

1	Contest
2	Mathematics
3	Data structures
4	Numerical
5	Number theory
6	Combinatorial
7	Graph
8	Geometry
9	Strings
10	Various
11	JHU

Contest (1)

template.cpp	14 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() typedef long long ll; typedef pair<int, int> pii; typedef vector<int> vi; int main() { cin.tie(0)->sync_with_stdio(0); cin.exceptions(cin.failbit); } .bashrc	
alias g++='g++ -Wall -Wextra -Wshadow -D_GLIBCXX_DEBUG - gdb3 -std=gnu++20 -fmax-errors=2 -fsanitize=address, undefined -I.' // mkdir bits && cd bits && g++ /usr/include/x86_64-linux- gnu/c++/13/bits/stdc++.h -o stdc++.h.gch // test: g++ template.cpp -H init.vim	
// .config/nvim/init.vim set ic ts=4 sw=4 nu im jk <esc> no ; : ca hash w !cpp -dD -P -fpreprocessed \\\ tr -d '[:space:]' \\ md5sum \\\ cut -c-6 .gdbinit	
set debuginfod enabled on	

1	troubleshoot.txt	52 lines
Pre-submit: 1 Write a few simple test cases if sample is not enough. Are time limits close? If so, generate max cases. Is the memory usage fine? 3 Could anything overflow? Make sure to submit the right file. 5 Wrong answer: Print your solution! Print debug output, as well. 8 Are you clearing all data structures between test cases? Can your algorithm handle the whole range of input? Read the full problem statement again. 10 Do you handle all corner cases correctly? Have you understood the problem correctly? Any uninitialized variables? 11 Any overflows? Confusing N and M, i and j, etc.? Are you sure your algorithm works? 17 What special cases have you not thought of? Are you sure the STL functions you use work as you think? 21 Add some assertions, maybe resubmit. Create some testcases to run your algorithm on. Go through the algorithm for a simple case. 22 Go through this list again. Explain your algorithm to a teammate. Ask the teammate to look at your code. Go for a small walk, e.g. to the toilet. Is your output format correct? (including whitespace) 24 Rewrite your solution from the start or let a teammate do it. Runtime error: Have you tested all corner cases locally? Any uninitialized variables? Are you reading or writing outside the range of any vector? Any assertions that might fail? Any possible division by 0? (mod 0 for example) Any possible infinite recursion? Invalidated pointers or iterators? Are you using too much memory? Debug with resubmits (e.g. remapped signals, see Various). Time limit exceeded: Do you have any possible infinite loops? What is the complexity of your algorithm? Are you copying a lot of unnecessary data? (References) How big is the input and output? (consider scanf) Avoid vector, map. (use arrays/unordered_map) What do your teammates think about your algorithm? Memory limit exceeded: What is the max amount of memory your algorithm should need ? Are you clearing all data structures between test cases?		
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 $x = -b/2a$.		

$ax + by = e \Rightarrow \begin{cases} x = \frac{ed - bf}{ad - bc} \\ y = \frac{af - ec}{ad - bc} \end{cases}$	
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 $a_n = c_1a_{n-1} + \dots + c_ka_{n-k}$, and r_1, \dots, r_k are distinct roots of $x^k - c_1x^{k-1} - \dots - c_k$, there are d_1, \dots, d_k s.t.	
$a_n = d_1r_1^n + \dots + d_kr_k^n.$	
Non-distinct roots r become polynomial factors, e.g.	
$a_n = (d_1n + d_2)r^n.$	
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 $r = \sqrt{a^2 + b^2}, \phi = \operatorname{atan2}(b, a)$.	
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):

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

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

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

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

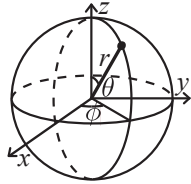
2.4.2 Quadrilaterals

With side lengths a, b, c, d , diagonals e, f , diagonals angle θ , 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° , $ef = ac + bd$, and $A = \sqrt{(p-a)(p-b)(p-c)(p-d)}$.

2.4.3 Spherical coordinates



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

2.5 Derivatives/Integrals

$$\begin{aligned} \frac{d}{dx} \arcsin x &= \frac{1}{\sqrt{1-x^2}} & \frac{d}{dx} \arccos x &= -\frac{1}{\sqrt{1-x^2}} \\ \frac{d}{dx} \tan x &= 1 + \tan^2 x & \frac{d}{dx} \arctan x &= \frac{1}{1+x^2} \\ \int \tan ax &= -\frac{\ln |\cos ax|}{a} & \int x \sin ax &= \frac{\sin ax - ax \cos ax}{a^2} \\ \int e^{-x^2} &= \frac{\sqrt{\pi}}{2} \operatorname{erf}(x) & \int x e^{ax} dx &= \frac{e^{ax}}{a^2} (ax - 1) \end{aligned}$$

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

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

$$\begin{aligned} 1 + 2 + 3 + \dots + n &= \frac{n(n+1)}{2} \\ 1^2 + 2^2 + 3^2 + \dots + n^2 &= \frac{n(2n+1)(n+1)}{6} \\ 1^3 + 2^3 + 3^3 + \dots + n^3 &= \frac{n^2(n+1)^2}{4} \\ 1^4 + 2^4 + 3^4 + \dots + n^4 &= \frac{n(n+1)(2n+1)(3n^2+3n-1)}{30} \end{aligned}$$

2.7 Series

$$\begin{aligned} e^x &= 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots, (-\infty < x < \infty) \\ \ln(1+x) &= x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots, (-1 < x \leq 1) \\ \sqrt{1+x} &= 1 + \frac{x}{2} - \frac{x^2}{8} + \frac{2x^3}{32} - \frac{5x^4}{128} + \dots, (-1 \leq x \leq 1) \\ \sin x &= x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \dots, (-\infty < x < \infty) \\ \cos x &= 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots, (-\infty < x < \infty) \end{aligned}$$

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

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

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

$\operatorname{Bin}(n, p)$ is approximately $\operatorname{Po}(np)$ 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 $\operatorname{Fs}(p)$, $0 \leq p \leq 1$.

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

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

Poisson distribution

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

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

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

2.8.2 Continuous distributions

Uniform distribution

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

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

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

Exponential distribution

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

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

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

Normal distribution

Most real random values with mean μ and variance σ^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.

π 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 . π_j / π_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, π_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). $\lim_{k \rightarrow \infty} \mathbf{P}^k = \mathbf{1} \pi$.

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

```
#include <bits/extc++.h> // 893
using namespace __gnu_pbds;

template<class T>
using Tree = tree<T, null_type, less<T>, rb_tree_tag,
    tree_order_statistics_node_update>; // 988

void example() {
    Tree<int> t, t2; t.insert(8);
    auto it = t.insert(10).first;
    assert(it == t.lower_bound(9)); // 6bd
    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
} // cbb
```

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).
d77092, 7 lines

#include <bits/extc++.h> // 1e4
// To use most bits rather than just the lowest ones:
struct chash { // large odd number for C
    const uint64_t C = 1l(4e18 * acos(0)) | 7l;
    ll operator()(ll x) const { return __builtin_bswap64(x*C)
        ; }
}; // 198
__gnu_pbds::gp_hash_table<ll,int,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: $\mathcal{O}(\log N)$

```
struct Tree { // 026
    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) {} // c86
    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) // e90
        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);
        } // 490
        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: $\mathcal{O}(\log N)$.

```
"../various/BumpAllocator.h"
34cef5, 50 lines

const int inf = 1e9; // 317
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) {} // f58
    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);
    } // 22c
    else val = v[lo];
}
int query(int L, int R) {
    if (R <= lo || hi <= L) return -inf;
    if (L <= lo && hi <= R) return val; // 2ff
    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; // 1bd
    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);
} // f3e
}
void add(int L, int R, int x) {
    if (R <= lo || hi <= L) return;
    if (L <= lo && hi <= R) {
        if (mset != inf) mset += x; // 415
        else madd += x;
        val += x;
    }
    else {
        push(), l->add(L, R, x), r->add(L, R, x); // cac
        val = max(l->val, r->val);
    }
}
}
void push() {
    if (!l) {} // 53d
    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; //
        333
else if (madd)
    l->add(lo, hi, madd), r->add(lo, hi, madd), madd = 0;
}
};
```

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 { // f73
    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); } // cbd
    void rollback(int t) {
        for (int i = time(); i --> t;)
            e[st[i].first] = st[i].second;
        st.resize(t);
    } // e73
    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]}); // 274
        st.push_back({b, e[b]});
        e[a] += e[b]; e[b] = a;
        return true;
    }
}; // 214
```

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> // 03e
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)); // 4c9
```

```
    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][c];
    }
    T sum(int u, int l, int d, int r) {
        return p[d][r] - p[d][l] - p[u][r] + p[u][l]; //286
    }
};
```

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 { //1aa
    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) //c99
            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{}; //bb8
        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); //358
        M a, b(*this);
        rep(i,0,N) a.d[i][i] = 1;
        while (p) {
            if (p&1) a = a*b;
            b = b*b; //1d8
            p >>= 1;
        }
        return a;
    }
}; //214
```

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

8ec1e7, 30 lines

```
struct Line { //7e3
    mutable ll k, m, p;
    bool operator<(const Line& o) const { return k < o.k; }
    bool operator<(ll x) const { return p < x; }
};
//d77
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); } //66e
    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, x->k - y->k);
        return x->p >= y->p; //bec
    }
    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));
    } //890
```

```
    while ((y = x) != begin() && (--x)->p >= y->p)
        isect(x, erase(y));
    }
    ll query(ll x) {
        assert(!empty()); //b07
        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: $\mathcal{O}(\log N)$

1754b4, 53 lines

```
struct Node { //829
    Node *l = 0, *r = 0;
    int val, y, c = 1;
    Node(int val) : val(val), y(rand()) {}
    void recalc();
}; //3ef

int cnt(Node* n) { return n ? n->c : 0; }
void Node::recalc() { c = cnt(l) + cnt(r) + 1; }

template<class F> void each(Node* n, F f) { //5d5
    if (n) { each(n->l, f); f(n->val); each(n->r, f); }
}

pair<Node*, Node*> split(Node* n, int k) {
    if (!n) return {}; //de3
    if (cnt(n->l) >= k) { // "n->val >= k" for lower_bound(k)
        auto [L,R] = split(n->l, k);
        n->l = R;
        n->recalc();
        return {L, n}; //635
    } else {
        auto [L,R] = split(n->r, k - cnt(n->l) - 1); // and just "k"
        n->r = L;
        n->recalc();
        return {n, R}; //438
    }
}
```

```
Node* merge(Node* l, Node* r) {
    if (!l) return r; //b38
    if (!r) return l;
    if (l->y > r->y) {
        l->r = merge(l->r, r);
        return l->recalc(), l;
    } else { //260
        r->l = merge(l, r->l);
        return r->recalc(), r;
    }
} //32c
Node* ins(Node* t, Node* n, int pos) {
    auto [l,r] = split(t, pos);
    return merge(merge(l, n), r);
}
//828
// 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 - l);
    if (k <= l) t = merge(ins(a, b, k), c); //cd9
    else t = merge(a, ins(c, b, k - r));
}
```

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 { //711
    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;
    } //cc4
    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;
    } //477
    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) { //fc5
            if (pos + pw <= sz(s) && s[pos + pw-1] < sum)
                pos += pw, sum -= s[pos-1];
        }
        return pos;
    } //e03
};
```

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 { //e22
    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);
    } //57f
    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());
    } //358
    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) { //688
        ll sum = 0;
        for (; x; x &= x - 1)
            sum += ft[x-1].query(ind(x-1, y));
        return sum;
    } //e03
};
```

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> //722
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);//f6c
            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) {//a3d
    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)]);
}//214
```

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)//342
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)//cb0
    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) {//623
                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);//d22
                res[qi] = calc();
            }
            return res;
        }
    //842
    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 {
            //263
            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++;//23e
            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);//064
                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; }
                    //440
                    while (!L[b] <= L[a] && R[a] <= R[b]))
                        I[i++] = b, b = par[b];
                    while (a != b) step(par[a]);
                    while (i-->) step(I[i]);
                    if (end) res[qi] = calc();//695
                }
            }
            return res;
        }
    }
```

Numerical (4)

4.1 Polynomials and recurrences

Polynomial.h

