Massachusetts Institute of Technology

MIT NULL

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adapted from KACTL and MIT NULL

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Contest (1)

template.cpp
55 lines

```
#include <bits/stdc++.h>

using namespace std;

typedef long long ll;
typedef long double ld;
typedef double db;
typedef string str;

typedef pair<int, int> pi;
typedef pair<ll,ll> pl;
typedef pair<ld,ld> pd;
typedef complex<ld> cd;

typedef vector<int> vi;
typedef vector<ll> vl;
typedef vector<ld> vd;
typedef vector<str> vs;
typedef vector<pi> vpi;
typedef vector<pl> vpl;
typedef vector<cd> vcd;

#define FOR(i,a,b) for (int i = (a); i < (b); ++i)
#define F0R(i,a) FOR(i,0,a)
#define ROF(i,a,b) for (int i = (b)-1; i >= (a); --i)
#define R0F(i,a) ROF(i,0,a)
#define trav(a,x) for (auto& a : x)

#define mp make_pair
#define pb push_back
#define eb emplace_back
#define f first
#define s second
#define lb lower_bound
#define ub upper_bound

#define sz(x) (int)x.size()
#define all(x) begin(x), end(x)
#define rall(x) rbegin(x), rend(x)
#define rsz resize
#define ins insert

const int MOD = 1e9+7; // 998244353 = (119<<23)+1
const ll INF = 1e18;
const int MX = 2e5+5;
const ld PI = 4*atan((ld)1);

template<class T> bool ckmin(T& a, const T& b) { return a > b ?
    a = b, 1 : 0; }
template<class T> bool ckmax(T& a, const T& b) { return a < b ?
    a = b, 1 : 0; }

mt19937 rng((uint32_t)chrono::steady_clock::now().
    time_since_epoch().count());

int main() {
    cin.sync_with_stdio(0); cin.tie(0);
}
```

.bashrc
6 lines

```
co() {
    g++ -std=c++11 -O2 -Wall -Wl,-stack_size -Wl,0x10000000 -o
       $1 $1.cc
}
run() {
    co $1 && ./$1
}
```

.vimrc
4 lines

```
set cin aw ai is ts=4 sw=4 tm=50 nu noeb ru cul
sy on | im jk <esc> | im kj <esc>
set mouse=a
set ww+=<,>,[,]
```

hash.sh
3 lines

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

troubleshoot.txt
52 lines

```
Pre-submit:
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?
Could anything overflow?
Make sure to submit the right file.

Wrong answer:
Print your solution! Print debug output, as well.
Are you clearing all datastructures between test cases?
Can your algorithm handle the whole range of input?
Read the full problem statement again.
Do you handle all corner cases correctly?
Have you understood the problem correctly?
Any uninitialized variables?
Any overflows?
Confusing N and M, i and j, etc.?
Are you sure your algorithm works?
What special cases have you not thought of?
Are you sure the STL functions you use work as you think?
Add some assertions, maybe resubmit.
Create some testcases to run your algorithm on.
Go through the algorithm for a simple case.
Go through this list again.
Explain your algorithm to a team mate.
Ask the team mate to look at your code.
Go for a small walk, e.g. to the toilet.
Is your output format correct? (including whitespace)
Rewrite your solution from the start or let a team mate 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 team mates think about your algorithm?

Memory limit exceeded:
What is the max amount of memory your algorithm should need?
Are you clearing all datastructures 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 $x = -b/2a$.

$$\begin{array}{c} ax + by = e \\ cx + dy = f \end{array} \Rightarrow \begin{array}{c} x = \dfrac{ed - bf}{ad - bc} \\ y = \dfrac{af - ec}{ad - bc} \end{array}$$

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

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

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

2.2 Recurrences

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

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

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

2.3 Trigonometry

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

$$\tan(v+w) = \frac{\tan v + \tan w}{1 - \tan v \tan w}$$
$$\sin v + \sin w = 2 \sin \frac{v+w}{2} \cos \frac{v-w}{2}$$
$$\cos v + \cos w = 2 \cos \frac{v+w}{2} \cos \frac{v-w}{2}$$
$$(V+W)\tan(v-w)/2 = (V-W)\tan(v+w)/2$$

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

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

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

2.4 Geometry

2.4.1 Triangles

Side lengths: a, b, c

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

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

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

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

Length of median (divides triangle into two equal-area triangles): $m_a = \frac{1}{2}\sqrt{2b^2+2c^2-a^2}$

Length of bisector (divides angles in two):

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

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

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

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

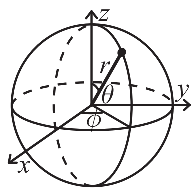
2.4.2 Quadrilaterals

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

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

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



$$x = r \sin\theta \cos\phi \qquad r = \sqrt{x^2+y^2+z^2}$$
$$y = r \sin\theta \sin\phi \qquad \theta = \operatorname{acos}(z/\sqrt{x^2+y^2+z^2})$$
$$z = r \cos\theta \qquad \phi = \operatorname{atan2}(y, x)$$

2.5 Derivatives/Integrals

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

Integration by parts:

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

2.6 Sums

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

$$1 + 2 + 3 + \cdots + n = \frac{n(n+1)}{2}$$
$$1^2 + 2^2 + 3^2 + \cdots + n^2 = \frac{n(2n+1)(n+1)}{6}$$
$$1^3 + 2^3 + 3^3 + \cdots + n^3 = \frac{n^2(n+1)^2}{4}$$
$$1^4 + 2^4 + 3^4 + \cdots + n^4 = \frac{n(n+1)(2n+1)(3n^2+3n-1)}{30}$$

2.7 Series

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

2.8 Probability theory

Let X be a discrete random variable with probability $p_X(x)$ of assuming the value x. It will then have an expected value (mean) $\mu = \mathbb{E}(X) = \sum_x xp_X(x)$ 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,

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

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 $\mathrm{Bin}(n,p)$, $n = 1,2,\ldots$, $0 \le p \le 1$.

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

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

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

First success distribution

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

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

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

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 $\mathrm{Po}(\lambda)$, $\lambda = t\kappa$.

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

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

2.8.2 Continuous distributions

Uniform distribution

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

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

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

Exponential distribution

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

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

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

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 $X_1, X_2, \ldots$ 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). $\lim_{k\to\infty} \mathbf{P}^k = \mathbf{1}\pi$.

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)

3.1 STL

MapComparator.h

Description: custom comparator for map / set d0cc31, 8 lines

```
struct cmp {
  bool operator()(const int& l, const int& r) const {
    return l > r;
  }
};

set<int,cmp> s; // FOR(i,10) s.insert(rand()); trav(i,s) ps(i);
map<int,int,cmp> m;
```

CustomHash.h

Description: avoid hacks with custom hash, gp_hash_table is generally faster than unordered_map

<ext/pb_ds/assoc_container.hpp> 584363, 25 lines

```
using namespace __gnu_pbds;

struct chash {
  static uint64_t splitmix64(uint64_t x) {
    // http://xorshift.di.unimi.it/splitmix64.c
    x += 0x9e3779b97f4a7c15;
    x = (x ^ (x >> 30)) * 0xbf58476d1ce4e5b9;
    x = (x ^ (x >> 27)) * 0x94d049bb133111eb;
    return x ^ (x >> 31);
  }

  size_t operator()(uint64_t x) const {
    static const uint64_t FIXED_RANDOM =
      chrono::steady_clock::now()
      .time_since_epoch().count();
    return splitmix64(x + FIXED_RANDOM);
  }
};

template<class K, class V> using um = unordered_map<K, V, chash
  ↪>;
template<class K, class V> using ht = gp_hash_table<K, V, chash
  ↪>;

template<class K, class V> V get(ht<K,V>& u, K x) {
  return u.find(x) == end(u) ? 0 : u[x];
}
```

OrderStatisticTree.h

Description: A set (not multiset!) with support for finding the n'th element, and finding the index of an element.
Time: $\mathcal{O}(\log N)$

<ext/pb_ds/tree_policy.hpp>, <ext/pb_ds/assoc_container.hpp> c5d6f2, 18 lines

```
using namespace __gnu_pbds;

template <class T> using Tree = tree<T, null_type, less<T>,
  rb_tree_tag, tree_order_statistics_node_update>;
// to get a map, change null_type

#define ook order_of_key
#define fbo find_by_order

void treeExample() {
  Tree<int> t, t2; t.insert(8);
  auto it = t.insert(10).f;
  assert(it == t.lb(9));
  assert(t.ook(10) == 1);
  assert(t.ook(11) == 2);
  assert(*t.fbo(0) == 8);
  t.join(t2); // assuming T < T2 or T > T2, merge t2 into t
}
```

Rope.h

Description: insert element at n-th position, cut a substring and re-insert somewhere else
Time: $\mathcal{O}(\log N)$ per operation? not well tested

<ext/rope> 521dea, 19 lines

```
using namespace __gnu_cxx;

void ropeExample() {
  // CONSTRUCTION
  rope<int> v(5, 0); // initialize with 5 zeroes
  FOR(i,sz(v)) v.mutable_reference_at(i) = i+1;
  // rope<int> v; FOR(i,5) v.pb(i+1);

  // CUTTING AND INSERTING
  rope<int> cur = v.substr(1,2);
  v.erase(1,2); // erase 2 elements starting from 1st element
  v.insert(v.mutable_begin()+2,cur);

  // PRINTING
  for (rope<int>::iterator it = v.mutable_begin();
    it != v.mutable_end(); ++it)
    cout << *it << " "; // 1 4 2 3 5
  // FOR(i,sz(v)) cout << v[i] << " ";  // 1 4 5
}
```

LineContainer.h

Description: Given set of lines, computes greatest y-coordinate for any x
Time: $\mathcal{O}(\log N)$

8bec91, 34 lines

```
struct Line {
  mutable ll k, m, p; // slope, y-intercept, last optimal x
  ll eval (ll x) { return k*x+m; }
  bool operator<(const Line& o) const { return k < o.k; }
  bool operator<(ll x) const { return p < x; }
};

struct LC : multiset<Line,less<>> {
  // for doubles, use inf = 1/.0, div(a,b) = a/b
  const ll inf = LLONG_MAX;
  // floored division
  ll div(ll a, ll b) { return a/b-((a^b) < 0 && a%b); }
  // last x such that first line is better
  ll bet(const Line& x, const Line& y) {
    if (x.k == y.k) return x.m >= y.m ? inf : -inf;
    return div(y.m-x.m,x.k-y.k);
  }
  // updates x->p, determines if y is unneeded
  bool isect(iterator x, iterator y) {
    if (y == end()) { x->p = inf; return 0; }
    x->p = bet(*x,*y); return x->p >= y->p;
  }
  void add(ll k, ll m) {
    auto z = insert({k,m,0}), y = z++, x = y;
    while (isect(y, z)) z = erase(z);
    if (x != begin() && isect(--x, y)) isect(x, y = erase(y));
    while ((y = x) != begin() && (--x)->p >= y->p) isect(x,
      ↪erase(y));
  }
  ll query(ll x) {
    assert(!empty());
    auto l = *lb(x);
    return l.k*x+l.m;
  }
};
```

3.2 1D Range Queries

RMQ.h

Description: 1D range minimum query
Time: $\mathcal{O}(N \log N)$ build, $\mathcal{O}(1)$ query

0a1f4a, 25 lines

```
template<class T> struct RMQ {
  constexpr static int level(int x) {
    return 31-__builtin_clz(x);
  } // floor(log_2(x))
  vector<vi> jmp;
  vector<T> v;
  int comb(int a, int b) {
    return v[a] == v[b] ? min(a,b) : (v[a] < v[b] ? a : b);
  } // index of minimum

  void init(const vector<T>& _v) {
    v = _v; jmp = {vi(sz(v))}; iota(all(jmp[0]),0);
    for (int j = 1; 1<<j <= sz(v); ++j) {
      jmp.pb(vi(sz(v)-(1<<j)+1));
      FOR(i,sz(jmp[j])) jmp[j][i] = comb(jmp[j-1][i],
            jmp[j-1][i+(1<<(j-1))]);
    }
  }

  int index(int l, int r) { // get index of min element
    int d = level(r-l+1);
    return comb(jmp[d][l],jmp[d][r-(1<<d)+1]);
  }
  T query(int l, int r) { return v[index(l,r)]; }
};
```

BIT.h

Description: N-D range sum query with point update
Time: $\mathcal{O}\left((\log N)^D\right)$

e39d3e, 19 lines

```
template <class T, int ...Ns> struct BIT {
  T val = 0;
  void upd(T v) { val += v; }
  T query() { return val; }
};

template <class T, int N, int... Ns> struct BIT<T, N, Ns...> {
  BIT<T,Ns...> bit[N+1];
  template<typename... Args> void upd(int pos, Args... args) {
    for (; pos <= N; pos += (pos&-pos)) bit[pos].upd(args...);
  }
  template<typename... Args> T sum(int r, Args... args) {
    T res = 0; for (; r; r -= (r&-r)) res += bit[r].query(args
      ↪...);
    return res;
  }
  template<typename... Args> T query(int l, int r, Args... args
    ↪) {
    return sum(r,args...)-sum(l-1,args...);
  }
}; // BIT<int,10,10> gives a 2D BIT
```

BITrange.h

Description: 1D range increment and sum query
Time: $\mathcal{O}(\log N)$

"BIT.h" 77a935, 13 lines

```
template<class T, int SZ> struct BITrange {
  BIT<T,SZ> bit[2]; // piecewise linear functions
  // let cum[x] = sum_{i=1}^{x}a[i]
  void upd(int hi, T val) { // add val to a[1..hi]
    // if x <= hi, cum[x] += val*x
    bit[1].upd(1,val), bit[1].upd(hi+1,-val);
    // if x > hi, cum[x] += val*hi
    bit[0].upd(hi+1,hi*val);
  }
  void upd(int lo, int hi, T val) { upd(lo-1,-val), upd(hi,val)
    ↪; }
  T sum(int x) { return bit[1].sum(x)*x+bit[0].sum(x); }
  T query(int x, int y) { return sum(y)-sum(x-1); }
};
```

SegTree.h

Description: 1D point update, range query
Time: $\mathcal{O}(\log N)$

bf15d6, 21 lines

```
template<class T> struct Seg {
  const T ID = 0; // comb(ID,b) must equal b
  T comb(T a, T b) { return a+b; } // easily change this to min
    ↪ or max
  int n; vector<T> seg;
  void init(int _n) { n = _n; seg.rsz(2*n); }

  void pull(int p) { seg[p] = comb(seg[2*p],seg[2*p+1]); }
  void upd(int p, T value) {  // set value at position p
    seg[p += n] = value;
    for (p /= 2; p; p /= 2) pull(p);
  }

  T query(int l, int r) {  // sum on interval [l, r]
    T ra = ID, rb = ID; // non-commutative operations work
    for (l += n, r += n+1; l < r; l /= 2, r /= 2) {
      if (l&1) ra = comb(ra,seg[l++]);
      if (r&1) rb = comb(seg[--r],rb);
    }
    return comb(ra,rb);
  }
};
```

SegTreeBeats.h

Description: supports modifications in the form `ckmin(a_i,t)` for all $l \le i \le r$, range max and sum queries
Time: $\mathcal{O}(\log N)$

f98405, 65 lines

```
template<int SZ> struct SegTreeBeats {
  int N;
  ll sum[2*SZ];
  int mx[2*SZ][2], maxCnt[2*SZ];
```

```
  void pull(int ind) {
    FOR(i,2) mx[ind][i] = max(mx[2*ind][i],mx[2*ind+1][i]);
    maxCnt[ind] = 0;
    FOR(i,2) {
      if (mx[2*ind+i][0] == mx[ind][0])
        maxCnt[ind] += maxCnt[2*ind+i];
      else ckmax(mx[ind][1],mx[2*ind+i][0]);
    }
    sum[ind] = sum[2*ind]+sum[2*ind+1];
  }
  void build(vi& a, int ind = 1, int L = 0, int R = -1) {
    if (R == -1) { R = (N = sz(a))-1; }
    if (L == R) {
      mx[ind][0] = sum[ind] = a[L];
      maxCnt[ind] = 1; mx[ind][1] = -1;
      return;
    }
    int M = (L+R)/2;
    build(a,2*ind,L,M); build(a,2*ind+1,M+1,R); pull(ind);
  }

  void push(int ind, int L, int R) {
    if (L == R) return;
    FOR(i,2)
      if (mx[2*ind^i][0] > mx[ind][0]) {
        sum[2*ind^i] -= (ll)maxCnt[2*ind^i]*
                (mx[2*ind^i][0]-mx[ind][0]);
        mx[2*ind^i][0] = mx[ind][0];
      }
  }
  void upd(int x, int y, int t, int ind = 1, int L = 0, int R = -1) {
    if (R == -1) R += N;
    if (R < x || y < L || mx[ind][0] <= t) return;
    push(ind,L,R);
    if (x <= L && R <= y && mx[ind][1] < t) {
      sum[ind] -= (ll)maxCnt[ind]*(mx[ind][0]-t);
      mx[ind][0] = t;
      return;
    }
    if (L == R) return;
    int M = (L+R)/2;
    upd(x,y,t,2*ind,L,M); upd(x,y,t,2*ind+1,M+1,R); pull(ind);
  }
  ll qsum(int x, int y, int ind = 1, int L = 0, int R = -1) {
    if (R == -1) R += N;
    if (R < x || y < L) return 0;
    push(ind,L,R);
    if (x <= L && R <= y) return sum[ind];
    int M = (L+R)/2;
    return qsum(x,y,2*ind,L,M)+qsum(x,y,2*ind+1,M+1,R);
  }
  int qmax(int x, int y, int ind = 1, int L = 0, int R = -1) {
    if (R == -1) R += N;
    if (R < x || y < L) return -1;
    push(ind,L,R);
    if (x <= L && R <= y) return mx[ind][0];
    int M = (L+R)/2;
    return max(qmax(x,y,2*ind,L,M), qmax(x,y,2*ind+1,M+1,R));
  }
};
```

PersSegTree.h

Description: persistent segtree with lazy updates, assumes that `lazy[cur]` is included in `val[cur]` before propagating `cur`
Time: $\mathcal{O}(\log N)$

41d052, 59 lines

