BRAC University

BRACU_Crows

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Contest (1)

instructions.txt (19 lines)

```
1. vi .bashrc: export PATH="$PATH:$HOME/cp"
2. mkdir -p cp/bits/ && cd cp && vi cf (Type)
3. chmod +x cf; restart terminal
4. Type stdc++.h, template.cpp, hash.sh
-------- Kate --------
1. Go to Settings->Configure Kate.
 1. Editing->Default input mode->Vim
 2. Vi input mode->Insert mode->jk = <esc>
 3. Appearance->Turn off dynamic w.w.
 4. Color Themes->Gruvbox
 5. Terminal->Turn off hide console
    (View->Tool Views->Show sidebars is on)
2. Hotkey: Focus Terminal Panel=F4->"Reassign"
-------- Windows --------
1. Using cmd: echo %PATH%. Using Powershell:
     echo $env:PATH
2. Add path using cmd: set PATH=%PATH%;C:\
     Program Files\CodeBlocks\MinGW\bin
   It should be the directory where g++ is.
3. If we're using g++ of CodeBlocks, fsanitize
     won't be available :(
4. Write cf.bat at some directory. Ensure that
     directory is in PATH.
```

cf.sh (3 lines)

```
#!/bin/bash
code=$1
g++ ${code}.cpp -o $code -std=c++20 -g -DDeBuG
      -Wall -Wshadow -fsanitize=address,
     undefined && ./$code
```

hash.sh (1 lines)

```
cpp -dD -P -fpreprocessed | tr -d '[:space:]'|
      md5sum |cut -c-6
```

stdc++.h (90f4a7, 29 lines)

```
#include <bits/stdc++.h>
using namespace std;
#define TT template <typename T

TT,typename=void> struct cerrok:false_type {};
TT> struct cerrok <T, void_t<decltype(cerr <<
     declval<T>() )>> : true_type {};

TT> constexpr void p1 (const T &x);
TT, typename V> void p1(const pair<T, V> &x) {
  cerr << "{"; p1(x.first); cerr << ", ";
  p1(x.second); cerr << "}";
}
TT> constexpr void p1 (const T &x) {
  if constexpr (cerrok<T>::value) cerr << x;
  else { int f = 0; cerr << '{';
    for (auto &i: x)
      cerr << (f++ ? ", " : ""), p1(i);
    cerr << "}";
} }
void p2() { cerr << "]\n"; }
TT, typename... V> void p2(T t, V... v) {
  p1(t);
  if (sizeof...(v)) cerr << ", ";
  p2(v...);
}

#ifdef DeBuG
#define dbg(x...) {cerr << "\t\e[93m"<<
     __func__<<":"<<__LINE__<<" [" << #x << "]
     = ["; p2(x); cerr << "\e[0m";}
#endif
```

template.cpp (640c64, 19 lines)

```
// BRACU_Crows
#include "bits/stdc++.h"
using namespace std;

#ifndef DeBuG
  #define dbg(...)
#endif

#define sz(x) (int)(x).size()
#define all(x) begin(x), end(x)
#define rep(i,a,b) for(int i=a;i<(b);++i)
using ll = long long; using pii=pair<int,int>;
using pll = pair<ll,ll>; using vi=vector<int>;
template<class T> using V = vector<T>;

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

stress.sh (14 lines)

```
#!/bin/bash
cf gen > in             # input generator
cf bf < in > exp        # bruteforce
cf code < in > out      # buggy code name

for ((i = 1; ; ++i)) do
   echo $i
   ./gen > in
   ./bf < in > exp
   ./code < in > out    # buggy code name
   diff -w exp out || break
done
# Shows expected first, then user
notify-send "bug found!!!!"
```

cf.bat (5 lines)

```
@echo off
setlocal
set prog=%1
g++ %prog%.cpp -o %prog% -DDeBuG -std=c++17 -g
      -Wall -Wshadow && .\%prog%
endlocal
```

Mathematics (2)

2.1 Equations

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

Cramer: Given an equation $Ax = b$, the solution to a variable x_i is given by

$$x_i = \frac{\det A_i'}{\det A} \quad \text{[where } A_i' \text{ is } A \text{ with the } i\text{'th column replaced by } b.\text{]}$$

Vieta: Let $P(x) = a_n x^n + ... + a_0$, be a polynomial with complex coefficients and degree n, having complex roots $r_n, ..., r_1$. Then for any integer $0 \le k \le n$,

$$\sum_{1 \le i_1 < i_2 < ... < i_k \le n} r_{i_1} r_{i_2} ... r_{i_k} = (-1)^k \frac{a_{n-k}}{a_n}$$

Rational Root Theorem: If $\frac{p}{q}$ is a reduced rational root of a polynomial with **integer coeffs**, then $p \mid a_0$ and $q \mid a_n$

2.2 Ceils and Floors

For $x, y \in \mathbb{R}$, $m, n \in \mathbb{Z}$:

- $\lfloor x \rfloor \le x < \lfloor x \rfloor + 1$; $\lceil x \rceil - 1 < x \le \lceil x \rceil$
- $-\lfloor x \rfloor = \lceil -x \rceil$; $-\lceil x \rceil = \lfloor -x \rfloor$
- $\lfloor x + n \rfloor = \lfloor x \rfloor + n$, $\lceil x + n \rceil = \lceil x \rceil + n$
- $\lfloor x \rfloor = m \Leftrightarrow x - 1 < m \le x < m + 1$
- $\lceil x \rceil = n \Leftrightarrow n - 1 < x \le n < x + 1$
- If $n > 0$, $\lfloor \frac{\lfloor x \rfloor + m}{n} \rfloor = \lfloor \frac{x+m}{n} \rfloor$
- If $n > 0$, $\lceil \frac{\lceil x \rceil + m}{n} \rceil = \lceil \frac{x+m}{n} \rceil$
- If $n > 0$, $\lfloor \frac{\lfloor \frac{x}{m} \rfloor}{n} \rfloor = \lfloor \frac{x}{mn} \rfloor$
- If $n > 0$, $\lceil \frac{\lceil \frac{x}{m} \rceil}{n} \rceil = \lceil \frac{x}{mn} \rceil$
- For $m, n > 0$, $\sum_{k=1}^{n-1} \lfloor \frac{km}{n} \rfloor = \frac{(m-1)(n-1)+\gcd(m,n)-1}{2}$

2.3 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. $a_n = (d_1 n + d_2) r^n$.

2.4 Trigonometry

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

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

V, W are sides opposite to angles v, w.
$a \cos x + b \sin x = r \cos(x - \phi)$
$a \sin x + b \cos x = r \sin(x + \phi)$
where $r = \sqrt{a^2 + b^2}, \phi = \text{atan2}(b, a)$.

2.5 Geometry

2.5.1 Triangles

Side lengths: a, b, c

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

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

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

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

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

Length of bisector (divides angles in two):
$s_a = \sqrt{bc\left[1 - (a/(b+c))^2\right]}$

Law of sines, cosines & tangents:
$\frac{\sin\alpha}{a} = \frac{\sin\beta}{b} = \frac{\sin\gamma}{c} = \frac{1}{2R}$.....(1)
$a^2 = b^2 + c^2 - 2bc\cos\alpha$.....(2)
$\frac{a+b}{a-b} = \frac{\tan((\alpha+\beta)/2)}{\tan((\alpha-\beta)/2)}$.....(3)

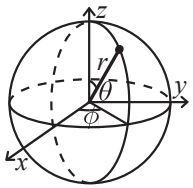
2.5.2 Quadrilaterals

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

2.5.3 Spherical coordinates



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

2.6 Derivatives/Integrals

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

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

2.7 Sums

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

$$1^4 + 2^4 + 3^4 + \cdots + n^4 = S_2 \times \frac{3n^2+3n-1}{5} = S_4$$

$$b\sum_{k=0}^{n-1}(a+kd)r^k = \frac{ab-(a+nd)br^n}{1-r} + \frac{dbr(1-r^n)}{(1-r)^2}$$

To compute $1^k + ... + n^k$ in $\mathcal{O}(k \lg k + k \lg MOD)$ compute first $t = k+2$ sums $y_1, ..., y_t$, then interpolate. Let $P = \prod_{i=1}^{t}(n-i)$. Then answer for n is

$$\sum_{i=1}^{t}\frac{P}{n-i}\cdot\frac{(-1)^{t-i}y_i}{(i-1)!(t-i)!}$$

Also $S_k = \frac{1}{k+1}\sum_{j=0}^{k}(-1)^j\binom{k+1}{j}B_j n^{k+1-j}$ where B_i are Bernoulli numbers.

2.8 Series

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

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

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

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

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

$$(1-x)^{-r} = \sum_{i=0}^{\infty}\binom{r+i-1}{i}x^i, (r \in \mathbb{R})$$

2.9 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,

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

2.9.1 Discrete distributions

Binomial distribution

The number of successes in n independent yes/no experiments, each which yields success with probability p is $\operatorname{Bin}(n, p)$, $n = 1, 2, \ldots$, $0 \leq p \leq 1$.

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

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

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

First success distribution

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

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

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

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

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

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

2.9.2 Continuous distributions

Uniform distribution

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

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

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

Exponential distribution

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

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

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

Normal distribution

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

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

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

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

2.10 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 $t_i = 1 + \sum_{k\in\mathbf{G}} p_{ki}t_k$.

2.11 Trivia

Pythagorean triples: The Pythagorean triples are uniquely generated by $a = k \cdot (m^2 - n^2)$, $b = k \cdot (2mn)$, $c = k \cdot (m^2 + n^2)$ with $m > n > 0$, $k > 0$, $\gcd(m, n) = 1$, both m, n not odd.
Primes: $p = 962592769$ is such that $2^{21} \mid p - 1$, which may be useful. For hashing use 970592641 (31-bit number), 31443539979727 (45-bit), 3006703054056749 (52-bit). There are 78498 primes less than 1 000 000.
Primitive roots modulo n exists iff $n = 1, 2, 4$ or, $n = p^k, 2p^k$ where p is an odd prime. Furthermore, the number of roots are $\phi(\phi(n))$.
To Find Generator g of M, factor $M-1$ and get the distinct primes p_i. If $g^{(M-1)/p_i} \neq 1(MODM)$ for each p_i then g is a valid root. Try all g until a hit is found (usually found very quick).
Esitmates: $\sum_{d|n} d = O(n \log\log n)$.
Prime count: 5133 upto 5e4. 9592 upto 1e5. 17984 upto 2e5. 78498 upto 1e6. 5761455 upto 1e8.
max NOD $\leq n$: 100 for $n = 5e4$. 500 for $n = 1e7$. 2000 for $n = 1e10$. 200 000 for $n = 1e19$.
max Unique Prime Factors: 6 upto 5e5. 7 upto 9e6. 8 upto 2e8. 9 upto 6e9. 11 upto 7e12. 15 upto 3e19.
Quadratic Residue: $(\frac{a}{p})$ is 0 if $p|a$, 1 if a is a quadratic residue, -1 otherwise. Euler: $(\frac{a}{p}) = a^{(p-1)/2}(\mod p)$ (prime). Jacobi: if $n = p_1^{e_1}\cdots p_k^{e_k}$ then $(\frac{a}{n}) = \prod(\frac{a}{p_i})^{e_i}$.
Chicken McNugget. If a, b coprime, there are $\frac{1}{2}(a-1)(b-1)$ numbers not of form $ax + by$ $(x, y \geq 0)$, the largest being $ab - a - b$.

Data structures (3)

OrderStatisticTree.h

Description: A set (not multiset!) with support for finding the n'th element, and finding the index of an element. To get a map, change `null_type`.
Time: $\mathcal{O}(\log N)$ 782797, 14 lines

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

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

void example() {
  Tree<int> t, t2; t.insert(8);
  auto it = t.insert(10).first;
  assert(it == t.lower_bound(9));
  assert(t.order_of_key(10) == 1);
  assert(t.order_of_key(11) == 2);
  assert(*t.find_by_order(0) == 8);
  t.join(t2); // assuming T< T2 or T> T2,
      merge t2 into t
}
```