```
c9b7b0, 17 lines
struct Poly {//1b7
    vector<double> a;
    double operator() (double x) const {
        double val = 0;
        for (int i = sz(a); i-->) (val *= x) += a[i];
        return val;//06d
    }
    void diff() {
        rep(i,1,sz(a)) a[i-1] = i*a[i];
        a.pop_back();
    }//b82
    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();
    }//e03
};
```

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)
    {//840
    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);//9c1
    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];//189
        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;//a7f
                else h = m;
            }
            ret.push_back((l + h) / 2);
        }
    }
    //808
    return ret;
}
```

PolyInterpolate.h

Description: Given n points $(x[i], y[i])$, computes an $n-1$ -degree polynomial p that passes through them: $p(x) = a[0]*x^0 + \dots + a[n-1]*x^{n-1}$. For numerical precision, pick $x[k] = c*\cos(k/(n-1)*\pi), k = 0 \dots n-1$.
Time: $\mathcal{O}(n^2)$

```
08bf48, 13 lines
typedef vector<double> vd;//159
vd interpolate(vd x, vd y, int n) {
    vd res(n), temp(n);
    rep(k,0,n-1) rep(i,k+1,n)
        y[i] = (y[i] - y[k]) / (x[i] - x[k]);
    double last = 0; temp[0] = 1;//746
    rep(k,0,n) rep(i,0,n) {
        res[i] += y[k] * temp[i];
        swap(last, temp[i]);
        temp[i] -= last * x[k];
    }//0e1
    return res;
}
```

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) {//b21
    int n = sz(s), L = 0, m = 0;
    vector<ll> C(n), B(n), T;
    C[0] = B[0] = 1;

    ll b = 1;//4c7
    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;//1b2
        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;
    }
    //255
    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;//bb1
ll linearRec(Poly S, Poly tr, ll k) {
    int n = sz(tr);

    auto combine = [&](Poly a, Poly b) {
        Poly res(n * 2 + 1);//251
        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);//12f
        return res;
    };
}
```

```
Poly pol(n + 1), e(pol);
pol[0] = e[1] = 1;//df7

for (++k; k; k /= 2) {
    if (k % 2) pol = combine(pol, e);
    e = combine(e, e);
};//c0e

ll res = 0;
rep(i,0,n) res = (res + pol[i + 1] * S[i]) % mod;
return res;
};//cbb
```

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 ϵ *ps*. 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: $\mathcal{O}(\log((b-a)/\epsilon))$

```
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.

```
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.

```
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 y) { return quad(-1, 1, [&](double z) { return x*x + y*y + z*z < 1; }}}));

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

```
typedef double T; // long double, Rational, double + modP
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: $\mathcal{O}(N^3)$

```
double det(vector<vector<double>>& a) {
    int n = sz(a); double res = 1;
    rep(i,0,n) {
        int b = i;
        rep(j,i+1,n) if (fabs(a[j][i]) > fabs(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) {
            double 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: $\mathcal{O}(N^3)$

```
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;//bc6
}
ans = ans * a[i][i] % mod;
if (!ans) return 0;
} //b19
return (ans + mod) % mod;
}
```

SolveLinear.h
Description: Solves $A * x = b$. If there are multiple solutions, an arbitrary one is returned. Returns rank, or -1 if no solutions. Data in A and b is lost.
Time: $\mathcal{O}(n^2m)$

```
typedef vector<double> vd; //2cf
const double eps = 1e-12;

int solveLinear(vector<vd>& A, vd& b, vd& x) {
    int n = sz(A), m = sz(x), rank = 0, br, bc;
    if (n) assert(sz(A[0]) == m); //940
    vi col(m); iota(all(col), 0);

    rep(i,0,n) {
        double v, bv = 0;
        rep(r,i,n) rep(c,i,m) //ddb
            if ((v = fabs(A[r][c])) > bv)
                br = r, bc = c, bv = v;
        if (bv <= eps) {
            rep(j,i,n) if (fabs(b[j]) > eps) return -1;
            break; //de0
        }
        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]); //328
        bv = 1/A[i][i];
        rep(j,i+1,n) {
            double fac = A[j][i] * bv;
            b[j] -= fac * b[i];
            rep(k,i+1,m) A[j][k] -= fac*A[i][k]; //af1
        }
        rank++;
    }

    x.assign(m, 0); //3c5
    for (int i = rank; i--;) {
        b[i] /= A[i][i];
        x[col[i]] = b[i];
        rep(j,0,i) b[j] -= A[j][i] * b[i];
    } //807
    return rank; // (multiple solutions if rank < m)
}
```

SolveLinear2.h
Description: To get all uniquely determined values of x back from SolveLinear, make the following changes:

```
"SolveLinear.h"
08e495, 7 lines

rep(j,0,n) if (j != i) // instead of rep(j,i+1,n) //22b
// ... then at the end:
x.assign(m, undefined);
rep(i,0,rank) {
    rep(j,rank,m) if (fabs(A[i][j]) > eps) goto fail;
    x[col[i]] = b[i] / A[i][i]; //4e3
fail;; }
```

```
SolveLinearBinary.h
Description: Solves Ax = b over F2. If there are multiple solutions,
one is returned arbitrarily. Returns rank, or -1 if no solutions. Destroys
A and b.
Time: O(n^2m)
fa2d7a, 34 lines

typedef bitset<1000> bs; //d90

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); //2c9
    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; //13e
        }
        int bc = (int)A[br]._Find_next(i-1);
        swap(A[i], A[br]);
        swap(b[i], b[br]);
        swap(col[i], col[bc]); //b88
        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]; //76c
            A[j] ^= A[i];
        }
        rank++;
    }
} //7a7
x = bs();
for (int i = rank; i--;) {
    if (!b[i]) continue;
    x[col[i]] = 1;
    rep(j,0,i) b[j] ^= A[j][i]; //df7
}
return rank; // (multiple solutions if rank < m)
}
```

MatrixInverse.h
Description: Invert matrix A . Returns rank; result is stored in A unless singular ($\text{rank} < n$). 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 $A \bmod p$, and k is doubled in each step.
Time: $\mathcal{O}(n^3)$

```
int matInv(vector<vector<double>>& A) { //9a9
    int n = sz(A); vi col(n);
    vector<vector<double>> tmp(n, vector<double>(n));
    rep(i,0,n) tmp[i][i] = 1, col[i] = i;

    rep(i,0,n) { //214
        int r = i, c = i;
        rep(j,i,n) rep(k,i,n)
            if (fabs(A[j][k]) > fabs(A[r][c]))
                r = j, c = k;
        if (fabs(A[r][c]) < 1e-12) return i; //e5b
        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]);
        double v = A[i][i]; //afc
        rep(j,i+1,n) {
            double 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]; //c80
        }
        rep(j,i+1,n) A[i][j] /= v;
    }
```

```
rep(j,0,n) tmp[i][j] /= v;
A[i][i] = 1;
} //bfb

for (int i = n-1; i > 0; --i) rep(j,0,i) {
    double v = A[j][i];
    rep(k,0,n) tmp[j][k] -= v*tmp[i][k];
} //e74

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

$$\begin{pmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \\ \vdots \\ b_{n-1} \end{pmatrix} = \begin{pmatrix} d_0 & p_0 & 0 & 0 & \cdots & 0 \\ q_0 & d_1 & p_1 & 0 & \cdots & 0 \\ 0 & q_1 & d_2 & p_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & q_{n-3} & d_{n-2} & p_{n-2} \\ 0 & 0 & \cdots & 0 & q_{n-2} & d_{n-1} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_{n-1} \end{pmatrix}.$$

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; //399
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//464
            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]; //d50
            b[i+1] -= b[i]*sub[i]/diag[i];
        }
    }
    for (int i = n; i--;) {
        if (tr[i]) { //054
            swap(b[i], b[i-1]);
            diag[i-1] = diag[i];
            b[i] /= super[i-1];
        } else {
            b[i] /= diag[i]; //20b
            if (i) b[i-1] -= b[i]*super[i-1];
        }
    }
    return b;
} //cbb
```

4.4 Fourier transforms

FastFourierTransform.h

Description: $\text{fft}(a)$ computes $\hat{f}(k) = \sum_x a[x] \exp(2\pi i \cdot kx/N)$ for all k . N must be a power of 2. Useful for convolution: $\text{conv}(a, b) = c$, 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 $N = 2^{22}$)

```
typedef complex<double> C; //1ec
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) //
    c50
    for (static int k = 2; k < n; k *= 2) {
        R.resize(n); rt.resize(n);
        auto x = polar(1.0L, acos(-1.0L) / k);
        rep(i, k, 2*k) rt[i] = R[i] = i&1 ? R[i/2] * x : R[i/2];
    } //292
    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) { //577
            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;
        }
    } //15f
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); //d93
    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]); //36e
    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

typedef vector<ll> vl; //2c4
template<int M> vl convMod(const vl &a, const vl &b) {
    if (a.empty() || b.empty()) return {};
    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); //c4f
    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); //3eb
        outl[j] = (L[i] + conj(L[j])) * R[i] / (2.0 * n);
        outs[j] = (L[i] - conj(L[j])) * R[i] / (2.0 * n) / li;
    }
}
```

```
fft(outl), fft(outs);
rep(i, 0, sz(res)) { //58f
    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;
}
return res; //510
}
```

NumberTheoreticTransform.h

Description: $\text{ntt}(a)$ 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 $2^a b + 1$, where the convolution result has size at most 2^a . For arbitrary modulo, see FFTMod. $\text{conv}(a, b) = c$, where $c[x] = \sum a[i]b[x-i]$. For manual convolution: NTT the inputs, multiply 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

const ll mod = (119 << 23) + 1, root = 62; // =
998244353 //0ca
// For p < 2^30 there is also e.g. 5 << 25, 7 << 26, 479 <<
21
// and 483 << 21 (same root). The last two are > 10^9.
typedef vector<ll> vl;
void ntt(vl &a) {
    int n = sz(a), L = 31 - __builtin_clz(n); //cc5
    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; //4a0
    }
    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) //ed7
        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);
        } //dfc
    }
}
```

```
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; //d58
    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) //f18
        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 $c[z] = \sum_{z=x \oplus y} a[x] \cdot b[y]$, 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) { //ae8
    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/0af
        pii(u + v, u - v); // XOR
    }
}
if (inv) for (int& x : a) x /= sz(a); // XOR only
} //dc4
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;
} //cbb
```

Number theory (5)

5.1 Modular arithmetic

ModularArithmetic.h

Description: Operators for modular arithmetic. You need to set mod to some number first and then you can use the structure.

```
"euclid.h"
35bfea, 18 lines

const ll mod = 17; // change to something else //9af
struct Mod {
    ll x;
    Mod(ll xx) : x(xx) {}
    Mod operator+(Mod b) { return Mod((x + b.x) % mod); }
    Mod operator-(Mod b) { return Mod((x - b.x + mod) % mod); }
    } //dd1
    Mod operator*(Mod b) { return Mod((x * b.x) % mod); }
    Mod operator/(Mod b) { return *this * invert(b); }
    Mod invert(Mod a) {
        ll x, y, g = euclid(a.x, mod, x, y);
        assert(g == 1); return Mod((x + mod) % mod); //13e
    }
    Mod operator^(ll e) {
        if (!e) return Mod(1);
        Mod r = *this ^ (e / 2); r = r * r;
        return e&1 ? *this * r : r; //935
    }
};
```

ModInverse.h

Description: Pre-computation of modular inverses. Assumes LIM \leq mod and that mod is a prime.