```
template<class T, int SZ> struct pseg {
  static const int LIMIT = 10000000; // adjust
  int l[LIMIT], r[LIMIT], nex = 0;
  T val[LIMIT], lazy[LIMIT];

  int copy(int cur) {
    int x = nex++;
    val[x] = val[cur], l[x] = l[cur], r[x] = r[cur], lazy[x] = lazy[cur];
    return x;
  }
  T comb(T a, T b) { return min(a,b); }
  void pull(int x) { val[x] = comb(val[l[x]],val[r[x]]); }
  void push(int cur, int L, int R) {
    if (!lazy[cur]) return;
    if (L != R) {
      l[cur] = copy(l[cur]);
      val[l[cur]] += lazy[cur], lazy[l[cur]] += lazy[cur];
      r[cur] = copy(r[cur]);
      val[r[cur]] += lazy[cur], lazy[r[cur]] += lazy[cur];
    }
    lazy[cur] = 0;
  }

  T query(int cur, int lo, int hi, int L, int R) {
    if (lo <= L && R <= hi) return val[cur];
    if (R < lo || hi < L) return INF;
    int M = (L+R)/2;
    return lazy[cur]+comb(query(l[cur],lo,hi,L,M),
          query(r[cur],lo,hi,M+1,R));
  }
  int upd(int cur, int lo, int hi, T v, int L, int R) {
    if (R < lo || hi < L) return cur;
    int x = copy(cur);
    if (lo <= L && R <= hi) {
      val[x] += v, lazy[x] += v;
      return x;
    }
    push(x,L,R);
    int M = (L+R)/2;
    l[x] = upd(l[x],lo,hi,v,L,M), r[x] = upd(r[x],lo,hi,v,M+1,R);
    pull(x); return x;
  }
  int build(vector<T>& arr, int L, int R) {
    int cur = nex++;
    if (L == R) {
      if (L < sz(arr)) val[cur] = arr[L];
      return cur;
    }

    int M = (L+R)/2;
    l[cur] = build(arr,L,M), r[cur] = build(arr,M+1,R);
    pull(cur); return cur;
  }

  vi loc;
  void upd(int lo, int hi, T v) { loc.pb(upd(loc.back(),lo,hi,v,0,SZ-1)); }
  T query(int ti, int lo, int hi) { return query(loc[ti],lo,hi,0,SZ-1); }
  void build(vector<T>& arr) { loc.pb(build(arr,0,SZ-1)); }
};
```

Treap.h

Description: easy BBST, use split and merge to implement insert and delete
Time: $\mathcal{O}(\log N)$

b45b6a, 74 lines

```
typedef struct tnode* pt;

struct tnode {
  int pri, val; pt c[2]; // essential
  int sz; ll sum; // for range queries
  bool flip; // lazy update

  tnode (int _val) {
    pri = rand()+(rand()<<15); val = _val; c[0] = c[1] = NULL;
    sz = 1; sum = val;
    flip = 0;
  }
};

int getsz(pt x) { return x?x->sz:0; }
ll getsum(pt x) { return x?x->sum:0; }
pt prop(pt x) {
  if (!x || !x->flip) return x;
  swap(x->c[0],x->c[1]);
  x->flip = 0;
  FOR(i,2) if (x->c[i]) x->c[i]->flip ^= 1;
  return x;
}
pt calc(pt x) {
  assert(!x->flip);
  prop(x->c[0]), prop(x->c[1]);
  x->sz = 1+getsz(x->c[0])+getsz(x->c[1]);
  x->sum = x->val+getsum(x->c[0])+getsum(x->c[1]);
  return x;
}
void tour(pt x, vi& v) {
  if (!x) return;
  prop(x);
  tour(x->c[0],v); v.pb(x->val); tour(x->c[1],v);
}

pair<pt,pt> split(pt t, int v) { // >= v goes to the right
  if (!t) return {t,t};
  prop(t);
  if (t->val >= v) {
    auto p = split(t->c[0], v); t->c[0] = p.s;
    return {p.f,calc(t)};
  } else {
    auto p = split(t->c[1], v); t->c[1] = p.f;
    return {calc(t),p.s};
  }
}
pair<pt,pt> splitsz(pt t, int sz) { // sz nodes go to left
  if (!t) return {t,t};
  prop(t);
  if (getsz(t->c[0]) >= sz) {
    auto p = splitsz(t->c[0],sz); t->c[0] = p.s;
    return {p.f,calc(t)};
  } else {
    auto p = splitsz(t->c[1],sz-getsz(t->c[0])-1); t->c[1] = p.f;
    return {calc(t),p.s};
  }
}
pt merge(pt l, pt r) {
  if (!l || !r) return l ? l : r;
  prop(l), prop(r);
  pt t;
  if (l->pri > r->pri) l->c[1] = merge(l->c[1],r), t = l;
  else r->c[0] = merge(l,r->c[0]), t = r;
  return calc(t);
}
pt ins(pt x, int v) { // insert v
  auto a = split(x,v), b = split(a.s,v+1);
  return merge(a.f,merge(new tnode(v),b.s));
}
pt del(pt x, int v) { // delete v
```

```
  auto a = split(x,v), b = split(a.s,v+1);
  return merge(a.f,b.s);
}
```

Number Theory (4)

4.1 Modular Arithmetic

Modular.h

Description: modular arithmetic operations

"CppIO.h" bb8237, 41 lines

```
template<class T> struct modular {
  T val;
  explicit operator T() const { return val; }
  modular() { val = 0; }
  modular(const ll& v) {
    val = (-MOD <= v && v <= MOD) ? v : v % MOD;
    if (val < 0) val += MOD;
  }

  // friend ostream& operator<<(ostream& os, const modular& a)
    ↪{ return os << a.val; }
  friend void pr(const modular& a) { pr(a.val); }
  friend void re(modular& a) { ll x; re(x); a = modular(x); }

  friend bool operator==(const modular& a, const modular& b) {
    ↪return a.val == b.val; }
  friend bool operator!=(const modular& a, const modular& b) {
    ↪return !(a == b); }
  friend bool operator<(const modular& a, const modular& b) {
    ↪return a.val < b.val; }

  modular operator-() const { return modular(-val); }
  modular& operator+=(const modular& m) { if ((val += m.val) >=
    ↪ MOD) val -= MOD; return *this; }
  modular& operator-=(const modular& m) { if ((val -= m.val) <
    ↪0) val += MOD; return *this; }
  modular& operator*=(const modular& m) { val = (ll)val*m.val%
    ↪MOD; return *this; }
  friend modular pow(modular a, ll p) {
    modular ans = 1; for (; p; p /= 2, a *= a) if (p&1) ans *=
      ↪a;
    return ans;
  }
  friend modular inv(const modular& a) {
    assert(a != 0); return pow(a,MOD-2);
  }
  modular& operator/=(const modular& m) { return (*this) *= inv
    ↪(m); }

  friend modular operator+(modular a, const modular& b) {
    ↪return a += b; }
  friend modular operator-(modular a, const modular& b) {
    ↪return a -= b; }
  friend modular operator*(modular a, const modular& b) {
    ↪return a *= b; }

  friend modular operator/(modular a, const modular& b) {
    ↪return a /= b; }
};

typedef modular<int> mi;
typedef pair<mi,mi> pmi;
typedef vector<mi> vmi;
typedef vector<pmi> vpmi;
```

ModFact.h

Description: pre-compute factorial mod inverses for MOD, assumes MOD is prime and $SZ < MOD$

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

290e34, 10 lines

```
vl invs, fac, ifac;
void genFac(int SZ) {
  invs.rsz(SZ), fac.rsz(SZ), ifac.rsz(SZ);
  invs[1] = 1; FOR(i,2,SZ) invs[i] = MOD-MOD/i*invs[MOD%i]%MOD;
  fac[0] = ifac[0] = 1;
  FOR(i,1,SZ) {
    fac[i] = fac[i-1]*i%MOD;
    ifac[i] = ifac[i-1]*invs[i]%MOD;
  }
}
```

ModMulLL.h

Description: multiply two 64-bit integers mod another if 128-bit is not available, works for $0 \leq a, b < mod < 2^{63}$

cc0f9d, 14 lines

```
typedef unsigned long long ul;

// equivalent to (ul)(__int128(a)*b%mod)
ul modMul(ul a, ul b, const ul mod) {
  ll ret = a*b-mod*(ul)((ld)a*b/mod);
  return ret+((ret<0)-(ret>=(ll)mod))*mod;
}
ul modPow(ul a, ul b, const ul mod) {
  if (b == 0) return 1;
  ul res = modPow(a,b/2,mod);
  res = modMul(res,res,mod);
  if (b&1) return modMul(res,a,mod);
  return res;
}
```

ModSqrt.h

Description: square root of integer mod a prime

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

"Modular.h" a9a4c4, 26 lines

```
template<class T> T sqrt(modular<T> a) {
  auto p = pow(a,(MOD-1)/2); if (p != 1) return p == 0 ? 0 :
    ↪-1; // check if zero or does not have sqrt
  T s = MOD-1, e = 0; while (s % 2 == 0) s /= 2, e ++;
  modular<T> n = 1; while (pow(n,(MOD-1)/2) == 1) n = (T)(n)+1;
    ↪ // find non-square residue

  auto x = pow(a,(s+1)/2), b = pow(a,s), g = pow(n,s);
  int r = e;
  while (1) {
    auto B = b; int m = 0; while (B != 1) B *= B, m ++;
    if (m == 0) return min((T)x,MOD-(T)x);
    FOR(i,r-m-1) g *= g;
    x *= g; g *= g; b *= g; r = m;
  }
}

/* Explanation:
 * Initially, x^2=ab, ord(b) = 2^m, ord(g) = 2^r where m<r
 * g = g^{2^{r-m-1}} -> ord(g) = 2^{m+1}
 * if x'=x*g, then b' = b*g^2
    (b')^{2^{m-1}} = (b*g^2)^{2^{m-1}}
                   = b^{2^{m-1}}*g^{2^m}
                   = -1*-1
                   = 1
  -> ord(b')|ord(b)/2
 * m decreases by at least one each iteration
 */
```

ModSum.h

Description: Sums of mod'ed arithmetic progressions

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

50ee96, 15 lines

```
typedef unsigned long long ul;

ul sumsq(ul to) { return (to-1)*to/2; } // sum of 0..to-1

ul divsum(ul to, ul c, ul k, ul m) { // sum_{i=0}^{to-1}floor((
  ↪ki+c)/m)
  ul res = k/m*sumsq(to)+c/m*to;
  k %= m; c %= m; if (!k) return res;
  ul to2 = (to*k+c)/m;
  return res+(to-1)*to2-divsum(to2,m-1-c,m,k);
}

ll modsum(ul 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);
}
```

4.2 Primality

PrimeSieve.h

Description: tests primality up to SZ

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

abbd65, 11 lines

```
template<int SZ> struct Sieve {
  bitset<SZ> isprime;
  vi pr;
  Sieve() {
    isprime.set(); isprime[0] = isprime[1] = 0;
    for (int i = 4; i < SZ; i += 2) isprime[i] = 0;
    for (int i = 3; i*i < SZ; i += 2) if (isprime[i])
      for (int j = i*i; j < SZ; j += i*2) isprime[j] = 0;
    FOR(i,2,SZ) if (isprime[i]) pr.pb(i);
  }
};
```

FactorFast.h

Description: Factors integers up to 2^{60}

Time: $\mathcal{O}\left(N^{1/4}\right)$ gcd calls, less for numbers with small factors

"PrimeSieve.h", "ModMulLL.h" 6485f4, 45 lines

```
Sieve<1<<20> S = Sieve<1<<20>(); // should take care of all
  ↪primes up to n^{1/3}

bool millerRabin(ll p) { // test primality
  if (p == 2) return true;
  if (p == 1 || p % 2 == 0) return false;
  ll s = p-1; while (s % 2 == 0) s /= 2;
  FOR(i,30) { // strong liar with probability <= 1/4
    ll a = rand() % (p-1) + 1, tmp = s;
    ll mod = modPow(a, tmp, p);
    while (tmp != p - 1 && mod != 1 && mod != p - 1) {
      mod = modMul(mod, mod, p);
      tmp *= 2;
    }
    if (mod != p - 1 && tmp % 2 == 0) return false;
  }
  return true;
}

ll f(ll a, ll n, ll &has) { return (modMul(a,a,n)+has)%n; }
vpl pollardsRho(ll d) {
  vpl res;
  auto& pr = S.pr;
```

```
  for (int i = 0; i < sz(pr) && pr[i]*pr[i] <= d; i++) if (d %
     ↪pr[i] == 0) {
    int co = 0; while (d % pr[i] == 0) d /= pr[i], co ++;
    res.pb({pr[i],co});
  }
  if (d > 1) { // d is now a product of at most 2 primes.
    if (millerRabin(d)) res.pb({d,1});
    else while (1) {
      ll has = rand() % 2321 + 47;
      ll x = 2, y = 2, c = 1;
      for (; c == 1; c = __gcd(abs(x-y), d)) {
        x = f(x, d, has);
        y = f(f(y, d, has), d, has);
      } // should cycle in ~sqrt(smallest nontrivial divisor)
         ↪turns
      if (c != d) {
        d /= c; if (d > c) swap(d,c);
        if (c == d) res.pb({c,2});
        else res.pb({c,1}), res.pb({d,1});
        break;
      }
    }
  }
  return res;
}
```

4.3 Divisibility

Euclid.h

Description: euclid finds $\{x, y\}$ such that $ax + by = \gcd(a, b)$ such that $|ax|, |by| \leq \frac{ab}{\gcd(a,b)}$, should work for $ab < 2^{62}$
Time: $\mathcal{O}(\log ab)$

338527, 9 lines

```
pl euclid(ll a, ll b) {
  if (!b) return {1,0};
  pl p = euclid(b,a%b);
  return {p.s,p.f-a/b*p.s};
}
ll invGeneral(ll a, ll b) {
  pl p = euclid(a,b); assert(p.f*a+p.s*b == 1); // gcd is 1
  return p.f+(p.f<0)*b;
}
```

CRT.h

Description: Chinese Remainder Theorem, combine $a.f \pmod{a.s}$ and $b.f \pmod{b.s}$ into something $\pmod{\mathrm{lcm}(a.s, b.s)}$, should work for $ab < 2^{62}$

"Euclid.h" a7ebbe, 10 lines

```
pl solve(pl a, pl b) {
  if (a.s < b.s) swap(a,b);
  ll x,y; tie(x,y) = euclid(a.s,b.s);
  ll g = a.s*x+b.s*y, l = a.s/g*b.s;
  if ((b.f-a.f)%g) return {-1,-1}; // no solution
  // ?*a.s+a.f \equiv b.f \pmod{b.s}
  // ?=(b.f-a.f)/g*(a.s/g)^{-1} \pmod{b.s/g}
  x = (b.f-a.f)%b.s*x%b.s/g*a.s+a.f;
  return {x+(x<0)*l,l};
}
```

Combinatorial (5)

IntPerm.h

Description: convert permutation of $\{0, 1, ..., N-1\}$ to integer in $[0, N!)$ and back
Usage: `assert(encode(decode(5,37)) == 37);`
Time: $\mathcal{O}(N)$

f295dd, 20 lines

```
vi decode(int n, int a) {
  vi el(n), b; iota(all(el),0);
  F0R(i,n) {
    int z = a%sz(el);
    b.pb(el[z]); a /= sz(el);
    swap(el[z],el.back()); el.pop_back();
  }
  return b;
}

int encode(vi b) {
  int n = sz(b), a = 0, mul = 1;
  vi pos(n); iota(all(pos),0); vi el = pos;
  F0R(i,n) {
    int z = pos[b[i]]; a += mul*z; mul *= sz(el);
    swap(pos[el[z]],pos[el.back()]);
    swap(el[z],el.back()); el.pop_back();
  }
  return a;
}
```

MatroidIntersect.h

Description: computes a set of maximum size which is independent in both graphic and colorful matroids, aka a spanning forest where no two edges are of the same color
Time: $\mathcal{O}(GI^{1.5})$ calls to oracles, where G is the size of the ground set and I is the size of the independent set

"DSU.h" e3ecce, 107 lines