HashMap.h

Description: Hash map with mostly the same API as unordered_map, but ~3x faster. Uses 1.5x memory. Initial capacity must be a power of 2 (if provided). d77092, 7 lines

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

SegmentTree.h

Time: $\mathcal{O}(\log N)$ 9f8f73, 61 lines

```
template<class S> struct segtree {
  int n; V<S> t;
  void init(int _) { n = _; t.assign(n+n-1, S
      ()); }
  void init(const V<S>& v) {
    n = sz(v); t.assign(n + n - 1, S());
    build(0,0,n-1,v);
  } template <typename... T>
  void upd(int l, int r, const T&... v) {
    assert(0 <= l && l <= r && r < n);
    upd(0, 0, n-1, l, r, v...);
  }
  S get(int l, int r) {
    assert(0 <= l && l <= r && r < n);
    return get(0, 0, n-1, l, r);
  }
private:
  inline void push(int u, int b, int e) {
    if (t[u].lazy == 0) return;
    int mid = (b+e)>>1, rc = u+((mid-b+1)<<1);
    t[u+1].upd(b, mid, t[u].lazy);
    t[rc].upd(mid+1, e, t[u].lazy);
    t[u].lazy = 0;
  }
  void build(int u,int b,int e,const V<S>&v) {
    if (b == e) return void(t[u] = v[b]);
    int mid = (b+e)>>1, rc = u+((mid-b+1)<<1);
    build(u+1, b,mid,v); build(rc, mid+1,e,v);
    t[u] = t[u+1] + t[rc];
  } template<typename... T>
  void upd(int u, int b, int e, int l, int r,
      const T&... v) {
    if (l <= b && e <= r) return t[u].upd(b, e
        , v...);
    push(u, b, e);
    int mid = (b+e)>>1, rc = u+((mid-b+1)<<1);
    if (l<=mid) upd(u+1, b, mid, l, r, v...);
    if (mid<r) upd(rc, mid+1, e, l, r, v...);
    t[u] = t[u+1] + t[rc];
  }
  S get(int u, int b, int e, int l, int r) {
    if (l <= b && e <= r) return t[u];
    push(u, b, e);
    S res; int mid = (b+e)>>1, rc = u+((mid-b
        +1)<<1);
    if (r<=mid) res = get(u+1, b, mid, l, r);
    else if (mid<l) res = get(rc,mid+1,e,l,r);
    else res = get(u+1, b, mid, l, r) + get(rc
        , mid+1, e, l, r);
    t[u] = t[u+1] + t[rc]; return res;
  }
}; // Hash upto here = 773c09
/* (1) Declaration:
Create a node class. Now, segtree<node> T;
T.init(10) creates everything as node()
Consider using V<node> leaves to build
(2) upd(l, r, ...v): update range [l, r]
order in ...v must be same as node.upd() fn */
struct node {
  ll sum = 0, lazy = 0;
  node () {} // write full constructor
  node operator+(const node &obj) {
    return {sum + obj.sum, 0};    }
  void upd(int b, int e, ll x) {
    sum += (e - b + 1) * x, lazy += x;
} };
```

UnionFindRollback.h

Description: Disjoint-set data structure with undo. If undo is not needed, skip st, time() and rollback().
Usage: `int t = uf.time(); ...; uf.rollback(t);`
Time: $\mathcal{O}(\log(N))$ de4ad0, 21 lines

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

LineContainer.h

Description: Container where you can add lines of the form kx+m, and query maximum values at points x. Useful for dynamic programming ("convex hull trick").
Time: $\mathcal{O}(\log N)$ 8ec1c7, 30 lines

```
struct Line {
  mutable ll k, m, p;
  bool operator<(const Line& o) const { return
      k < o.k; }
  bool operator<(ll x) const { return p < x; }
};

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

Lichao.h

Description: Add line segment, query minimum y at some x. Provide list of all query x points to constructor (offline solution). Use `add_segment(line, l, r)` to add a line segment $y = ax + b$ defined by $x \in [l, r)$. Use `query(x)` to get min at x.
Time: Both operations are $\mathcal{O}(\log \text{maxn})$. 566134, 43 lines

```
struct LiChaoTree {
  using Line = pair <ll, ll>;
  const ll linf = numeric_limits<ll>::max();
  int n; vector<ll> xl; vector<Line> dat;
  LiChaoTree(const vector<ll>& _xl):xl(_xl){
    n = 1; while(n < xl.size())n <<= 1;
    xl.resize(n,xl.back());
    dat = vector<Line>(2*n-1, Line(0,linf));
  }
  ll eval(Line f,ll x){return f.first * x + f.
      second;}
  void _add_line(Line f,int k,int l,int r){
    while (l != r) {
      int m = (l + r) / 2;
      ll lx = xl[l],mx = xl[m],rx = xl[r - 1];
      Line &g = dat[k];
      if(eval(f,lx) < eval(g,lx) && eval(f,rx)
          < eval(g,rx)) {
        g = f; return;
      }
      if(eval(f,lx) >= eval(g,lx) && eval(f,rx
          ) >= eval(g,rx))
        return;
      if(eval(f,mx) < eval(g,mx))swap(f,g);
      if(eval(f,lx) < eval(g,lx)) k = k * 2 +
          1, r = m;
      else k = k * 2 + 2, l = m;
    }
  }
  void add_line(Line f){_add_line(f,0,0,n);}
  void add_segment(Line f,ll lx,ll rx){
    int l = lower_bound(xl.begin(), xl.end(),
        lx) - xl.begin();
    int r = lower_bound(xl.begin(), xl.end(),
        rx) - xl.begin();
    int a0 = l, b0 = r, sz = 1; l += n;r += n;
    while(l < r){
      if(r & 1) r--, b0 -= sz, _add_line(f,r -
          1,b0,b0 + sz);
      if(l & 1) _add_line(f,l - 1,a0,a0 + sz),
          l++, a0 += sz;
      l >>= 1, r >>= 1, sz <<= 1;
    }
  }
  ll query(ll x) {
    int i = lower_bound(xl.begin(), xl.end(),x
        ) - xl.begin();
    i += n - 1; ll res = eval(dat[i],x);
    while (i) i = (i - 1) / 2, res = min(res,
        eval(dat[i], x));
    return res;
  }
};
```

Treap.h

Description: A short self-balancing tree. It acts as a sequential container with log-time splits/joins, and is easy to augment with additional data.
Time: $\mathcal{O}(\log N)$ 1754b4, 53 lines

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

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

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

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

```
    n->r = L;
    n->recalc();
    return {n, R};
  }
}

Node* merge(Node* l, Node* r) {
  if (!l) return r;
  if (!r) return l;
  if (l->y > r->y) {
    l->r = merge(l->r, r);
    return l->recalc(), l;
  } else {
    r->l = merge(l, r->l);
    return r->recalc(), r;
  }
}

Node* ins(Node* t, Node* n, int pos) {
  auto [l,r] = split(t, pos);
  return merge(merge(l, n), r);
}

// Example application: move the range [l, r)
    to index k
void move(Node*& t, int l, int r, int k) {
  Node *a, *b, *c;
  tie(a,b) = split(t, l); tie(b,c) = split(b,
      r - l);
  if (k <= l) t = merge(ins(a, b, k), c);
  else t = merge(a, ins(c, b, k - r));
}
```

FenwickTree.h

Description: update(i,x): a[i] += x; query(i): sum in [0, i); lower_bound(sum): min pos st sum of [0, pos] >= sum, returns n if all < sum, or -1 if empty sum.
Time: Both operations are $\mathcal{O}(\log N)$.

f74d01, 16 lines