```
6f684f, 3 lines

const ll mod = 1000000007, LIM = 200000; //6f6
ll* inv = new ll[LIM] - 1; inv[1] = 1;
rep(i, 2, LIM) inv[i] = mod - (mod / i) * inv[mod % i] % mod;
```

ModPow.h

```
b83c45, 8 lines

const ll mod = 1000000007; // faster if const //8bc
```

```
ll modpow(ll b, ll e) {
    ll ans = 1;
    for (; e; b = b * b % mod, e /= 2)
        if (e & 1) ans = ans * b % mod; //7e5
    return ans;
}
```

ModLog.h

Description: Returns the smallest $x > 0$ s.t. $a^x = b \pmod m$, or -1 if no such x exists. $\text{modLog}(a, 1, m)$ 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) { //260
    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) return j;//d16
    if (__gcd(m, e) == __gcd(m, b))
        rep(i,2,n+2) if (A.count(e == e * f % m))
            return n * i - A[e];
    return -1;
} //cbb
```

ModSum.h

Description: Sums of mod'ed 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.

<pre>typedef unsigned long long ull; //df3 ull sumsq(ull to) { return to / 2 * ((to-1) 1); }</pre>	5c5bc5, 16 lines
--	------------------

```
ull divsum(ull to, ull c, ull k, ull m) {
    ull res = k / m * sumsq(to) + c / m * to;
    k %= m; c %= m; //e1a
    if (!k) return res;
    ull to2 = (to * k + c) / m;
    return res + (to - 1) * to2 - divsum(to2, m-1 - c, m, k);
}
//1ae
ll modsum(ull to, ll c, ll k, ll m) {
    c = ((c % m) + m) % m;
    k = ((k % m) + m) % m;
    return to * c + k * sumsq(to) - m * divsum(to, c, k, m);
} //cbb
```

ModMulLL.h

Description: Calculate $a \cdot b \bmod c$ (or $a^b \bmod c$) 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

<pre>typedef unsigned long long ull; //a9c ull modmul(ull a, ull b, ull M) { ll ret = a * b - M * ull(1.L / M * a * b); return ret + M * (ret < 0) - M * (ret >= (ll)M); } ull modpow(ull b, ull e, ull mod) { //51d ull ans = 1; for (; e; b = modmul(b, b, mod), e /= 2) if (e & 1) ans = modmul(ans, b, mod); return ans; } //cbb</pre>	bbbd8f, 11 lines
--	------------------

ModSqrt.h

Description: Tonelli-Shanks algorithm for modular square roots. Finds x s.t. $x^2 = a \pmod p$ ($-x$ gives the other solution).
Time: $\mathcal{O}(\log^2 p)$ worst case, $\mathcal{O}(\log p)$ for most p

<pre>"ModPow.h" ll sqrt(ll a, ll p) { //473 a %= p; if (a < 0) a += p; if (a == 0) return 0; assert(modpow(a, (p-1)/2, p) == 1); // else no solution if (p % 4 == 3) return modpow(a, (p+1)/4, p); // a^(n+3)/8 or 2^(n+3)/8 * 2^(n-1)/4 works if p % 8 == 5 //a48 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; //c4b 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) //faf t = t * t % p; if (m == 0) return x;</pre>	19a793, 24 lines
---	------------------

```
    ll gs = modpow(g, 1LL << (r - m - 1), p);
    g = gs * gs % p;
    x = x * gs % p; //a28
    b = b * g % p;
}
}
```

5.2 Primality

FastEratosthenes.h
Description: Prime sieve for generating all primes smaller than LIM.
Time: $\text{LIM}=1\text{e}9 \approx 1.5\text{s}$

<pre>const int LIM = 1e6; //058 bitset<LIM> isPrime; vi eratosthenes() { const 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; //083 for (int i = 3; i <= S; i += 2) if (!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) { //62d 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); //c68 } for (int i : pr) isPrime[i] = 1; return pr; }</pre>	6b2912, 20 lines
---	------------------

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 $a^b \bmod c$.

<pre>"ModMulLL.h" bool isPrime(ull n) { //60a 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; //81c while (p != 1 && p != n - 1 && a % n && i--) p = modmul(p, p, n); if (p != n-1 && i != s) return 0; } return 1; //84a }</pre>	60dcd1, 12 lines
---	------------------

Factor.h

Description: Pollard-rho randomized factorization algorithm. Returns prime factors of a number, in arbitrary order (e.g. 2299 -> {11, 19, 11}).
Time: $\mathcal{O}\left(n^{1/4}\right)$, less for numbers with small factors.

<pre>"ModMulLL.h", "MillerRabin.h" ull pollard(ull n) { //47d 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; //049 x = f(x), y = f(f(y)); } }</pre>	d8d98d, 18 lines
--	------------------

```
    return __gcd(prd, n);
}
vector<ull> factor(ull n) { //c19
    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)); //363
    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 $a \pmod b$.

<pre>ll euclid(ll a, ll b, ll &x, ll &y) { //33b if (!b) return x = 1, y = 0, a; ll d = euclid(b, a % b, y, x); return y -= a/b * x, d; }</pre>	33ba8f, 5 lines
---	-----------------

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 $0 \leq x < \text{lcm}(m, n)$. Assumes $mn < 2^{62}$.
Time: $\log(n)$

<pre>"euclid.h" ll crt(ll a, ll m, ll b, ll n) { //eae 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; //6ac }</pre>	04d93a, 7 lines
---	-----------------

5.3.1 Bézout’s identity

For $a \neq 0, b \neq 0$, 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* ϕ 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 $n = p_1^{k_1} p_2^{k_2} \dots p_r^{k_r}$ then $\phi(n) = (p_1 - 1)p_1^{k_1-1} \dots (p_r - 1)p_r^{k_r-1}$. $\phi(n) = n \cdot \prod_{p|n} (1 - 1/p)$. $\sum_{d|n} \phi(d) = n$, $\sum_{1 \leq k \leq n, \gcd(k,n)=1} k = n\phi(n)/2, n > 1$
Euler’s thm: a, n coprime $\Rightarrow a^{\phi(n)} \equiv 1 \pmod n$.
Fermat’s little thm: p prime $\Rightarrow a^{p-1} \equiv 1 \pmod p \ \forall a$.

<pre>const int LIM = 5000000; //70b 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) //103 for (int j = i; j < LIM; j += i) phi[j] -= phi[j] / i; }</pre>	cf7d6d, 8 lines
--	-----------------

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 ∞ ; 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
//32b
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), //5ad
        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. //8fe
            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}; //5c7
        }
        LP = P; P = NP;
        LQ = Q; Q = NQ;
    }
} //cbb
```

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; }; //386
```

```
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
    //262
    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) { //7e2
            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;
            } //bf0
        }
        hi.p += lo.p * adv;
        hi.q += lo.q * adv;
        dir = !dir;
        swap(lo, hi); //f58
        A = B; B = !adv;
    }
}
```

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

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

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:

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

Other useful formulas/forms:

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

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

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

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: O(n)
044568, 6 lines
int permToInt(vi& v) { //cf9
    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;
} //cbb
```

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.

$$D(n) = (n-1)(D(n-1)+D(n-2)) = nD(n-1)+(-1)^n = \left\lfloor \frac{n!}{e} \right\rfloor$$

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

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

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 $\binom{k_1+\cdots+k_n}{k_1,k_2,\ldots,k_n}=\frac{(\sum k_i)!}{k_1!k_2!\ldots k_n!}$.a0a312, 5 lines

```
11 multinomial(vi& v) { //a0a
    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).

$$B[0,\ldots]=[1,-\frac{1}{2},\frac{1}{6},0,-\frac{1}{30},0,\frac{1}{42},\ldots]$$

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:

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

6.3.2 Stirling numbers of the first kind

Number of permutations on n items with k cycles.

$$\begin{aligned} c(n,k) &= c(n-1,k-1) + (n-1)c(n-1,k), \quad c(0,0) = 1 \\ \sum_{k=0}^n c(n,k)x^k &= x(x+1)\ldots(x+n-1) \end{aligned}$$

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

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 s.t. $\pi(j) > \pi(j+1)$, $k+1$ j:s s.t. $\pi(j) \geq j$, k j:s 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. $B(n)=1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, \ldots$ 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 : $n_1n_2\cdots n_kn^{k-2}$
with degrees d_i : $(n-2)!/((d_1-1)!\cdots(d_n-1)!)$

6.3.7 Catalan numbers

$$\begin{aligned} C_n &= \frac{1}{n+1} \binom{2n}{n} = \binom{2n}{n} - \binom{2n}{n+1} = \frac{(2n)!}{(n+1)!n!} \\ C_0 &= 1, \quad C_{n+1} = \frac{2(2n+1)}{n+2} C_n, \quad C_{n+1} = \sum C_i C_{n-i} \end{aligned}$$

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

- 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.

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: $\mathcal{O}(VE)$ 830a8f, 23 lines

```
const ll inf = LLONG_MAX; //019
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; //3a0
    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]; //e21
        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); //69b
        }
    }
    rep(i,0,lim) for (Ed e : eds) {
        if (nodes[e.a].dist == -inf)
            nodes[e.b].dist = -inf; //943
    }
}
```

}

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 , inf if no path, or -inf if the path goes through a negative-weight cycle.
Time: $\mathcal{O}(N^3)$ 531245, 12 lines

```
const ll inf = 1LL << 62; //279
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) { //ef8
            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; //eec
}
```

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) { //c7a
    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); //28e
    return q;
}
```

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 { //d82
    struct Edge {
        int dest, back;
        ll f, c;
    };
    vector<vector<Edge>> g; //bef
    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) {}
    //07d
    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});
    } //a02

    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; //124
        back.f -= f; back.c += f; ec[back.dest] -= f;
    }
}
```

```
11 calc(int s, int t) {
    int v = sz(g); H[s] = v; ec[t] = 1;
    vi co(2*v); co[0] = v-1;//a96
    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];//e2e
        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)//9ff
                    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];//7ed
            } else if (cur[u]->c && H[u] == H[cur[u]->dest]+1)
                addFlow(*cur[u], min(ec[u], cur[u]->c));
            else ++cur[u];
    }
} //a5b
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. $\mathcal{O}(VE)$ for setpi.

```
#include <bits/extc++.h>//2fb

const ll INF = numeric_limits<ll>::max() / 4;

struct MCMF {
    struct edge { //219
        int from, to, rev;
        ll cap, cost, flow;
    };
    int N;
    vector<vector<edge>> ed; //252
    vi seen;
    vector<ll> dist, pi;
    vector<edge*> par;

    MCMF(int N) : N(N), ed(N), seen(N), dist(N), pi(N), par(N) {} //98d

    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 }); //6ab
    }

    void path(int s) {
        fill(all(seen), 0);
        fill(all(dist), INF); //da3
        dist[s] = 0; ll di;

        __gnu_pbds::priority_queue<pair<ll, int>> q;
        vector<decltype(q)::point_iterator> its(N);
        q.push({ 0, s }); //aa9

        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]) { //344
    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()) //b01
            its[e.to] = q.push({ -dist[e.to], e.to });
        else
            q.modify(its[e.to], { -dist[e.to], e.to });
    }
} //f01
rep(i,0,N) pi[i] = min(pi[i] + dist[i], INF);
}

pair<ll, ll> maxflow(int s, int t) { //10b
    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); //64a

        totflow += fl;
        for (edge* x = par[t]; x; x = par[x->from]) {
            x->flow += fl;
            ed[x->to][x->rev].flow -= fl; //897
        }
    }
    rep(i,0,N) for(edge& e : ed[i]) totcost += e.cost * e.flow;
    return {totflow, totcost/2};
} //ca9

// 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; //486
    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; //222
    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.

