolygonIntersection.h

**Description:** Returns the area of the intersection of a circle with a ccw polygon.

**Time:**  $\mathcal{O}(n)$

---

```

"../../content/geometry/Point.h" 19add1, 19 lines

typedef Point<double> P;
#define arg(p, q) atan2(p.cross(q), p.dot(q))
double circlePoly(P c, double r, vector<P> ps) {
    auto tri = [&](P p, P q) {
        auto r2 = r * r / 2;
        P d = q - p;
        auto a = d.dot(p) / d.dist2(), b = (p.dist2() - r * r) / d.dist2();
        auto det = a * a - b;
        if (det <= 0) return arg(p, q) * r2;
        auto s = max(0., -a - sqrt(det)), t = min(1., -a + sqrt(det));
        if (t < 0 || 1 <= s) return arg(p, q) * r2;
        P u = p + d * s, v = q + d * (t - 1);
        return arg(p, u) * r2 + u.cross(v) / 2 + arg(v, q) * r2
    };
    auto sum = 0.0;
    rep(i, 0, sz(ps))
        sum += tri(ps[i] - c, ps[(i + 1) % sz(ps)] - c);
    return sum;
}

```

## circumcircle.h

**Description:** The circumcircle of a triangle is the circle intersecting all three vertices. ccRadius returns the radius of the circle going through points A, B and C and ccCenter returns the center of the same circle.

```

"Point.h" 1caa3a, 9 lines
typedef Point<double> P;
double ccRadius(const P& A, const P& B, const P& C) {
    return (B-A).dist2()* (C-B).dist2()* (A-C).dist2() /
        abs2((B-A).cross(C-A))/2;
}
P ccCenter(const P& A, const P& B, const P& C) {
    P b = C-A, c = B-A;
    return A + (b*c.dist2()-c*b.dist2()).perp()/b.cross(c)
        )/2;
}

```

## MinimumEnclosingCircle.h

**Description:** Computes the minimum circle that encloses a set of points.

```

Time: expected  $\mathcal{O}(n)$ 
"circumcircle.h" 09dd0a, 17 lines
pair<P, double> mec(vector<P> ps) {
  shuffle(all(ps), mt19937(time(0)));
  P o = ps[0];
  double r = 0, EPS = 1 + 1e-8;
  rep(i, 0, sz(ps)) if ((o - ps[i]).dist() > r * EPS) {
    o = ps[i], r = 0;
    rep(j, 0, i) if ((o - ps[j]).dist() > r * EPS) {
      o = (ps[i] + ps[j]) / 2;
      r = (o - ps[i]).dist();
      rep(k, 0, j) if ((o - ps[k]).dist() > r * EPS) {
        o = ccCenter(ps[i], ps[j], ps[k]);
        r = (o - ps[i]).dist();
      }
    }
  }
  return {o, r};
}

```

## CirclesUnionArea.h

**Description:** Returns the area of the sum of circles.

```
Time:  $\mathcal{O}(n^2 \log n)$ 
"CircleIntersection.h" 2be987, 34 lines
template<typename T> // double or long double
T CircleArea(Area<pair<P, T>> c) {
    const T PI = acos((T)-1);
    sort(all(c)); c.erase(unique(all(c)), c.end());
    T res = 0;
    for(auto &[p, r]: c) {
        int cnt = 0, cover = 0;

```

```

vector<pair<T, int>> eve = {{-PI, 0}};
for(auto &[q, s]: c) if(make_pair(p, r) !=
    make_pair(q, s)) {
    T dst = (p - q).dist();
    if(r + dst <= s) { cover = 1; break; }
    pair<P, P> inters;
    if(!circleInter(p, q, r, s, &inters)) continue;
    T le = (inters.first - p).angle();
    T re = (inters.second - p).angle();
    cnt += le > re;
    eve.pb({le, 1}), eve.pb({re, -1});
}
if(cover) continue;
sort(eve.begin() + 1, eve.end());
eve.pb({PI, 0});
T loc = 0;
rep(i, 1, SZ(eve)) {
    if(!cnt) {
        T a = eve[i-1].first, b = eve[i].first;
        loc += r * (b - a) +
            p.cross(P(cos(b)-cos(a), sin(b)-sin(a)));
    }
    cnt += eve[i].second;
}
res += r * loc;
}
return res / 2;
}

```

### 8.3 Polygons

# InsidePolygon.h

**Description:** Returns true if  $p$  lies within the polygon. If `strict` is true, it returns false for points on the boundary. The algorithm uses products in intermediate steps so watch out for overflow.

```
Usage: vector<P> v = {P{4,4}, P{1,2}, P{2,1}};  
bool in = inPolygon(v, P{3, 3}, false);
```

```

Time:  $\mathcal{O}(n)$ 
"Point.h", "OnSegment.h", "SegmentDistance.h" 2bf504, 11 lines
template<class P>
bool inPolygon(vector<P> &p, P a, bool strict = true) {
    int cnt = 0, n = sz(p);
    rep(i,0,n) {
        P q = p[(i + 1) % n];
        if (onSegment(p[i], q, a)) return !strict;
        //or: if (segDist(p[i], q, a) <= eps) return !
            strict;
        cnt ^= ((a.y<p[i].y) - (a.y<q.y)) * a.cross(p[i], q
            ) > 0;
    }
    return cnt;
}

```

## PolygonArea.h

**Description:** Returns twice the signed area of a polygon. Clockwise enumeration gives negative area. Watch out for overflow if using int as T!

```

"Point.h"                                     f12300, 6 lines
template<class T>
T polygonArea2(vector<Point<T>>& v) {
    T a = v.back().cross(v[0]);
    rep(i,0,sz(v)-1) a += v[i].cross(v[i+1]);
    return a;
}

```

## PolygonCenter.h

**Description:** Returns the center of mass for a polygon.

```

Time:  $\mathcal{O}(n)$ 
"Point.h" 9706dc, 9 lines
typedef Point<double> P;
P polygonCenter(const vector<P>& v) {
    P res(0, 0); double A = 0;
    for (int i = 0, j = sz(v) - 1; i < sz(v); j = i++) {
        res = res + (v[i] + v[j]) * v[j].cross(v[i]);
        A += v[j].cross(v[i]);
    }
    return res / A / 3;
}