```
struct FT {
  int n; V<ll> s;
  FT(int _n) : n(_n), s(_n) {}
  void update(int i, ll x) {
    for (; i < n; i |= i + 1) s[i] += x; }
  ll query(int i, ll r = 0) {
    for (; i > 0; i &= i - 1) r += s[i-1];
        return r; }
  int lower_bound(ll sum) {
    if (sum <= 0) return -1; int pos = 0;
    for (int pw = 1 << __lg(n); pw; pw >>= 1){
      if (pos+pw <= n && s[pos + pw-1] < sum)
        pos += pw, sum -= s[pos-1];
    }
    return pos;
  }
}; // Hash = d05c4f without lower_bound
```

FenwickTreeRange.h

Description: Range add Range sum with FT.
Time: Both operations are $\mathcal{O}(\log N)$.

8fc549, 11 lines

```
FT f1(n), f2(n);
// a[l...r] += v; 0<= l <= r < n
auto upd = [&](int l, int r, ll v) {
  f1.update(l, v), f1.update(r + 1, -v);
  f2.update(l, v*(l-1)), f2.update(r+1, -v*r);
}; // a[l] + ... + a[r]; 0<= l <= r < n
auto sum = [&](int l, int r) { ++r;
  ll sub = f1.query(l) * (l-1) - f2.query(l);
  ll add = f1.query(r) * (r-1) - f2.query(r);
  return add - sub;
};
```

FenwickTree2d.h

Description: Computes sums a[i,j] for all i<I, j<J, and increases single elements a[i,j]. Requires that the elements to be updated are known in advance (call fakeUpdate() before init()).
Time: $\mathcal{O}\left(\log^2 N\right)$. (Use persistent segment trees for $\mathcal{O}(\log N)$.)

"FenwickTree.h" d53ef2, 20 lines

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

RMQ.h

Description: Range Minimum Queries on an array. Returns min(V[a], V[a + 1], ... V[b - 1]) in constant time.
Usage: RMQ rmq(values); rmq.query(inclusive, exclusive);
Time: $\mathcal{O}(|V| \log |V| + Q)$

7d2211, 15 lines

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

MoTree.h

Description: Build Euler tour of $2N$ size - write node at first enter and last exit. Now, Path(u, v) with $in[u] < in[v]$ is a segment. If lca$(u, v) = u$ then it is $[in[u], in[v]]$. Otherwise it is $[out[u], in[v]]$ + LCA node. Nodes that appear exactly once in each segment are relevant, ignore others, handle LCA separately.
Time: $\mathcal{O}\left(Q\sqrt{N}\right)$

MoUpdate.h

Description: Set block size $B = (2n^2)^{1/3}$. Sort queries by $(\lfloor \frac{L}{B} \rfloor, \lfloor \frac{R}{B} \rfloor, t)$, where t = number of updates before this query. Then process queries in sorted order, modify L, R and then apply/undo the updates to answer.
Time: $\mathcal{O}\left(Bq + qn^2/B^2\right)$ or $\mathcal{O}\left(qn^{2/3}\right)$ with that B.

Numerical (4)

4.1 Polynomials and recurrences

BerlekampMassey.h

Description: Recovers any n-order linear recurrence relation from the first $2n$ terms of the recurrence. Useful for guessing linear recurrences after brute-forcing the first terms. Should work on any field, but numerical stability for floats is not guaranteed. Output will have size $\leq n$.
Usage: berlekampMassey({0, 1, 1, 3, 5, 11}) // {1, 2} --> c[n] = c[n-1] + 2c[n-2]
Time: $\mathcal{O}\left(N^2\right)$

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

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

  ll b = 1;
  rep(i,0,n) { ++m;
    ll d = s[i] % mod;
    rep(j,1,L+1) d = (d + C[j] * s[i - j]) %
        mod;
    if (!d) continue;
    T = C; ll coef = d * modpow(b, mod-2) %
        mod;
    rep(j,m,n) C[j] = (C[j] - coef * B[j - m])
        % mod;
    if (2 * L > i) continue;
    L = i + 1 - L; B = T; b = d; m = 0;
  }

  C.resize(L + 1); C.erase(C.begin());
  for (ll& x : C) x = (mod - x) % mod;
  return C;
}
```

LinearRecurrence.h

Description: Generates the k'th term of an n-order linear recurrence $S[i] = \sum_j S[i-j-1]tr[j]$, given $S[0 \ldots \geq n-1]$ and $tr[0 \ldots n-1]$. Faster than matrix multiplication. Useful together with Berlekamp–Massey.
Usage: linearRec({0, 1}, {1, 1}, k) // k'th Fibonacci number
Time: $\mathcal{O}\left(n^2 \log k\right)$

f4e444, 26 lines

```
typedef vector<ll> Poly;
ll linearRec(Poly S, Poly tr, ll k) {
  int n = sz(tr);

  auto combine = [&](Poly a, Poly b) {
    Poly res(n * 2 + 1);
    rep(i,0,n+1) rep(j,0,n+1)
      res[i + j] = (res[i + j] + a[i] * b[j])
          % mod;
    for (int i = 2 * n; i > n; --i) rep(j,0,n)
      res[i - 1 - j] = (res[i - 1 - j] + res[i
          ] * tr[j]) % mod;
    res.resize(n + 1);
    return res;
  };

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

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

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

Polynomial.h

c9b7b0, 17 lines

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

PolyRoots.h

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

"Polynomial.h" b00bfe, 23 lines

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

```
      ret.push_back((l + h) / 2);
    }
  }
  return ret;
}
```

PolyInterpolate.h

Description: Given n points (x[i], y[i]), computes an n-1-degree polynomial p that passes through them: $p(x) = a[0] * x^0 + ... + a[n-1] * x^{n-1}$. For numerical precision, pick $x[k] = c * \cos(k/(n-1) * \pi), k = 0 \dots n-1$. For fast interpolation in $O(n \log^2 n)$ use Lagrange. $P(x) = \sum_{i=1}^{n} y_i \prod_{j \neq i} \frac{x - x_j}{x_i - x_j}$. To compute values $\prod_{j \neq i}(x_i - x_j)$ fast, compute $A(x) = \prod_{i=1}^{n}(x - x_i)$ with divide and conquer. The required values are $A'(x_i)$, (values at derivative), compute fast with multipoint evaluation.
Time: $\mathcal{O}(n^2)$

08bf48, 13 lines

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

4.2 Fourier transforms

FastFourierTransform.h

Description: fft(a) computes $\hat{f}(k) = \sum_x a[x] \exp(2\pi i \cdot kx/N)$ for all k. N must be a power of 2. Useful for convolution: `conv(a, b) = c`, where $c[x] = \sum a[i]b[x-i]$. For convolution of complex numbers or more than two vectors: FFT, multiply pointwise, divide by n, reverse(start+1, end), FFT back. Rounding is safe if $(\sum a_i^2 + \sum b_i^2) \log_2 N < 9 \cdot 10^{14}$ (in practice 10^{16}; higher for random inputs). Otherwise, use NTT/FFTMod.
Time: $\mathcal{O}(N \log N)$ with $N = |A|+|B|$ (~1s for $N = 2^{22}$)

00ced6, 35 lines

```
typedef complex<double> C;
typedef vector<double> vd;
void fft(vector<C>& a) {
  int n = sz(a), L = 31 - __builtin_clz(n);
  static vector<complex<long double>> R(2, 1);
  static vector<C> rt(2, 1);  // (^ 10% faster if double)
  for (static int k = 2; k < n; k *= 2) {
    R.resize(n); rt.resize(n);
    auto x = polar(1.0L, acos(-1.0L) / k);
    rep(i,k,2*k) rt[i] = R[i] = i&1 ? R[i/2] * x : R[i/2];
  }
  vi rev(n);
  rep(i,0,n) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
  rep(i,0,n) if (i < rev[i]) swap(a[i], a[rev[i]]);
  for (int k = 1; k < n; k *= 2)
    for (int i = 0; i < n; i += 2 * k) rep(j,0,k) {
      C z = rt[j+k] * a[i+j+k]; // (25% faster if hand-rolled)
      a[i + j + k] = a[i + j] - z;
      a[i + j] += z;
    }
}
vd conv(const vd& a, const vd& b) {
  if (a.empty() || b.empty()) return {};
  vd res(sz(a) + sz(b) - 1);
  int L = 32 - __builtin_clz(sz(res)), n = 1 << L;
  vector<C> in(n), out(n);
  copy(all(a), begin(in));
  rep(i,0,sz(b)) in[i].imag(b[i]);
  fft(in);
  for (C& x : in) x *= x;
  rep(i,0,n) out[i] = in[-i & (n - 1)] - conj(in[i]);
  fft(out);
  rep(i,0,sz(res)) res[i] = imag(out[i]) / (4 * n);
  return res;
}
```

FastFourierTransformMod.h

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

"FastFourierTransform.h" b82773, 22 lines

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

NumberTheoreticTransform.h

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

"../number-theory/ModPow.h" ced03d, 35 lines