```
template<class T> T edmondsKarp(vector<unordered_map<int, T>>& //324
    graph, int source, int sink) {
    assert(source != sink);
    T flow = 0;
    vi par(sz(graph)), q = par;
    //cf9
    for (;) {
        fill(all(par), -1);
        par[source] = 0;
        int ptr = 1;
        q[0] = source; //623

        rep(i,0,ptr) {
            int x = q[i];
            for (auto e : graph[x]) {
                if (par[e.first] == -1 && e.second > 0) { //3a4
                    par[e.first] = x;
                    q[ptr++] = e.first;
```

```
if (e.first == sink) goto out;
        }
    } //3cd
    }
    return flow;
out:
    T inc = numeric_limits<T>::max();
    for (int y = sink; y != source; y = par[y]) //d19
        inc = min(inc, graph[par[y]][y]);

    flow += inc;
    for (int y = sink; y != source; y = par[y]) {
        int p = par[y]; //b79
        if ((graph[p][y] -= inc) <= 0) graph[p].erase(y);
        graph[y][p] += inc;
    }
} //cbb
```

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

```
pair<int, vi> globalMinCut(vector<vi> mat) { //f64
    pair<int, vi> best = {INT_MAX, {}};
    int n = sz(mat);
    vector<vi> co(n);
    rep(i,0,n) co[i] = {i};
    rep(ph,1,n) { //c8f
        vi w = mat[0];
        size_t s = 0, t = 0;
        rep(it,0,n-ph) { //  $\mathcal{O}(V^2) \rightarrow \mathcal{O}(E \log V)$  with prio.
            queue
            w[t] = INT_MIN;
            s = t, t = max_element(all(w)) - w.begin(); //0bb
            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]; //a2c
        rep(i,0,n) mat[i][s] = mat[s][i];
        mat[0][t] = INT_MIN;
    }
    return best;
} //cbb
```

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"
typedef array<ll, 3> Edge; //34e
vector<Edge> gomoryHu(int N, vector<Edge> ed) {
    vector<Edge> tree;
    vi par(N);
    rep(i,1,N) {
        PushRelabel D(N); // Dinic also works //3fd
        for (Edge t : ed) D.addEdge(t[0], t[1], t[2], t[2]);
        tree.push_back({i, par[i], D.calc(i, par[i])});
        rep(j,i+1,N)
```

```
        if (par[j] == par[i] && D.leftOfMinCut(j)) par[j] = i
            ;
    } //eec
    return tree;
}
```

7.3 Matching

hopcroftKarp.h

Description: Fast bipartite matching algorithm. Graph g should be a list of neighbors of the left partition, and $btoa$ should be a vector full of -1's of the same size as the right partition. Returns the size of the matching. $btoa[i]$ will be the match for vertex i on the right side, or -1 if it's not matched.

Usage: vi btoa(m, -1); hopcroftKarp(g, btoa);

Time: $\mathcal{O}(\sqrt{VE})$

```
bool dfs(int a, int L, vector<vi>& g, vi& btoa, vi& A, vi& B) { //d9e
    if (A[a] != L) return 0;
    A[a] = -1;
    for (int b : g[a]) if (B[b] == L + 1) {
        B[b] = 0;
        if (btoa[b] == -1 || dfs(btoa[b], L + 1, g, btoa, A, B))
            //613
            return btoa[b] = a, 1;
    }
    return 0;
} //ad4
int hopcroftKarp(vector<vi>& g, vi& btoa) {
    int res = 0;
    vi A(g.size()), B(btoa.size()), cur, next;
    for (;;) {
        fill(all(A), 0); //db3
        fill(all(B), 0);
        cur.clear();
        for (int a : btoa) if (a != -1) A[a] = -1;
        rep(a, 0, sz(g)) if (A[a] == 0) cur.push_back(a);
        for (int lay = 1;; lay++) { //559
            bool islast = 0;
            next.clear();
            for (int a : cur) for (int b : g[a]) {
                if (btoa[b] == -1) {
                    B[b] = lay; //1ca
                    islast = 1;
                }
                else if (btoa[b] != a && !B[b]) {
                    B[b] = lay;
                    next.push_back(btoa[b]); //1eb
                }
            }
            if (islast) break;
            if (next.empty()) return res;
            for (int a : next) A[a] = lay; //4f3
            cur.swap(next);
        }
        rep(a, 0, sz(g))
            res += dfs(a, 0, g, btoa, A, B);
    } //67c
}
```

DFSMatching.h

Description: Simple bipartite matching algorithm. Graph g should be a list of neighbors of the left partition, and $btoa$ should be a vector full of -1's of the same size as the right partition. Returns the size of the matching. $btoa[i]$ will be the match for vertex i on the right side, or -1 if it's not matched.

Usage: vi btoa(m, -1); dfsMatching(g, btoa);

Time: $\mathcal{O}(VE)$

522b98, 22 lines

```
bool find(int j, vector<vi>& g, vi& btoa, vi& vis) { //400
    if (btoa[j] == -1) return 1;
    vis[j] = 1; int di = btoa[j];
    for (int e : g[di])
        if (!vis[e] && find(e, g, btoa, vis)) {
            btoa[e] = di; //a0e
            return 1;
        }
    return 0;
}
int dfsMatching(vector<vi>& g, vi& btoa) { //52f
    vi vis;
    rep(i, 0, sz(g)) {
        vis.assign(sz(btoa), 0);
        for (int j : g[i])
            if (find(j, g, btoa, vis)) { //e5b
                btoa[j] = i;
                break;
            }
    }
    return sz(btoa) - (int)count(all(btoa), -1); //ff5
}
```

MinimumVertexCover.h

Description: Finds a minimum vertex cover in a bipartite graph. The size is the same as the size of a maximum matching, and the complement is a maximum independent set.

"DFSMatching.h" da4196, 20 lines

```
vi cover(vector<vi>& g, int n, int m) { //60f
    vi match(m, -1);
    int res = dfsMatching(g, match);
    vector<bool> lfound(n, true), seen(m);
    for (int it : match) if (it != -1) lfound[it] = false;
    vi q, cover; //0db
    rep(i, 0, n) if (lfound[i]) q.push_back(i);
    while (!q.empty()) {
        int i = q.back(); q.pop_back();
        lfound[i] = 1;
        for (int e : g[i]) if (!seen[e] && match[e] != -1) { //dc5
            seen[e] = true;
            q.push_back(match[e]);
        }
    }
    rep(i, 0, n) if (!lfound[i]) cover.push_back(i); //849
    rep(i, 0, m) if (seen[i]) cover.push_back(n+i);
    assert(sz(cover) == res);
    return cover;
}
```

WeightedMatching.h

Description: Given a weighted bipartite graph, matches every node on the left with a node on the right such that no nodes are in two matchings and the sum of the edge weights is minimal. Takes $cost[N][M]$, where $cost[i][j]$ = cost for $L[i]$ to be matched with $R[j]$ and returns (min cost, match), where $L[i]$ is matched with $R[match[i]]$. Negate costs for max cost. Requires $N \leq M$.

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

1e0fe9, 31 lines

```
pair<int, vi> hungarian(const vector<vi> &a) { //64f
    if (a.empty()) return {0, {}};
    int n = sz(a) + 1, m = sz(a[0]) + 1;
    vi u(n), v(m), p(m), ans(n - 1);
    rep(i, 1, n) {
        p[0] = i; //0b5
        int j0 = 0; // add "dummy" worker 0
        vi dist(m, INT_MAX), pre(m, -1);
        vector<bool> done(m + 1);
        do { // dijkstra
            done[j0] = true; //14f
            int i0 = p[j0], j1, delta = INT_MAX;
```

```
        rep(j, 1, m) if (!done[j]) {
            auto cur = a[i0 - 1][j - 1] - u[i0] - v[j];
            if (cur < dist[j]) dist[j] = cur, pre[j] = j0;
            if (dist[j] < delta) delta = dist[j], j1 = j; //865
        }
        rep(j, 0, m) {
            if (done[j]) u[p[j]] += delta, v[j] -= delta;
            else dist[j] -= delta;
        } //aaf
        j0 = j1;
    } while (p[j0]);
    while (j0) { // update alternating path
        int j1 = pre[j0];
        p[j0] = p[j1], j0 = j1; //88f
    }
}
rep(j, 1, m) if (p[j]) ans[p[j] - 1] = j - 1;
return {-v[0], ans}; // min cost
} //cbb
```

GeneralMatching.h

Description: Matching for general graphs. Fails with probability N/mod .

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

"./numerical/MatrixInverse-mod.h" cb1912, 40 lines

```
vector<pii> generalMatching(int N, vector<pii>& ed) { //19e
    vector<vector<ll>> mat(N, vector<ll>(N)), A;
    for (pii pa : ed) {
        int a = pa.first, b = pa.second, r = rand() % mod;
        mat[a][b] = r, mat[b][a] = (mod - r) % mod;
    } //063

    int r = matInv(A = mat), M = 2*N - r, fi, fj;
    assert(r % 2 == 0);

    if (M != N) do { //f88
        mat.resize(M, vector<ll>(M));
        rep(i, 0, N) {
            mat[i].resize(M);
            rep(j, N, M) {
                int r = rand() % mod; //338
                mat[i][j] = r, mat[j][i] = (mod - r) % mod;
            }
        }
    } while (matInv(A = mat) != M);
    //92b
    vi has(M, 1); vector<pii> ret;
    rep(it, 0, M/2) {
        rep(i, 0, M) if (has[i])
            rep(j, i+1, M) if (A[i][j] && mat[i][j]) {
                fi = i; fj = j; goto done; //e0a
            }
        assert(0); done:
        if (fj < N) ret.emplace_back(fi, fj);
        has[fi] = has[fj] = 0;
        rep(sw, 0, 2) {
            ll a = modpow(A[fi][fj], mod-2); //b7f
            rep(i, 0, M) if (has[i] && A[i][fj]) {
                ll b = A[i][fj] * a % mod;
                rep(j, 0, M) A[i][j] = (A[i][j] - A[fi][j] * b) % mod;
            }
            swap(fi, fj); //3c7
        }
    }
    return ret;
}
```

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

```
vi val, comp, z, cont; //ed2
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)); //b9e

    if (low == val[j]) {
        do {
            x = z.back(); z.pop_back();
            comp[x] = ncmps; //f1f
            cont.push_back(x);
        } while (x != j);
        f(cont); cont.clear();
        ncmps++;
    } //658
    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); //5bc
    Time = ncmps = 0;
    rep(i, 0, n) if (comp[i] < 0) dfs(i, g, f);
}
```

76b5c9, 24 lines

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

```
vi num, st; //3e8
vector<vector<pii>> ed;
int Time;
template<class F>
int dfs(int at, int par, F& f) {
    int me = num[at] = ++Time, top = me; //112
    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); //c2b
        } else {
            int si = sz(st);
            int up = dfs(y, e, f);
            top = min(top, up);
            if (up == me) //c92
                st.push_back(e);
            f(vi(st.begin() + si, st.end()));
            st.resize(si);
        }
    }
}
```

c6b7c7, 32 lines

```
    }
    else if (up < me) st.push_back(e); //1a1
    else { /* e is a bridge */ }
}
}
return top;
} //85e

template<class F>
void bicomps(F f) {
    num.assign(sz(ed), 0);
    rep(i, 0, sz(ed)) if (!num[i]) dfs(i, -1, f); //888
}
```

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});` // ≤ 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 { //7c0
    int N;
    vector<vi> gr;
    vi values; // 0 = false, 1 = true

    TwoSat(int n = 0) : N(n), gr(2*n) {} //54e

    int addVar() { // (optional)
        gr.emplace_back();
        gr.emplace_back();
        return N++; //662
    }

    void either(int f, int j) {
        f = max(2*f, -1-2*f);
        j = max(2*j, -1-2*j); //3b0
        gr[f].push_back(j^1);
        gr[j].push_back(f^1);
    }

    void setValue(int x) { either(x, x); }
} //41c

void atMostOne(const vi& li) { // (optional)
    if (sz(li) <= 1) return;
    int cur = ~li[0];
    rep(i, 2, sz(li)) {
        int next = addVar(); //f5e
        either(cur, ~li[i]);
        either(cur, next);
        either(~li[i], next);
        cur = ~next;
    } //276
    either(cur, ~li[1]);
}
```

```
vi val, comp, z; int time = 0;
int dfs(int i) { //7e3
    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(); //0c0
        comp[x] = low;
    }
}
```

```
    if (values[x>>1] == -1)
        values[x>>1] = x&1;
} while (x != i);
return val[i] = low; //749
}

bool solve() {
    values.assign(N, -1);
    val.assign(2*N, 0); comp = val; //4fa
    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;
}
} //214
```

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 nodes in the Eulerian path/cycle with `src` at both start and end, or empty list if no cycle/path exists. To get edge indices back, add `.second` to `s` and `ret`.

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

780b64, 15 lines