```
int R;
map<int,int> m;

struct Element {
  pi ed;
  int col;
  bool in_independent_set = 0;
  int independent_set_position;
  Element(int u, int v, int c) { ed = {u,v}; col = c; }
};

vi independent_set;
vector<Element> ground_set;
bool col_used[300];

struct GBasis {
  DSU D;
  void reset() { D.init(sz(m)); }
  void add(pi v) { assert(D.unite(v.f,v.s)); }
  bool independent_with(pi v) { return !D.sameSet(v.f,v.s); }
};

GBasis basis, basis_wo[300];

bool graph_oracle(int inserted) {
  return basis.independent_with(ground_set[inserted].ed);
}
bool graph_oracle(int inserted, int removed) {
  int wi = ground_set[removed].independent_set_position;
  return basis_wo[wi].independent_with(ground_set[inserted].ed)
     ↪;
}
void prepare_graph_oracle() {
  basis.reset();
  F0R(i,sz(independent_set)) basis_wo[i].reset();
  F0R(i,sz(independent_set)) {
    pi v = ground_set[independent_set[i]].ed; basis.add(v);
    F0R(j,sz(independent_set)) if (i != j) basis_wo[j].add(v);
  }
}
bool colorful_oracle(int ins) {
  ins = ground_set[ins].col;
  return !col_used[ins];
}
bool colorful_oracle(int ins, int rem) {
  ins = ground_set[ins].col;
  rem = ground_set[rem].col;
  return !col_used[ins] || ins == rem;
}
void prepare_colorful_oracle() {
  F0R(i,R) col_used[i] = 0;
  trav(t,independent_set) col_used[ground_set[t].col] = 1;
}

bool augment() {
  prepare_graph_oracle();
  prepare_colorful_oracle();

  vi par(sz(ground_set),MOD);
  queue<int> q;
  F0R(i,sz(ground_set)) if (colorful_oracle(i)) {
    assert(!ground_set[i].in_independent_set);
    par[i] = -1; q.push(i);
  }
  int lst = -1;
  while (sz(q)) {
    int cur = q.front(); q.pop();
    if (ground_set[cur].in_independent_set) {
      F0R(to,sz(ground_set)) if (par[to] == MOD) {
        if (!colorful_oracle(to,cur)) continue;
        par[to] = cur; q.push(to);
      }
    } else {
      if (graph_oracle(cur)) { lst = cur; break; }
      trav(to,independent_set) if (par[to] == MOD) {
        if (!graph_oracle(cur,to)) continue;
        par[to] = cur; q.push(to);
      }
    }
  }
  if (lst == -1) return 0;
  do {
    ground_set[lst].in_independent_set ^= 1;
    lst = par[lst];
  } while (lst != -1);
  independent_set.clear();
  F0R(i,sz(ground_set)) if (ground_set[i].in_independent_set) {
    ground_set[i].independent_set_position = sz(independent_set
       ↪);
    independent_set.pb(i);
  }
  return 1;
}

void solve() {
  cin >> R;
  m.clear(); ground_set.clear(); independent_set.clear();
  F0R(i,R) {
    int a,b,c,d; cin >> a >> b >> c >> d;
    ground_set.pb(Element(a,b,i));
    ground_set.pb(Element(c,d,i));
    m[a] = m[b] = m[c] = m[d] = 0;
  }
  int co = 0;
  trav(t,m) t.s = co++;
  trav(t,ground_set) t.ed.f = m[t.ed.f], t.ed.s = m[t.ed.s];
  while (augment());
}
```

PermGroup.h

Description: Schreier-Sims, count number of permutations in group and test whether permutation is a member of group

Time: ?

590e00, 50 lines

```
int n;
vi inv(vi v) { vi V(sz(v)); FOR(i,sz(v)) V[v[i]] = i; return V;
    ↪ }
vi id() { vi v(n); iota(all(v),0); return v; }
vi operator*(const vi& a, const vi& b) {
  vi c(sz(a)); FOR(i,sz(a)) c[i] = a[b[i]];
  return c;
}

const int N = 15;
struct Group {
  bool flag[N];
  vi sigma[N]; // sigma[t][k] = t, sigma[t][x] = x if x > k
  vector<vi> gen;
  void clear(int p) {
    memset(flag,0, sizeof flag);
    flag[p] = 1; sigma[p] = id();
    gen.clear();
  }
} g[N];

bool check(const vi& cur, int k) {
  if (!k) return 1;
  int t = cur[k];
  return g[k].flag[t] ? check(inv(g[k].sigma[t])*cur,k-1) : 0;
}
void updateX(const vi& cur, int k);
void ins(const vi& cur, int k) {
  if (check(cur,k)) return;
  g[k].gen.pb(cur);
  FOR(i,n) if (g[k].flag[i]) updateX(cur*g[k].sigma[i],k);
}
void updateX(const vi& cur, int k) {
  int t = cur[k];
  if (g[k].flag[t]) ins(inv(g[k].sigma[t])*cur,k-1); // fixes k
    ↪ -> k
  else {
    g[k].flag[t] = 1, g[k].sigma[t] = cur;
    trav(x,g[k].gen) updateX(x*cur,k);
  }
}

ll order(vector<vi> gen) {
  assert(sz(gen)); n = sz(gen[0]); FOR(i,n) g[i].clear(i);
  trav(a,gen) ins(a,n-1); // insert perms into group one by one
  ll tot = 1;
  FOR(i,n) {
    int cnt = 0; FOR(j,i+1) cnt += g[i].flag[j];
    tot *= cnt;
  }
  return tot;
}
```

Numerical (6)

6.1 Matrix

Matrix.h

Description: 2D matrix operations

c6abe5, 36 lines

```
template<class T> struct Mat {
  int r,c;
  vector<vector<T>> d;
  Mat(int _r, int _c) : r(_r), c(_c) { d.assign(r,vector<T>(c))
    ↪; }
  Mat() : Mat(0,0) {}
  Mat(const vector<vector<T>>& _d) : r(sz(_d)), c(sz(_d[0])) {
    ↪d = _d; }
  friend void pr(const Mat& m) { pr(m.d); }

  Mat& operator+=(const Mat& m) {
    assert(r == m.r && c == m.c);
    FOR(i,r) FOR(j,c) d[i][j] += m.d[i][j];
    return *this;
  }
  Mat& operator-=(const Mat& m) {
    assert(r == m.r && c == m.c);
    FOR(i,r) FOR(j,c) d[i][j] -= m.d[i][j];
    return *this;
  }
  Mat operator*(const Mat& m) {
    assert(c == m.r); Mat x(r,m.c);
    FOR(i,r) FOR(j,c) FOR(k,m.c) x.d[i][k] += d[i][j]*m.d[j][k
      ↪];
    return x;
  }

  Mat operator+(const Mat& m) { return Mat(*this)+=m; }
  Mat operator-(const Mat& m) { return Mat(*this)-=m; }
  Mat& operator*=(const Mat& m) { return *this = (*this)*m; }

  friend Mat pow(Mat m, ll p) {
    assert(m.r == m.c);
    Mat r(m.r,m.c);
    FOR(i,m.r) r.d[i][i] = 1;
    for (; p; p /= 2, m *= m) if (p&1) r *= m;
    return r;
  }
};
```

MatrixInv.h

Description: calculates determinant via gaussian elimination

Time: $\mathcal{O}(N^3)$, determinant of 1000×1000 matrix of modular ints in 1s if you reduce # of operations by half

"Matrix.h" 00ad8c, 31 lines

```
template<class T> T gauss(Mat<T>& m) {
  int n = m.r;
  T prod = 1; int nex = 0;
  FOR(i,n) {
    int row = -1; // for ld use EPS rather than 0
    FOR(j,nex,n) if (m.d[j][i] != 0) { row = j; break; }
    if (row == -1) { prod = 0; continue; }
    if (row != nex) prod *= -1, swap(m.d[row],m.d[nex]);
    prod *= m.d[nex][i];
    auto x = 1/m.d[nex][i]; FOR(k,i,m.c) m.d[nex][k] *= x;
    FOR(j,n) if (j != nex) {
      auto v = m.d[j][i];
      if (v != 0) FOR(k,i,m.c) m.d[j][k] -= v*m.d[nex][k];
    }
    nex ++;
  }
  return prod;
}

template<class T> Mat<T> inv(Mat<T> m) {
  int n = m.r;
  Mat<T> x(n,2*n);
  FOR(i,n) {
    x.d[i][i+n] = 1;
    FOR(j,n) x.d[i][j] = m.d[i][j];
  }
  if (gauss(x) == 0) return Mat<T>(0,0);
  Mat<T> r(n,n);
  FOR(i,n) FOR(j,n) r.d[i][j] = x.d[i][j+n];
  return r;
}
```

MatrixTree.h

Description: Kirchhoff's Matrix Tree Theorem: given adjacency matrix, calculates # of spanning trees

"MatrixInv.h", "Modular.h" cdb606, 13 lines

```
mi numSpan(Mat<mi> m) {
  int n = m.r;
  Mat<mi> res(n-1,n-1);
  FOR(i,n) FOR(j,i+1,n) {
    mi ed = m.d[i][j];
    res.d[i][i] += ed;
    if (j != n-1) {
      res.d[j][j] += ed;
      res.d[i][j] -= ed, res.d[j][i] -= ed;
    }
  }
  return gauss(res);
}
```

6.2 Polynomials

VecOp.h

Description: polynomial operations using vectors

6a45c8, 73 lines

```
namespace VecOp {
  template<class T> vector<T> rev(vector<T> v) { reverse(all(v)
    ↪); return v; }
  template<class T> vector<T> shift(vector<T> v, int x) { v.
    ↪insert(v.begin(),x,0); return v; }
  template<class T> vector<T> integ(const vector<T>& v)  {
    vector<T> res(sz(v)+1);
    FOR(i,sz(v)) res[i+1] = v[i]/(i+1);
    return res;
  }
  template<class T> vector<T> dif(const vector<T>& v)  {
    if (!sz(v)) return v;
    vector<T> res(sz(v)-1); FOR(i,1,sz(v)) res[i-1] = i*v[i];
    return res;
  }
  template<class T> vector<T>& remLead(vector<T>& v) {
    while (sz(v) && v.back() == 0) v.pop_back();
    return v;
  }
  template<class T> T eval(const vector<T>& v, const T& x) {
    T res = 0; ROF(i,sz(v)) res = x*res+v[i];
    return res;
  }

  template<class T> vector<T>& operator+=(vector<T>& l, const
    ↪vector<T>& r) {
    l.rsz(max(sz(l),sz(r))); FOR(i,sz(r)) l[i] += r[i]; return
      ↪l;
  }
  template<class T> vector<T>& operator-=(vector<T>& l, const
    ↪vector<T>& r) {
    l.rsz(max(sz(l),sz(r))); FOR(i,sz(r)) l[i] -= r[i]; return
      ↪l;
  }
  template<class T> vector<T>& operator*=(vector<T>& l, const T
    ↪& r) { trav(t,l) t *= r; return l;  }
```

```
template<class T> vector<T>& operator/=(vector<T>& l, const T& r) { trav(t,l) t /= r; return l; }

template<class T> vector<T> operator+(vector<T> l, const vector<T>& r) { return l += r; }
template<class T> vector<T> operator-(vector<T> l, const vector<T>& r) { return l -= r; }
template<class T> vector<T> operator*(vector<T> l, const T& r) { return l *= r; }
template<class T> vector<T> operator*(const T& r, const vector<T>& l) { return l*r; }
template<class T> vector<T> operator/(vector<T> l, const T& r) { return l /= r;  }

template<class T> vector<T> operator*(const vector<T>& l, const vector<T>& r) {
  if (min(sz(l),sz(r)) == 0) return {};
  vector<T> x(sz(l)+sz(r)-1); FOR(i,sz(l)) FOR(j,sz(r)) x[i+j] += l[i]*r[j];
  return x;
}
template<class T> vector<T>& operator*=(vector<T>& l, const vector<T>& r) { return l = l*r; }

template<class T> pair<vector<T>,vector<T>> qr(vector<T> a, vector<T> b) { // quotient and remainder
  assert(sz(b)); auto B = b.back(); assert(B != 0);
  B = 1/B; trav(t,b) t *= B;

  remLead(a); vector<T> q(max(sz(a)-sz(b)+1,0));
  while (sz(a) >= sz(b)) {
    q[sz(a)-sz(b)] = a.back();
    a -= a.back()*shift(b,sz(a)-sz(b));
    remLead(a);
  }

  trav(t,q) t *= B;
  return {q,a};
}
template<class T> vector<T> quo(const vector<T>& a, const vector<T>& b) { return qr(a,b).f; }
template<class T> vector<T> rem(const vector<T>& a, const vector<T>& b) { return qr(a,b).s; }

template<class T> vector<T> interpolate(vector<pair<T,T>> v) {
  vector<T> ret, prod = {1};
  FOR(i,sz(v)) prod *= vector<T>({-v[i].f,1});
  FOR(i,sz(v)) {
    T todiv = 1; FOR(j,sz(v)) if (i != j) todiv *= v[i].f-v[j].f;
    ret += qr(prod,{-v[i].f,1}).f*(v[i].s/todiv);
  }
  return ret;
}
}

using namespace VecOp;
```

PolyRoots.h

Description: Finds the real roots of a polynomial.
Usage: `poly_roots({{2,-3,1}},-1e9,1e9) // solve x^2-3x+2 = 0`
Time: $\mathcal{O}\left(N^2 \log(1/\epsilon)\right)$

"VecOp.h" fbe593, 19 lines

```
vd polyRoots(vd p, ld xmin, ld xmax) {
  if (sz(p) == 2) { return {-p[0]/p[1]}; }
  auto dr = polyRoots(dif(p),xmin,xmax);
  dr.pb(xmin-1); dr.pb(xmax+1); sort(all(dr));
  vd ret;
  FOR(i,sz(dr)-1) {
    auto l = dr[i], h = dr[i+1];
    bool sign = eval(p,l) > 0;
    if (sign ^ (eval(p,h) > 0)) {
      FOR(it,60) { // while (h - l > 1e-8)
        auto m = (l+h)/2, f = eval(p,m);
        if ((f <= 0) ^ sign) l = m;
        else h = m;
      }
      ret.pb((l+h)/2);
    }
  }
  return ret;
}
```

Karatsuba.h

Description: multiply two polynomials
Time: $\mathcal{O}\left(N^{\log_2 3}\right)$

21f372, 26 lines

```
int size(int s) { return s > 1 ? 32-__builtin_clz(s-1) : 0; }

void karatsuba(ll *a, ll *b, ll *c, ll *t, int n) {
  int ca = 0, cb = 0; FOR(i,n) ca += !!a[i], cb += !!b[i];
  if (min(ca, cb) <= 1500/n) { // few numbers to multiply
    if (ca > cb) swap(a, b);
    FOR(i,n) if (a[i]) FOR(j,n) c[i+j] += a[i]*b[j];
  } else {
    int h = n >> 1;
    karatsuba(a, b, c, t, h); // a0*b0
    karatsuba(a+h, b+h, c+n, t, h); // a1*b1
    FOR(i,h) a[i] += a[i+h], b[i] += b[i+h];
    karatsuba(a, b, t, t+n, h); // (a0+a1)*(b0+b1)
    FOR(i,h) a[i] -= a[i+h], b[i] -= b[i+h];
    FOR(i,n) t[i] -= c[i]+c[i+n];
    FOR(i,n) c[i+h] += t[i], t[i] = 0;
  }
}

vl conv(vl a, vl b) {
  int sa = sz(a), sb = sz(b); if (!sa || !sb) return {};
  int n = 1<<size(max(sa,sb)); a.rsz(n), b.rsz(n);
  vl c(2*n), t(2*n); FOR(i,2*n) t[i] = 0;
  karatsuba(&a[0], &b[0], &c[0], &t[0], n);
  c.rsz(sa+sb-1); return c;
}
```

FFT.h

Description: multiply two polynomials
Time: $\mathcal{O}(N \log N)$

"Modular.h" d0f375, 43 lines

```
typedef complex<db> cd;
const int MOD = (119 << 23) + 1, root = 3; // = 998244353
// NTT: For p < 2^30 there is also e.g. (5 << 25, 3),
// (7 << 26, 3), (479 << 21, 3) and (483 << 21, 5).
// The last two are > 10^9.