```
const ll mod = (119 << 23) + 1, root = 62; // = 998244353
// For p < 2^30 there is also e.g. 5 << 25, 7 << 26, 479 << 21
// and 483 << 21 (same root). The last two are > 10^9.
typedef vector<ll> vl;
void ntt(vl &a) {
  int n = sz(a), L = 31 - __builtin_clz(n);
  static vl rt(2, 1);
  for (static int k = 2, s = 2; k < n; k *= 2, s++) {
    rt.resize(n);
    ll z[] = {1, modpow(root, mod >> s)};
    rep(i,k,2*k) rt[i] = rt[i / 2] * z[i & 1] % mod;
  }
  vi rev(n);
  rep(i,0,n) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
  rep(i,0,n) if (i < rev[i]) swap(a[i], a[rev[i]]);
  for (int k = 1; k < n; k *= 2)
    for (int i = 0; i < n; i += 2 * k) rep(j,0,k) {
      ll z = rt[j + k] * a[i + j + k] % mod, &ai = a[i + j];
      a[i + j + k] = ai - z + (z > ai ? mod : 0);
      ai += (ai + z >= mod ? z - mod : z);
    }
}
vl conv(const vl &a, const vl &b) {
  if (a.empty() || b.empty()) return {};
  int s = sz(a) + sz(b) - 1, B = 32 - __builtin_clz(s),
      n = 1 << B;
  int inv = modpow(n, mod - 2);
  vl L(a), R(b), out(n);
  L.resize(n), R.resize(n);
  ntt(L), ntt(R);
  rep(i,0,n)
    out[-i & (n - 1)] = (ll)L[i] * R[i] % mod * inv % mod;
  ntt(out);
  return {out.begin(), out.begin() + s};
}
```

FastSubsetTransform.h

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

464cf3, 16 lines

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

FastSubsetConvolution.h

Description: $ans[i] = \sum_{j \subseteq i} f_j g_{i \oplus j}$
Time: $\mathcal{O}(n^2 2^n)$ or, $\mathcal{O}(N \log^2 N)$

7571e4, 28 lines

```
int f[N], g[N], fh[LG][N], gh[LG][N], h[LG][N], ans[N];
void conv() {
for (int mask = 0; mask < 1 << n; ++mask) {
 fh[__builtin_popcount(mask)][mask]=f[mask];
 gh[__builtin_popcount(mask)][mask]=g[mask];
}
for (int i = 0; i <= n; ++i) {
 for (int j = 0; j < n; ++j)
  for (int mask = 0; mask < 1 << n; ++mask)
   if (mask & 1 << j) {
    fh[i][mask] += fh[i][mask ^ 1 << j];
    gh[i][mask] += gh[i][mask ^ 1 << j];
   }
}
for (int mask = 0; mask < 1 << n; ++mask) {
 for (int i = 0; i <= n; ++i)
  for (int j = 0; j <= i; ++j)
   h[i][mask]+=fh[j][mask] * gh[i-j][mask];
}
for (int i = 0; i <= n; ++i) {
 for (int j = 0; j < n; ++j)
  for (int mask = 0; mask < 1 << n; ++mask)
   if (mask & 1 << j)
    h[i][mask] -= h[i][mask ^ 1 << j];
}
for (int mask = 0; mask < 1 << n; ++mask)
 ans[mask]=h[__builtin_popcount(mask)][mask];
}
```

GCDconvolution.h

Description: Computes $c_1, ..., c_n$, where $c_k = \sum_{\gcd(i,j)=k} a_i b_j$. Generate all primes upto n into pr first using sieve.
Time: $\mathcal{O}(N \log \log N)$

bc0c7a, 19 lines

```
void fw_mul_transform (V<ll> &a) {
  int n = sz(a) - 1;
  for (const auto p : pr) {
    if (p > n) break;
    for (int i = n/p; i>0; --i) a[i]+=a[i*p];
} } // A[i] = \sum_{j} a[i * j]
void bw_mul_transform (V<ll> &a) {
  int n = sz(a) - 1;
  for (const auto p : pr) {
    if (p > n) break;
    for (int i=1; i*p <= n; ++i) a[i]-=a[i*p];
```

```
} } // From A get a
V<ll>gcd_conv (const V<ll>&a, const V<ll>&b){
  assert(sz(a) == sz(b)); int n = sz(a);
  auto A = a, B = b;
  fw_mul_transform(A); fw_mul_transform(B);
  for (int i = 1; i < n; ++i) A[i] *= B[i];
  bw_mul_transform(A); return A;
}
```

LCMconvolution.h

Description: Computes $c_1, ..., c_n$, where $c_k = \sum_{lcm(i,j)=k} a_i b_j$. Generate all primes upto n into pr first using sieve.
Time: $\mathcal{O}(N \log \log N)$

1c5704, 19 lines

```
void fw_div_transform (V<ll> &a) {
  int n = sz(a) - 1;
  for (const auto p : pr) {
    if (p > n) break;
    for (int i=1; i*p <= n; ++i) a[i*p]+=a[i];
} } // A[i] = \sum_{d | i} a[d]
void bw_div_transform (V<ll> &a) {
  int n = sz(a) - 1;
  for (const auto p : pr) {
    if (p > n) break;
    for (int i=n/p; i>0; --i) a[i*p]-=a[i];
} } // From A get a
V<ll>lcm_conv (const V<ll>&a, const V<ll>&b){
  assert(sz(a) == sz(b)); int n = sz(a);
  auto A = a, B = b;
  fw_div_transform(A); fw_div_transform(B);
  for (int i = 1; i < n; ++i) A[i] *= B[i];
  bw_div_transform(A); return A;
}
```

4.3 Matrices

Matrix.h

Description: Basic operations on square matrices.
Usage:

```
Matrix<int, 3> A;
A.d = {{{{1,2,3}}, {{4,5,6}}, {{7,8,9}}}};
array<int, 3> vec = {1,2,3};
vec = (A^N) * vec;
```

6ab5db, 26 lines

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

Determinant.h

Description: Calculates determinant of a matrix. Destroys the matrix.
Time: $\mathcal{O}(N^3)$

bd5cec, 15 lines

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

IntDeterminant.h

Description: Calculates determinant using modular arithmetics. Modulos can also be removed to get a pure-integer version.
Time: $\mathcal{O}(N^3)$

3313dc, 18 lines

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

SolveLinear.h

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

44c9ab, 38 lines

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

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

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

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

SolveLinear2.h

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

"SolveLinear.h" 08e495, 7 lines

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

SolveLinearBinary.h

Description: Solves $Ax = b$ over $\mathbb{F}_2$. If there are multiple solutions, one is returned arbitrarily. Returns rank, or -1 if no solutions. Destroys A and b.
Time: $\mathcal{O}(n^2 m)$

fa2d7a, 34 lines

```
typedef bitset<1000> bs;

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

  x = bs();
  for (int i = rank; i--;) {
    if (!b[i]) continue;
    x[col[i]] = 1;
    rep(j,0,i) b[j] ^= A[j][i];
  }
  return rank; // (multiple solutions if rank
      < m)
}
```

XorBasis.h

Description: Maintain the basis of bit vectors.
Time: $\mathcal{O}(D^2/64)$ per insert

0daa2d, 19 lines

```
const int D = 1000; // use ll if < 64
struct Xor_Basis {
  V<int> who; V<bitset<D>> a;
  Xor_Basis () : who(D, -1) {}
  bool insert (bitset<D> x) {
    for (int i = 0; i < D; ++i)
      if (x[i] && who[i]!=-1) x^=a[who[i]];
    int pivot = -1;
    for (int i = 0; i < D; ++i)
      if (x[i]) { pivot = i; break; }
    if (pivot == -1) return false;
    // ^ null vector detected
    who[pivot] = sz(a);
    for (int i = 0; i < sz(a); ++i)
      if (a[i][pivot] == 1) a[i] ^= x;
    a.push_back(x);
    return true;
  }
};
```

MatrixInverse.h

Description: Invert matrix A. Returns rank; result is stored in A unless singular (rank < n). Can easily be extended to prime moduli; for prime powers, repeatedly set $A^{-1} = A^{-1}(2I - AA^{-1}) \pmod{p^k}$ where A^{-1} starts as the inverse of A mod p, and k is doubled in each step.
Time: $\mathcal{O}(n^3)$

ebfff6, 35 lines

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

  rep(i,0,n) {
    int r = i, c = i;
    rep(j,i,n) rep(k,i,n)
      if (fabs(A[j][k]) > fabs(A[r][c]))
        r = j, c = k;
    if (fabs(A[r][c]) < 1e-12) return i;
    A[i].swap(A[r]); tmp[i].swap(tmp[r]);
    rep(j,0,n)
      swap(A[j][i], A[j][c]), swap(tmp[j][i],
          tmp[j][c]);
    swap(col[i], col[c]);
    double v = A[i][i];
```

```
    rep(j,i+1,n) {
      double f = A[j][i] / v;
      A[j][i] = 0;
      rep(k,i+1,n) A[j][k] -= f*A[i][k];
      rep(k,0,n) tmp[j][k] -= f*tmp[i][k];
    }
    rep(j,i+1,n) A[i][j] /= v;
    rep(j,0,n) tmp[i][j] /= v;
    A[i][i] = 1;
  }

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

  rep(i,0,n) rep(j,0,n) A[col[i]][col[j]] =
      tmp[i][j];
  return n;
}
```

Tridiagonal.h

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

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

This is useful for solving problems on the type

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

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

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

Fails if the solution is not unique.
If $|d_i| > |p_i| + |q_{i-1}|$ for all i, or $|d_i| > |p_{i-1}| + |q_i|$, or the matrix is positive definite, the algorithm is numerically stable and neither `tr` nor the check for `diag[i] == 0` is needed.
Time: $\mathcal{O}(N)$

115ed4, 25 lines

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

4.4 Optimization

GoldenSectionSearch.h

Description: Finds the argument minimizing the function f in the interval $[a, b]$ assuming f is unimodal on the interval, i.e. has only one local minimum and no local maximum. The maximum error in the result is eps. Works equally well for maximization with a small change in the code. See TernarySearch.h in the Various chapter for a discrete version.
Usage: `double func(double x) { return 4+x+.3*x*x; }`
`double xmin = gss(-1000,1000,func);`
Time: $\mathcal{O}(\log((b-a)/\epsilon))$

31d45b, 14 lines

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

HillClimbing.h

Description: Poor man's optimization for unimodal functions.