```

# PolygonCut.h

**Description:**  
Returns a vector with the vertices of a polygon with everything to the left of the line going from s to e cut away.



```
Usage: vector<P> p = ...;
p = polygonCut(p, P(0,0), P(1,0));
"Point.h" d07181, 13 lines

typedef Point<double> P;
vector<P> polygonCut(const vector<P>& poly, P s, P e) {
    vector<P> res;
    rep(i,0,sz(poly)) {
        P cur = poly[i], prev = i ? poly[i-1] : poly.back()
        ;
        auto a = s.cross(e, cur), b = s.cross(e, prev);
        if ((a < 0) != (b < 0))
            res.push_back(cur + (prev - cur) * (a / (a - b)))
            ;
        if (a < 0)
            res.push_back(cur);
    }
    return res;
}
```

# PolygonUnion.h

**Description:** Calculates the area of the union of  $n$  polygons (not necessarily convex). The points within each polygon must be given in CCW order. (Epsilon checks may optionally be added to `sideOf/sgn`, but shouldn't be needed.)

**Time:**  $\mathcal{O}(N^2)$ , where  $N$  is the total number of points

```

"Point.h", "sideOf.h"                                     3931c6, 33 lines
typedef Point<double> P;
double rat(P a, P b) { return sgn(b.x) ? a.x/b.x : a.y/
    b.y;};
double polyUnion(vector<vector<P>>& poly) {
    double ret = 0;
    rep(i,0,sz(poly)) rep(v,0,sz(poly[i])) {
        P A = poly[i][v], B = poly[i][(v + 1) % sz(poly[i])];
        vector<pair<double, int>> segs = {{0, 0}, {1, 0}};
        rep(j,0,sz(poly[i])) if (i != j) {
            rep(u,0,sz(poly[j])) {
                P C = poly[j][u], D = poly[j][(u + 1) % sz(poly[j])];
                int sc = sideOf(A, B, C), sd = sideOf(A, B, D);
                if (sc != sd) {
                    double sa = C.cross(D, A), sb = C.cross(D, B);
                    if (min(sc, sd) < 0)
                        segs.emplace_back(sa / (sa - sb), sgn(sc - sd));
                } else if (!sc && !sd && j<i && sgn((B-A).dot(D-C))>0){
                    segs.emplace_back(rat(C - A, B - A), 1);
                    segs.emplace_back(rat(D - A, B - A), -1);
                }
            }
        }
    }
    sort(all(segs));
    for (auto& s : segs) s.first = min(max(s.first, 0.0), 1.0);
    double sum = 0;
    int cnt = segs[0].second;
    rep(j,1,sz(segs)) {
        if (!cnt) sum += segs[j].first - segs[j - 1].first;
        cnt += segs[j].second;
    }
    ret += A.cross(B) * sum;
}
return ret / 2;
}

```

# PolygonTangents.h

**Description:** Polygon tangents from a given point. The polygon must be ccw and have no collinear points. Returns a pair of indices of the given polygon. Should work for a point on border (for a point being polygon vertex returns previous and next one).

**Time:**  $\mathcal{O}(\log n)$   
 "Point.h" 096fab, 21 lines

```
#define pdir(i) (ph ? p - poly[(i)%n] : poly[(i)%n] - p)
#define cmp(i,j) sgn(pdir(i).cross(poly[(i)%n]-poly[(j)%n]))
#define extr(i) cmp(i+1,i) >= 0 && cmp(i,i-1+n) < 0
template <class P>
array<int, 2> polygonTangents(vector<P>& poly, P p) {
    auto bs = [&](int ph) {
        int n = sz(poly), lo = 0, hi = n;

```

```

if(extr(0)) return 0;
while(lo + 1 < hi) {
    int m = (lo + hi) / 2;
    if(extr(m)) return m;
    int ls = cmp(lo + 1, lo), ms = cmp(m + 1, m);
    (ls < ms || (ls == ms && ls == cmp(lo, m)) ? hi :
     lo) = m;
}
return lo;
};
array<int, 2> res = {bs(0), bs(1)};
if(res[0] == res[1]) res[0] = (res[0] + 1) % sz(poly)
;
if(poly[res[0]] == p) res[0] = (res[0] + 1) % sz(poly)
;
return res;
}

```

## ConvexHull.h

**Description:** Returns a vector of the points of the convex hull in counter-clockwise order. Points on the edge of the hull between two other points are not considered part of the hull.

**Time:**  $\mathcal{O}(n \log n)$   
 "Point.h" 310954, 13 lines

```
typedef Point<ll> P;
vector<P> convexHull(vector<P> pts) {
    if (sz(pts) <= 1) return pts;
    sort(all(pts));
    vector<P> h(sz(pts)+1);
    int s = 0, t = 0;
    for (int it = 2; it--; s = --t, reverse(all(pts)))
        for (P p : pts) {
            while (t >= s + 2 && h[t-2].cross(h[t-1], p) <=
                    0) t--;
            h[t++] = p;
        }
    return {h.begin(), h.begin() + t - (t == 2 && h[0] ==
            h[1])};
}
```

## ConvexHullOnline.h

**Description:** Allows online point insertion. If exists, left vertical segment is included; right one is excluded. To get a lower hull add  $(-x, -y)$  instead of  $(x, y)$ .

**Time:** amortized  $\mathcal{O}(\log n)$  per add  
 "Point.h" 10c55b, 16 lines

```
using P = Point<ll>;
struct UpperHull : set<P> {
    bool rm(auto it) {
        if (it==begin() || it==end() || next(it)==end() ||
            it->cross(*prev(it), *next(it)) > 0)
            return false;
        erase(it); return true;
    }
    bool add(P p) { // true iff added
        auto [it, ok] = emplace(p);
        if (!ok || rm(it)) return false;
        while (rm(next(it)));
        while (it != begin() && rm(prev(it)));
        return true;
    }
};
```

## ConvexHullOnline2.h

**Description:** Fully dynamic upper / lower convex hull, can be used for computing onion layers. All points should be known in advance. Points on the edges are included in the hull. Return indices are the same as in the input.