```
vi eulerWalk(vector<vector<pii>>& gr, int nedges, int src
=0) { //fda
    int n = sz(gr);
    vi D(n), its(n), eu(nedges), ret, s = {src};
    D[src]++; // to allow Euler paths, not just cycles
    while (!s.empty()) {
        int x = s.back(), y, e, &it = its[x], end = sz(gr[x]);
        //e35
        if (it == end) { ret.push_back(x); s.pop_back();
            continue; }
        tie(y, e) = gr[x][it++];
        if (!eu[e]) {
            D[x]--, D[y]++;
            eu[e] = 1; s.push_back(y); //8f2
        }
    }
    for (int x : D) if (x < 0 || sz(ret) != nedges+1) return
    {};
    return {ret.rbegin(), ret.rend()};
}
```

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: $\mathcal{O}(NM)$

e210e2, 31 lines

```
vi edgeColoring(int N, vector<pii> eds) { //d26
    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) { //945
        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) //665
            loc[d] = ++ind, cc[ind] = d, fan[ind] = v;
        cc[loc[d]] = c;
        for (int cd = c; 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) { //e70
            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;//75c
}
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++);//
        b06
}
rep(i,0,sz(eds))
    for (tie(u, v) = eds[i]; adj[u][ret[i]] != v;) ++ret[i]
        ;
return ret;
};//cbb
```

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: $\mathcal{O}\left(3^{n/3}\right)$, much faster for sparse graphs

```
typedef bitset<128> B; //abb
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]; //7d8
    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;
    } //67c
}
```

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; //b92
struct Maxclique {
    double limit=0.025, pk=0;
    struct Vertex { int i, d=0; };
    typedef vector<Vertex> vv;
    vb e; //5b2
    vv V;
    vector<vi> C;
    vi qmax, q, S, old;
    void init(vv& r) {
        for (auto& v : r) v.d = 0; //dab
        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;
    } //a6a
    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; //6b0
            q.push_back(R.back().i);
            vv T;
            for(auto v:R) if (e[R.back().i][v.i]) T.push_back({v.i});
        }
```

```
if (sz(T)) {
    if (S[lev]++ / ++pk < limit) init(T); //feb
    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]; }; //547
        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);
    } //08b
    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; //15f
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)
    ) {} //02b
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.

//d41

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) //bcb
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]]; //47a
return jmp;
}

int jmp(vector<vi>& tbl, int nod, int steps){
    rep(i,0,sz(tbl)) //66f
        if(steps&(1<<i)) nod = tbl[i][nod];
    return nod;
}

int lca(vector<vi>& tbl, vi& depth, int a, int b) {} //57b
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]; //30e
    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 {} //169
int T = 0;
vi time, path, ret;
RMQ<int> rmq;

LCA(vector<vi>& C) : time(sz(C)), rmq((dfs(C,0,-1), ret))
    {} //e10
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); //3f8
    }
}

int lca(int a, int b) {
    if (a == b) return a; //3f5
    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)
    ];}
}; //214
```

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 LCA's 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; //386
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); //a92
    int m = sz(li)-1;
    rep(i,0,m) {
        int a = li[i], b = li[i+1];
        li.push_back(lca.lca(a, b));
    } //c76
    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) {} //ff8
        int a = li[i], b = li[i+1];
        ret.emplace_back(rev[lca.lca(a, b)], b);
    }
    return ret;
} //cbb
```

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: $\mathcal{O}\left((\log N)^2\right)$

```
"../data-structures/LazySegmentTree.h"
9547af, 46 lines

template <bool VALS_EDGES> struct HLD {} //431
int N, tim = 0;
vector<vi> adj;
vi par, siz, rt, pos;
Node *tree;
```

```

HLD(vector<vi> adj_)//72a
: N(sz(adj_)), adj(adj_), par(N, -1), siz(N, 1),
rt(N), pos(N), tree(new Node(0, N)) { dfsSz(0); dfsHld
(0); }
void dfsSz(int v) {
for (int& u : adj[v]) {
adj[u].erase(find(all(adj[u]), v)); //e07
par[u] = v;
dfsSz(u);
siz[v] += siz[u];
if (siz[u] > siz[adj[v][0]]) swap(u, adj[v][0]);
} //09d
}
void dfsHld(int v) {
pos[v] = tim++;
for (int u : adj[v]) {
rt[u] = (u == adj[v][0] ? rt[v] : u); //0b4
dfsHld(u);
}
}
template <class B> void process(int u, int v, B op) {
for (; v = par[rt[v]]) { //001
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); //31c
}
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 //ad4
int res = -1e9;
process(u, v, [&](int l, int r) {
res = max(res, tree->query(l, r));
});
return res; //4b8
}
int querySubtree(int v) { // modifySubtree is similar
return tree->query(pos[v] + VALS_EDGES, pos[v] + siz[v
]);
}
}; //214

```

LinkCutTree.h

Description: Represents a forest of unrooted trees. You can add and remove edges (as long as the result is still a forest), and check whether two nodes are in the same tree.

Time: All operations take amortized $\mathcal{O}(\log N)$.

0fb462, 90 lines

```

struct Node { // Splay tree. Root's pp contains tree's
parent. //a4e
Node *p = 0, *pp = 0, *c[2];
bool flip = 0;
Node() { c[0] = c[1] = 0; fix(); }
void fix() {
if (c[0]) c[0]->p = this; //b8f
if (c[1]) c[1]->p = this;
// (+ update sum of subtree elements etc. if wanted)
}
void pushFlip() {
if (!flip) return; //dfd
flip = 0; swap(c[0], c[1]);
if (c[0]) c[0]->flip ^= 1;
if (c[1]) c[1]->flip ^= 1;
}
int up() { return p ? p->c[1] == this : -1; } //3a9
void rot(int i, int b) {
int h = i ^ b;

```

```

Node *x = c[i], *y = b == 2 ? x : x->c[h], *z = b ? y :
x;
if ((y->p = p)) p->c[up()] = y;
c[i] = z->c[i ^ 1]; //eb7
if (b < 2) {
x->c[h] = y->c[h ^ 1];
y->c[h ^ 1] = x;
}
z->c[i ^ 1] = this; //430
fix(); x->fix(); y->fix();
if (p) p->fix();
swap(pp, y->pp);
}
void splay() { //4c8
for (pushFlip(); p; ) {
if (p->p) p->p->pushFlip();
p->pushFlip(); pushFlip();
int c1 = up(), c2 = p->up();
if (c2 == -1) p->rot(c1, 2); //9e8
else p->p->rot(c2, c1 != c2);
}
}
Node* first() {
pushFlip(); //828
return c[0] ? c[0]->first() : (splay(), this);
}
};

struct LinkCut { //d99
vector<Node> node;
LinkCut(int N) : node(N) {}

void link(int u, int v) { // add an edge (u, v)
assert(!connected(u, v)); //166
makeRoot(&node[u]);
node[u].pp = &node[v];
}
void cut(int u, int v) { // remove an edge (u, v)
Node *x = &node[u], *top = &node[v]; //0b9
makeRoot(top); x->splay();
assert(top == (x->pp ? x->c[0]));
if (x->pp) x->pp = 0;
else {
x->c[0] = top->p = 0; //158
x->fix();
}
}
bool connected(int u, int v) { // are u, v in the same
tree?
Node* nu = access(&node[u])->first(); //781
return nu == access(&node[v])->first();
}
void makeRoot(Node* u) {
access(u);
u->splay(); //09d
if (u->c[0]) {
u->c[0]->p = 0;
u->c[0]->flip ^= 1;
u->c[0]->pp = u;
u->c[0] = 0; //41e
u->fix();
}
}
Node* access(Node* u) {
u->splay(); //4e7
while (Node* pp = u->pp) {
pp->splay(); u->pp = 0;
if (pp->c[1]) {
pp->c[1]->p = 0; pp->c[1]->pp = pp; }
pp->c[1] = u; pp->fix(); u = pp; //f4d
}
}

```

```
return u;
```

```
};
```

DirectedMST.h

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

Time: $\mathcal{O}(E \log V)$

../data-structures/UnionFindRollback.h"

39e620, 60 lines

```

struct Edge { int a, b; ll w; }; //59f
struct Node {
Edge key;
Node *l, *r;
ll delta;
void prop() { //936
key.w += delta;
if (l) l->delta += delta;
if (r) r->delta += delta;
delta = 0;
} //5dc
Edge top() { prop(); return key; }
};
Node *merge(Node *a, Node *b) {
if (!a || !b) return a ? b;
a->prop(), b->prop(); //72a
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); } //8
e9

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
}); //0f3
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>>> cycs; //4c6
rep(s, 0, n) {
int u = s, qi = 0, w;
while (seen[u] < 0) {
if (!heap[u]) return {-1, {}};
Edge e = heap[u]->top(); //2b0
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; //fff
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;
cycs.push_front({u, time, {&Q[qi], &Q[end]}}); //984
}
}
rep(i, 0, qi) in[uf.find(Q[i].b)] = Q[i];
}
} //b55
for (auto& [u, t, comp] : cycs) { // 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; //ffd
}
rep(i, 0, n) par[i] = in[i].a;
return {res, par};
}

```


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 `mat[a][b]--`, `mat[b][b]++` (and `mat[b][a]--`, `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 any row/column).

7.8.2 Erdős–Gallai 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

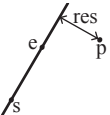
Description: Class to handle points in the plane. T can be e.g. double or long long. (Avoid int.)

47ec0a, 28 lines

```
template <class T> int sgn(T x) { return (x > 0) - (x < 0); }
//fa7
template<class T>
struct Point {
    typedef Point P;
    T x, y;
    explicit Point(T x=0, T y=0) : x(x), y(y) {}//4f8
    bool operator<(P p) const { return tie(x,y) < tie(p.x,p.y); }
    bool operator==(P p) const { return tie(x,y)==tie(p.x,p.y); }
    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); }//e11
    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; }//0c3
    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//9f3
    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) {}//25e
    return os << "(" << p.x << ", " << p.y << ")"; }
};
```

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> //f6b
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"

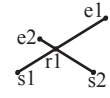
5c88f4, 6 lines

```
typedef Point<double> P; //b95
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;
} //cbb
```

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"

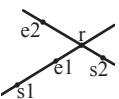
9d57f2, 13 lines

```
template<class P> vector<P> segInter(P a, P b, P c, P d) {
    //dec
    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)}; //8a0
    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); //814
    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> //47e
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); //16d
    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> //059
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); //7c7 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"

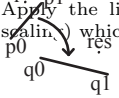
c597e8, 3 lines

```
template<class P> bool onSegment(P s, P e, P p) { //c59
    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; //d52
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();
    } //cbb
```

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 at 0 and i
```

```
struct Angle { //6c9
    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 { //a5b
        assert(x || y);
        return y < 0 || (y == 0 && x < 0);
    }
    Angle t90() const { return {-y, x, t + (half() && x >= 0)
        }; }
    Angle t180() const { return {-x, -y, t + half()}; } //de0
    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 * (1l)b.x) < //41b
        make_tuple(b.t, b.half(), a.x * (1l)b.y);
}
```

```
// Given two points, this calculates the smallest angle
    between
// them, i.e., the angle that covers the defined line
    segment. //f86
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()));
} //b11
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) r.t--;
    return r.t180() < a ? r.t360() : r;
} //073
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
        )};
}
```

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; //deb
bool circleInter(P a,P b,double r1,double r2,pair<P, P>*
    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; //367
    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;
} //cbb
```

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> //c18
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; //446
    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(); //918
    return out;
}
```

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

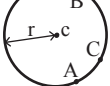
typedef Point<double> P; //a6c
#define arg(p, q) atan2(p.cross(q), p.dot(q))
double circlePoly(P c, double r, vector<P> ps) {
    auto tri = [&](P p, P q) {
        auto r2 = r * r / 2;
        P d = q - p; //eda
        auto a = d.dot(p)/d.dist2(), b = (p.dist2()-r*r)/d.
            dist2();
        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; //12b
        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)) //a61
        sum += tri(ps[i] - c, ps[(i + 1) % sz(ps)] - c);
    return sum;
}
```

circumcircle.h

Description: The circumcirle 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; //032
```