8eeeaf, 14 lines

```
typedef array<double, 2> P;

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

Integrate.h

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

4756fc, 7 lines

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

IntegrateAdaptive.h

Description: Fast integration using an adaptive Simpson's rule.
Usage: `double sphereVolume = quad(-1, 1, [](double x) {`
`return quad(-1, 1, [&](double y) {`
`return quad(-1, 1, [&](double z) {`
`return x*x + y*y + z*z < 1; });});});`

9ddd79, 15 lines

```
typedef double d;
#define S(a,b) (f(a) + 4*f((a+b) / 2) + f(b))
    * (b-a) / 6

template <class F>
d rec(F& f, d a, d b, d eps, d S) {
  d c = (a + b) / 2;
  d S1 = S(a, c), S2 = S(c, b), T = S1 + S2;
  if (abs(T - S) <= 15 * eps || b - a < 1e-10)
    return T + (T - S) / 15;
  return rec(f, a, c, eps / 2, S1) + rec(f, c,
      b, eps / 2, S2);
}
template<class F>
d quad(d a, d b, F f, d eps = 1e-8) {
  return rec(f, a, b, eps, S(a, b));
}
```

Simplex.h

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

aa8530, 68 lines

```
typedef double T; // long double, Rational,
    double + mod<P>...
typedef vector<T> vd;
typedef vector<vd> vvd;

const T eps = 1e-8, inf = 1/.0;
#define MP make_pair
#define ltj(X) if(s == -1 || MP(X[j],N[j]) <
    MP(X[s],N[s])) s=j

struct LPSolver {
  int m, n;
  vi N, B;
  vvd D;

  LPSolver(const vvd& A, const vd& b, const vd
      & c) :
    m(sz(b)), n(sz(c)), N(n+1), B(m), D(m+2,
        vd(n+2)) {
      rep(i,0,m) rep(j,0,n) D[i][j] = A[i][j];
      rep(i,0,m) { B[i] = n+i; D[i][n] = -1; D
          [i][n+1] = b[i];}
      rep(j,0,n) { N[j] = j; D[m][j] = -c[j];
          }
      N[n] = -1; D[m+1][n] = 1;
    }

  void pivot(int r, int s) {
    T *a = D[r].data(), inv = 1 / a[s];
    rep(i,0,m+2) if (i != r && abs(D[i][s]) >
        eps) {
      T *b = D[i].data(), inv2 = b[s] * inv;
      rep(j,0,n+2) b[j] -= a[j] * inv2;
      b[s] = a[s] * inv2;
    }
    rep(j,0,n+2) if (j != s) D[r][j] *= inv;
    rep(i,0,m+2) if (i != r) D[i][s] *= -inv;
    D[r][s] = inv;
    swap(B[r], N[s]);
  }

  bool simplex(int phase) {
    int x = m + phase - 1;
    for (;;) {
      int s = -1;
      rep(j,0,n+1) if (N[j] != -phase) ltj(D[x
          ]);
      if (D[x][s] >= -eps) return true;
      int r = -1;
      rep(i,0,m) {
        if (D[i][s] <= eps) continue;
        if (r == -1 || MP(D[i][n+1] / D[i][s],
            B[i])
                < MP(D[r][n+1] / D[r][s],
                    B[r])) r = i;
      }
      if (r == -1) return false;
      pivot(r, s);
    }
  }

  T solve(vd &x) {
    int r = 0;
    rep(i,1,m) if (D[i][n+1] < D[r][n+1]) r =
        i;
    if (D[r][n+1] < -eps) {
      pivot(r, n);
      if (!simplex(2) || D[m+1][n+1] < -eps)
          return -inf;
      rep(i,0,m) if (B[i] == -1) {
        int s = 0;
        rep(j,1,n+1) ltj(D[i]);
        pivot(i, s);
      }
    }
    bool ok = simplex(1); x = vd(n);
    rep(i,0,m) if (B[i] < n) x[B[i]] = D[i][n
        +1];
    return ok ? D[m][n+1] : inf;
  }
};
```

Number theory (5)

5.1 Modular arithmetic

ModInverse.h

Description: Pre-computation of modular inverses. Assumes LIM $\leq$ mod and that mod is a prime. 6f684f, 3 lines

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

ModPow.h

b83e45, 8 lines

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

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

ModLog.h

Description: Returns the smallest $x > 0$ s.t. $a^x = b \pmod m$, or -1 if no such x exists. modLog(a,1,m) can be used to calculate the order of a.
Time: $\mathcal{O}\left(\sqrt{m}\right)$ c040b8, 11 lines

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

ModSum.h

Description: Sums of mod'ed arithmetic progressions. modsum(to, c, k, m) $= \sum_{i=0}^{\text{to}-1} (ki + c)\%m$. divsum is similar but for floored division.
Time: $\log(m)$, with a large constant. 5c5bc5, 16 lines

```
typedef unsigned long long ull;
ull sumsq(ull to) { return to / 2 * ((to-1) |
    1); }

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

ll modsum(ull to, ll c, ll k, ll m) {
  c = ((c % m) + m) % m;
  k = ((k % m) + m) % m;
  return to * c + k * sumsq(to) - m * divsum(
      to, c, k, m);
}
```

ModMulLL.h

Description: Calculate $a \cdot b \bmod c$ (or $a^b \bmod c$) for $0 \leq a, b \leq c \leq 7.2 \cdot 10^{18}$.
Time: $\mathcal{O}(1)$ for modmul, $\mathcal{O}(\log b)$ for modpow 1bbbd8f, 11 lines

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

ModSqrt.h

Description: Tonelli-Shanks algorithm for modular square roots. Finds x s.t. $x^2 = a \pmod p$ ($-x$ gives the other solution).
Time: $\mathcal{O}\left(\log^2 p\right)$ worst case, $\mathcal{O}(\log p)$ for most p
"ModPow.h" 19a793, 24 lines

```
ll sqrt(ll a, ll p) {
  a %= p; if (a < 0) a += p;
  if (a == 0) return 0;
  assert(modpow(a, (p-1)/2, p) == 1); // else
      no solution
  if (p % 4 == 3) return modpow(a, (p+1)/4, p)
      ;
  // a^(n+3)/8 or 2^(n+3)/8 * 2^(n-1)/4 works
      if p % 8 == 5
  ll s = p - 1, n = 2;
  int r = 0, m;
  while (s % 2 == 0)
    ++r, s /= 2;
  while (modpow(n, (p - 1) / 2, p) != p - 1)
      ++n;
  ll x = modpow(a, (s + 1) / 2, p);
  ll b = modpow(a, s, p), g = modpow(n, s, p);
  for (;; r = m) {
    ll t = b;
    for (m = 0; m < r && t != 1; ++m)
      t = t * t % p;
    if (m == 0) return x;
    ll gs = modpow(g, 1LL << (r - m - 1), p);
    g = gs * gs % p;
    x = x * gs % p;
    b = b * g % p;
  }
}
```

5.2 Primality

LinearSieve.h

Description: Can be used to precompute multiplicative functions using $f(px) = f(p)f(x)$ when $p \nmid x$. We compute $f(px) = f(p^{e+1} \cdot x/p^e) = f(p^{e+1})f(x/p^e)$ by multiplicativity (bookkeeping e, the max power of p dividing x where p is the smallest prime dividing x). If $f(px)$ can be computed easily when $p \mid x$ then we can simplify the code.
Time: $\mathcal{O}(n)$ e696bd, 16 lines

```
int func[N],cnt[N]; bool isc[N]; V<int> prime;
void sieve (int n) {
  fill(isc, isc + n, false); func[1] = 1;
  for (int i = 2; i < n; ++i) {
    if (!isc[i]) {
      prime.push_back(i); func[i]=1; cnt[i]=1;
    }
    for (int j = 0; j < prime.size () && i *
        prime[j] < n; ++j) {
      isc[i * prime[j]] = true;
      if (i % prime[j] == 0) {
        func[i * prime[j]] = func[i] / cnt[i]
            * (cnt[i] + 1);
        cnt[i * prime[j]] = cnt[i] + 1; break;
      } else {
        func[i * prime[j]] = func[i] * func[
            prime[j]];
        cnt[i * prime[j]] = 1;
} } } }
```

phiFunction.h

Description: *Euler's* ϕ function is defined as $\phi(n) :=$ # of positive integers $\leq n$ that are coprime with n. $\phi(1) = 1$, p prime $\Rightarrow \phi(p^k) = (p-1)p^{k-1}$, m, n coprime $\Rightarrow \phi(mn) = \phi(m)\phi(n)$. If $n = p_1^{k_1} p_2^{k_2} ... p_r^{k_r}$ then $\phi(n) = (p_1 - 1)p_1^{k_1 - 1} ... (p_r - 1)p_r^{k_r - 1}$. $\phi(n) = n \cdot \prod_{p|n}(1 - 1/p)$. $\sum_{d|n} \phi(d) = n$, $\sum_{1 \leq k \leq n, \gcd(k,n)=1} k = n\phi(n)/2, n > 1$
Euler's thm: a, n coprime $\Rightarrow a^{\phi(n)} \equiv 1 \pmod n$.
Fermat's little thm: p prime $\Rightarrow a^{p-1} \equiv 1 \pmod p, \forall a$. cf7d6d, 8 lines

```
const int LIM = 5000000;
int phi[LIM];