**Time:**  $\mathcal{O}(\log^2 n)$ , as fast as other  $\mathcal{O}(\log n)$  hulls

"Point.h"	78db53, 70 lines
-----------	------------------

```
template<class T>
struct DynHull {
    using P = Point<T>;
    struct Node { int l, r; }; vector<P> ps;
    int n; vi in, id; int s; vector<Node> t; vector<T> m;
    DynHull(vector<P> _ps, bool lower = 0, int start =
        -1)
    {
        ps(_ps), n(sz(ps)), in(n), id(n) {
            if(start == -1) start = n;
            s = 1; while (s < n) s = 2;
            t.resize(s * 2, {-1, -1}); m.resize(s);
            vector<pair<P, int>> pts;
            rep(i, 0, n) pts.push_back({ps[i] * (lower ? -1 :
                1), i});
            sort(all(pts));
        }
    }
};
```



**HullDiameter.h**  
**Description:** Returns the two points with max distance on a convex hull (ccw, no duplicate/collinear points).  
**Time:**  $\mathcal{O}(n)$

# LineHullIntersection.h

**Description:** Line-convex polygon intersection. The polygon must be ccw and have no collinear points. lineHull(line, poly) returns a pair describing the intersection of a line with the polygon:  $\bullet (-1, -1)$  if no collision,  $\bullet (i, -1)$  if touching the corner  $i$ ,  $\bullet (i, i)$  if along side  $(i, i + 1)$ ,  $\bullet (i, j)$  if crossing sides  $(i, i + 1)$  and  $(j, j + 1)$ . In the last case, if a corner  $i$  is crossed, this is treated as happening on side  $(i, i + 1)$ . The points are returned in the same order as the line hits the polygon. extrVertex returns the point of a hull with the max projection onto a line.

**Time:**  $\mathcal{O}(\log n)$

```
"Point.h" 7cf45b, 39 lines

#define cmp(i, j)  sgn(dir.perp().cross(poly[(i)%n]-poly
    [(j)%n]))
#define extr(i)  cmp(i + 1, i) >= 0 && cmp(i, i - 1 + n)
    < 0
template <class P> int extrVertex(vector<P>& poly, P
    dir) {
    int n = sz(poly), lo = 0, hi = n;
    if (extr(0)) return 0;
    while (lo + 1 < hi) {
        int m = (lo + hi) / 2;
        if (extr(m)) return m;
        int ls = cmp(lo + 1, lo), ms = cmp(m + 1, m);
        (ls < ms || (ls == ms && ls == cmp(lo, m)) ? hi :
            lo) = m;
    }
    return lo;
}
```

Minkowski.h	
<b>Description:</b> Computes Minkowski sum of two convex polygons in ccw order. Vertices are required to be in ccw order.	
<b>Time:</b> $\mathcal{O}(n + m)$	
<code>"Point.h", "Angle.h"</code>	7d8a28, 18 lines

```

using T = ll; // has to fit 2*|pts|**2
using P = Point<T>; // only cross needed
using SuperT = __int128_t; // has to fit 6*|pts|**3
const SuperT EPS = 1e-12; // |pts| <= 10^6 (for T=dbl)
struct Line {
    T a,b,c;
    Line(T a_=0, T b_=0, T c_=0): a(a_), b(b_), c(c_) {}
    //ax + by + c >= 0 (coords <= 10^9)
    Line(P p, P q): a(p.y-q.y), b(q.x-p.x), c(p.cross(q)) {}
    //p->q ccw (coords <= 10^6)
    Line operator- () const {return Line(-a, -b, -c); }
    bool up() const { return a?(a<0):(b>0); }
    P v() const {return P(a,b);}
    P vx() {return P(b,c); } P vy() {return P(a,c); }
    T wek(Line p) const {return v().cross(p.v());}
    bool operator<(Line b) const {
        if (up() != b.up()) return up() > b.up();
        return wek(b) > 0;
    }
};

bool parallel(Line a, Line b) {return !a.wek(b);}
bool same(Line a, Line b) {
    return parallel(a,b) && !a.vy().cross(b.vy()) && !a.vx().cross(b.vx());
}

T weaker (Line a, Line b) {
    if (abs(a.a)> abs(a.b)) return a.c*abs(b.a) - b.c*a.a;
    return a.c*abs(b.b) - b.c*a.a;
}

array<SuperT, 3> intersect(Line a, Line b) {
    SuperT det = a.wek(b);
    SuperT x = a.vx().cross(b.vx());
    SuperT y = a.vy().cross(b.vy());
    // if (det==0) return {x / det, -y / det, 1.0};
    if (det > 0) return {x, -y, det};
    return {-x, y, -det};
}

struct HPI {
    bool empty=0, pek=0;
    set<Line> s;
    typedef set<Line>::iterator iter;
    iter next(iter it){return ++it == s.end() ? s.begin() : it;}
    iter prev(iter it){return it == s.begin() ? --s.end() : --it;}
    bool hide(Line a, Line b, Line c) { // do a,b hide c?
        if (parallel(a,b) ) {
            if (weaker(a, -b) < 0) empty = 1;
            return 0;
        }
        if (a.wek(b) < 0) swap(a,b);
        auto {rx, ry, rdet} = intersect(a,b);
        auto v = rx*c.a + ry*c.b + rdet*c.c;
        if (a.wek(c) >=0 && c.wek(b) >=0 && v >= -EPS)
            return 1;
        if (a.wek(c) < 0 && c.wek(b) < 0) {
            if (v < -EPS) empty = 1;
            else if (v <= EPS) pek = 1;
        }
        return 0;
    }
}

void delAndMove(iter& i, int nxt) {
    iter j = i;