```
double ccRadius(const P& A, const P& B, const P& C) {
    return (B-A).dist()*(C-B).dist()*(A-C).dist() /
        abs((B-A).cross(C-A))/2;
}
P ccCenter(const P& A, const P& B, const P& C) { //793
    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) { //b50
    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; //d54
        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]); //4ec
                r = (o - ps[i]).dist();
            }
        }
    }
    return {o, r}; //2ac
}
```

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> //1c1
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; //fa7
        //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;
} //cbb
```

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> //b19
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;
} //cbb
```

PolygonCenter.h

Description: Returns the center of mass for a polygon.

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

"Point.h"	9706dc, 9 lines
<pre>typedef Point<double> P; //082 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]); //168 } return res / A / 3; }</pre>	

PolygonCut.h

Description:

Returns a vector with the vertices of a polygon with every-thing 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
<pre>typedef Point<double> P; //366 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); //0bd if ((a < 0) != (b < 0)) res.push_back(cur + (prev - cur) * (a / (a - b))); if (a < 0) res.push_back(cur); } //0e1 return res; }</pre>	

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
<pre>typedef Point<ll> P; //3e3 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; //f18 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; } //aa0 return {h.begin(), h.begin() + t - (t == 2 && h[0] == h[1])}; }</pre>	

HullDiameter.h

Description: Returns the two points with max distance on a convex hull (ccw, no duplicate/collinear points).

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

"Point.h"	c571b8, 12 lines
<pre>typedef Point<ll> P; //5c7 array<P, 2> hullDiameter(vector<P> S) {</pre>	

<pre>int n = sz(S), j = n < 2 ? 0 : 1; pair<ll, array<P, 2>> res({0, {S[0], S[0]}}); rep(i,0,j) for (; j = (j + 1) % n) { //56c res = max(res, {(S[i] - S[j]).dist2(), {S[i], S[j]}}) ; if ((S[(j + 1) % n] - S[j]).cross(S[i + 1] - S[i]) >= 0) break; } return res.second; //52a }</pre>	
--	--

PointInsideHull.h

Description: Determine whether a point t lies inside a convex hull (CCW order, with no collinear points). Returns true if point lies within the hull. If strict is true, points on the boundary aren't included.

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

"Point.h", "sideOf.h", "OnSegment.h"	71446b, 14 lines
<pre>typedef Point<ll> P; //7a3 bool inHull(const vector<P>& l, P p, bool strict = true) { int a = 1, b = sz(l) - 1, r = !strict; if (sz(l) < 3) return r && onSegment(l[0], l.back(), p); if (sideOf(l[0], l[a], l[b]) > 0) swap(a, b); //4a6 if (sideOf(l[0], l[a], p) >= r sideOf(l[0], l[b], p) <= -r) return false; while (abs(a - b) > 1) { int c = (a + b) / 2; (sideOf(l[0], l[c], p) > 0 ? b : a) = c; //0da } return sgn(l[a].cross(l[b], p)) < r; }</pre>	

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
<pre>#define cmp(i, j) sgn(dir.perp().cross(poly[(i)%n]-poly[(j)%n])) //b9d #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) { //51a 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; } //e8c return lo; }</pre>	

<pre>#define cmpL(i) sgn(a.cross(poly[i], b)) template <class P> //7fd array<int, 2> lineHull(P a, P b, vector<P>& poly) { int endA = extrVertex(poly, (a - b).perp()); int endB = extrVertex(poly, (b - a).perp()); if (cmpL(endA) < 0 cmpL(endB) > 0) return {-1, -1}; //04b array<int, 2> res;</pre>	
--	--

<pre>rep(i,0,2) { int lo = endB, hi = endA, n = sz(poly); while ((lo + 1) % n != hi) { int m = (lo + hi + (lo < hi ? 0 : n)) / 2; //ec0 (cmpL(m) == cmpL(endB) ? lo : hi) = m; } res[i] = (lo + !cmpL(hi)) % n; swap(endA, endB); } //6ab if (res[0] == res[1]) return {res[0], -1}; if (!cmpL(res[0]) && !cmpL(res[1])) switch ((res[0] - res[1] + sz(poly) + 1) % sz(poly)) { case 0: return {res[0], res[0]}; case 2: return {res[1], res[1]}; //08a } return res; }</pre>	
--	--

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
<pre>typedef Point<ll> P; //9e7 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()}}; //e83 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); //cb2 for (; lo != hi; ++lo) ret = min(ret, {(lo - p).dist2(), {lo, p}}); S.insert(p); } return ret.second; //982 }</pre>	

kdTree.h

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

"Point.h"	bac5b0, 63 lines
<pre>typedef long long T; //632 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; } //c56 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; //5b4 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(); //a82 } }</pre>	

<pre>Node(vector<P>&& vp) : pt(vp[0]) { for (P p : vp) { x0 = min(x0, p.x); x1 = max(x1, p.x); //151 y0 = min(y0, p.y); y1 = max(y1, p.y); } }</pre>	
--	--

```
    if (vp.size() > 1) {
        // split on x if width >= height (not ideal...)
        sort(all(vp), x1 - x0 >= y1 - y0 ? on_x : on_y); //1d2
        // 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()}); //ace
    }
};

struct KDTree { //72b
    Node* root;
    KDTree(const vector<P>& vp) : root(new Node({all(vp)})) {
    }

    pair<T, P> search(Node *node, const P& p) {
        if (!node->first) { //119
            // 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);
        }
        //a89
        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 //bfa
        auto best = search(f, p);
        if (bsec < best.first)
            best = min(best, search(s, p));
        return best;
    } //13a

    // 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); //213
    }
};
```

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 'circ'. Returns triangles in order {t[0][0], t[0][1], t[0][2], t[1][0], ... }, all counter-clockwise. **Time:** $O(n \log n)$

```
"Point.h" eefdf5, 88 lines
typedef Point<ll> P; //503
typedef struct Quad* Q;
typedef __int128_t ll1; // (can be ll if coords are < 2e4)
P arb(LLONG_MAX, LLONG_MAX); // not equal to any other point

struct Quad { //8bb
    Q rot, o; P p = arb; bool mark;
    P& F() { return r()->p; }
    Q& r() { return rot->rot; }
    Q prev() { return rot->o->rot; }
    Q next() { return r()->prev(); } //0bd
} *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; //520
```

FastDelaunay PolyhedronVolume Point3D 3dHull

```
    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{new Quad{0}}}};
    H = r->o; r->r()->r() = r; //60f
    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) { //5b1
    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()); //3cc
    splice(q->r(), b);
    return q;
}

pair<Q,Q> rec(const vector<P>& s) { //a03
    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]); //d54
        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 //f35
    #define valid(e) (e->F().cross(H(base)) > 0)
    Q A, B, ra, rb;
    int half = sz(s) / 2;
    tie(ra, A) = rec({all(s) - half});
    tie(B, rb) = rec({sz(s) - half + all(s)}); //c17
    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; //a99

    #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()); //475
            splice(e->r(), e->r()->prev()); \
            e->o = H; H = e; e = t; \
        }
    for (;) {
        DEL(LC, base->r(), o); DEL(RC, base, prev()); //031
        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()); //907
    }
    return { ra, rb };
}
```

```
vector<P> triangulate(vector<P> pts) { //e5d
    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; //02b
    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; //24a
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> //27c
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;
} //cbb
```

Point3D.h

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

8058ae, 32 lines

```
template<class T> struct Point3D { //c7b
    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 { //5e8
        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); }
    //9b1
    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);
        //58a
    }
    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); } //a2c
    //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(); } //e88
    //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)*(1-c) + (*this)*c - cross(u)*s;
    } //e03
};
```

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: $O(n^2)$

```
"Point3D.h" 5b45fc, 49 lines
typedef Point3D<double> P3; //e28
```

```
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); } //c34
    int a, b;
};

struct F { P3 q; int a, b, c; };
//36b
vector<F> hull3d(const vector<P3>& A) {
    assert(sz(A) >= 4);
    vector<vector<PR>> E(sz(A), vector<PR>(sz(A), {-1, -1}));
    #define E(x,y) E[f.x][f.y]
    vector<F> FS; //de0
    auto mf = [&](int i, int j, int k, int l) {
        P3 q = (A[j] - A[i]).cross((A[k] - A[i]));
        if (q.dot(A[l]) > q.dot(A[i]))
            q = q * -1;
        F f{q, i, j, k}; //923
        E(a,b).ins(k); E(a,c).ins(j); E(b,c).ins(i);
        FS.push_back(f);
    };
    rep(i,0,4) rep(j,i+1,4) rep(k,j+1,4)
        mf(i, j, k, 6 - i - j - k); //e21

    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])) { //b63
                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(); //0df
            }
            int nw = sz(FS);
            rep(j,0,nw) {
                F f = FS[j]; //945
            #define C(a, b, c) if (E(a,b).cnt() != 2) mf(f.a, f.b, i, f
                .c);
                C(a, b, c); C(a, c, b); C(b, c, a);
            }
            for (F& it : FS) if ((A[it.b] - A[it.a]).cross(//ab3
                A[it.c] - A[it.a]).dot(it.q) <= 0) swap(it.c, it.b);
            return FS;
        };
    };
```

sphericalDistance.h

Description: Returns the shortest distance on the sphere with radius radius between the points with azimuthal angles (longitude) f1 (ϕ_1) and f2 (ϕ_2) from x axis and zenith angles (latitude) t1 (θ_1) and t2 (θ_2) from z axis (0 = north pole). All angles measured in radians. The algorithm starts by converting the spherical coordinates to cartesian coordinates so if that is what you have you can use only the two last rows. dx*radius is then the difference between the two points in the x direction and d*radius is the total distance between the points.

```
double sphericalDistance(double f1, double t1, //6da
    double f2, double t2, double radius) {
    double dx = sin(t2)*cos(f2) - sin(t1)*cos(f1);
    double dy = sin(t2)*sin(f2) - sin(t1)*sin(f1);
    double dz = cos(t2) - cos(t1);
    double d = sqrt(dx*dx + dy*dy + dz*dz); //65e
    return radius*2*asin(d/2);
}
```

Strings (9)

KMP.h

Description: pi[x] computes the length of the longest prefix of s that ends at x, other than s[0...x] itself (abacaba -> 0010123). Can be used to find all occurrences of a string.

```
Time:  $\mathcal{O}(n)$ 
d4375c, 16 lines

vi pi(const string& s) { //f6d
    vi p(sz(s));
    rep(i,1,sz(s)) {
        int g = p[i-1];
        while (g && s[i] != s[g]) g = p[g-1];
        p[i] = g + (s[i] == s[g]); //0ff
    }
    return p;
}
```

```
vi match(const string& s, const string& pat) { //752
    vi p = pi(pat + '\0' + s), res;
    rep(i,sz(p)-sz(s),sz(p))
        if (p[i] == sz(pat)) res.push_back(i - 2 * sz(pat));
    return res;
} //cbb
```

Zfunc.h

Description: z[i] computes the length of the longest common prefix of s[i:] and s, except z[0] = 0. (abacaba -> 0010301)

```
Time:  $\mathcal{O}(n)$ 
ee09e2, 12 lines

vi Z(const string& S) { //fc3
    vi z(sz(S));
    int l = -1, r = -1;
    rep(i,1,sz(S)) {
        z[i] = i >= r ? 0 : min(r - i, z[i - l]);
        while (i + z[i] < sz(S) && S[i + z[i]] == S[z[i]]) //8ec
            z[i]++;
        if (i + z[i] > r)
            l = i, r = i + z[i];
    }
    return z; //939
}
```

Manacher.h

Description: For each position in a string, computes p[0][i] = half length of longest even palindrome around pos i, p[1][i] = longest odd (half rounded down).