constexpr int size(int s) { return s > 1 ? 32-__builtin_clz(s-1) : 0; }
void genRoots(vcd& roots) { // primitive n-th roots of unity
  int n = sz(roots); double ang = 2*PI/n;
  // is there a way to compute these trig functions more quickly w/o issues?
  FOR(i,n) roots[i] = cd(cos(ang*i),sin(ang*i));
}
void genRoots(vmi& roots) {
  int n = sz(roots); mi r = pow(mi(root),(MOD-1)/n);
  roots[0] = 1; FOR(i,1,n) roots[i] = roots[i-1]*r;
}

template<class T> void fft(vector<T>& a, const vector<T>& roots, bool inv = 0) {
  int n = sz(a);
  // sort numbers from 0 to n-1 by reverse bit representation
  for (int i = 1, j = 0; i < n; i++) {
    int bit = n>>1;
    for (; j&bit; bit >>= 1) j ^= bit;
    j ^= bit; if (i < j) swap(a[i], a[j]);
  }
  for (int len = 2; len <= n; len <<= 1)
    for (int i = 0; i < n; i += len)
      FOR(j,len/2) {
        int ind = n/len*j; if (inv && ind) ind = n-ind;
        auto u = a[i+j], v = a[i+j+len/2]*roots[ind];
        a[i+j] = u+v, a[i+j+len/2] = u-v;
      }
  if (inv) { T i = T(1)/T(n); trav(x,a) x *= i; }
}

template<class T> vector<T> mult(vector<T> a, vector<T> b) {
  if (!min(sz(a),sz(b))) return {};
  int s = sz(a)+sz(b)-1, n = 1<<size(s);
  vector<T> roots(n); genRoots(roots);
  a.rsz(n), fft(a,roots); b.rsz(n), fft(b,roots);
  FOR(i,n) a[i] *= b[i];
  fft(a,roots,1); a.rsz(s); return a;
}
```

FFTmod.h

Description: multiply two polynomials with arbitrary MOD ensures precision by splitting in half

"FFT.h" a8a6ed, 31 lines

```
vl multMod(const vl& a, const vl& b) {
  if (!min(sz(a),sz(b))) return {};
  int s = sz(a)+sz(b)-1, n = 1<<size(s), cut = sqrt(MOD);
  vcd roots(n); genRoots(roots);

  vcd ax(n), bx(n);
  // ax(x)=a1(x)+i*a0(x)
  FOR(i,sz(a)) ax[i] = cd((int)a[i]/cut, (int)a[i]%cut);
  // bx(x)=b1(x)+i*b0(x)
  FOR(i,sz(b)) bx[i] = cd((int)b[i]/cut, (int)b[i]%cut);
  fft(ax,roots), fft(bx,roots);

  vcd v1(n), v0(n);
  FOR(i,n) {
    int j = (i ? (n-i) : i);
    // v1 = a1*(b1+b0*cd(0,1));
    v1[i] = (ax[i]+conj(ax[j]))*cd(0.5,0)*bx[i];
    // v0 = a0*(b1+b0*cd(0,1));
    v0[i] = (ax[i]-conj(ax[j]))*cd(0,-0.5)*bx[i];
  }
  fft(v1,roots,1), fft(v0,roots,1);

  vl ret(n);
  FOR(i,n) {
    ll V2 = (ll)round(v1[i].real()); // a1*b1
    ll V1 = (ll)round(v1[i].imag())+(ll)round(v0[i].real()); // a0*b1+a1*b0
    ll V0 = (ll)round(v0[i].imag()); // a0*b0
    ret[i] = ((V2%MOD*cut+V1)%MOD*cut+V0)%MOD;
  }
  ret.rsz(s); return ret;
} // ~0.8s when sz(a)=sz(b)=1<<19
```

PolyInv.h

Description: computes v^{-1} such that $vv^{-1} \equiv 1 \pmod{x^p}$

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

"FFT.h" d6dd68, 11 lines

```
template<class T> vector<T> inv(vector<T> v, int p) {
  v.rsz(p); vector<T> a = {T(1)/v[0]};
  for (int i = 1; i < p; i *= 2) {
    if (2*i > p) v.rsz(2*i);
    auto l = vector<T>(begin(v),begin(v)+i), r = vector<T>(
        begin(v)+i,begin(v)+2*i);
    auto c = mult(a,l); c = vector<T>(begin(c)+i,end(c));
    auto b = mult(a*T(-1),mult(a,r)+c); b.rsz(i);
    a.insert(end(a),all(b));
  }
  a.rsz(p); return a;
}
```

PolyDiv.h

Description: divide two polynomials

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

"PolyInv.h" a70b14, 7 lines

```
template<class T> pair<vector<T>,vector<T>> divi(const vector<T
  >& f, const vector<T>& g) { // f = q*g+r
  if (sz(f) < sz(g)) return {{},f};
  auto q = mult(inv(rev(g),sz(f)-sz(g)+1),rev(f));
  q.rsz(sz(f)-sz(g)+1); q = rev(q);
  auto r = f-mult(q,g); r.rsz(sz(g)-1);
  return {q,r};
}
```

PolySqrt.h

Description: square root of polynomial

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

"PolyInv.h" 0063be, 7 lines

```
template<class T> vector<T> sqrt(vector<T> v, int p) { // S*S =
   v mod x^p, p is power of 2
  assert(v[0] == 1); if (p == 1) return {1};
  v.rsz(p); auto S = sqrt(v,p/2);
  auto ans = S+mult(v,inv(S,p));
  ans.rsz(p); ans *= T(1)/T(2);
  return ans;
}
```

6.3 Misc

LinRec.h

Description: Berlekamp-Massey, computes linear recurrence of order N for sequence of $2N$ terms

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

"VecOp.h", "Modular.h" 32c214, 31 lines

```
struct LinRec {
  vmi x; // original sequence
  vmi C, rC;
  void init(const vmi& _x) {
    x = _x; int n = sz(x), m = 0;
    vmi B; B = C = {1}; // B is fail vector
    mi b = 1; // B gives 0,0,0,...,b
    FOR(i,n) {
      m ++;
      mi d = x[i]; FOR(j,1,sz(C)) d += C[j]*x[i-j];
      if (d == 0) continue; // recurrence still works
      auto _B = C; C.rsz(max(sz(C),m+sz(B)));
      mi coef = d/b; FOR(j,m,m+sz(B)) C[j] -= coef*B[j-m]; //
        recurrence that gives 0,0,0,...,d
      if (sz(_B) < m+sz(B)) { B = _B; b = d; m = 0; }
    }
    rC = C; reverse(all(rC)); // polynomial for getPo
    C.erase(begin(C)); trav(t,C) t *= -1; // x[i]=sum_{j=0}^{sz
      (C)-1}C[j]*x[i-j-1]
  }

  vmi getPo(int n) {
    if (n == 0) return {1};
    vmi x = getPo(n/2); x = rem(x*x,rC);
    if (n&1) { vmi v = {0,1}; x = rem(x*v,rC); }
    return x;
  }
  mi eval(int n) {
    vmi t = getPo(n);
    mi ans = 0; FOR(i,sz(t)) ans += t[i]*x[i];
    return ans;
  }
};
```

Integrate.h

Description: Integration of a function over an interval using Simpson's rule. The error should be proportional to dif^4, although in practice you will want to verify that the result is stable to desired precision when epsilon changes.

693e87, 7 lines

```
// db f(db x) { return x*x+3*x+1; }
db quad(db (*f)(db), db a, db b) {
  const int n = 1000;
  db dif = (b-a)/2/n, tot = f(a)+f(b);
  FOR(i,1,2*n) tot += f(a+i*dif)*(i&1?4:2);
  return tot*dif/3;
}
```

IntegrateAdaptive.h

Description: Fast integration using adaptive Simpson's rule

b48168, 16 lines

```
// db f(db x) { return x*x+3*x+1; }
db simpson(db (*f)(db), db a, db b) {
  db c = (a+b) / 2;
  return (f(a) + 4*f(c) + f(b)) * (b-a) / 6;
}
db rec(db (*f)(db), db a, db b, db eps, db S) {
  db c = (a+b) / 2;
  db S1 = simpson(f, a, c);
  db S2 = simpson(f, 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);
}
db quad(db (*f)(db), db a, db b, db eps = 1e-8) {
  return rec(f, a, b, eps, simpson(f, a, b));
}
```

Simplex.h

Description: Solves a general linear maximization problem: maximize $c^T x$ subject to $Ax \le b$, $x \ge 0$. 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: $\mathcal{O}(NM \cdot \#pivots)$, where a pivot may be e.g. an edge relaxation. $\mathcal{O}\left(2^N\right)$ in the general case.

5200a8, 73 lines

```
typedef double T;
typedef vector<T> vd;
typedef vector<vd> vvd;
const T eps = 1e-8, inf = 1/.0;

#define ltj(X) if (s == -1 || mp(X[j],N[j]) < mp(X[s],N[s])) s=
  j

struct LPSolver {
  int m, n; // # contraints, # variables
  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)) {
      FOR(i,m) FOR(j,n) D[i][j] = A[i][j];
      FOR(i,m) {
        B[i] = n+i, D[i][n] = -1, D[i][n+1] = b[i];
        // B[i]: add basic variable for each constraint,
          convert ineqs to eqs
        // D[i][n]: artificial variable for testing feasibility
      }
      FOR(j,n) {
        N[j] = j; // non-basic variables, all zero
        D[m][j] = -c[j]; // minimize -c^T x
      }
      N[n] = -1; D[m+1][n] = 1;
    }

  void pivot(int r, int s) { // r = row, c = column
    T *a = D[r].data(), inv = 1/a[s];
    FOR(i,m+2) if (i != r && abs(D[i][s]) > eps) {
      T *b = D[i].data(), binv = b[s]*inv;
      FOR(j,n+2) b[j] -= a[j]*binv; // make column
        corresponding to s all zeroes
      b[s] = a[s]*binv; // swap N[s] with B[r]
    }
    // equation corresponding to r scaled so x_r coefficient
      equals 1
    FOR(j,n+2) if (j != s) D[r][j] *= inv;
    FOR(i,m+2) if (i != r) D[i][s] *= -inv;
    D[r][s] = inv; swap(B[r], N[s]); // swap basic w/ non-basic
  }
  bool simplex(int phase) {
    int x = m+phase-1;
    while (1) {
      int s = -1; FOR(j,n+1) if (N[j] != -phase) ltj(D[x]); //
        find most negative col for nonbasic variable
      if (D[x][s] >= -eps) return true; // can't get better sol
         by increasing non-basic variable, terminate
      int r = -1;
      FOR(i,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;
        // find smallest positive ratio, aka max we can
          increase nonbasic variable
      }
      if (r == -1) return false; // increase N[s] infinitely ->
         unbounded
      pivot(r,s);
    }
  }

  T solve(vd &x) {
    int r = 0; FOR(i,1,m) if (D[i][n+1] < D[r][n+1]) r = i;
    if (D[r][n+1] < -eps) { // x=0 not feasible, run simplex to
       find smth feasible
      pivot(r, n); // N[n] = -1 is artificial variable,
        initially set to smth large
      if (!simplex(2) || D[m+1][n+1] < -eps) return -inf;
      // D[m+1][n+1] is max possible value of the negation of
      // artificial variable, optimal value should be zero
```

```
      // if exists feasible solution
      F0R(i,m) if (B[i] == -1) { // ?
        int s = 0; F0R(j,1,n+1) ltj(D[i]);
        pivot(i,s);
      }
    }
    bool ok = simplex(1); x = vd(n);
    F0R(i,m) if (B[i] < n) x[B[i]] = D[i][n+1];
    return ok ? D[m][n+1] : inf;
  }
};
```

Graphs (7)

7.1 Fundamentals

DSU.h

Description: Disjoint Set Union, add edges and test connectivity
Time: $\mathcal{O}(\alpha(N))$
cc5aa3, 13 lines

```
struct DSU {
  vi e; void init(int n) { e = vi(n,-1); }
  // path compression
  int get(int x) { return e[x] < 0 ? x : e[x] = get(e[x]); }
  bool sameSet(int a, int b) { return get(a) == get(b); }
  int size(int x) { return -e[get(x)]; }
  bool unite(int x, int y) { // union-by-rank
    x = get(x), y = get(y); if (x == y) return 0;
    if (e[x] > e[y]) swap(x,y);
    e[x] += e[y]; e[y] = x;
    return 1;
  }
};
```

ManhattanMST.h

Description: Compute minimum spanning tree of points where edges are manhattan distances
Time: $\mathcal{O}(N \log N)$
"MST.h" dc76d4, 62 lines

```
int N;
vector<array<int,3>> cur;
vector<pair<ll,pi>> ed;
vi ind;

struct {
  map<int,pi> m;
  void upd(int a, pi b) {
    auto it = m.lb(a);
    if (it != m.end() && it->s <= b) return;
    m[a] = b; it = m.find(a);
    while (it != m.begin() && prev(it)->s >= b) m.erase(prev(it
      ↪));
  }
  pi query(int y) { // over all a > y
    // get min possible value of b
    auto it = m.ub(y);
    if (it == m.end()) return {2*MOD,2*MOD};
    return it->s;
  }
} S;

void solve() {
  sort(all(ind),[](int a, int b) { return cur[a][0] > cur[b
    ↪][0]; });
  S.m.clear();
  int nex = 0;
  trav(x,ind) { // cur[x][0] <= ?, cur[x][1] < ?
    while (nex < N && cur[ind[nex]][0] >= cur[x][0]) {
      int b = ind[nex++];
      S.upd(cur[b][1],{cur[b][2],b});
    }
    pi t = S.query(cur[x][1]);
    if (t.s != 2*MOD) ed.pb({(ll)t.f-cur[x][2],{x,t.s}});
  }
}

ll mst(vpi v) {
  N = sz(v); cur.rsz(N); ed.clear();
  ind.clear(); F0R(i,N) ind.pb(i);
  sort(all(ind),[&v](int a, int b) { return v[a] < v[b]; });
  F0R(i,N-1) if (v[ind[i]] == v[ind[i+1]])
    ed.pb({0,{ind[i],ind[i+1]}});
  F0R(i,2) { // ok to consider just two quadrants?
    F0R(i,N) {
      auto a = v[i];
      cur[i][2] = a.f+a.s;
    }
    F0R(i,N) { // first octant
      auto a = v[i];
      cur[i][0] = a.f-a.s;
      cur[i][1] = a.s;
    }
    solve();
    F0R(i,N) { // second octant
      auto a = v[i];
      cur[i][0] = a.f;
      cur[i][1] = a.s-a.f;
    }
    solve();
    trav(a,v) a = {a.s,-a.f}; // rotate 90 degrees, repeat
  }
  return kruskal(N,ed);
}
```

7.2 Trees

LCAjumps.h

Description: calculates least common ancestor in tree with binary jumping
Time: $\mathcal{O}(N \log N)$
a5a7dd, 35 lines

```
template<int SZ> struct LCA {
  static const int BITS = 32-__builtin_clz(SZ);
  int N, R = 1; // vertices from 1 to N, R = root
  vi adj[SZ];
  int par[BITS][SZ], depth[SZ];

  // INITIALIZE
  void addEdge(int u, int v) { adj[u].pb(v), adj[v].pb(u); }
  void dfs(int u, int prev){
    par[0][u] = prev;
    depth[u] = depth[prev]+1;
    trav(v,adj[u]) if (v != prev) dfs(v, u);
  }
  void init(int _N) {
    N = _N; dfs(R, 0);
    FOR(k,1,BITS) FOR(i,1,N+1)
      par[k][i] = par[k-1][par[k-1][i]];
  }

  // QUERY
  int getPar(int a, int b) {
    R0F(k,BITS) if (b&(1<<k)) a = par[k][a];
    return a;
  }
  int lca(int u, int v){
    if (depth[u] < depth[v]) swap(u,v);
    u = getPar(u,depth[u]-depth[v]);
    R0F(k,BITS) if (par[k][u] != par[k][v])
      u = par[k][u], v = par[k][v];
    return u == v ? u : par[0][u];
  }
  int dist(int u, int v) {
    return depth[u]+depth[v]-2*depth[lca(u,v)];
  }
};
```

CentroidDecomp.h

Description: The centroid of a tree of size N is a vertex such that after removing it, all resulting subtrees have size at most $\frac{N}{2}$. Can support tree path queries and updates
Time: $\mathcal{O}(N \log N)$
81e9e4, 45 lines

```
template<int SZ> struct CD {
  vi adj[SZ];
  bool done[SZ];
  int sub[SZ], par[SZ];
  vl dist[SZ];
  pi cen[SZ];
  void addEdge(int a, int b) { adj[a].pb(b), adj[b].pb(a); }

  void dfs (int x) {
    sub[x] = 1;
    trav(y,adj[x]) if (!done[y] && y != par[x]) {
      par[y] = x; dfs(y);
      sub[x] += sub[y];
    }
  }
  int centroid(int x) {
    par[x] = -1; dfs(x);
    for (int sz = sub[x];;) {
      pi mx = {0,0};
      trav(y,adj[x]) if (!done[y] && y != par[x])
        ckmax(mx,{sub[y],y});
      if (mx.f*2 <= sz) return x;
      x = mx.s;
    }
  }

  void genDist(int x, int p) {
    dist[x].pb(dist[p].back()+1);
    trav(y,adj[x]) if (!done[y] && y != p) {
      cen[y] = cen[x];
      genDist(y,x);
    }
  }
  void gen(int x, bool fst = 0) {
    done[x = centroid(x)] = 1; dist[x].pb(0);
    if (fst) cen[x].f = -1;
    int co = 0;
    trav(y,adj[x]) if (!done[y]) {
      cen[y] = {x,co++};
      genDist(y,x);
    }
    trav(y,adj[x]) if (!done[y]) gen(y);
  }
  void init() { gen(1,1); }
};
```

HLD.h

Description: Heavy-Light Decomposition
Time: any tree path is split into $\mathcal{O}(\log N)$ parts
"LazySegTree.h" c07386, 50 lines