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

FastEratosthenes.h

Description: Prime sieve for generating all primes smaller than LIM.
Time: LIM=1e9 $\approx$ 1.5s 6b2912, 20 lines

```
const int LIM = 1e6;
bitset<LIM> isPrime;
vi eratosthenes() {
  const int S = (int)round(sqrt(LIM)), R = LIM
      / 2;
  vi pr = {2}, sieve(S+1); pr.reserve(int(LIM/
      log(LIM)*1.1));
  vector<pii> cp;
  for (int i = 3; i <= S; i += 2) if (!sieve[i
      ]) {
    cp.push_back({i, i * i / 2});
    for (int j = i * i; j <= S; j += 2 * i)
      sieve[j] = 1;
  }
  for (int L = 1; L <= R; L += S) {
    array<bool, S> block{};
    for (auto &[p, idx] : cp)
      for (int i=idx; i < S+L; idx = (i+=p))
        block[i-L] = 1;
    rep(i,0,min(S, R - L))
      if (!block[i]) pr.push_back((L + i) * 2
          + 1);
  }
  for (int i : pr) isPrime[i] = 1;
  return pr;
}
```

MillerRabin.h

Description: Deterministic Miller-Rabin primality test. Guaranteed to work for numbers up to $7 \cdot 10^{18}$; for larger numbers, use Python and extend A randomly.
Time: 7 times the complexity of $a^b \bmod c$.
"ModMulLL.h" 60dcd1, 12 lines

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

Factor.h

Description: Pollard-rho randomized factorization algorithm. Returns prime factors of a number, in arbitrary order (e.g. 2299 -> {11, 19, 11}).
Time: $\mathcal{O}\left(n^{1/4}\right)$, less for numbers with small factors.
"ModMulLL.h", "MillerRabin.h" d8d98d, 18 lines

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

5.3 Divisibility

euclid.h

Description: Finds two integers x and y, such that $ax + by = \gcd(a, b)$. If you just need gcd, use the built in __gcd instead. If a and b are coprime, then x is the inverse of $a \pmod b$. 33ba8f, 5 lines

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

CRT.h

Description: Chinese Remainder Theorem.
crt(a, m, b, n) computes x such that $x \equiv a \pmod m$, $x \equiv b \pmod n$. If $|a| < m$ and $|b| < n$, x will obey $0 \leq x < \text{lcm}(m, n)$. Assumes $mn < 2^{62}$.
Time: $\log(n)$
"euclid.h" 04d93a, 7 lines

```
ll crt(ll a, ll m, ll b, ll n) {
```

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

5.3.1 Bézout's identity

For $a \neq, b \neq 0$, then $d = gcd(a, b)$ is the smallest positive integer for which there are integer solutions to $ax + by = d$. If (x, y) is one solution, then all solutions are given by $(x + kb/d, y - ka/d)$, $k \in \mathbb{Z}$. Find one solution using egcd.

5.4 Fractions

FracBinarySearch.h

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

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

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

27ab3e, 25 lines

```
struct Frac { ll p, q; };

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

5.5 Mobius Function

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

Mobius Inversion:

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

Other useful formulas/forms:

$\sum_{d|n} \mu(d) = [n = 1]$, $\phi(n) = \sum_{d|n} \mu(d) \frac{n}{d}$

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

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

If f multiplicative,
$\sum_{d|n} \mu(d) f(d) = \prod_{\text{prime } p|n} (1 - f(p))$ and
$\sum_{d|n} \mu^2(d) f(d) = \prod_{\text{prime } p|n} (1 + f(p))$.

If $s_f(n) = \sum_{i=1}^{n} f(i)$ is a prefix sum of mulitplicative f then $s_{f*g}(n) = \sum_{1 \leq xy \leq n} f(x) g(y)$.
Then $s_f(n) = \{s_{f*g}(n) - \sum_{d=2}^{n} s_f(\lfloor n/d \rfloor) g(d)\}/g(1)$ where $f * g(n) = \sum_{d|n} f(d) g(n/d)$ (Dirichlet).

Precompute (linear sieve) $O(n^{2/3})$ first values of s_f for complexity $O(n^{2/3})$.

Useful sums and convolutions: $\epsilon = \mu * \mathbf{1}$, $\mathrm{id} = \phi * \mathbf{1}$, $\mathrm{id} = g * \mathrm{id}_2$, where $\epsilon(n) = [n = 1]$, $\mathbf{1}(n) = 1$, $\mathrm{id}(n) = n$, $\mathrm{id}_k(n) = n^k$, $g(n) = \sum_{d|n} \mu(d) nd$.

coprime pairs in $[1, n]$ is $\sum_{d=1}^{n} \mu(d) \lfloor n/d \rfloor^2$. Sum of GCD pairs in $[1, n]$ is $\sum_{d=1}^{n} \phi(d) \lfloor n/d \rfloor^2$. Sum of LCM pairs in $[1, n]$ is $\sum_{d=1}^{n} (\frac{\lfloor n/d \rfloor (\lfloor n/d \rfloor) + 1}{2})^2 g(d)$, where g is defined above with $g(p^k) = p^k - p^{k+1}$.

Combinatorial (6)

6.1 Permutations

IntPerm.h

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

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

044568, 6 lines

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

multinomial.h

Description: Computes $\binom{v_0 + \cdots + v_{n-1}}{v_0, \ldots, v_{n-1}}$

a0a312, 6 lines

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

Cycles Let $g_S(n)$ be the number of n-permutations whose cycle lengths all belong to the set S. Then $\sum_{n \geq 0} g_S(n) \frac{x^n}{n!} = \exp\left(\sum_{n \in S} \frac{x^n}{n}\right)$

Derangements Permutations of a set such that none of the elements appear in their original position. $D(n) = (n-1)(D(n-1) + D(n-2)) = nD(n-1) + (-1)^n = \left\lfloor \frac{n!}{e} \right\rceil$

Burnside's Lemma Given a group G of symmetries and a set X, the number of elements of X *up to symmetry* equals $\frac{1}{|G|} \sum_{g \in G} |X^g|$, where X^g are the elements fixed by g ($g.x = x$). If $f(n)$ counts "configurations" (of some sort) of length n, we can ignore rotational symmetry using $G = \mathbb{Z}_n$ to get $g(n) = \frac{1}{n} \sum_{k=0}^{n-1} f(\gcd(n, k)) = \frac{1}{n} \sum_{k|n} f(k) \phi(n/k)$.

Partition function Number of ways of writing n as a sum of positive integers, disregarding the order of the summands. $p(0) = 1$, $p(n) = \sum_{k \in \mathbb{Z} \setminus \{0\}} (-1)^{k+1} p(n - k(3k-1)/2)$.
$p(n) \sim 0.145/n \cdot \exp(2.56\sqrt{n})$
First few values: 1, 1, 2, 3, 5, 7, 11, 15, 22, 30.
$p(20) = 627, p(50) \approx 2e5, p(100) \approx 2e8$.

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

Bernoulli numbers EGF of Bernoulli numbers is $B(t) = \frac{t}{e^t - 1}$ (FFT-able). $\sum \frac{B_i}{i!} x^i = \frac{x}{1 - e^{-x}}$.
$B[0, \ldots] = [1, -\frac{1}{2}, \frac{1}{6}, 0, -\frac{1}{30}, 0, \frac{1}{42}, \ldots]$.
Sums of powers:

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

Stirling numbers of the first kind Number of permutations on n items with k cycles.
$c(n, k) = c(n-1, k-1) + (n-1)c(n-1, k)$,
$c(0, 0) = 1. \sum_{k=0}^{n} c(n, k) x^k = x(x+1)\ldots(x+n-1)$
$c(8, k) =$
$8, 0, 5040, 13068, 13132, 6769, 1960, 322, 28, 1$
$c(n, 2) =$
$0, 0, 1, 3, 11, 50, 274, 1764, 13068, 109584, ..$

Stirling numbers of the second kind Partitions of n distinct elements into exactly k non-empty subsets. $S(n, k) = S(n-1, k-1) + kS(n-1, k)$.
$S(n, 1) = S(n, n) = 1$.
$S(n, k) = \frac{1}{k!} \sum_{j=0}^{k} (-1)^{k-j} \binom{k}{j} j^n$.

Eulerian numbers Number of n-permutations with exactly k rises (positions i with $p_i > p_{i-1}$).
$E(n, k) = (n-k)E(n-1, k-1) + (k+1)E(n-1, k)$.
$E(n, 0) = E(n, n-1) = 1$.
$E(n, k) = \sum_{j=0}^{k} (-1)^j \binom{n+1}{j} (k+1-j)^n$.

Bell numbers Total number of partitions of n distinct elements. $B(n) =$
$1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, \ldots$.
$B(3) = 5 = \{a|b|c, a|bc, b|ac, c|ab, abc\}$. For p prime, $B(p^m + n) \equiv mB(n) + B(n+1) \pmod{p}$.

Catalan numbers
$C_n = \frac{1}{n+1} \binom{2n}{n} = \binom{2n}{n} - \binom{2n}{n+1} = \frac{(2n)!}{(n+1)!n!}$
$C_0 = 1$, $C_{n+1} = \frac{2(2n+1)}{n+2} C_n$, $C_{n+1} = \sum C_i C_{n-i}$
$C_n = 1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786, ..$
- UR path from $(0, 0)$ to (n, n) below $y = x$.
- strings with n pairs of parenthesis, correctly nested.
- binary trees with with $n + 1$ leaves (0 or 2 children).
- ordered trees with $n + 1$ vertices.
- ways a convex polygon with $n + 2$ sides can be cut into triangles by connecting vertices with straight lines.
- permutations of $[n]$ with no 3-term increasing subseq.

Labeled unrooted trees: # on n vertices: n^{n-2}
on k existing trees of size n_i: $n_1 n_2 \cdots n_k n^{k-2}$
with degrees d_i: $(n-2)!/((d_1 - 1)! \cdots (d_n - 1)!)$
ways to connect k components with $k-1$ edges: $s_1 \cdots s_k \cdot n^{k-2}$

Number of Spanning Trees Create an $N \times N$ matrix `mat`, and for each edge $a \to b \in G$, do `mat[a][b]--, mat[b][b]++` (and `mat[b][a]--, mat[a][a]++` if G is undirected). Remove the ith row and column and take the determinant; this yields the number of directed spanning trees rooted at i (if G is undirected, remove any row/column).

Erdős–Gallai theorem A simple graph with node degrees $d_1 \geq \cdots \geq d_n$ exists iff $d_1 + \cdots + d_n$ is even and for every $k = 1 \ldots n$,

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

Sprague-Grundy Theorem: Viewing the game as a DAG, where a player moves from one node v to any neighbor v_i, the grundy value $G(v) = mex\{v_i\}$ gives an equivalent pile of nim. If the game breaks into several equivalent games where player can move at any single part, take xorsum to combine (just like nim). Use DP/pattern hunting.

Graph (7)

7.1 Shortest Paths

BellmanFord.h

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

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

830a8f, 23 lines