```

**PointLocation.h**  
**description:** Computes (not necessarily convex) polygon tree structure. Also for each query point computes its location (including boundaries).

```

name:  $O(n \log n)$ 
directedSegment.h"
00f077f, 47 lines

template<class P>
aircvi,vi> pointLoc(vector<vector<P>> polys, vector<P>
    pts) {
vector<tuple<P, int, int>> eve; // {point, event_type
    , id}
vector<pair<dirSeg<P>, int>> segs; // {s, e, poly_id
    , i}
rep(i, 0, sz(polys)) rep(j, 0, sz(polys[i])) {
    dirSeg<P> seg(polys[i][j], polys[i][j+1]*sz(polys[
        i]));
    eve.push_back({seg.s, 0, sz(segs)}), eve.push_back({
        seg.e, 2, sz(segs)});
    segs.push_back({seg, i});
}
rep(i, 0, sz(pts)) eve.push_back({pts[i], 1, i});
sort(all(eve));
vi par(sz(polys), -2), ans(sz(pts), -1);
auto cmp = [](auto a, auto b) {
    return make_pair(a.first.cmp(b.first), a.second) <
        make_pair(0, b.second);
};
set<pair<dirSeg<P>, int>, decltype(cmp)> s(cmp);
for(auto &[_ , eve_tp, id]: eve) {
    if(eve_tp == 1) { // point query
        P p = pts[id];
        auto it = s.lower_bound({dirSeg(p, p), 0});
        if(it != s.begin()) { // on vertical segment?
            auto prv = prev(it);
            if(!sgn(p.cross(prv->first.s, prv->first.e)))
                it--;
        }
        if(it == s.end()) ans[id] = -1;
    } else {
        auto [seg, seg_id] = *it;
        int poly_id = segs[seg_id].second; //
            strictness there!
        ans[id] = !seg.rev && sgn(p.cross(seg.s, seg.e)
            )
    }
}

```

```

    ? par[poly_id] : poly_id;
}
}
if(eve_tp == 0) { // add segment
    auto it = next(s.insert({segs[id].first, id})).first();
    int poly_id = segs[id].second;
    if(par[poly_id] == -2) {
        if(it == s.end()) par[poly_id] = -1;
        else {
            int up_rev = it->first.rev, up_id = segs[it->second].second;
            par[poly_id] = !up_rev ? par[up_id] : up_id;
        }
    }
    if(eve_tp == 2) s.erase({segs[id].first, id}); // del segment
}
return {par, ans};
}

```

## 8.4 Misc. Point Set Problems

### ClosestPair.h

**Description:** Finds the closest pair of points.

**Time:**  $\mathcal{O}(n \log n)$

"Point.h"	ac41a6, 17 lines
-----------	------------------

```

typedef Point<ll> P;
pair<P, P> closest(vector<P> v) {
    assert(sz(v) > 1);
    set<P> S;
    sort(all(v), [](P a, P b) { return a.y < b.y; });
    pair<ll, pair<P, P>> ret{LLONG_MAX, {P(), P()}};
    int j = 0;
    for (P p : v) {
        P d(1 + (ll)sqrt(ret.first), 0);
        while (v[j].y <= p.y - d.x) S.erase(v[j++]);
        auto lo = S.lower_bound(p - d), hi = S.upper_bound(p + d);
        for (; lo != hi; ++lo)
            ret = min(ret, {(lo - p).dist2(), (*lo, p)});
        S.insert(p);
    }
    return ret.second;
}

```

### ManhattanMST.h

**Description:** Given  $N$  points, returns up to  $4*N$  edges, which are guaranteed to contain a minimum spanning tree for the graph with edge weights  $w(p, q) = -p.x - q.x + -p.y - q.y$ . Edges are in the form (distance, src, dst). Use a standard MST algorithm on the result to find the final MST.

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

"Point.h"	df6f59, 23 lines
-----------	------------------

```

typedef Point<int> P;
vector<array<int, 3>> manhattanMST(vector<P> ps) {
    vi id(sz(ps));
    iota(all(id), 0);
    vector<array<int, 3>> edges;
    rep(k, 0, 4) {
        sort(all(id), [&](int i, int j) {
            return (ps[i]-ps[j]).x < (ps[j]-ps[i]).y; });
        map<int, int> sweep;
        for (int i : id) {
            for (auto it = sweep.lower_bound(-ps[i].y);
                 it != sweep.end(); sweep.erase(it++)) {
                int j = it->second;
                P d = ps[i] - ps[j];
                if (d.y > d.x) break;
                edges.push_back({d.y + d.x, i, j});
            }
            sweep[-ps[i].y] = i;
        }
        for (P& p : ps) if (k & 1) p.x = -p.x; else swap(p.x, p.y);
    }
    return edges;
}

```

### kdTree.h

**Description:** KD-tree (2d, can be extended to 3d)

"Point.h"	bac5b0, 63 lines
-----------	------------------

```

typedef long long T;
typedef Point<T> P;
const T INF = numeric_limits<T>::max();
bool on_x(const P& a, const P& b) { return a.x < b.x; }
bool on_y(const P& a, const P& b) { return a.y < b.y; }

```

```

struct Node {
    P pt; // if this is a leaf, the single point in it
    T x0 = INF, x1 = -INF, y0 = INF, y1 = -INF; // bounds
    Node *first = 0, *second = 0;
    T distance(const P& p) { // min squared distance to a point
        T x = (p.x < x0 ? x0 : p.x > x1 ? x1 : p.x);
        T y = (p.y < y0 ? y0 : p.y > y1 ? y1 : p.y);
        return (P(x,y) - p).dist2();
    }
    Node(vector<P>&& vp) : pt(vp[0]) {
        for (P p : vp) {
            x0 = min(x0, p.x); x1 = max(x1, p.x);
            y0 = min(y0, p.y); y1 = max(y1, p.y);
        }
        if (vp.size() > 1) {
            // split on x if width >= height (not ideal...)
            sort(all(vp), x1 - x0 >= y1 - y0 ? on_x : on_y);
            // divide by taking half the array for each child (not
            // best performance with many duplicates in the middle)
            int half = sz(vp)/2;
            first = new Node({vp.begin(), vp.begin() + half});
            second = new Node({vp.begin() + half, vp.end()});
        }
    }
};

struct KDTree {
    Node* root;
    KDTree(const vector<P>& vp) : root(new Node({all(vp)})) {}
    pair<T, P> search(Node *node, const P& p) {
        if (!node->first) {
            // uncomment if we should not find the point itself:
            // if (p == node->pt) return {INF, P()};
            return make_pair((p - node->pt).dist2(), node->pt);
        }
        Node *f = node->first, *s = node->second;
        T bfirst = f->distance(p), bsec = s->distance(p);
        if (bfirst > bsec) swap(bsec, bfirst), swap(f, s);
        // search closest side first, other side if needed
        auto best = search(f, p);
        if (bsec < best.first)
            best = min(best, search(s, p));
        return best;
    }
    // find nearest point to a point, and its squared distance
    // (requires an arbitrary operator< for Point)
    pair<T, P> nearest(const P& p) {
        return search(root, p);
    }
};