```
template<int SZ, bool VALUES_IN_EDGES> struct HLD {
  int N; vi adj[SZ];
  int par[SZ], sz[SZ], depth[SZ];
  int root[SZ], pos[SZ];
  LazySeg<ll,SZ> tree;
  void addEdge(int a, int b) { adj[a].pb(b), adj[b].pb(a); }

  void dfs_sz(int v = 1) {
    if (par[v]) adj[v].erase(find(all(adj[v]),par[v]));
    sz[v] = 1;
    trav(u,adj[v]) {
      par[u] = v; depth[u] = depth[v]+1;
      dfs_sz(u); sz[v] += sz[u];
      if (sz[u] > sz[adj[v][0]]) swap(u, adj[v][0]);
    }
  }
  void dfs_hld(int v = 1) {
    static int t = 0;
    pos[v] = t++;
    trav(u,adj[v]) {
      root[u] = (u == adj[v][0] ? root[v] : u);
      dfs_hld(u);
    }
  }
  void init(int _N) {
    N = _N; par[1] = depth[1] = 0; root[1] = 1;
    dfs_sz(); dfs_hld();
  }

  template <class BinaryOperation>
  void processPath(int u, int v, BinaryOperation op) {
    for (; root[u] != root[v]; v = par[root[v]]) {
      if (depth[root[u]] > depth[root[v]]) swap(u, v);
      op(pos[root[v]], pos[v]);
    }
    if (depth[u] > depth[v]) swap(u, v);
    op(pos[u]+VALUES_IN_EDGES, pos[v]);
  }

  void modifyPath(int u, int v, int val) { // add val to
    ↪vertices/edges along path
    processPath(u, v, [this, &val](int l, int r) { tree.upd(l,
      ↪r, val); });
  }
  void modifySubtree(int v, int val) { // add val to vertices/
    ↪edges in subtree
    tree.upd(pos[v]+VALUES_IN_EDGES,pos[v]+sz[v]-1,val);
  }
  ll queryPath(int u, int v) { // query sum of path
    ll res = 0; processPath(u, v, [this, &res](int l, int r) {
      ↪res += tree.qsum(l, r); });
    return res;
  }
};
```

7.3 DFS Algorithms

SCC.h

Description: Kosaraju's Algorithm, DFS two times to generate SCCs in topological order

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

f53f41, 24 lines

```
template<int SZ> struct SCC {
  int N, comp[SZ];
  vi adj[SZ], radj[SZ], todo, allComp;
  bitset<SZ> visit;
  void addEdge(int a, int b) { adj[a].pb(b), radj[b].pb(a); }

  void dfs(int v) {
    visit[v] = 1;
    trav(w,adj[v]) if (!visit[w]) dfs(w);
    todo.pb(v);
  }
  void dfs2(int v, int val) {
    comp[v] = val;
    trav(w,radj[v]) if (comp[w] == -1) dfs2(w,val);
  }

  void init(int _N) { // fills allComp
    N = _N;
    FOR(i,N) comp[i] = -1, visit[i] = 0;
    FOR(i,N) if (!visit[i]) dfs(i);
    reverse(all(todo)); // now todo stores vertices in order of
      ↪ topological sort
    trav(i,todo) if (comp[i] == -1) dfs2(i,i), allComp.pb(i);
  }
};
```

2SAT.h

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

Usage: TwoSat ts;
ts.either(0, ~3); // Var 0 is true or var 3 is false
ts.setVal(2); // Var 2 is true
ts.atMostOne({0,~1,2}); // <= 1 of vars 0, ~1 and 2 are true
ts.solve(N); // Returns true iff it is solvable
ts.ans[0..N-1] holds the assigned values to the vars

"SCC.h" 6c209d, 38 lines

```
template<int SZ> struct TwoSat {
  SCC<2*SZ> S;
  bitset<SZ> ans;
  int N = 0;
  int addVar() { return N++; }

  void either(int x, int y) {
    x = max(2*x,-1-2*x), y = max(2*y,-1-2*y);
    S.addEdge(x^1,y); S.addEdge(y^1,x);
  }
  void implies(int x, int y) { either(~x,y); }
  void setVal(int x) { either(x,x); }
  void atMostOne(const vi& li) {
    if (sz(li) <= 1) return;
    int cur = ~li[0];
    FOR(i,2,sz(li)) {
      int next = addVar();
      either(cur,~li[i]);
      either(cur,next);
      either(~li[i],next);
      cur = ~next;
    }
    either(cur,~li[1]);
  }

  bool solve(int _N) {
    if (_N != -1) N = _N;
    S.init(2*N);
    for (int i = 0; i < 2*N; i += 2)
      if (S.comp[i] == S.comp[i^1]) return 0;
    reverse(all(S.allComp));
    vi tmp(2*N);
    trav(i,S.allComp) if (tmp[i] == 0)
      tmp[i] = 1, tmp[S.comp[i^1]] = -1;
    FOR(i,N) if (tmp[S.comp[2*i]] == 1) ans[i] = 1;
    return 1;
  }
};
```

EulerPath.h

Description: Eulerian Path for both directed and undirected graphs

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

fd7ad7, 30 lines

```
template<int SZ, bool directed> struct Euler {
  int N, M = 0;
  vpi adj[SZ];
  vpi::iterator its[SZ];
  vector<bool> used;

  void addEdge(int a, int b) {
    if (directed) adj[a].pb({b,M});
    else adj[a].pb({b,M}), adj[b].pb({a,M});
    used.pb(0); M ++;
  }

  vpi solve(int _N, int src = 1) {
    N = _N;
    FOR(i,1,N+1) its[i] = begin(adj[i]);
    vector<pair<pi,int>> ret, s = {{{src,-1},-1}};
    while (sz(s)) {
      int x = s.back().f.f;
      auto& it = its[x], end = adj[x].end();
      while (it != end && used[it->s]) it ++;
      if (it == end) {
        if (sz(ret) && ret.back().f.s != s.back().f.f) return
          ↪{}; // path isn't valid
        ret.pb(s.back()), s.pop_back();
      } else { s.pb({{it->f,x},it->s}); used[it->s] = 1; }
    }
    if (sz(ret) != M+1) return {};
    vpi ans; trav(t,ret) ans.pb({t.f.f,t.s});
    reverse(all(ans)); return ans;
  }
};
```

BCC.h

Description: biconnected components

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

3e4563, 38 lines

```
template<int SZ> struct BCC {
  int N;
  vpi adj[SZ], ed;
  void addEdge(int u, int v) {
    adj[u].pb({v,sz(ed)}), adj[v].pb({u,sz(ed)});
    ed.pb({u,v});
  }

  int disc[SZ];
  vi st; vector<vi> fin;
  int bcc(int u, int p = -1) { // return lowest disc
    static int ti = 0;
    disc[u] = ++ti; int low = disc[u];
    int child = 0;
    trav(i,adj[u]) if (i.s != p) {
      if (!disc[i.f]) {
        child ++; st.pb(i.s);
        int LOW = bcc(i.f,i.s); ckmin(low,LOW);
        // disc[u] < LOW -> bridge
        if (disc[u] <= LOW) {
          // if (p != -1 || child > 1) -> u is articulation
            ↪point
          vi tmp; while (st.back() != i.s) tmp.pb(st.back()),
            ↪st.pop_back();
          tmp.pb(st.back()), st.pop_back();
          fin.pb(tmp);
```

```
        }
      } else if (disc[i.f] < disc[u]) {
        ckmin(low,disc[i.f]);
        st.pb(i.s);
      }
    }
    return low;
  }

  void init(int _N) {
    N = _N; FOR(i,N) disc[i] = 0;
    FOR(i,N) if (!disc[i]) bcc(i); // st should be empty after
      ↪each iteration
  }
};
```

7.4 Flows

Dinic.h

Description: fast flow

Time: $\mathcal{O}\left(N^2M\right)$ flow, $\mathcal{O}\left(M\sqrt{N}\right)$ bipartite matching

b096a0, 45 lines

```
template<int SZ> struct Dinic {
  typedef ll F; // flow type
  struct Edge { int to, rev; F flow, cap; };

  int N,s,t;
  vector<Edge> adj[SZ];
  typename vector<Edge>::iterator cur[SZ];
  void addEdge(int u, int v, F cap) {
    assert(cap >= 0); // don't try smth dumb
    Edge a{v, sz(adj[v]), 0, cap}, b{u, sz(adj[u]), 0, 0};
    adj[u].pb(a), adj[v].pb(b);
  }

  int level[SZ];
  bool bfs() { // level = shortest distance from source
    // after computing flow, edges {u,v} such that level[u] \
      ↪neq -1, level[v] = -1 are part of min cut
    FOR(i,N) level[i] = -1, cur[i] = begin(adj[i]);
    queue<int> q({s}); level[s] = 0;
    while (sz(q)) {
      int u = q.front(); q.pop();
      trav(e,adj[u]) if (level[e.to] < 0 && e.flow < e.cap)
        q.push(e.to), level[e.to] = level[u]+1;
    }
    return level[t] >= 0;
  }
  F sendFlow(int v, F flow) {
    if (v == t) return flow;
    for (; cur[v] != end(adj[v]); cur[v]++) {
      Edge& e = *cur[v];
      if (level[e.to] != level[v]+1 || e.flow == e.cap)
        ↪continue;
      auto df = sendFlow(e.to,min(flow,e.cap-e.flow));
      if (df) { // saturated at least one edge
        e.flow += df; adj[e.to][e.rev].flow -= df;
        return df;
      }
    }
    return 0;
  }
  F maxFlow(int _N, int _s, int _t) {
    N = _N, s = _s, t = _t; if (s == t) return -1;
    F tot = 0;
    while (bfs()) while (auto df = sendFlow(s,numeric_limits<F
      ↪>::max())) tot += df;
    return tot;
  }
};
```

MCMF.h

Description: minimum-cost maximum flow, assume no negative cycles

Time: $\mathcal{O}\left(FM \log M\right)$ if caps are integers and F is max flow

003506, 54 lines

```
template<class T> using pqg = priority_queue<T,vector<T>,
  ↪greater<T>>;
template<class T> T poll(pqg<T>& x) {
  T y = x.top(); x.pop();
  return y;
}

template<int SZ> struct mcmf {
  typedef ll F; typedef ll C;
  struct Edge { int to, rev; F flow, cap; C cost; int id; };
  vector<Edge> adj[SZ];
  void addEdge(int u, int v, F cap, C cost) {
    assert(cap >= 0);
    Edge a{v, sz(adj[v]), 0, cap, cost}, b{u, sz(adj[u]), 0, 0,
      ↪ -cost};
    adj[u].pb(a), adj[v].pb(b);
  }

  int N, s, t;
  pi pre[SZ]; // previous vertex, edge label on path
  pair<C,F> cost[SZ]; // tot cost of path, amount of flow
  C totCost, curCost; F totFlow;
  void reweight() { // makes all edge costs non-negative
    // all edges on shortest path become 0
    FOR(i,N) trav(p,adj[i]) p.cost += cost[i].f-cost[p.to].f;
  }
  bool spfa() { // reweight ensures that there will be negative
    ↪ weights
    // only during the first time you run this
    FOR(i,N) cost[i] = {INF,0};
    cost[s] = {0,INF};
    pqg<pair<C,int>> todo; todo.push({0,s});
    while (sz(todo)) {
      auto x = poll(todo); if (x.f > cost[x.s].f) continue;
      trav(a,adj[x.s]) if (x.f+a.cost < cost[a.to].f && a.flow
        ↪< a.cap) {
        // if costs are doubles, add some EPS to ensure that
        // you do not traverse some 0-weight cycle repeatedly
        pre[a.to] = {x.s,a.rev};
        cost[a.to] = {x.f+a.cost,min(a.cap-a.flow,cost[x.s].s)
          ↪};
        todo.push({cost[a.to].f,a.to});
      }
    }
    curCost += cost[t].f; return cost[t].s;
  }
  void backtrack() {
    F df = cost[t].s; totFlow += df, totCost += curCost*df;
    for (int x = t; x != s; x = pre[x].f) {
      adj[x][pre[x].s].flow -= df;
      adj[pre[x].f][adj[x][pre[x].s].rev].flow += df;
    }
  }
  pair<F,C> calc(int _N, int _s, int _t) {
    N = _N; s = _s, t = _t; totFlow = totCost = curCost = 0;
    while (spfa()) reweight(), backtrack();
    return {totFlow, totCost};
  }
};
```

GomoryHu.h

Description: returns edges of Gomory-Hu tree, max flow between pair of vertices of undirected graph is given by min edge weight along tree path

Time: $\mathcal{O}\left(N\right)$ calls to Dinic

"Dinic.h" fe44db, 57 lines

```
template<int SZ> struct GomoryHu {
  int N;
  vector<pair<pi,int>> ed;
  void addEdge(int a, int b, int c) { ed.pb({{a,b},c}); }

  vector<vi> cor = {{}}; // groups of vertices
  map<int,int> adj[2*SZ]; // current edges of tree
  int side[SZ];

  int gen(vector<vi> cc) {
    Dinic<SZ> D = Dinic<SZ>();
    vi comp(N+1); FOR(i,sz(cc)) trav(t,cc[i]) comp[t] = i;
    trav(t,ed) if (comp[t.f.f] != comp[t.f.s]) {
      D.addEdge(comp[t.f.f],comp[t.f.s],t.s);
      D.addEdge(comp[t.f.s],comp[t.f.f],t.s);
    }
    int f = D.maxFlow(0,1);
    FOR(i,sz(cc)) trav(j,cc[i]) side[j] = D.level[i] >= 0; //
      ↪min cut
    return f;
  }

  void fill(vi& v, int a, int b) {
    trav(t,cor[a]) v.pb(t);
    trav(t,adj[a]) if (t.f != b) fill(v,t.f,a);
  }

  void addTree(int a, int b, int c) { adj[a][b] = c, adj[b][a]
    ↪= c; }
  void delTree(int a, int b) { adj[a].erase(b), adj[b].erase(a)
    ↪; }

  vector<pair<pi,int>> init(int _N) {
    N = _N;
    FOR(i,1,N+1) cor[0].pb(i);
    queue<int> todo; todo.push(0);
    while (sz(todo)) {
      int x = todo.front(); todo.pop();
      vector<vi> cc; trav(t,cor[x]) cc.pb({t});
      trav(t,adj[x]) {
        cc.pb({});
        fill(cc.back(),t.f,x);
      }
      int f = gen(cc); // run max flow
      cor.pb({}), cor.pb({});
      trav(t,cor[x]) cor[sz(cor)-2+side[t]].pb(t);
      FOR(i,2) if (sz(cor[sz(cor)-2+i]) > 1)
        todo.push(sz(cor)-2+i);
      FOR(i,sz(cor)-2) if (i != x && adj[i].count(x)) {
        addTree(i,sz(cor)-2+side[cor[i][0]],adj[i][x]);
        delTree(i,x);
      } // modify tree edges
      addTree(sz(cor)-2,sz(cor)-1,f);
    }
    vector<pair<pi,int>> ans;
    FOR(i,sz(cor)) trav(j,adj[i]) if (i < j.f)
      ans.pb({{cor[i][0],cor[j.f][0]},j.s});
    return ans;
  }
};
```

7.5 Matching

DFSmatch.h

Description: naive bipartite matching
Time: $\mathcal{O}(NM)$

37ad8b, 25 lines

```
template<int SZ> struct MaxMatch {
  int N, flow = 0, match[SZ], rmatch[SZ];
  bitset<SZ> vis;
  vi adj[SZ];
  MaxMatch() {
    memset(match,0,sizeof match);
    memset(rmatch,0,sizeof rmatch);
  }
  void connect(int a, int b, bool c = 1) {
    if (c) match[a] = b, rmatch[b] = a;
    else match[a] = rmatch[b] = 0;
  }
  bool dfs(int x) {
    if (!x) return 1;
    if (vis[x]) return 0;
    vis[x] = 1;
    trav(t,adj[x]) if (t != match[x] && dfs(rmatch[t]))
      return connect(x,t),1;
    return 0;
  }
  void tri(int x) { vis.reset(); flow += dfs(x); }
  void init(int _N) {
    N = _N; FOR(i,1,N+1) if (!match[i]) tri(i);
  }
};
```

Hungarian.h

Description: given array of (possibly negative) costs to complete each of N jobs w/ each of M workers ($N \le M$), finds min cost to complete all jobs such that each worker is assigned to at most one job
Time: $\mathcal{O}(N^2M)$

d8824c, 34 lines