```
const ll inf = LLONG_MAX;
struct Ed { int a, b, w, s() { return a < b ?
     a : -a; }};
struct Node { ll dist = inf; int prev = -1; };

void bellmanFord(vector<Node>& nodes, vector<
     Ed>& eds, int s) {
  nodes[s].dist = 0;
```

```
  sort(all(eds), [](Ed a, Ed b) { return a.s()
       < b.s(); });

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

FloydWarshall.h

Description: Calculates all-pairs shortest path in a directed graph that might have negative edge weights. Input is an distance matrix m, where $m[i][j] =$ `inf` if i and j are not adjacent. As output, $m[i][j]$ is set to the shortest distance between i and j, `inf` if no path, or `-inf` if the path goes through a negative-weight cycle.
Time: $\mathcal{O}\left(N^3\right)$

531245, 12 lines

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

Johnson.h

Description: APSP on weighted directed graphs with no negative cycles. Add a dummy node q connected by 0-weighted edge to each other node. Then run Bellman from q to find minimum weight $h(v)$ of a path $q \rightsquigarrow v$ (terminate if negative cycle found). Next, reweight the original graph: $\forall u \to v$ with weight $w(u,v)$, assign new weight $w(u,v) + h(u) - h(v)$. Now $D(u,v) =$ Dijkstra$(u,v) + h(v) - h(u)$.
Time: $\mathcal{O}(Bellman) + \mathcal{O}(V) * \mathcal{O}(Dijkstra)$

7.2 Network flow

Dinic.h

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

d7f0f1, 40 lines

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

PushRelabel.h

Description: Push-relabel using the highest label selection rule and the gap heuristic. Quite fast in practice. To obtain the actual flow, look at positive values only.
Time: $\mathcal{O}\left(V^2\sqrt{E}\right)$

2fd373, 40 lines

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

MinCostMaxFlow.h

Description: Min-cost max-flow. If costs can be negative, call setpi before maxflow, but note that negative cost cycles are not supported. To obtain the actual flow, look at positive values only.
Time: $\mathcal{O}(FE\log(V))$ where F is max flow. $\mathcal{O}(VE)$ for setpi.

15e3e9, 62 lines

```
#include <bits/extc++.h>
const ll INF = numeric_limits<ll>::max() / 4;

struct MCMF {
  struct edge {
    int from, to, rev;  ll cap, cost, flow;
  };
  int N; V<V<edge>> ed; vi seen;
  V<ll> dist, pi; V<edge*> par;
  MCMF(int N) : N(N), ed(N), seen(N),
    dist(N), pi(N), par(N) {}
  void addEdge(int from, int to, ll cap, ll
      cost) {
    if (from == to) return;
    ed[from].push_back(edge{ from,to,sz(ed[to
        ]),cap,cost,0 });
    ed[to].push_back(edge{ to,from,sz(ed[from
        ])-1,0,-cost,0 });
  }
  void path(int s) {
    fill(all(seen), 0); fill(all(dist), INF);
    dist[s] = 0; ll di;
    __gnu_pbds::priority_queue<pair<ll,int>>q;
    V<decltype(q)::point_iterator> its(N);
    q.push({ 0, s });
    while (!q.empty()) {
      s = q.top().second; q.pop();
      seen[s] = 1; di = dist[s] + pi[s];
      for (edge& e : ed[s]) if (!seen[e.to]) {
        ll val = di - pi[e.to] + e.cost;
        if (e.cap-e.flow>0 && val<dist[e.to]){
          dist[e.to] = val;  par[e.to] = &e;
          if (its[e.to] == q.end())
            its[e.to] = q.push({ -dist[e.to],
                e.to });
          else q.modify(its[e.to], { -dist[e.
              to], e.to });
    } } }
    rep(i,0,N) pi[i] = min(pi[i] + dist[i],
        INF);
  } // Hash without maxflow() setpi() = 061a45
  pair<ll, ll> maxflow(int s, int t) {
    ll totflow = 0, totcost = 0;
    while (path(s), seen[t]) {
      ll fl = INF;
      for (edge* x = par[t]; x; x = par[x->
          from])
        fl = min(fl, x->cap - x->flow);

      totflow += fl;
      for (edge* x = par[t]; x; x = par[x->
          from]) {
        x->flow += fl;
        ed[x->to][x->rev].flow -= fl;
      }
    }
    rep(i,0,N) for(edge& e : ed[i]) totcost +=
        e.cost * e.flow;
    return {totflow, totcost/2};
  } // Hash without setpi() = d04eb5
  void setpi(int s) {
    fill(all(pi), INF); pi[s] = 0;
    int it = N, ch = 1; ll v;
    while (ch-- && it--)
      rep(i,0,N) if (pi[i] != INF)
        for (edge& e : ed[i]) if (e.cap)
          if ((v = pi[i] + e.cost) < pi[e.to])
            pi[e.to] = v, ch = 1;
    assert(it >= 0); // negative cost cycle
  }
};
```

MinCut.h

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

GlobalMinCut.h

Description: Find a global minimum cut in an undirected graph, as represented by an adjacency matrix.
Time: $\mathcal{O}\left(V^3\right)$

8b0e19, 21 lines

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

GomoryHu.h

Description: Given a list of edges representing an undirected flow graph, returns edges of the Gomory-Hu tree. The max flow between any pair of vertices is given by minimum edge weight along the Gomory-Hu tree path.
Time: $\mathcal{O}(V)$ Flow Computations

"PushRelabel.h" 0418b3, 12 lines

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

7.3 Matching

HopcroftKarp.h

Description: Fast bipartite matching algorithm. Graph g should be a list of neighbors of the left partition, and $btoa$ should be a vector full of -1's of the same size as the right partition. Returns the size of the matching. $btoa[i]$ will be the match for vertex i on the right side, or -1 if it's not matched.
Usage: `vi btoa(m, -1); hopcroftKarp(g, btoa);`
Time: $\mathcal{O}\left(\sqrt{V}E\right)$

728df7, 34 lines

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

MinimumVertexCover.h

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

"HopcroftKarp.h" 23c286, 18 lines

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

WeightedMatching.h

Description: Given a weighted bipartite graph, matches every node on the left with a node on the right such that no nodes are in two matchings and the sum of the edge weights is minimal. Takes cost[N][M], where cost[i][j] = cost for L[i] to be matched with R[j] and returns (min cost, match), where L[i] is matched with R[match[i]]. Negate costs for max cost. Requires $N \leq M$.
Time: $\mathcal{O}\left(N^2M\right)$

1e0fe9, 34 lines

```
pair<int, vi> hungarian(const vector<vi> &a) {
  if (a.empty()) return {0, {}};
  int n = sz(a) + 1, m = sz(a[0]) + 1;
  vi u(n), v(m), p(m), ans(n - 1);
  rep(i,1,n) {
    p[0] = i;
    int j0 = 0; // add "dummy" worker 0
    vi dist(m, INT_MAX), pre(m, -1);
    vector<bool> done(m + 1);
    do { // dijkstra
      done[j0] = true;
      int i0 = p[j0], j1, delta = INT_MAX;
      rep(j,1,m) if (!done[j]) {
        auto cur = a[i0-1][j-1] - u[i0]-v[j];
        if (cur < dist[j])
          dist[j] = cur, pre[j] = j0;
        if (dist[j] < delta)
          delta = dist[j], j1 = j;
      }
      rep(j,0,m) {
        if (done[j])
          u[p[j]] += delta, v[j] -= delta;
        else dist[j] -= delta;
      }
      j0 = j1;
    } while (p[j0]);
    while (j0) { // update alternating path
      int j1 = pre[j0];
      p[j0] = p[j1], j0 = j1;
    }
  }
  rep(j,1,m) if (p[j]) ans[p[j] - 1] = j - 1;
  return {-v[0], ans}; // min cost
}
```

GeneralMatching.h

Description: Matching for general graphs. Fails with probability N/mod.
Time: $\mathcal{O}\left(N^3\right)$

"../numerical/MatrixInverse-mod.h" 9eead0, 37 lines

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

7.4 DFS algorithms

SCC.h

Description: Finds strongly connected components in a directed graph. If vertices u, v belong to the same component, we can reach u from v and vice versa.
Usage: `scc(graph, [&](vi& v) { ... }) visits all components in reverse topological order. comp[i] holds the component index of a node (a component only has edges to components with lower index). ncomps will contain the number of components.`
Time: $\mathcal{O}(E+V)$

76b5c9, 21 lines

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

BiconnectedComponents.h

Description: Finds all biconnected components in an undirected graph, and runs a callback for the edges in each. In a biconnected component there are at least two distinct paths between any two nodes. Note that a node can be in several components. An edge which is not in a component is a bridge. A node is a cut point if (1) Exists in multiple bccs, or (2) Endpoint of a bridge with degree > 1 (self loops don't count as degree).
Usage: `int eid = 0; g.resize(N);`
`for each edge (a,b) {`
`g[a].emplace_back(b, eid);`
`g[b].emplace_back(a, eid++); }`
`bicomps([&](const vi& edgelist) {...});`
Time: $\mathcal{O}(E+V)$

c5905f, 26 lines

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

BlockCutTree.h

Description: Finds the block-cut tree of a bidirectional graph. Tree nodes are either cut points or a block. All edges are between a block and a cut point. Combining all nodes in a block with its neighbor cut points give the whole BCC.