```

### FastDelaunay.h

**Description:** Fast Delaunay triangulation. Each circumcircle contains none of the input points. There must be no duplicate points. If all points are on a line, no triangles will be returned. Should work for doubles as well, though there may be precision issues in 'circl'. Returns triangles in order  $\{t[0][0], t[0][1], t[0][2], t[1][0], \dots\}$ , all counter-clockwise.

**Time:**  $\mathcal{O}(n \log n)$

"Point.h"	eeefd5, 88 lines
-----------	------------------

```

typedef Point<ll> P;
typedef struct Quad* Q;
typedef __int128_t ll1; // (can be ll if coords are < 2^64)
P arb(LLONG_MAX, LLONG_MAX); // not equal to any other point
struct Quad {
    Q rot, o; P p = arb; bool mark;
    P& F() { return r()->p; }
    Q& r() { return rot->rot; }
    Q prev() { return rot->o->prev; }
    Q next() { return r()->prev; }
} *H;
bool circ(P p, P a, P b, P c) { // is p in the circumcircle?
    ll1 p2 = p.dist2(), A = a.dist2()-p2,
        B = b.dist2()-p2, C = c.dist2()-p2;
    return p.cross(a,b)*C + p.cross(b,c)*A + p.cross(c,a)*B > 0;
}
Q makeEdge(P orig, P dest) {
    Q r = H ? H : new Quad(new Quad(new Quad{0}));
}

```

```

H = r->o; r->r()->r() = r;
rep(i,0,4) r = r->rot, r->p = arb, r->o = i & 1 ? r : r->r();
r->p = orig; r->F() = dest;
return r;
}

void splice(Q a, Q b) {
    swap(a->o->rot->o, b->o->rot->o); swap(a->o, b->o);
}

Q connect(Q a, Q b) {
    Q q = makeEdge(a->F(), b->p);
    splice(q, a->next());
    splice(q->r(), b);
    return q;
}

pair<Q,Q> rec(const vector<P>& s) {
    if (sz(s) <= 3) {
        Q a = makeEdge(s[0], s[1]), b = makeEdge(s[1], s.back());
        if (sz(s) == 2) return {a, a->r()};
        splice(a->r(), b);
        auto side = s[0].cross(s[1], s[2]);
        Q c = side ? connect(b, a) : 0;
        return {side < 0 ? c->r() : a, side < 0 ? c : b->r()};
    }
}

#define H(e) e->F(), e->p
#define valid(e) (e->F().cross(H(base)) > 0)
Q A, B, ra, rb;
tie(ra, A) = rec(all(s) - half);
tie(B, rb) = rec((sz(s) - half + all(s)));
while ((B->p.cross(H(A)) < 0 && (A = A->next())) || (A->p.cross(H(B)) > 0 && (B = B->r()->o)));
Q base = connect(B->r(), A);
if (A->p == ra->p) ra = base->r();
if (B->p == rb->p) rb = base;
#define DEL(e, init, dir) Q e = init->dir; if (valid(e))
while (circ(e->dir->F(), H(base), e->F())) { \
    Q t = e->dir; \
    splice(e, e->prev()); \
    splice(e->r(), e->r()->prev()); \
    e->o = H; H = e; e = t; \
}

for(;;) {
    DEL(LC, base->r(), o); DEL(RC, base, prev());
    if (!valid(LC) && !valid(RC)) break;
    if (!valid(LC) || (valid(RC) && circ(H(RC), H(LC))))
        base = connect(RC, base->r());
    else
        base = connect(base->r(), LC->r());
}
return {ra, rb};
}

vector<P> triangulate(vector<P> pts) {
    sort(all(pts)); assert(unique(all(pts)) == pts.end());
}

if (sz(pts) < 2) return {};
Q e = rec(pts).first;
vector<Q> q = {e};
int qi = 0;
while (e->o->F().cross(e->F(), e->p) < 0) e = e->o;
#define ADD { Q c = e; do { c->mark = 1; pts.push_back(c->p); \
    q.push_back(c->r()); c = c->next(); } while (c != e);
ADD; pts.clear();
while (qi < sz(q)) if (!(e = q[qi++])->mark) ADD;
return pts;
}

```

## 8.5 3D

### PolyhedronVolume.h

**Description:** Magic formula for the volume of a polyhedron. Faces should point outwards.

	3058c3, 6 lines
--	-----------------

```

template<class V, class L>
double signedPolyVolume(const V& p, const L& trilst) {
    double v = 0;
    for (auto i : trilst) v += p[i.a].cross(p[i.b]).dot(p[i.c]);
    return v / 6;
}