```
Time:  $\mathcal{O}(N)$ 
e7ad79, 13 lines

array<vi, 2> manacher(const string& s) { //510
    int n = sz(s);
    array<vi, 2> p = {vi(n+1), vi(n)};
    rep(z,0,2) for (int i=0,l=0,r=0; i < n; i++) {
        int t = r-i+!z;
        if (i<r) p[z][i] = min(t, p[z][l+t]); //f50
        int L = i-p[z][i], R = i+p[z][i]-!z;
        while (L>=1 && R+1<n && s[L-1] == s[R+1])
            p[z][i]++, L--, R++;
        if (R>r) l=L, r=R;
    } //291
    return p;
}
```

MinRotation.h

Description: Finds the lexicographically smallest rotation of a string.

Usage: rotate(v.begin(), v.begin()+minRotation(v), v.end());

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

```
d07a42, 8 lines

int minRotation(string s) { //20f
    int a=0, N=sz(s); s += s;
    rep(b,0,N) rep(k,0,N) {
        if (a+k == b || s[a+k] < s[b+k]) {b += max(0, k-1);
            break;}
    }
```

```
    if (s[a+k] > s[b+k]) { a = b; break; }
} //3a8
return a;
}
```

SuffixArray.h

Description: Builds suffix array for a string. sa[i] is the starting index of the suffix which is i 'th in the sorted suffix array. The returned vector is of size $n + 1$, and sa[0] = n. The lcp array contains longest common prefixes for neighbouring strings in the suffix array: lcp[i] = lcp(sa[i], sa[i-1]), lcp[0] = 0. The input string must not contain any nul chars.

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

```
635552, 22 lines

struct SuffixArray { //73d
    vi sa, lcp;
    SuffixArray(string s, int lim=256) { // or vector<int>
        s.push_back(0); int n = sz(s), k = 0, a, b;
        vi x(all(s)), y(n), ws(max(n, lim));
        sa = lcp = y, iota(all(sa), 0); //032
        for (int j = 0, p = 0; p < n; j = max(1, j * 2), lim =
            p) {
            p = j, iota(all(y), n - j);
            rep(i,0,n) if (sa[i] >= j) y[p++] = sa[i] - j;
            fill(all(ws), 0);
            rep(i,0,n) ws[x[i]]++; //f08
            rep(i,1,lim) ws[i] += ws[i - 1];
            for (int i = n; i--;) sa[--ws[x[y[i]]]] = y[i];
            swap(x, y), p = 1, x[sa[0]] = 0;
            rep(i,1,n) a = sa[i - 1], b = sa[i], x[b] =
                (y[a] == y[b] && y[a + j] == y[b + j]) ? p - 1 : p
                    ++; //726
        }
        for (int i = 0, j; i < n - 1; lcp[x[i++]] = k)
            for (k && k--, j = sa[x[i] - 1];
                s[i + k] == s[j + k]; k++);
    } //e03
};
```

SuffixTree.h

Description: Ukkonen's algorithm for online suffix tree construction. Each node contains indices [l, r] into the string, and a list of child nodes. Suffixes are given by traversals of this tree, joining [l, r] substrings. The root is 0 (has l = -1, r = 0), non-existent children are -1. To get a complete tree, append a dummy symbol – otherwise it may contain an incomplete path (still useful for substring matching, though).

Time: $\mathcal{O}(26N)$

```
aae0b8, 50 lines

struct SuffixTree { //b1f
    enum { N = 200010, ALPHA = 26 }; // N ~ 2*maxlen+10
    int toi(char c) { return c - 'a'; }
    string a; // v = cur node, q = cur position
    int t[N][ALPHA], l[N], r[N], p[N], s[N], v=0, q=0, m=2;
    //b11
    void ukkadd(int i, int c) { suff:
        if (r[v]<=q) {
            if (t[v][c]==-1) { t[v][c]=m; l[m]=i;
                p[m++]=v; v=s[v]; q=r[v]; goto suff; }
            v=t[v][c]; q=l[v]; //99f
        }
        if (q==-1 || c==toi(a[q])) q++; else {
            l[m+1]=i; p[m+1]=m; l[m]=l[v]; r[m]=q;
            p[m]=p[v]; t[m][c]=m+1; t[m][toi(a[q])]=v;
            l[v]=q; p[v]=m; t[p[m]][toi(a[l[m]])]=m; //604
            v=s[p[m]]; q=l[m];
            while (q<r[m]) { v=t[v][toi(a[q])]; q+=r[v]-l[v]; }
            if (q==r[m]) s[m]=v; else s[m]=m+2;
            q=r[v]-(q-r[m]); m+=2; goto suff;
        } //478
    }
```

```
SuffixTree(string a) : a(a) {
    fill(r,r+N,sz(a));
    memset(s, 0, sizeof s);//f11
    memset(t, -1, sizeof t);
    fill(t[1],t[1]+ALPHA,0);
    s[0] = 1; l[0] = l[1] = -1; r[0] = r[1] = p[0] = p[1] = 0;

    rep(i,0,sz(a)) ukkadd(i, toi(a[i]));
}//d1a

// example: find longest common substring (uses ALPHA = 28)
pii best;
int lcs(int node, int i1, int i2, int olen) {
    if (l[node] <= i1 && i1 < r[node]) return 1;//636
    if (l[node] <= i2 && i2 < r[node]) return 2;
    int mask = 0, len = node ? olen + (r[node] - l[node]) : 0;
    rep(c,0,ALPHA) if (t[node][c] != -1)
        mask |= lcs(t[node][c], i1, i2, len);
    if (mask == 3)//a3a
        best = max(best, {len, r[node] - len});
    return mask;
}

static pii LCS(string s, string t) {
    SuffixTree st(s + (char)('z' + 1) + t + (char)('z' + 2)
    );//78c
    st.lcs(0, sz(s), sz(s) + 1 + sz(t), 0);
    return st.best;
}
};
```

Hashing.h

Description: Self-explanatory methods for string hashing.*2a67, 44 lines*

// Arithmetic mod 2^64-1. 2x slower than mod 2^64 and more //d41

// code, but works on evil test data (e.g. Thue-Morse, where

// ABBA... and BAAB... of length 2^10 hash the same mod 2^64).

// "typedef ull H;" instead if you think test data is random,

// or work mod 10^9+7 if the Birthday paradox is not a problem.

typedef uint64_t ull;*//98c*

```
struct H {
    ull x; H(ull x=0) : x(x) {}
    H operator+(H o) { return x + o.x + (x + o.x < x); }
    H operator-(H o) { return *this + ~o.x; }
    H operator*(H o) { auto m = (__uint128_t)x * o.x;//884
        return H((ull)m) + (ull)(m >> 64); }
    ull get() const { return x + !~x; }
    bool operator==(H o) const { return get() == o.get(); }
    bool operator<(H o) const { return get() < o.get(); }
};//7dd

static const H C = (11)1e11+3; // (order ~ 3e9; random also ok)

struct HashInterval {
    vector<H> ha, pw;
    HashInterval(string& str) : ha(sz(str)+1), pw(ha) {//c1e
        pw[0] = 1;
        rep(i,0,sz(str))
            ha[i+1] = ha[i] * C + str[i],
            pw[i+1] = pw[i] * C;
    }//b8f
    H hashInterval(int a, int b) { // hash [a, b)
        return ha[b] - ha[a] * pw[b - a];
    }
};
```

```
//4b7
vector<H> getHashes(string& str, int length) {
    if (sz(str) < length) return {};
    H h = 0, pw = 1;
    rep(i,0,length)
        h = h * C + str[i], pw = pw * C;//7ab
    vector<H> ret = {h};
    rep(i,length,sz(str)) {
        ret.push_back(h = h * C + str[i] - pw * str[i-length]);
    }
    return ret;//413
}

H hashString(string& s){H h{}; for(char c:s) h=h*C+c;return h;}
```

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 $\mathcal{O}(NM)$.*135677, 66 lines*

```
struct AhoCorasick {//724
    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)); }//cc2
    };
    vector<Node> N;
    vi backp;
    void insert(string& s, int j) {
        assert(!s.empty());//757
        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;//20b
        }
        if (N[n].end == -1) N[n].start = j;
        backp.push_back(N[n].end);
        N[n].end = j;
        N[n].nmatches++;//77c
    }
    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);//12a

        queue<int> q;
        for (q.push(0); !q.empty(); q.pop()) {
            int n = q.front(), prev = N[n].back;
            rep(i,0,alpha) {//57b
                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
                )//338
                = N[y].end;
                N[ed].nmatches += N[y].nmatches;
                q.push(ed);
            }
        }
```

```
    }//c05
}
}

vi find(string word) {
    int n = 0;
    vi res; // 11 count = 0; //a68
    for (char c : word) {
        n = N[n].next[c - first];
        res.push_back(N[n].end);
        // count += N[n].nmatches;
    }//bb1
    return res;
}

vector<vi> findAll(vector<string>& pat, string word) {
    vi r = find(word);
    vector<vi> res(sz(word));//008
    rep(i,0,sz(word)) {
        int ind = r[i];
        while (ind != -1) {
            res[i - sz(pat[ind]) + 1].push_back(ind);
            ind = backp[ind];//8f0
        }
    }
    return res;
}
}//214
```

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 added. Intervals are [inclusive, exclusive).
Time: $\mathcal{O}(\log N)$

```
set<pii>::iterator addInterval(set<pii>& is, int L, int R)
{//ba1
    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);//ea6
    }
    if (it != is.begin() && (--it)->second >= L) {
        L = min(L, it->first);
        R = max(R, it->second);
        is.erase(it);//05d
    }
    return is.insert(before, {L,R});
}
```

```
void removeInterval(set<pii>& is, int L, int R) {//858
    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;//61f
    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: $\mathcal{O}(N \log N)$

```
template<class T>//0e2
```



```
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;//ed8
    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]));//607
            at++;
        }
        if (mx.second == -1) return {};
        cur = mx.first;
        R.push_back(mx.second);//26b
    }
    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 call-back g for each such interval.

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

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

```
template<class F, class G, class T>//570
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;//05f
    } else {
        int mid = (from + to) >> 1;
        rec(from, mid, f, g, i, p, f(mid));
        rec(mid+1, to, f, g, i, p, q);
    }//729
}
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);//a6c
    rec(from, to-1, f, g, i, p, q);
    g(i, to, q);
}
```

10.2 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: $\mathcal{O}(\log(b - a))$

```
template<class F>//7d4
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)//ec4
        else b = mid+1;
    }
    rep(i, a+1, b+1) if (f(a) < f(i)) a = i; // (B)
    return a;
} //cbb
```

LIS.h

Description: Compute indices for the longest increasing subsequence.

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

```
template<class I> vi lis(const vector<I>& S) {//47f
    if (S.empty()) return {};
    vi prev(sz(S));
    typedef pair<I, int> p;
    vector<p> res;
    rep(i, 0, sz(S)) {//a50
        // 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;//476
    }
    int L = sz(res), cur = res.back().second;
    vi ans(L);
    while (L--) ans[L] = cur, cur = prev[cur];
    return ans;//342
}
```

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: $\mathcal{O}(N \max(w_i))$

```
int knapsack(vi w, int t) {//e2b
    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);//14a
    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])//45b
            v[x-w[j]] = max(v[x-w[j]], j);
    }
    for (a = t; v[a+m-t] < 0; a--);
    return a;
} //cbb
```

10.3 Dynamic programming

KnuthDP.h

Description: When doing DP on intervals: $a[i][j] = \min_{i < k < j} (a[i][k] + a[k][j]) + f(i, j)$, 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: $\mathcal{O}(N^2)$

//d41

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: $\mathcal{O}((N + (hi - lo)) \log N)$

```
struct DP { // Modify at will://ff9
    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); }
}
```

//ec8

```
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)))//680
        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);
} //a30
void solve(int L, int R) { rec(L, R, INT_MIN, INT_MAX); }
};
```

10.4 Debugging tricks

- signal(SIGSEGV, [](int) { _Exit(0); }); converts segfaults into Wrong Answers. Similarly one can catch SIGABRT (assertion failures) and SIGFPE (zero divisions). _GLIBCXX_DEBUG failures generate SIGABRT (or SIGSEGV on gcc 5.4.0 apparently).
- feenableexcept(29); kills the program on NaNs (1), 0-divs (4), infinities (8) and denormals (16).

10.5 Optimization tricks

__builtin_ia32_ldmxcsr(40896); disables denormals (which make floats 20x slower near their minimum value).

10.5.1 Bit hacks

- $x \ \& \ -x$ is the least bit in x .
- for (int x = m; x;) { --x &= m; ... } loops over all subset masks of m (except m itself).
- $c = x \& -x$, $r = x + c$; $((r \wedge x) >> 2) / c$ | r is the next number after x with the same number of bits set.
- rep(b, 0, K) rep(i, 0, (1 << K)) if (i & 1 << b) D[i] += D[i^(1 << b)]; computes all sums of subsets.

10.5.2 Pragmas

- #pragma GCC optimize ("Ofast,unroll-loops") will make GCC auto-vectorize loops and optimizes floating points better.
- #pragma GCC target ("avx2,tune=native") can double performance of vectorized code, but causes crashes on old machines.
- #pragma GCC optimize ("trapv") kills the program on integer overflows (but is really slow).

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 $[0, 2b)$.

751a02, 8 lines

typedef unsigned long long ull;//010

```
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;//430
    }
};
```

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();//c51
    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);//818
    }
    return buf[bc++]; // returns 0 on EOF
}

int readInt() { //f26
    int a, c;
    while ((a = gc()) < 40);
    if (a == '-') return -readInt();
    while ((c = gc()) >= 48) a = a * 10 + c - 48;
    return a - 48;//d34
}
```

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 0.05us + 16 bytes per allocation.