```
int hungarian(const vector<vi>& a) {
  int n = sz(a)-1, m = sz(a[0])-1; // jobs 1..n, workers 1..m
  vi u(n+1), v(m+1); // potentials
  vi p(m+1); // p[j] -> job picked by worker j
  FOR(i,1,n+1) { // find alternating path with job i
    p[0] = i; int j0 = 0; // add "dummy" worker 0
    vi dist(m+1,INT_MAX), pre(m+1,-1); // prev vertex on
      ↪shortest path
    vector<bool> done(m+1, false);
    do { // dijkstra
      done[j0] = true; // fix dist[j0], update dists from j0
      int i0 = p[j0], j1; int delta = INT_MAX;
      FOR(j,1,m+1) if (!done[j]) {
        auto cur = a[i0][j]-u[i0]-v[j];
        if (ckmin(dist[j],cur)) pre[j] = j0;
        if (ckmin(delta,dist[j])) j1 = j;
      }
      FOR(j,m+1) { // subtract constant from all edges going
        // from done -> not done vertices, lowers all
        // remaining dists by constant
        if (done[j]) u[p[j]] += delta, v[j] -= delta;
        else dist[j] -= delta;
      }
      j0 = j1;
    } while (p[j0]); // potentials adjusted so that all edge
      ↪weights are non-negative
    // perfect matching has zero weight and
    // costs of augmenting paths do not change
    while (j0) { // update jobs picked by workers on
      ↪alternating path
      int j1 = pre[j0];
      p[j0] = p[j1];
      j0 = j1;
    }
  }
  return -v[0]; // min cost
}
```

UnweightedMatch.h

Description: general unweighted matching, 1-based indexing
Time: $\mathcal{O}(N^2M)$

b6ba8d, 72 lines

```
template<int SZ> struct UnweightedMatch {
  int vis[SZ], par[SZ], orig[SZ], match[SZ], aux[SZ], t, N;
  vi adj[SZ];
  queue<int> Q;
  void addEdge(int u, int v) { adj[u].pb(v), adj[v].pb(u); }
  void init(int _N) {
    N = _N; t = 0;
    FOR(i,N+1) {
      adj[i].clear();
      match[i] = aux[i] = par[i] = 0;
    }
  }
  void augment(int u, int v) {
    int pv = v, nv;
    do {
      pv = par[v]; nv = match[pv];
      match[v] = pv; match[pv] = v;
      v = nv;
    } while(u != pv);
  }
  int lca(int v, int w) {
    ++t;
    while (1) {
      if (v) {
        if (aux[v] == t) return v;
        aux[v] = t;
        v = orig[par[match[v]]];
      }
      swap(v, w);
    }
  }
  void blossom(int v, int w, int a) {
    while (orig[v] != a) {
      par[v] = w; w = match[v];
      if (vis[w] == 1) Q.push(w), vis[w] = 0;
      orig[v] = orig[w] = a;
      v = par[w];
    }
  }
  bool bfs(int u) {
    fill(vis+1, vis+1+N, -1); iota(orig + 1, orig + N + 1, 1);
    Q = queue<int>(); Q.push(u); vis[u] = 0;
    while (sz(Q)) {
      int v = Q.front(); Q.pop();
      trav(x,adj[v]) {
        if (vis[x] == -1) {
          par[x] = v; vis[x] = 1;
          if (!match[x]) return augment(u, x), true;
          Q.push(match[x]); vis[match[x]] = 0;
        } else if (vis[x] == 0 && orig[v] != orig[x]) {
          int a = lca(orig[v], orig[x]);
          blossom(x, v, a); blossom(v, x, a);
        }
      }
    }
    return false;
  }
  int calc() {
    int ans = 0;
    // find random matching (not necessary, constant
      ↪improvement)
    vi V(N-1); iota(all(V), 1);
    shuffle(all(V), mt19937(0x94949));
    trav(x,V) if(!match[x])
      trav(y,adj[x]) if (!match[y]) {
        match[x] = y, match[y] = x;
        ++ans; break;
      }

    FOR(i,1,N+1) if (!match[i] && bfs(i)) ++ans;
    return ans;
  }
};
```

7.6 Misc

MaximalCliques.h

Description: Finds all maximal cliques
Time: $\mathcal{O}\left(3^{N/3}\right)$

585e12, 19 lines

```
typedef bitset<128> B;
int N;
B adj[128];

void cliques(B P = ~B(), B X={}, B R={}) { // possibly in
  ↪clique, not in clique, in clique
  if (!P.any()) {
    if (!X.any()) {
      // do smth with maximal clique
    }
    return;
  }
  auto q = (P|X)._Find_first();
  auto cands = P&~adj[q]; // clique must contain q or non-
    ↪neighbor of q
  FOR(i,N) if (cands[i]) {
    R[i] = 1;
    cliques(P&adj[i],X&adj[i],R);
    R[i] = P[i] = 0; X[i] = 1;
  }
}
```

LCT.h

Description: Link-Cut Tree, use `vir` for subtree size queries
Time: $\mathcal{O}(\log N)$

06a240, 96 lines

```
typedef struct snode* sn;

struct snode {
  sn p, c[2]; // parent, children
  int val; // value in node
  int sum, mn, mx; // sum of values in subtree, min and max
    ↪prefix sum
  bool flip = 0;
  // int vir = 0; stores sum of virtual children

  snode(int v) {
    p = c[0] = c[1] = NULL;
    val = v; calc();
  }

  friend int getSum(sn x) { return x?x->sum:0; }
  friend int getMn(sn x) { return x?x->mn:0; }
  friend int getMx(sn x) { return x?x->mx:0; }
```

```
  void prop() {
    if (!flip) return;
    swap(c[0],c[1]); tie(mn,mx) = mp(sum-mx,sum-mn);
    FOR(i,2) if (c[i]) c[i]->flip ^= 1;
    flip = 0;
  }
  void calc() {
    FOR(i,2) if (c[i]) c[i]->prop();
    int s0 = getSum(c[0]), s1 = getSum(c[1]); sum = s0+val+s1;
      ↪// +vir
    mn = min(getMn(c[0]),s0+val+getMn(c[1]));
    mx = max(getMx(c[0]),s0+val+getMx(c[1]));
  }

  int dir() {
    if (!p) return -2;
    FOR(i,2) if (p->c[i] == this) return i;
    return -1; // p is path-parent pointer, not in current
      ↪splay tree
  }
  bool isRoot() { return dir() < 0; }

  friend void setLink(sn x, sn y, int d) {
    if (y) y->p = x;
    if (d >= 0) x->c[d] = y;
  }
  void rot() { // assume p and p->p propagated
    assert(!isRoot()); int x = dir(); sn pa = p;
    setLink(pa->p, this, pa->dir());
    setLink(pa, c[x^1], x);
    setLink(this, pa, x^1);
    pa->calc(); calc();
  }
  void splay() {
    while (!isRoot() && !p->isRoot()) {
      p->p->prop(), p->prop(), prop();
      dir() == p->dir() ? p->rot() : rot();
      rot();
    }
    if (!isRoot()) p->prop(), prop(), rot();
    prop();
  }

  void access() { // bring this to top of tree
    for (sn v = this, pre = NULL; v; v = v->p) {
      v->splay();
      // if (pre) v->vir -= pre->sz;
      // if (v->c[1]) v->vir += v->c[1]->sz;
      v->c[1] = pre; v->calc();
      pre = v;
      // v->sz should remain the same if using vir
    }
    splay(); assert(!c[1]); // left subtree of this is now path
      ↪ to root, right subtree is empty
  }
  void makeRoot() { access(); flip ^= 1; }
  void set(int v) { splay(); val = v; calc(); } // change value
    ↪ in node, splay suffices instead of access because it
    ↪doesn't affect values in nodes above it

  friend sn lca(sn x, sn y) {
    if (x == y) return x;
    x->access(), y->access(); if (!x->p) return NULL; // access
      ↪ at y did not affect x, so they must not be connected
    x->splay(); return x->p ? x->p : x;
  }
  friend bool connected(sn x, sn y) { return lca(x,y); }
  friend int balanced(sn x, sn y) {
    x->makeRoot(); y->access();
    return y->sum-2*y->mn;
  }

  friend bool link(sn x, sn y) { // make x parent of y
    if (connected(x,y)) return 0; // don't induce cycle
    y->makeRoot(); y->p = x;
    // x->access(); x->sz += y->sz; x->vir += y->sz;
    return 1; // success!
  }
  friend bool cut(sn x, sn y) { // x is originally parent of y
    x->makeRoot(); y->access();
    if (y->c[0] != x || x->c[0] || x->c[1]) return 0; // splay
      ↪tree with y should not contain anything else besides x
    x->p = y->c[0] = NULL; y->calc(); return 1; // calc is
      ↪redundant as it will be called elsewhere anyways?
  }
};
```

DirectedMST.h

Description: computes minimum weight directed spanning tree, edge from $inv[i] \to i$ for all $i \neq r$

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

"DSUrb.h" 314387, 64 lines

```
struct Edge { int a, b; ll w; };
struct Node {
  Edge key;
  Node *l, *r;
  ll delta;
  void prop() {
    key.w += delta;
    if (l) l->delta += delta;
    if (r) r->delta += delta;
    delta = 0;
  }
  Edge top() { prop(); return key; }
};
Node *merge(Node *a, Node *b) {
  if (!a || !b) return a ?: b;
  a->prop(), b->prop();
  if (a->key.w > b->key.w) swap(a, b);
  swap(a->l, (a->r = merge(b, a->r)));
  return a;
}
void pop(Node*& a) { a->prop(); a = merge(a->l, a->r); }

pair<ll,vi> dmst(int n, int r, const vector<Edge>& g) {
  DSUrb dsu; dsu.init(n); // DSU with rollback if need to
    ↪return edges
  vector<Node*> heap(n); // store edges entering each vertex in
    ↪ increasing order of weight
  trav(e,g) heap[e.b] = merge(heap[e.b], new Node{e});
  ll res = 0; vi seen(n,-1); seen[r] = r;
  vpi in(n,{-1,-1});
  vector<pair<int,vector<Edge>>> cycs;
  FOR(s,n) {
    int u = s, w;
    vector<pair<int,Edge>> path;
    while (seen[u] < 0) {
      if (!heap[u]) return {-1,{}};
      seen[u] = s;
      Edge e = heap[u]->top(); path.pb({u,e});
      heap[u]->delta -= e.w, pop(heap[u]);
      res += e.w, u = dsu.get(e.a);
      if (seen[u] == s) { // compress verts in cycle
        Node* cyc = 0; cycs.pb({u,{}});
        do {
          cyc = merge(cyc, heap[w = path.back().f]);
          cycs.back().s.pb(path.back().s);
          path.pop_back();
        } while (dsu.unite(u, w));
        u = dsu.get(u); heap[u] = cyc, seen[u] = -1;
      }
    }
    trav(t,path) in[dsu.get(t.s.b)] = {t.s.a,t.s.b}; // found
      ↪path from root
  }
  while (sz(cycs)) { // expand cycs to restore sol
    auto c = cycs.back(); cycs.pop_back();
    pi inEdge = in[c.f];
    trav(t,c.s) dsu.rollback();
    trav(t,c.s) in[dsu.get(t.b)] = {t.a,t.b};
    in[dsu.get(inEdge.s)] = inEdge;
  }
  vi inv;
  FOR(i,n) {
    assert(i == r ? in[i].s == -1 : in[i].s == i);
    inv.pb(in[i].f);
  }
  return {res,inv};
}
```

DominatorTree.h

Description: a dominates b iff every path from 1 to b passes through a

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

17cd41, 46 lines

```
template<int SZ> struct Dominator {
  vi adj[SZ], ans[SZ]; // input edges, edges of dominator tree
  vi radj[SZ], child[SZ], sdomChild[SZ];
  int label[SZ], rlabel[SZ], sdom[SZ], dom[SZ], co;
  int root = 1;

  int par[SZ], bes[SZ];
  int get(int x) {
    // DSU with path compression
    // get vertex with smallest sdom on path to root
    if (par[x] != x) {
      int t = get(par[x]); par[x] = par[par[x]];
      if (sdom[t] < sdom[bes[x]]) bes[x] = t;
    }
    return bes[x];
  }

  void dfs(int x) { // create DFS tree
    label[x] = ++co; rlabel[co] = x;
    sdom[co] = par[co] = bes[co] = co;
    trav(y,adj[x]) {
      if (!label[y]) {
        dfs(y);
        child[label[x]].pb(label[y]);
      }
      radj[label[y]].pb(label[x]);
    }
  }
  void init() {
    dfs(root);
    ROF(i,1,co+1) {
      trav(j,radj[i]) ckmin(sdom[i],sdom[get(j)]);
      if (i > 1) sdomChild[sdom[i]].pb(i);
      trav(j,sdomChild[i]) {
        int k = get(j);
        if (sdom[j] == sdom[k]) dom[j] = sdom[j];
        else dom[j] = k;
      }
      trav(j,child[i]) par[j] = i;
    }
    FOR(i,2,co+1) {
      if (dom[i] != sdom[i]) dom[i] = dom[dom[i]];
```

```
      ans[rlabel[dom[i]]].pb(rlabel[i]);
    }
  }
};
```

EdgeColor.h

Description: naive implementation of Misra & Gries edge coloring, by Vizing's Theorem a simple graph with max degree d can be edge colored with at most $d+1$ colors

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

723f0a, 54 lines

```
template<int SZ> struct EdgeColor {
  int N = 0, maxDeg = 0, adj[SZ][SZ], deg[SZ];
  EdgeColor() {
    memset(adj,0,sizeof adj);
    memset(deg,0,sizeof deg);
  }
  void addEdge(int a, int b, int c) {
    adj[a][b] = adj[b][a] = c;
  }
  int delEdge(int a, int b) {
    int c = adj[a][b];
    adj[a][b] = adj[b][a] = 0;
    return c;
  }
  vector<bool> genCol(int x) {
    vector<bool> col(N+1); FOR(i,N) col[adj[x][i]] = 1;
    return col;
  }
  int freeCol(int u) {
    auto col = genCol(u);
    int x = 1; while (col[x]) x ++; return x;
  }
  void invert(int x, int d, int c) {
    FOR(i,N) if (adj[x][i] == d)
      delEdge(x,i), invert(i,c,d), addEdge(x,i,c);
  }
  void addEdge(int u, int v) { // follows wikipedia steps
    // check if you can add edge w/o doing any work
    assert(N); ckmax(maxDeg,max(++deg[u],++deg[v]));
    auto a = genCol(u), b = genCol(v);
    FOR(i,1,maxDeg+2) if (!a[i] && !b[i]) return addEdge(u,v,i)
      ↪;

    // 2. find maximal fan of u starting at v
    vector<bool> use(N); vi fan = {v}; use[v] = 1;
    while (1) {
      auto col = genCol(fan.back());
      if (sz(fan) > 1) col[adj[fan.back()][u]] = 0;
      int i = 0; while (i < N && (use[i] || col[adj[u][i]])) i
        ↪++;
      if (i < N) fan.pb(i), use[i] = 1;
      else break;
    }

    // 3/4. choose free cols for endpoints of fan, invert cd_u
      ↪path
    int c = freeCol(u), d = freeCol(fan.back()); invert(u,d,c);
    // 5. find i such that d is free on fan[i]
    int i = 0; while (i < sz(fan) && genCol(fan[i])[d]
      && adj[u][fan[i]] != d) i ++;
    assert (i != sz(fan));
    // 6. rotate fan from 0 to i
    FOR(j,i) addEdge(u,fan[j],delEdge(u,fan[j+1]));
    // 7. add new edge
    addEdge(u,fan[i],d);
  }
};
```

Geometry (8)

8.1 Primitives

Point.h

Description: use in place of complex<T>

d378f4, 44 lines

```
typedef ld T;
template <class T> int sgn(T x) { return (x > 0) - (x < 0); }

namespace Point {
  typedef pair<T,T> P;
  typedef vector<P> vP;

  P dir(T ang) {
    auto c = exp(ang*complex<T>(0,1));
    return P(c.real(),c.imag());
  }

  T norm(P x) { return x.f*x.f+x.s*x.s; }
  T abs(P x) { return sqrt(norm(x)); }
  T angle(P x) { return atan2(x.s,x.f); }
  P conj(P x) { return P(x.f,-x.s); }

  P operator+(const P& l, const P& r) { return P(l.f+r.f,l.s+r.
    ↪s); }
  P operator-(const P& l, const P& r) { return P(l.f-r.f,l.s-r.
    ↪s); }
  P operator*(const P& l, const T& r) { return P(l.f*r,l.s*r);
    ↪}
  P operator*(const T& l, const P& r) { return r*l; }
  P operator/(const P& l, const T& r) { return P(l.f/r,l.s/r);
    ↪}
  P operator*(const P& l, const P& r) { return P(l.f*r.f-l.s*r.
    ↪s,l.s*r.f+l.f*r.s); }
  P operator/(const P& l, const P& r) { return l*conj(r)/norm(r
    ↪); }