```

### Point3D.h

**Description:** Class to handle points in 3D space. T can be e.g. double or long long.

```

template<class T> struct Point3D {
    typedef Point3D P;
    typedef const P& R;
    T x, y, z;
    explicit Point3D(T x=0, T y=0, T z=0) : x(x), y(y), z(z) {}
    bool operator<(R p) const {
        return tie(x, y, z) < tie(p.x, p.y, p.z);
    }
    bool operator==(R p) const {
        return tie(x, y, z) == tie(p.x, p.y, p.z);
    }
    P operator+(R p) const { return P(x+p.x, y+p.y, z+p.z); }
    P operator-(R p) const { return P(x-p.x, y-p.y, z-p.z); }
    P operator*(T d) const { return P(x*d, y*d, z*d); }
    P operator/(T d) const { return P(x/d, y/d, z/d); }
    T dot(R p) const { return x*p.x + y*p.y + z*p.z; }
    P cross(R p) const {
        return P(y*p.z - z*p.y, z*p.x - x*p.z, x*p.y - y*p.x);
    }
    T dist2() const { return x*x + y*y + z*z; }
    double dist() const { return sqrt((double)dist2()); }
    //Azimuthal angle (longitude) to x-axis in interval [-pi, pi]
    double phi() const { return atan2(y, x); }
    //Zenith angle (latitude) to the z-axis in interval [0, pi]
    double theta() const { return atan2(sqrt(x*x+y*y), z); }
    P unit() const { return *this/(T)dist(); } //makes dist()==1
    //returns unit vector normal to *this and p
    P normal(P p) const { return cross(p,unit()); }
    //returns point rotated 'angle' radians ccw around axis
    P rotate(double angle, P axis) const {
        double s = sin(angle), c = cos(angle); P u = axis.unit();
        return u*dot(u)*s*(1-c) + (*this)*c - cross(u)*s;
    }
};

```

### 3dHull.h

**Description:** Computes all faces of the 3-dimension hull of a point set. \*No four points must be coplanar\*, or else random results will be returned. All faces will point outwards.

**Time:**  $\mathcal{O}(n^2)$

"Point3D.h"	5b45fc, 49 lines
-------------	------------------

```

typedef Point3D<double> P3;
struct PR {
    void ins(int x) { (a == -1 ? a : b) = x; }
    void rem(int x) { (a == x ? a : b) = -1; }
    int cnt() { return (a != -1) + (b != -1); }
    int a, b;
};
vector<P> triangulate(vector<P> pts) {
    sort(all(pts)); assert(unique(all(pts)) == pts.end());
}

if (sz(pts) < 2) return {};
Q e = rec(pts).first;
vector<Q> q = {e};
int qi = 0;
while (e->o->F().cross(e->F(), e->p) < 0) e = e->o;
#define ADD { Q c = e; do { c->mark = 1; pts.push_back(c->p); \
    q.push_back(c->r()); c = c->next(); } while (c != e);
ADD; pts.clear();
while (qi < sz(q)) if (!(e = q[qi++])->mark) ADD;
return pts;
}

template<class V, class L>
double signedPolyVolume(const V& p, const L& trilst) {
    double v = 0;
    for (auto i : trilst) v += p[i.a].cross(p[i.b]).dot(p[i.c]);
    return v / 6;
}

template<class T> struct Point3D {
    typedef Point3D P;
    typedef const P& R;
    T x, y, z;
    explicit Point3D(T x=0, T y=0, T z=0) : x(x), y(y), z(z) {}
    bool operator<(R p) const {
        return tie(x, y, z) < tie(p.x, p.y, p.z);
    }
    bool operator==(R p) const {
        return tie(x, y, z) == tie(p.x, p.y, p.z);
    }
    P operator+(R p) const { return P(x+p.x, y+p.y, z+p.z); }
    P operator-(R p) const { return P(x-p.x, y-p.y, z-p.z); }
    P operator*(T d) const { return P(x*d, y*d, z*d); }
    P operator/(T d) const { return P(x/d, y/d, z/d); }
    T dot(R p) const { return x*p.x + y*p.y + z*p.z; }
    P cross(R p) const {
        return P(y*p.z - z*p.y, z*p.x - x*p.z, x*p.y - y*p.x);
    }
    T dist2() const { return x*x + y*y + z*z; }
    double dist() const { return sqrt((double)dist2()); }
    //Azimuthal angle (longitude) to x-axis in interval [-pi, pi]
    double phi() const { return atan2(y, x); }
    //Zenith angle (latitude) to the z-axis in interval [0, pi]
    double theta() const { return atan2(sqrt(x*x+y*y), z); }
    P unit() const { return *this/(T)dist(); } //makes dist()==1
    //returns unit vector normal to *this and p
    P normal(P p) const { return cross(p,unit()); }
    //returns point rotated 'angle' radians ccw around axis
    P rotate(double angle, P axis) const {
        double s = sin(angle), c = cos(angle); P u = axis.unit();
        return u*dot(u)*s*(1-c) + (*this)*c - cross(u)*s;
    }
};
rep(i,0,4) rep(j,i+1,4) rep(k,j+1,4)
    mf(i, j, k, 6 - i - j - k);
rep(i,4,sz(A)) {
    rep(j,0,sz(FS)) {
        F f = FS[j];
        if(f.q.dot(A[i]) > f.q.dot(A[f.a])) {
            E(a,b).rem(f.c);
            E(a,c).rem(f.b);
            E(b,c).rem(f.a);
            swap(FS[j--], FS.back());
            FS.pop_back();
        }
    }
    int nw = sz(FS);
    rep(j,0,nw) {
        F f = FS[j];
#define define C(a, b, c) if (E(a,b).cnt() != 2) mf(f.a, f.b, i, f.c);

```

## AhoCorasick.h

**Description:** Aho-Corasick automaton, used for multiple pattern matching. Initialize with AhoCorasick ac(patterns); the automaton start node will be at index 0. find(word) returns for each position the index of the longest word that ends there, or -1 if none. findAll(−, word) finds all words (up to  $N\sqrt{N}$  many if no duplicate patterns) that start at each position (shortest first). Duplicate patterns are allowed; empty patterns are not. To find the longest words that start at each position, reverse all input. For large alphabets, split each symbol into chunks, with sentinel bits for symbol boundaries.