745db2, 8 lines

```
// Either globally or in a single class://c17
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];//ef5
}

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 { //bda
    unsigned ind;
    ptr(T* p = 0) : ind(p ? unsigned((char*)p - buf) : 0) {
        assert(ind < sizeof buf);
    }
    T& operator*() const { return *(T*)(buf + ind); } //95f
    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>>> ed(N);

bb66d4, 14 lines

```
char buf[450 << 20] alignas(16); //2c8
size_t buf_ind = sizeof buf;

template<class T> struct small {
    typedef T value_type;
    small() {} //8ec
```

```
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);//ad1
}

void deallocate(T*, size_t) {}
};
```

SIMD.h
Description: Cheat sheet of SSE/AVX intrinsics, for doing arithmetic on several numbers at once. Can provide a constant factor improvement of about 4, orthogonal to loop unrolling. Operations follow the pattern "_mm(256)?name_(si(128|256)|epi(8|16|32|64)|pd|ps)". Not all are described here; grep for _mm_ in /usr/lib/gcc/*/4.9/include/ for more. If AVX is unsupported, try 128-bit operations, "emmintrin.h" and #define _SSE_ and _MMX_ before including it. For aligned memory use _mm_malloc(size, 32) or int buf[N] alignas(32), but prefer loadu/storeu.

c9ac08, 43 lines

```
#pragma GCC target ("avx2") // or sse4.1//eed
#include "emmintrin.h"

typedef __m256i mi;
#define L(x) _mm256_loadu_si256((mi*)&(x))
//d41
// High-level/specific methods:
// load(u)?_si256, store(u)?_si256, setzero_si256,
// _mm_malloc
// blendv_(epi8|ps|pd) (z?y:x), movemask_epi8 (hibits of
// bytes)
// i32gather_epi32(addr, x, 4): map addr[] over 32-b parts
// of x
// sad_epu8: sum of absolute differences of u8, outputs 4
// xi64//d41
// maddubs_epi16: dot product of unsigned i7's, outputs 16
// xi15
// madd_epi16: dot product of signed i16's, outputs 8xi32
// extractf128_si256(, i) (256->128), cutsi128_si32 (128->
// lo32)
// permute2f128_si256(x,x,1) swaps 128-bit lanes
// shuffle_epi32(x, 3*64+2*16+1*4+0) == x for each lane//
// d41
// shuffle_epi8(x, y) takes a vector instead of an imm

// Methods that work with most data types (append e.g.
// _epi32):
// set1, blend (i8?x:y), add, adds (sat.), mullo, sub, and/
// or,
// andnot, abs, min, max, sign(1,x), cmp(gt|eq), unpack(lo|
// hi)//512

int sumi32(mi m) { union {int v[8]; mi m;} u; u.m = m;
    int ret = 0; rep(i,0,8) ret += u.v[i]; return ret; }
mi zero() { return _mm256_setzero_si256(); }
mi one() { return _mm256_set1_epi32(-1); } //28e
bool all_zero(mi m) { return _mm256_testz_si256(m, m); }
bool all_one(mi m) { return _mm256_testc_si256(m, one()); }

ll example_filteredDotProduct(int n, short* a, short* b) {
    int i = 0; ll r = 0; //730
    mi zero = _mm256_setzero_si256(), acc = zero;
    while (i + 16 <= n) {
        mi va = L(a[i]), vb = L(b[i]); i += 16;
        va = _mm256_and_si256(_mm256_cmpgt_epil6(vb, va), va);
        mi vp = _mm256_madd_epi16(va, vb); //b47
        acc = _mm256_add_epi64(_mm256_unpacklo_epi32(vp, zero),
            _mm256_add_epi64(acc, _mm256_unpackhi_epi32(vp, zero)
            ));
    }
}
```

```
union {ll v[4]; mi m;} u; u.m = acc; rep(i,0,4) r += u.v[
    i];
for (;i<n;++i) if (a[i] < b[i]) r += a[i]*b[i]; // <-
    equiv//c30
return r;
}
```

JHU (11)
11.1 Extra Equations
Legendres: the largest x s.t. $k^x|n!$ is

$$\left\lfloor \frac{n}{k} \right\rfloor + \left\lfloor \frac{n}{k^2} \right\rfloor + \dots + \left\lfloor \frac{n}{k^i} \right\rfloor + \dots$$

Chicken McNugget: for any two pos relatively prime integers m, n, the greatest integer that cannot be written as $am + bn$ for non-neg a, b is $mn - m - n$. Additionally there are exactly $\frac{(m-1)(n-1)}{2}$ pos integers which cannot be expressed in the form $am + bn$.

Pick's: area of a polygon whose vertices are all lattice points in a coord plane is

$$A = I + \frac{1}{2}B - 1$$

I is number of interior lattice points, B is number of border lattice points

Shoelace: Suppose polygon P has vertices $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$, listed clockwise. Then area of P is

$$A = \frac{1}{2} |(x_1y_2 + x_2y_3 + \dots + x_ny_1) - (y_1x_2 + y_2x_3 + \dots + y_nx_1)|$$

$$\binom{2n}{n} = \sum_{k=0}^n \binom{n}{k}^2$$

Dense.h
Description: Dense Dijkstra's
Time: $\mathcal{O}(V^2)$

5eeb07, 24 lines

```
vector<vector<pair<int, int>>> vec; //270
vector<ll> dists;
vector<int> paths;
vector<bool> visited;
void denseDjik(int start) {
    dists[start] = 0; //358
    for (int i = 0; i < n; i++) {
        int v = -1;
        for (int j = 0; j < n; j++) {
            if (!visited[j] && (v == -1 || dists[j] < dists
                [v]))
                v = j; //ab6
        }
        if (dists[v] == INF) break;
        visited[v] = true;
        for (auto e : vec[v]) {
            int to = e.first; //235
            int len = e.second;
            if (dists[v] + len < dists[to]) {
                dists[to] = dists[v] + len;
                paths[to] = v;
            }
        }
    }
}
```



```
    } //088  
  }  
}
```

11.2 Pi

numbers::pi

11.3 Dynamic bitset

Dynamic-bitset.h

4edc0d, 10 lines

```
 .#include <tr2/dynamic_bitset> //4ed  
 tr2::dynamic_bitset<__uint128_t> bs;  
 // void    append (block_type __block)  
 // void    append (initializer_list< block_type > __il)  
 // size_type find_first () const  
 // size_type find_next (size_t __prev) const //d41  
 // bool    is_proper_subset_of (const dynamic_bitset &__b)  
 //        const  
 // bool    is_subset_of (const dynamic_bitset &__b) const  
 // void    push_back (bool __bit)  
 // void    resize (size_type __nbits, bool __value=false)
```

Techniques (A)

techniques.txt	159 lines
Recursion	
Divide and conquer	
Finding interesting points in N log N	
Algorithm analysis	
Master theorem	
Amortized time complexity	
Greedy algorithm	
Scheduling	
Max contiguous subvector sum	
Invariants	
Huffman encoding	
Graph theory	
Dynamic graphs (extra book-keeping)	
Breadth first search	
Depth first search	
* Normal trees / DFS trees	
Dijkstra's algorithm	
MST: Prim's algorithm	
Bellman-Ford	
Konig's theorem and vertex cover	
Min-cost max flow	
Lovasz toggle	
Matrix tree theorem	
Maximal matching, general graphs	
Hopcroft-Karp	
Hall's marriage theorem	
Graphical sequences	
Floyd-Warshall	
Euler cycles	
Flow networks	
* Augmenting paths	
* Edmonds-Karp	
Bipartite matching	
Min. path cover	
Topological sorting	
Strongly connected components	
2-SAT	
Cut vertices, cut-edges and biconnected components	
Edge coloring	
* Trees	
Vertex coloring	
* Bipartite graphs (=> trees)	
* 3^n (special case of set cover)	
Diameter and centroid	
K'th shortest path	
Shortest cycle	
Dynamic programming	
Knapsack	
Coin change	
Longest common subsequence	
Longest increasing subsequence	
Number of paths in a dag	
Shortest path in a dag	
Dynprog over intervals	
Dynprog over subsets	
Dynprog over probabilities	
Dynprog over trees	
3^n set cover	
Divide and conquer	
Knuth optimization	
Convex hull optimizations	
RMQ (sparse table a.k.a 2^k-jumps)	
Bitonic cycle	
Log partitioning (loop over most restricted)	
Combinatorics	
Computation of binomial coefficients	
Pigeon-hole principle	

Inclusion/exclusion
Catalan number
Pick's theorem
Number theory
Integer parts
Divisibility
Euclidean algorithm
Modular arithmetic
* Modular multiplication
* Modular inverses
* Modular exponentiation by squaring
Chinese remainder theorem
Fermat's little theorem
Euler's theorem
Phi function
Frobenius number
Quadratic reciprocity
Pollard-Rho
Miller-Rabin
Hensel lifting
Vieta root jumping
Game theory
Combinatorial games
Game trees
Mini-max
Nim
Games on graphs
Games on graphs with loops
Grundy numbers
Bipartite games without repetition
General games without repetition
Alpha-beta pruning
Probability theory
Optimization
Binary search
Ternary search
Unimodality and convex functions
Binary search on derivative
Numerical methods
Numeric integration
Newton's method
Root-finding with binary/ternary search
Golden section search
Matrices
Gaussian elimination
Exponentiation by squaring
Sorting
Radix sort
Geometry
Coordinates and vectors
* Cross product
* Scalar product
Convex hull
Polygon cut
Closest pair
Coordinate-compression
Quadtrees
KD-trees
All segment-segment intersection
Sweeping
Discretization (convert to events and sweep)
Angle sweeping
Line sweeping
Discrete second derivatives
Strings
Longest common substring
Palindrome subsequences
Knuth-Morris-Pratt
Tries
Rolling polynomial hashes
Suffix array

Suffix tree
Aho-Corasick
Manacher's algorithm
Letter position lists
Combinatorial search
Meet in the middle
Brute-force with pruning
Best-first (A*)
Bidirectional search
Iterative deepening DFS / A*
Data structures
LCA (2^k-jumps in trees in general)
Pull/push-technique on trees
Heavy-light decomposition
Centroid decomposition
Lazy propagation
Self-balancing trees
Convex hull trick (wcipeg.com/wiki/Convex_hull_trick)
Monotone queues / monotone stacks / sliding queues
Sliding queue using 2 stacks
Persistent segment tree