  P& operator+=(P& l, const P& r) { return l = l+r; }
  P& operator-=(P& l, const P& r) { return l = l-r; }
  P& operator*=(P& l, const T& r) { return l = l*r; }
  P& operator/=(P& l, const T& r) { return l = l/r; }
  P& operator*=(P& l, const P& r) { return l = l*r; }
  P& operator/=(P& l, const P& r) { return l = l/r; }

  P unit(P x) { return x/abs(x); }
  T dot(P a, P b) { return (conj(a)*b).f; }
  T cross(P a, P b) { return (conj(a)*b).s; }
  T cross(P p, P a, P b) { return cross(a-p,b-p); }
  P rotate(P a, T b) { return a*P(cos(b),sin(b)); }

  P reflect(P p, P a, P b) { return a+conj((p-a)/(b-a))*(b-a);
    ↪}
  P foot(P p, P a, P b) { return (p+reflect(p,a,b))/(T)2; }
  bool onSeg(P p, P a, P b) { return cross(a,b,p) == 0 && dot(p
    ↪-a,p-b) <= 0; }
};

using namespace Point;
```

AngleCmp.h

Description: sorts points in ccw order about origin, atan2 returns real in $(-\pi,\pi]$ so points on negative x-axis come last

Usage:
```
vP v;
sort(all(v),[](P a, P b) { return
atan2(a.s,a.f) < atan2(b.s,b.f); });
sort(all(v),angleCmp); // should give same result
```

"Point.h" f43f90, 7 lines

```
template<class T> int half(pair<T,T> x) {
  return x.s == 0 ? x.f < 0 : x.s > 0;
}
bool angleCmp(P a, P b) {
  int A = half(a), B = half(b);
  return A == B ? cross(a,b) > 0 : A < B;
}
```

SegDist.h

Description: computes distance between P and line (segment) AB

"Point.h" d105ae, 8 lines

```
T lineDist(P p, P a, P b) {
  return abs(cross(p,a,b))/abs(a-b);
}
T segDist(P p, P a, P b) {
  if (dot(p-a,b-a) <= 0) return abs(p-a);
  if (dot(p-b,a-b) <= 0) return abs(p-b);
  return lineDist(p,a,b);
}
```

LineIntersect.h

Description: computes the intersection point(s) of lines AB, CD; returns $\{-1,\{0,0\}\}$ if infinitely many, $\{0,\{0,0\}\}$ if none, $\{1,x\}$ if x is the unique point

"Point.h" d86521, 8 lines

```
P extension(P a, P b, P c, P d) {
  T x = cross(a,b,c), y = cross(a,b,d);
  return (d*x-c*y)/(x-y);
}
pair<int,P> lineIntersect(P a, P b, P c, P d) {
  if (cross(b-a,d-c) == 0) return {-(cross(a,c,d) == 0),P(0,0)
    ↪};
  return {1,extension(a,b,c,d)};
}
```

SegIntersect.h

Description: computes the intersection point(s) of line segments AB, CD

"Point.h" 993634, 12 lines

```
vP segIntersect(P a, P b, P c, P d) {
  T x = cross(a,b,c), y = cross(a,b,d);
  T X = cross(c,d,a), Y = cross(c,d,b);
  if (sgn(x)*sgn(y) < 0 && sgn(X)*sgn(Y) < 0)
    return {(d*x-c*y)/(x-y)};
  set<P> s;
  if (onSeg(a,c,d)) s.insert(a);
  if (onSeg(b,c,d)) s.insert(b);
  if (onSeg(c,a,b)) s.insert(c);
  if (onSeg(d,a,b)) s.insert(d);
  return {all(s)};
}
```

8.2 Polygons

Area.h

Description: area, center of mass of a polygon with constant mass per unit area

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

"Point.h" 11ed70, 16 lines

```
T area(const vP& v) {
  T area = 0;
  FOR(i,sz(v)) {
    int j = (i+1)%sz(v); T a = cross(v[i],v[j]);
    area += a;
  }
```

```
  return abs(area)/2;
}
P centroid(const vP& v) {
  P cen(0,0); T area = 0; // 2*signed area
  FOR(i,sz(v)) {
    int j = (i+1)%sz(v); T a = cross(v[i],v[j]);
    cen += a*(v[i]+v[j]); area += a;
  }
  return cen/area/(T)3;
}
```

InPoly.h

Description: tests whether a point is inside, on, or outside of the perimeter of a polygon
Time: $\mathcal{O}(N)$

"Point.h" 8f2d6a, 10 lines

```
string inPoly(const vP& p, P z) {
  int n = sz(p), ans = 0;
  FOR(i,n) {
    P x = p[i], y = p[(i+1)%n];
    if (onSeg(z,x,y)) return "on";
    if (x.s > y.s) swap(x,y);
    if (x.s <= z.s && y.s > z.s && cross(z,x,y) > 0) ans ^= 1;
  }
  return ans ? "in" : "out";
}
```

ConvexHull.h

Description: top-bottom convex hull
Time: $\mathcal{O}(N \log N)$

"Point.h" d3f0ca, 24 lines

```
// typedef ll T;

pair<vi,vi> ulHull(const vP& P) {
  vi p(sz(P)), u, l; iota(all(p), 0);
  sort(all(p), [&P](int a, int b) { return P[a] < P[b]; });
  trav(i,p) {
    #define ADDP(C, cmp) while (sz(C) > 1 && cross(\
      P[C[sz(C)-2]],P[C.back()],P[i]) cmp 0) C.pop_back(); C.pb
        ↪(i);
    ADDP(u, >=); ADDP(l, <=);
  }
  return {u,l};
}

vi hullInd(const vP& P) {
  vi u,l; tie(u,l) = ulHull(P);
  if (sz(l) <= 1) return l;
  if (P[l[0]] == P[l[1]]) return {0};
  l.insert(end(l),rbegin(u)+1,rend(u)-1); return l;
}
vP hull(const vP& P) {
  vi v = hullInd(P);
  vP res; trav(t,v) res.pb(P[t]);
  return res;
}
```

PolyDiameter.h

Description: rotating caliphers, gives greatest distance between two points in P
Time: $\mathcal{O}(N)$ given convex hull

"ConvexHull.h" 38208a, 10 lines

```
ld diameter(vP P) {
  P = hull(P);
  int n = sz(P), ind = 1; ld ans = 0;
  FOR(i,n)
    for (int j = (i+1)%n;;ind = (ind+1)%n) {
      ckmax(ans,abs(P[i]-P[ind]));
      if (cross(P[j]-P[i],P[(ind+1)%n]-P[ind]) <= 0) break;
    }
  return ans;
}
```

8.3 Circles

Circle.h

Description: ?

"Point.h" eb86de, 7 lines

```
typedef pair<P,T> circ;
bool on(circ x, P y) { return abs(y-x.f) == x.s; }
bool in(circ x, P y) {  return abs(y-x.f) <= x.s; }
T arcLength(circ x, P a, P b) {
  P d = (a-x.f)/(b-x.f);
  return x.s*acos(d.f);
}
```

CircleIntersect.h

Description: circle intersection points (assuming they exist) and area

"Circle.h" 6cf3f9, 14 lines

```
P intersectPoint(circ x, circ y, int t = 0) {
  T d = abs(x.f-y.f); // dist between centers
  T theta = acos((x.s*x.s+d*d-y.s*y.s)/(2*x.s*d)); // law of
     ↪cosines
  P tmp = (y.f-x.f)/d*x.s;
  return x.f+tmp*dir(t == 0 ? theta : -theta);
}
T intersectArea(circ x, circ y) { // not thoroughly tested
  T d = abs(x.f-y.f), a = x.s, b = y.s; if (a < b) swap(a,b);
  if (d >= a+b) return 0;
  if (d <= a-b) return PI*b*b;
  auto ca = (a*a+d*d-b*b)/(2*a*d), cb = (b*b+d*d-a*a)/(2*b*d);
  auto s = (a+b+d)/2, h = 2*sqrt(s*(s-a)*(s-b)*(s-d))/d;
  return a*a*acos(ca)+b*b*acos(cb)-d*h;
}
```

CircleTangents.h

Description: internal and external tangents between two circles

"Circle.h" bb7166, 23 lines

```
P tangent(P x, circ y, int t = 0) {
  y.s = abs(y.s); // abs needed because internal calls y.s < 0
  if (y.s == 0) return y.f;
  T d = abs(x-y.f);
  P a = pow(y.s/d,2)*(x-y.f)+y.f;
  P b = sqrt(d*d-y.s*y.s)/d*y.s*unit(x-y.f)*dir(PI/2);
  return t == 0 ? a+b : a-b;
}
vector<pair<P,P>> external(circ x, circ y) {
  vector<pair<P,P>> v;
  if (x.s == y.s) {
    P tmp = unit(x.f-y.f)*x.s*dir(PI/2);
    v.pb(mp(x.f+tmp,y.f+tmp));
    v.pb(mp(x.f-tmp,y.f-tmp));
  } else {
    P p = (y.s*x.f-x.s*y.f)/(y.s-x.s);
    FOR(i,2) v.pb({tangent(p,x,i),tangent(p,y,i)});
  }
  return v;
}
vector<pair<P,P>> internal(circ x, circ y) {
  x.s *= -1; return external(x,y);
}
```

Circumcenter.h

Description: returns {circumcenter,circumradius}

"Circle.h" cfb851, 5 lines

```
circ ccCenter(P a, P b, P c) {
  b -= a; c -= a;
  P res = b*c*(conj(c)-conj(b))/(b*conj(c)-conj(b)*c);
  return {a+res,abs(res)};
}
```

MinEnclosingCircle.h

Description: minimum enclosing circle
Time: expected $\mathcal{O}(N)$

"Circumcenter.h" 53963d, 13 lines

```
circ mec(vP ps) {
  shuffle(all(ps), rng);
  P o = ps[0]; T r = 0, EPS = 1 + 1e-8;
  FOR(i,sz(ps)) if (abs(o-ps[i]) > r*EPS) {
    o = ps[i], r = 0;
    FOR(j,i) if (abs(o-ps[j]) > r*EPS) {
      o = (ps[i]+ps[j])/2, r = abs(o-ps[i]);
      FOR(k,j) if (abs(o-ps[k]) > r*EPS)
        tie(o,r) = ccCenter(ps[i],ps[j],ps[k]);
    }
  }
  return {o,r};
}
```

8.4 Misc

ClosestPair.h

Description: line sweep to find two closest points
Time: $\mathcal{O}(N \log N)$

"Point.h" 34bbb1, 17 lines

```
pair<P,P> solve(vP v) {
  pair<ld,pair<P,P>> bes; bes.f = INF;
  set<P> S; int ind = 0;
  sort(all(v));
  FOR(i,sz(v)) {
    if (i && v[i] == v[i-1]) return {v[i],v[i]};
    for (; v[i].f-v[ind].f >= bes.f; ++ind)
      S.erase({v[ind].s,v[ind].f});
    for (auto it = S.ub({v[i].s-bes.f,INF});
      it != end(S) && it->f < v[i].s+bes.f; ++it) {
      P t = {it->s,it->f};
      ckmin(bes,{abs(t-v[i]),{t,v[i]}});
    }
    S.insert({v[i].s,v[i].f});
  }
  return bes.s;
}
```

DelaunayFast.h

Description: Delaunay Triangulation, concyclic points are OK (but not all collinear)
Time: $\mathcal{O}(N \log N)$

"Point.h" 765ba9, 94 lines

```
typedef ll T;

typedef struct Quad* Q;
typedef __int128_t lll; // (can be ll if coords are < 2e4)
P arb(LLONG_MAX,LLONG_MAX); // not equal to any other point

struct Quad {
  bool mark; Q o, rot; P p;
  P F() { return r()->p; }
  Q r() { return rot->rot; }
```

```
  Q prev() { return rot->o->rot; }
  Q next() { return r()->prev(); }
};

// test if p is in the circumcircle
bool circ(P p, P a, P b, P c) {
  ll ar = cross(a,b,c); assert(ar); if (ar < 0) swap(a,b);
  lll p2 = norm(p), A = norm(a)-p2,
    B = norm(b)-p2, C = norm(c)-p2;
  return cross(p,a,b)*C+cross(p,b,c)*A+cross(p,c,a)*B > 0;
}

Q makeEdge(P orig, P dest) {
  Q q[] = {new Quad{0,0,0,orig}, new Quad{0,0,0,arb},
       new Quad{0,0,0,dest}, new Quad{0,0,0,arb}};
  FOR(i,4) q[i]->o = q[-i & 3], q[i]->rot = q[(i+1) & 3];
  return *q;
}
void splice(Q a, Q b) {
  swap(a->o->rot->o, b->o->rot->o); swap(a->o, b->o);
}
Q connect(Q a, Q b) {
  Q q = makeEdge(a->F(), b->p);
  splice(q, a->next());
  splice(q->r(), b);
  return q;
}

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

#define H(e) e->F(), e->p
#define valid(e) (cross(e->F(),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)});
  while ((cross(B->p,H(A)) < 0 && (A = A->next())) ||
       (cross(A->p,H(B)) > 0 && (B = B->r()->o)));
  Q base = connect(B->r(), A);
  if (A->p == ra->p) ra = base->r();
  if (B->p == rb->p) rb = base;

#define DEL(e, init, dir) Q e = init->dir; if (valid(e)) \
    while (circ(e->dir->F(), H(base), e->F())) { \
      Q t = e->dir; \
      splice(e, e->prev()); \
      splice(e->r(), e->r()->prev()); \
      e = t; \
    }
  for (;;) {
    DEL(LC, base->r(), o);  DEL(RC, base, prev());
    if (!valid(LC) && !valid(RC)) break;
    if (!valid(LC) || (valid(RC) && circ(H(RC), H(LC))))
      base = connect(RC, base->r());
    else
      base = connect(base->r(), LC->r());
  }
  return {ra, rb};
}

vector<array<P,3>> triangulate(vector<P> pts) {
  sort(all(pts)); assert(unique(all(pts)) == pts.end());
  if (sz(pts) < 2) return {};

  Q e = rec(pts).f; vector<Q> q = {e};
  int qi = 0;
  while (cross(e->o->F(), 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;

  vector<array<P,3>> ret;
  FOR(i,sz(pts)/3) ret.pb({pts[3*i],pts[3*i+1],pts[3*i+2]});
  return ret;
}
```

8.5 3D

Point3D.h

Description: basic 3D geometry

a4d471, 45 lines

```
typedef ld T;

namespace Point3D {
  typedef array<T,3> P3;
  typedef vector<P3> vP3;

  T norm(const P3& x) {
    T sum = 0; FOR(i,sz(x)) sum += x[i]*x[i];
    return sum;
  }
  T abs(const P3& x) { return sqrt(norm(x)); }

  P3& operator+=(P3& l, const P3& r) { FOR(i,3) l[i] += r[i]; return l; }
  P3& operator-=(P3& l, const P3& r) { FOR(i,3) l[i] -= r[i]; return l; }
  P3& operator*=(P3& l, const T& r) { FOR(i,3) l[i] *= r; return l; }
  P3& operator/=(P3& l, const T& r) { FOR(i,3) l[i] /= r; return l; }

  P3 operator+(P3 l, const P3& r) { return l += r; }
  P3 operator-(P3 l, const P3& r) { return l -= r; }
  P3 operator*(P3 l, const T& r) { return l *= r; }
  P3 operator*(const T& r, const P3& l) { return l*r; }
  P3 operator/(P3 l, const T& r) { return l /= r; }

  T dot(const P3& a, const P3& b) {
    T sum = 0; FOR(i,3) sum += a[i]*b[i];
    return sum;
  }
  P3 cross(const P3& a, const P3& b) {
    return {a[1]*b[2]-a[2]*b[1],
        a[2]*b[0]-a[0]*b[2],
        a[0]*b[1]-a[1]*b[0]};
  }

  bool isMult(const P3& a, const P3& b) {
    auto c = cross(a,b);
    FOR(i,sz(c)) if (c[i] != 0) return 0;
    return 1;
  }
  bool collinear(const P3& a, const P3& b, const P3& c) { return isMult(b-a,c-a); }
  bool coplanar(const P3& a, const P3& b, const P3& c, const P3& d) {
    return isMult(cross(b-a,c-a),cross(b-a,d-a));
  }
}

using namespace Point3D;
```

Hull3D.h

Description: 3D convex hull where no four points coplanar, polyhedron volume

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

"Point3D.h" 1158ee, 48 lines

```
struct ED {
  void ins(int x) { (a == -1 ? a : b) = x; }
  void rem(int x) { (a == x ? a : b) = -1; }
  int cnt() { return (a != -1) + (b != -1); }
  int a, b;
};

struct F { P3 q; int a, b, c; };

vector<F> hull3d(const vP3& A) {
  assert(sz(A) >= 4);
  vector<vector<ED>> E(sz(A), vector<ED>(sz(A), {-1, -1}));
  #define E(x,y) E[f.x][f.y]
  vector<F> FS; // faces
  auto mf = [&](int i, int j, int k, int l) { // make face
    P3 q = cross(A[j]-A[i],A[k]-A[i]);
    if (dot(q,A[l]) > dot(q,A[i])) q *= -1; // make sure q points outward
    F f{q, i, j, k};
    E(a,b).ins(k); E(a,c).ins(j); E(b,c).ins(i);
    FS.pb(f);
  };
  FOR(i,4) FOR(j,i+1,4) FOR(k,j+1,4) mf(i, j, k, 6-i-j-k);