**Time:** construction takes  $\mathcal{O}(26N)$ , where  $N$  = sum of length of patterns. find(x) is  $\mathcal{O}(N)$ , where  $N$  = length of x. findAll is  $\mathcal{O}(NM)$ .

```
35677, 66 lines
struct AhoCorasick {
    enum {alpha = 26, first = 'A'}; // change this!
    struct Node {
        // (nmatches is optional)
        int back, next[alpha], start = -1, end = -1,
            nmatches = 0;
        Node(int v) { memset(next, v, sizeof(next)); }
    };
    vector<Node> N;
    vi backp;
    void insert(string& s, int j) {
        assert(!s.empty());
        int n = 0;
        for (char c : s) {
            int& m = N[n].next[c - first];
            if (m == -1) { n = m = sz(N); N.emplace_back(-1);
                else n = m;
            }
        }
        if (N[n].end == -1) N[n].start = j;
        backp.push_back(N[n].end);
        N[n].end = j;
        N[n].nmatches++;
    }
    AhoCorasick(vector<string>& pat) : N(1, -1) {
        rep(i, 0, sz(pat)) insert(pat[i], i);
        N[0].back = sz(N);
        N.emplace_back(0);
        queue<int> q;
        for (q.push(0); !q.empty(); q.pop()) {
            int n = q.front(), prev = N[n].back;
            rep(i, 0, alpha) {
                int& ed = N[n].next[i], y = N[prev].next[i];
                if (ed == -1) ed = y;
                else {
                    N[ed].back = y;
                    (N[ed].end == -1 ? N[ed].end : backp[N[ed].
                        start])
                        = N[y].end;
                    N[ed].nmatches += N[y].nmatches;
                    q.push(ed);
                }
            }
        }
    }
    vi find(string word) {
        int n = 0;
        vi res; // ll count = 0;
        for (char c : word) {
            n = N[n].next[c - first];
            res.push_back(N[n].end);
            // count += N[n].nmatches;
        }
        return res;
    }
    vector<vi> findAll(vector<string>& pat, string word)
    {
        vi r = find(word);
        vector<vi> res(sz(word));
        rep(i, 0, sz(word)) {
            int ind = r[i];
            while (ind != -1) {
                res[i - sz(pat[ind]) + 1].push_back(ind);
                ind = backp[ind];
            }
        }
        return res;
    }
};
```

## Various (10)

### 10.1 Intervals

#### IntervalContainer.h

**Description:** Add and remove intervals from a set of disjoint intervals. Will merge the added interval with any overlapping intervals in the set when adding. Intervals are [inclusive, exclusive).

```
Time: O(log N)
edce47, 23 lines
set<pii>::iterator addInterval(set<pii>& is, int L, int
    R) {
    if (L == R) return is.end();
    auto it = is.lower_bound({L, R}), before = it;
    while (it != is.end() && it->first <= R) {
        R = max(R, it->second);
        before = it = is.erase(it);
    }
    if (it != is.begin() && (--it)->second >= L) {
        L = min(L, it->first);
        R = max(R, it->second);
        is.erase(it);
    }
    return is.insert(before, {L, R});
}
void removeInterval(set<pii>& is, int L, int R) {
    if (L == R) return;
    auto it = addInterval(is, L, R);
    auto r2 = it->second;
    if (it->first == L) is.erase(it);
    else (int&)it->second = L;
    if (R != r2) is.emplace(R, r2);
}
```

#### IntervalCover.h

**Description:** Compute indices of smallest set of intervals covering another interval. Intervals should be [inclusive, exclusive). To support [inclusive, inclusive], change (A) to add || R.empty(). Returns empty set on failure (or if G is empty).

```
Time: O(N log N)
9e9d8d, 19 lines
template<class T>
vi cover(pair<T, T> G, vector<pair<T, T>> I) {
    vi S(sz(I)), R;
    iota(all(S), 0);
    sort(all(S), [&](int a, int b) { return I[a] < I[b];
        });
    T cur = G.first;
    int at = 0;
    while (cur < G.second) { // (A)
        pair<T, int> mx = make_pair(cur, -1);
        while (at < sz(I) && I[S[at]].first <= cur) {
            mx = max(mx, make_pair(I[S[at]].second, S[at]));
            at++;
        }
        if (mx.second == -1) return {};
        cur = mx.first;
        R.push_back(mx.second);
    }
    return R;
}
```

## ConstantIntervals.h

**Description:** Split a monotone function on [from, to) into a minimal set of half-open intervals on which it has the same value. Runs a callback g for each such interval.

**Usage:** constantIntervals(0, sz(v), [&](int x){return v[x];}, [&](int lo, int hi, T val){...});

```
Time: O(k log n k)
753a4c, 19 lines
template<class F, class G, class T>
void rec(int from, int to, F& f, G& g, int& i, T& p, T
    q) {
    if (p == q) return;
    if (from == to) {
        g(i, to, p);
        i = to; p = q;
    } else {
        int mid = (from + to) >> 1;
        rec(from, mid, f, g, i, p, f(mid));
        rec(mid+1, to, f, g, i, p, q);
    }
}
template<class F, class G>
void constantIntervals(int from, int to, F f, G g) {
    if (to <= from) return;
    int i = from; auto p = f(i), q = f(to-1);
```

```
    rec(from, to-1, f, g, i, p, q);
}
g(i, to, q);
}
```

### 10.2 Dynamic programming

#### KnuthDP.h

**Description:** When doing DP on intervals:  $a[i][j] = \min_{i \leq k < j} (a[i][k] + a[k][j]) + f(i, j)$ , where the (minimal) optimal  $k$  increases with both  $i$  and  $j$ , one can solve intervals in increasing order of length, and search  $k = p[i][j]$  for  $a[i][j]$  only between  $p[i][j - 1]$  and  $p[i + 1][j]$ . This is known as Knuth DP. Sufficient criteria for this are if  $f(b, c) \leq f(a, d)$  and  $f(a, c) + f(b, d) \leq f(a, d) + f(b, c)$  for all  $a \leq b \leq c \leq d$ . Consider also: LineContainer (ch. Data structures), monotone queues, ternary search.

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

#### DivideAndConquerDP.h

**Description:** Given  $a[i] = \min_{lo(i) \leq k < hi(i)} (f(i, k))$  where the (minimal) optimal  $k$  increases with  $i$ , computes  $a[i]$  for  $i = L..R - 1$ .

```
Time: O((N + (hi - lo)) log N)
d38d2b, 18 lines
struct DP { // Modify at will:
    int lo(int ind) { return 0; }
    int hi(int ind) { return ind; }
    ll f(int ind, int k) { return dp[ind][k]; }
    void store(int ind, int k, ll v) { res[ind] = pii(k,
        v); }
    void rec(int L, int R, int LO, int HI) {
        if (L >= R) return;
        int mid = (L + R) >> 1;
        pair<ll, int> best(LLONG_MAX, LO);
        rep(k, max(LO, lo(mid)), min(HI, hi(mid)))
            best = min(best, make_pair(f(mid, k), k));
        store(mid, best.second, best.first);
        rec(L, mid, LO, best.second+1);
        rec(mid+1, R, best.second, HI);
    }
    void solve(int L, int R) { rec(L, R, INT_MIN, INT_MAX
        ); }
};
```

### 10.3 Misc. algorithms

#### TernarySearch.h

**Description:** Find the smallest  $i$  in  $[a, b]$  that maximizes  $f(i)$ , assuming that  $f(a) < \dots < f(i) \geq \dots \geq f(b)$ . To reverse which of the sides allows non-strict inequalities, change the < marked with (A) to <=, and reverse the loop at (B). To minimize  $f$ , change it to >, also at (B).

**Usage:** int ind = ternSearch(0, n-1, [&](int i){return a[i];});

```
Time: O(log(b - a))
9155b4, 11 lines
template<class F>
int ternSearch(int a, int b, F f) {
    assert(a <= b);
    while (b - a >= 5) {
        int mid = (a + b) / 2;
        if (f(mid) < f(mid+1)) a = mid; // (A)
        else b = mid+1;
    }
    rep(i, a+1, b+1) if (f(a) < f(i)) a = i; // (B)
    return a;
}
```

#### LIS.h

**Description:** Compute indices for the longest increasing subsequence.

```
Time: O(N log N)
2932a0, 17 lines
template<class I> vi lis(const vector<I>& S) {
    if (S.empty()) return {};
    vi prev(sz(S));
    typedef pair<I, int> p;
    vector<p> res;
    rep(i, 0, sz(S)) {
        // change 0 -> i for longest non-decreasing
        // subsequence
        auto it = lower_bound(all(res), p{S[i], 0});
        if (it == res.end()) res.emplace_back(), it = res.
            end()-1;
        *it = {S[i], i};
        prev[i] = it == res.begin() ? 0 : (it-1)->second;
```

```
    }
    int L = sz(res), cur = res.back().second;
    vi ans(L);
    while (L-->) ans[L] = cur, cur = prev[cur];
    return ans;
}
```

#### FastKnapsack.h

**Description:** Given  $N$  non-negative integer weights  $w$  and a non-negative target  $t$ , computes the maximum  $S \leq t$  such that  $S$  is the sum of some subset of the weights.

```
Time: O(N max(w_i))
b20ccc, 16 lines
int knapsack(vi w, int t) {
    int a = 0, b = 0, x;
    while (b < sz(w) && a + w[b] <= t) a += w[b++];
    if (b == sz(w)) return a;
    int m = *max_element(all(w));
    vi u, v(2*m, -1);
    v[a+m-t] = b;
    rep(i, b, sz(w)) {
        u = v;
        rep(x, 0, m) v[x+w[i]] = max(v[x+w[i]], u[x]);
        for (x = 2*m; --x > m;) rep(j, max(0, u[x]), v[x])
            v[x-w[j]] = max(v[x-w[j]], j);
    }
    for (a = t; v[a+m-t] < 0; a--);
    return a;
}
```

#### FastMod.h

**Description:** Compute  $a\%b$  about 5 times faster than usual, where  $b$  is constant but not known at compile time. Returns a value congruent to  $a \pmod b$  in the range  $[0, \frac{b}{2})$ .

```
typedef unsigned long long ull;
struct FastMod {
    ull b, m;
    FastMod(ull b) : b(b), m(~1ULL / b) {}
    ull reduce(ull a) { // a % b + (0 or b)
        return a - (ull)((__uint128_t(m) * a) >> 64) * b;
    }
};
```

#### FastInput.h

**Description:** Read an integer from stdin. Usage requires your program to pipe in input from file.

**Usage:** ./a.out < input.txt

```
Time: About 5x as fast as cin/scanf.
7b3c70, 17 lines
inline char gc() { // like getchar()
    static char buf[1 << 16];
    static size_t bc, be;
    if (bc >= be) {
        buf[0] = 0, bc = 0;
        be = fread(buf, 1, sizeof(buf), stdin);
    }
    return buf[bc++]; // returns 0 on EOF
}
```

```
int readInt() {
    int a, c;
    while ((a = gc()) < 40);
    if (a == '-') return -readInt();
    while ((c = gc()) >= 48) a = a * 10 + c - 48;
    return a - 48;
}
```

#### BumpAllocator.h

**Description:** When you need to dynamically allocate many objects and don't care about freeing them. "new X" otherwise has an overhead of something like  $0.05u + 16$  bytes per allocation.

```
745db2, 8 lines
// Either globally or in a single class:
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*) {}
```

#### SmallPtr.h

**Description:** A 32-bit pointer that points into BumpAllocator memory.

```
"BumpAllocator.h"
2dd6c9, 10 lines
template<class T> struct ptr {
```

```
    unsigned ind;
    ptr(T* p = 0) : ind(p ? unsigned((char*)p - buf) : 0)
    {
        assert(ind < sizeof buf);
    }
    T& operator*() const { return *(T*)(buf + ind); }
    T* operator->() const { return &**this; }
    T& operator[](int a) const { return (&**this)[a]; }
    explicit operator bool() const { return ind; }
};
```

BumpAllocatorSTL.h

Description: BumpAllocator for STL containers.

Usage: vector<vector<int, small<int>>>>, 8640, 14 lines

```
char buf[450 << 20] alignas(16);
size_t buf_ind = sizeof buf;
template<class T> struct small {
    typedef T value_type;
    small() {}
    template<class U> small(const U&) {}
    T* allocate(size_t n) {
        buf_ind -= n * sizeof(T);
        buf_ind &= 0 - alignof(T);
        return (T*)(buf + buf_ind);
    }
    void deallocate(T*, size_t) {}
};
```