  FOR(i,4,sz(A)) {
    FOR(j,sz(FS)) {
      F f = FS[j];
      if (dot(f.q,A[i]) > dot(f.q,A[f.a])) { // face is visible, remove edges
        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();
      }
    }
    FOR(j,sz(FS)) { // add faces with new point
      F f = FS[j];
      #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);
    }
  }
  trav(it, FS) if (dot(cross(A[it.b]-A[it.a],A[it.c]-A[it.a]), it.q) <= 0)
    swap(it.c, it.b);
  return FS;
}

T signedPolyVolume(const vP3& p, const vector<F>& trilist) {
  T v = 0;
  trav(i,trilist) v += dot(cross(p[i.a],p[i.b]),p[i.c]);
  return v/6;
}
```

Strings (9)

9.1 Lightweight

KMP.h

Description: `f[i]` equals the length of the longest proper suffix of the i-th prefix of s that is a prefix of s
Time: $\mathcal{O}(N)$

08f252, 16 lines

```
vi kmp(string s) {
  int N = sz(s); vi f(N+1); f[0] = -1;
  FOR(i,1,N+1) {
    f[i] = f[i-1];
    while (f[i] != -1 && s[f[i]] != s[i-1]) f[i] = f[f[i]];
    f[i] ++;
  }
  return f;
}

vi getOc(string a, string b) { // find occurrences of a in b
  vi f = kmp(a+"@"+b), ret;
  FOR(i,sz(a),sz(b)+1) if (f[i+sz(a)+1] == sz(a))
    ret.pb(i-sz(a));
  return ret;
}
```

Z.h

Description: for each index i, computes the the maximum len such that `s.substr(0,len) == s.substr(i,len)`
Time: $\mathcal{O}(N)$

a4e01c, 17 lines

```
vi z(string s) {
  int N = sz(s); s += '#';
  vi ans(N); ans[0] = N;
  int L = 1, R = 0;
  FOR(i,1,N) {
    if (i <= R) ans[i] = min(R-i+1,ans[i-L]);
    while (s[i+ans[i]] == s[ans[i]]) ans[i] ++;
    if (i+ans[i]-1 > R) L = i, R = i+ans[i]-1;
  }
  return ans;
}
vi getPrefix(string a, string b) { // find prefixes of a in b
  vi t = z(a+b), T(sz(b));
  FOR(i,sz(T)) T[i] = min(t[i+sz(a)],sz(a));
  return T;
}
// pr(z("abcababcabcaba"),getPrefix("abcab","uwetrabcerabcab"))
  ↪;
```

Manacher.h

Description: Calculates length of largest palindrome centered at each character of string
Time: $\mathcal{O}(N)$

34a78b, 18 lines

```
vi manacher(string s) {
  string s1 = "@";
  trav(c,s) s1 += c, s1 += "#";
  s1[sz(s1)-1] = '&';

  vi ans(sz(s1)-1);
  int lo = 0, hi = 0;
  FOR(i,1,sz(s1)-1) {
    if (i != 1) ans[i] = min(hi-i,ans[hi-i+lo]);
    while (s1[i-ans[i]-1] == s1[i+ans[i]+1]) ans[i] ++;
    if (i+ans[i] > hi) lo = i-ans[i], hi = i+ans[i];
  }
  ans.erase(begin(ans));
  FOR(i,sz(ans)) if ((i&1) == (ans[i]&1)) ans[i] ++; // adjust
    ↪lengths
  return ans;
}
// ps(manacher("abacaba"))
```

MinRotation.h

Description: minimum rotation of string
Time: $\mathcal{O}(N)$

483a1a, 8 lines

```
int minRotation(string s) {
  int a = 0, N = sz(s); s += s;
  FOR(b,N) FOR(i,N) { // a is current best rotation found up to
    ↪ b-1
    if (a+i == b || s[a+i] < s[b+i]) { b += max(0, i-1); break;
      ↪ } // b to b+i-1 can't be better than a to a+i-1
    if (s[a+i] > s[b+i]) { a = b; break; } // new best found
  }
  return a;
}
```

LyndonFactorization.h

Description: A string is "simple" if it is strictly smaller than any of its own nontrivial suffixes. The Lyndon factorization of the string s is a factorization $s = w_1 w_2 \dots w_k$ where all strings w_i are simple and $w_1 \geq w_2 \geq \cdots \geq w_k$
Time: $\mathcal{O}(N)$

ff5520, 20 lines

```
vector<string> duval(const string& s) {
  int n = sz(s); vector<string> factors;
  for (int i = 0; i < n; ) {
    int j = i + 1, k = i;
    for (; j < n && s[k] <= s[j]; j++) {
      if (s[k] < s[j]) k = i;
      else k ++;
    }
    for (; i <= k; i += j-k) factors.pb(s.substr(i, j-k));
  }
  return factors;
}

int minRotation(string s) { // get min index i such that cyclic
  ↪ shift starting at i is min rotation
  int n = sz(s); s += s;
  auto d = duval(s); int ind = 0, ans = 0;
  while (ans+sz(d[ind]) < n) ans += sz(d[ind++]);
  while (ind && d[ind] == d[ind-1]) ans -= sz(d[ind--]);
  return ans;
}
```

9.2 Suffix Structures

ACfixed.h

Description: for each prefix, stores link to max length suffix which is also a prefix
Time: $\mathcal{O}(N\sum)$

3bdd91, 36 lines

```
struct ACfixed { // fixed alphabet
  struct node {
    array<int,26> to;
    int link;
  };
  vector<node> d;
  ACfixed() { d.eb(); }

  int add(string s) { // add word
    int v = 0;
    trav(C,s) {
      int c = C-'a';
      if (!d[v].to[c]) {
        d[v].to[c] = sz(d);
        d.eb();
      }
      v = d[v].to[c];
    }
    return v;
  }

  void init() { // generate links
    d[0].link = -1;
    queue<int> q; q.push(0);
    while (sz(q)) {
      int v = q.front(); q.pop();
      FOR(c,26) {
        int u = d[v].to[c]; if (!u) continue;
        d[u].link = d[v].link == -1 ? 0 : d[d[v].link].to[c];
        q.push(u);
      }
      if (v) FOR(c,26) if (!d[v].to[c])
        d[v].to[c] = d[d[v].link].to[c];
    }
  }
};
```

PalTree.h

Description: palindromic tree, computes number of occurrences of each palindrome within string
Time: $\mathcal{O}(N\sum)$

f004a8, 25 lines

```
template<int SZ> struct PalTree {
  static const int sigma = 26;
  int s[SZ], len[SZ], link[SZ], to[SZ][sigma], oc[SZ];
  int n, last, sz;
  PalTree() { s[n++] = -1; link[0] = 1; len[1] = -1; sz = 2; }

  int getLink(int v) {
    while (s[n-len[v]-2] != s[n-1]) v = link[v];
    return v;
  }
  void addChar(int c) {
    s[n++] = c;
    last = getLink(last);
    if (!to[last][c]) {
      len[sz] = len[last]+2;
      link[sz] = to[getLink(link[last])][c];
      to[last][c] = sz++;
    }
    last = to[last][c]; oc[last] ++;
  }
  void numOc() {
    vpi v; FOR(i,2,sz) v.pb({len[i],i});
    sort(rall(v)); trav(a,v) oc[link[a.s]] += oc[a.s];
  }
};
```

SuffixArray.h

Description: sa contains indices of suffixes in sorted order
Time: $\mathcal{O}(N \log N)$

b8d5cf, 50 lines

```
struct SuffixArray {
  string S; int N;
  void init(const string& _S) {
    S = _S; N = sz(S);
    genSa(); genLcp();
    // R.init(lcp);
  }
```

```
  vi sa, isa;
  void genSa() {
    sa.rsz(N); vi classes(N);
    FOR(i,N) sa[i] = N-1-i, classes[i] = S[i];
    stable_sort(all(sa), [this](int i, int j) { return S[i] < S
       ↪[j]; });
    for (int len = 1; len < N; len *= 2) {
      vi c(classes);
      FOR(i,N) { // compare first len characters of each suffix
        bool same = i && sa[i-1] + len < N
                && c[sa[i]] == c[sa[i-1]]
                && c[sa[i]+len/2] == c[sa[i-1]+len/2];
        classes[sa[i]] = same ? classes[sa[i-1]] : i;
      }
      vi nex(N), s(sa); iota(all(nex),0); // suffixes with <=
         ↪len chars will not change pos
      FOR(i,N) {
        int s1 = s[i]-len;
        if (s1 >= 0) sa[nex[classes[s1]]++] = s1; // order
           ↪pairs w/ same first len chars by next len chars
      }
    }
    isa.rsz(N); FOR(i,N) isa[sa[i]] = i;
  }

  vi lcp;
  void genLcp() { // KACTL
    lcp = vi(N-1);
    int h = 0;
    FOR(i,N) if (isa[i]) {
      int pre = sa[isa[i]-1];
      while (max(i,pre)+h < N && S[i+h] == S[pre+h]) h++;
      lcp[isa[i]-1] = h; // lcp of suffixes starting at pre and
         ↪ i
      if (h) h--; // if we cut off first chars of two strings
         ↪with lcp h, then remaining portions still have lcp h
         ↪-1
    }
  }
  /*RMQ<int> R;
  int getLCP(int a, int b) {
    if (max(a,b) >= N) return 0;
    if (a == b) return N-a;
    int t0 = isa[a], t1 = isa[b];
    if (t0 > t1) swap(t0,t1);
    return R.query(t0,t1-1);
  }*/
};
```

ReverseBW.h

Description: The Burrows-Wheeler Transform appends # to a string, sorts the rotations of the string in increasing order, and constructs a new string that contains the last character of each rotation. This function reverses the transform.

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

417cee, 8 lines

```
string reverseBW(string s) {
  vi nex(sz(s));
  vector<pair<char,int>> v; FOR(i,sz(s)) v.pb({s[i],i});
  sort(all(v)); FOR(i,sz(v)) nex[i] = v[i].s;
  int cur = nex[0]; string ret;
  for (; cur;cur = nex[cur]) ret += v[cur].f;
  return ret;
}
```

SuffixAutomaton.h

Description: constructs minimal DFA that recognizes all suffixes of a string

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

1cb9d7, 73 lines

```
struct SuffixAutomaton {
  struct state {
    int len = 0, firstPos = -1, link = -1;
    bool isClone = 0;
    map<char, int> next;
    vi invLink;
  };

  vector<state> st;
  int last = 0;
  void extend(char c) {
    int cur = sz(st); st.eb();
    st[cur].len = st[last].len+1, st[cur].firstPos = st[cur].
       ↪len-1;
    int p = last;
    while (p != -1 && !st[p].next.count(c)) {
      st[p].next[c] = cur;
      p = st[p].link;
    }
    if (p == -1) {
      st[cur].link = 0;
    } else {
      int q = st[p].next[c];
      if (st[p].len+1 == st[q].len) {
        st[cur].link = q;
      } else {
        int clone = sz(st); st.pb(st[q]);
        st[clone].len = st[p].len+1, st[clone].isClone = 1;
        while (p != -1 && st[p].next[c] == q) {
          st[p].next[c] = clone;
          p = st[p].link;
        }
        st[q].link = st[cur].link = clone;
      }
    }
    last = cur;
  }
  void init(string s) {
    st.eb(); trav(x,s) extend(x);
    FOR(v,1,sz(st)) st[st[v].link].invLink.pb(v);
  }

  // APPLICATIONS
  void getAllOccur(vi& oc, int v) {
    if (!st[v].isClone) oc.pb(st[v].firstPos);
    trav(u,st[v].invLink) getAllOccur(oc,u);
  }
  vi allOccur(string s) {
    int cur = 0;
    trav(x,s) {
      if (!st[cur].next.count(x)) return {};
      cur = st[cur].next[x];
    }
    vi oc; getAllOccur(oc,cur); trav(t,oc) t += 1-sz(s);
    sort(all(oc)); return oc;
  }

  vl distinct;
  ll getDistinct(int x) {
    if (distinct[x]) return distinct[x];
    distinct[x] = 1;
    trav(y,st[x].next) distinct[x] += getDistinct(y.s);
    return distinct[x];
  }
  ll numDistinct() { // # of distinct substrings including
     ↪empty
    distinct.rsz(sz(st));
    return getDistinct(0);
  }
  ll numDistinct2() { // another way to do above
    ll ans = 1;
    FOR(i,1,sz(st)) ans += st[i].len-st[st[i].link].len;
    return ans;
  }
};
```

SuffixTree.h

Description: Ukkonen's algorithm for suffix tree

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

678588, 61 lines

```
struct SuffixTree {
  string s; int node, pos;
  struct state {
    int fpos, len, link = -1;
    map<char,int> to;
    state(int fpos, int len) : fpos(fpos), len(len) {}
  };
  vector<state> st;
  int makeNode(int pos, int len) {
    st.pb(state(pos,len)); return sz(st)-1;
  }
  void goEdge() {
    while (pos > 1 && pos > st[st[node].to[s[sz(s)-pos]]].len)
       ↪{
      node = st[node].to[s[sz(s)-pos]];
      pos -= st[node].len;
    }
  }
  void extend(char c) {
    s += c; pos ++; int last = 0;
    while (pos) {
      goEdge();
      char edge = s[sz(s)-pos];
      int& v = st[node].to[edge];
      char t = s[st[v].fpos+pos-1];
      if (v == 0) {
        v = makeNode(sz(s)-pos,MOD);
        st[last].link = node; last = 0;
      } else if (t == c) {
        st[last].link = node;
        return;
      } else {
        int u = makeNode(st[v].fpos,pos-1);
        st[u].to[c] = makeNode(sz(s)-1,MOD); st[u].to[t] = v;
        st[v].fpos += pos-1; st[v].len -= pos-1;
        v = u; st[last].link = u; last = u;
      }
      if (node == 0) pos --;
      else node = st[node].link;
    }
  }
  void init(string _s) {
    makeNode(0,MOD); node = pos = 0;
    trav(c,_s) extend(c);
  }
  bool isSubstr(string _x) {
    string x; int node = 0, pos = 0;
    trav(c,_x) {
      x += c; pos ++;
      while (pos > 1 && pos > st[st[node].to[x[sz(x)-pos]]].len
         ↪) {
        node = st[node].to[x[sz(x)-pos]];
        pos -= st[node].len;
      }
      char edge = x[sz(x)-pos];
      if (pos == 1 && !st[node].to.count(edge)) return 0;
      int& v = st[node].to[edge];
```

```
      char t = s[st[v].fpos+pos-1];
      if (c != t) return 0;
    }
    return 1;
  }
};
```

9.3 Misc

TandemRepeats.h

Description: Main-Lorentz algorithm, finds all (x, y) such that s.substr(x,y-1) == s.substr(x+y,y-1)

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

"Z.h" 163c75, 54 lines

```
struct StringRepeat {
  string S;
  vector<array<int,3>> al;
  // (t[0],t[1],t[2]) -> there is a repeating substring
     ↪starting at x
  // with length t[0]/2 for all t[1] <= x <= t[2]

  vector<array<int,3>> solveLeft(string s, int m) {
    vector<array<int,3>> v;

    vi v2 = getPrefix(string(s.begin()+m+1,s.end()),string(s.
       ↪begin(),s.begin()+m+1));
    string V = string(s.begin(),s.begin()+m+2); reverse(all(V))
       ↪; vi v1 = z(V); reverse(all(v1));

    FOR(i,m+1) if (v1[i]+v2[i] >= m+2-i) {
      int lo = max(1,m+2-i-v2[i]), hi = min(v1[i],m+1-i);
      lo = i-lo+1, hi = i-hi+1; swap(lo,hi);
      v.pb({2*(m+1-i),lo,hi});
    }

    return v;
  }

  void divi(int l, int r) {
    if (l == r) return;
    int m = (l+r)/2; divi(l,m); divi(m+1,r);

    string t = string(S.begin()+l,S.begin()+r+1);
    m = (sz(t)-1)/2;
    auto a = solveLeft(t,m);
    reverse(all(t));
    auto b = solveLeft(t,sz(t)-2-m);

    trav(x,a) al.pb({x[0],x[1]+l,x[2]+l});
    trav(x,b) {
      int ad = r-x[0]+1;
      al.pb({x[0],ad-x[2],ad-x[1]});
    }
  }

  void init(string _S) {
    S = _S; divi(0,sz(S)-1);
  }

  vi genLen() { // min length of repeating substring starting
     ↪at each index
    priority_queue<pi,vpi,greater<pi>> m; m.push({MOD,MOD});
    vpi ins[sz(S)]; trav(a,al) ins[a[1]].pb({a[0],a[2]});
    vi len(sz(S));
    FOR(i,sz(S)) {
      trav(j,ins[i]) m.push(j);
      while (m.top().s < i) m.pop();
      len[i] = m.top().f;
    }
    return len;
  }
};
```