Usage: art[i] = true if cut point. Cut-points are relabeled within [1,ncut]. Higher labels are for blocks. Resets: art, g[1,n], tree[1,ptr], st, comp[1,cur], ptr, cur, in;
cbcc0e, 36 lines

```
bitset <N> art;
vector <int> g[N], tree[N], st, comp[N];
int n, m, ptr, cur, ncut, in[N],low[N],id[N];
void dfs (int u, int from = -1) {
  in[u] = low[u] = ++ptr; st.emplace_back(u);
  for (int v : g[u]) if (v ^ from) {
    if (!in[v]) {
      dfs(v, u);
      low[u] = min(low[u], low[v]);
      if (low[v] >= in[u]) {
        art[u] = in[u] > 1 or in[v] > 2;
        comp[++cur].emplace_back(u);
        while (comp[cur].back() ^ v) {
          comp[cur].emplace_back(st.back());
          st.pop_back();
      } }
    } else { low[u] = min(low[u], in[v]); }
} }
void buildTree() {
  ptr = 0;
  for (int i = 1; i <= n; ++i) {
    if (art[i]) id[i] = ++ptr;
  } ncut = ptr;
  for (int i = 1; i <= cur; ++i) {
    int x = ++ptr;
    for (int u : comp[i]) {
      if (art[u]) {
        tree[x].emplace_back(id[u]);
        tree[id[u]].emplace_back(x);
      } else { id[u] = x; }
} } }
int main() {
  for (int i = 1; i <= n; ++i)
    if (!in[i]) dfs(i);
  buildTree();
}
```

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

```
struct TwoSat {
  int N;
  vector<vi> gr;
  vi values; // 0 = false, 1 = true

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

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

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

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

  vi val, comp, z; int time = 0;
  int dfs(int i) {
    int low = val[i] = ++time, x; z.push_back(
        i);
    for(int e : gr[i]) if (!comp[e])
      low = min(low, val[e] ?: dfs(e));
    if (low == val[i]) do {
      x = z.back(); z.pop_back();
      comp[x] = low;
      if (values[x>>1] == -1)
        values[x>>1] = x&1;
    } while (x != i);
    return val[i] = low;
  }

  bool solve() {
    values.assign(N, -1);
    val.assign(2*N, 0); comp = val;
    rep(i,0,2*N) if (!comp[i]) dfs(i);
    rep(i,0,N) if (comp[2*i] == comp[2*i+1])
        return 0;
    return 1;
  }
};
```

EulerWalk.h

Description: Eulerian undirected/directed path/cycle algorithm. Input should be a vector of (dest, global edge index), where for undirected graphs, forward/backward edges have the same index. Returns a list of nodes in the Eulerian path/cycle with src at both start and end, or empty list if no cycle/path exists. To get edge indices back, add .second to s and ret.
Time: $\mathcal{O}(V+E)$
780b64, 15 lines

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

De-Bruijn Sequence: of order n on a k-size alphabet A is a cyclic sequence in which every possible length n string on A occurs exactly once as a substring. $B(k,n)$ has length k^n and number of distinct sequences is $\{(k!)^{k^{n-1}}\}/k^n$. Find an Euler tour on graph where nodes are $n-1$ length strings and each node has k outgoing edges for each character.

GrayCode.h

Description: Sequence of binary strings where each successive values differ in only 1 bit. Can be used to find Hamiltonian cycle on n-dimensional hypercube by calling $g(0), ..., g(2^n-1)$.
e87165, 5 lines

```
int g (int n) { return n ^ (n >> 1); }
int rev_g (int g) { int n = 0;
  for (; g; g >>= 1) n ^= g;
  return n;
}
```

7.5 Coloring

EdgeColoring.h

Description: Given a simple, undirected graph with max degree D, computes a $(D+1)$-coloring of the edges such that no neighboring edges share a color. (D-coloring is NP-hard, but can be done for bipartite graphs by repeated matchings of max-degree nodes.)
Time: $\mathcal{O}(NM)$
e210e2, 31 lines

```
vi edgeColoring(int N, vector<pii> eds) {
  vi cc(N + 1), ret(sz(eds)), fan(N), free(N),
      loc;
  for (pii e : eds) ++cc[e.first], ++cc[e.
      second];
  int u, v, ncols = *max_element(all(cc)) + 1;
  vector<vi> adj(N, vi(ncols, -1));
  for (pii e : eds) {
    tie(u, v) = e;
    fan[0] = v;
    loc.assign(ncols, 0);
    int at = u, end = u, d, c = free[u], ind =
        0, i = 0;
    while (d = free[v], !loc[d] && (v = adj[u
        ][d]) != -1)
      loc[d] = ++ind, cc[ind] = d, fan[ind] =
          v;
    cc[loc[d]] = c;
    for (int cd = d; at != -1; cd ^= c ^ d, at
        = adj[at][cd])
      swap(adj[at][cd], adj[end = at][cd ^ c ^
          d]);
    while (adj[fan[i]][d] != -1) {
      int left = fan[i], right = fan[++i], e =
          cc[i];
      adj[u][e] = left;
      adj[left][e] = u;
      adj[right][e] = -1;
      free[right] = e;
    }
    adj[u][d] = fan[i];
    adj[fan[i]][d] = u;
    for (int y : {fan[0], u, end})
      for (int& z = free[y] = 0; adj[y][z] !=
          -1; z++);
  }
  rep(i,0,sz(eds))
    for (tie(u, v) = eds[i]; adj[u][ret[i]] !=
        v;) ++ret[i];
  return ret;
}
```

7.6 Heuristics

MaximalCliques.h

Description: Runs a callback for all maximal cliques in a graph (given as a symmetric bitset matrix; self-edges not allowed). Callback is given a bitset representing the maximal clique.
Time: $\mathcal{O}\left(3^{n/3}\right)$, much faster for sparse graphs
b0d5b1, 12 lines

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

MaximumClique.h

Description: Quickly finds a maximum clique of a graph (given as symmetric bitset matrix; self-edges not allowed). Can be used to find a maximum independent set by finding a clique of the complement graph.
Time: Runs in about 1s for n=155 and worst case random graphs (p=.90). Runs faster for sparse graphs.
17e0b8, 49 lines

```
typedef vector<bitset<200>> vb;
struct Maxclique {
  double limit=0.025, pk=0;
  struct Vertex { int i, d=0; };
  typedef vector<Vertex> vv;
  vb e;
  vv V;
  vector<vi> C;
  vi qmax, q, S, old;
  void init(vv& r) {
    for (auto& v : r) v.d = 0;
    for (auto& v : r) for (auto j : r) v.d +=
        e[v.i][j.i];
    sort(all(r), [](auto a, auto b) { return a
        .d > b.d; });
    int mxD = r[0].d;
    rep(i,0,sz(r)) r[i].d = min(i, mxD) + 1;
  }
  void expand(vv& R, int lev = 1) {
    S[lev] += S[lev - 1] - old[lev];
    old[lev] = S[lev - 1];
```

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

MaximumIndependentSet.h

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

7.7 Trees

BinaryLifting.h

Description: Calculate power of two jumps in a tree, to support fast upward jumps and LCAs. Assumes the root node points to itself.
Time: construction $\mathcal{O}(N \log N)$, queries $\mathcal{O}(\log N)$

bfce85, 25 lines

```
vector<vi> treeJump(vi& P){
  int on = 1, d = 1;
  while(on < sz(P)) on *= 2, d++;
  vector<vi> jmp(d, P);
  rep(i,1,d) rep(j,0,sz(P))
    jmp[i][j] = jmp[i-1][jmp[i-1][j]];
  return jmp;
}

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

int lca(vector<vi>& tbl, vi& depth, int a, int
    b) {
  if (depth[a] < depth[b]) swap(a, b);
  a = jmp(tbl, a, depth[a] - depth[b]);
  if (a == b) return a;
  for (int i = sz(tbl); i--;) {
    int c = tbl[i][a], d = tbl[i][b];
    if (c != d) a = c, b = d;
  }
  return tbl[0][a];
}
```

LCA.h

Description: Data structure for computing lowest common ancestors in a tree (with 0 as root). C should be an adjacency list of the tree, either directed or undirected.
Time: $\mathcal{O}(N \log N + Q)$

"../data-structures/RMQ.h" 0f62fb, 21 lines

```
struct LCA {
  int T = 0;
  vi time, path, ret;
  RMQ<int> rmq;

  LCA(vector<vi>& C) : time(sz(C)), rmq((dfs(C
      ,0,-1), ret)) {}
  void dfs(vector<vi>& C, int v, int par) {
    time[v] = T++;
    for (int y : C[v]) if (y != par) {
      path.push_back(v), ret.push_back(time[v
          ]);
      dfs(C, y, v);
    }
  }

  int lca(int a, int b) {
    if (a == b) return a;
    tie(a, b) = minmax(time[a], time[b]);
    return path[rmq.query(a, b)];
  }
  //dist(a,b){return depth[a] + depth[b] - 2*
      depth[lca(a,b)];}
};
```

CompressTree.h

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

"LCA.h" 9775a0, 21 lines

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

HLD-easy.h

Description: Subtree of v: $[in_v, out_v)$. Path from v to the last vertex in ascending heavy path from v (which is nxt_v) will be in $[in_{nxt_v}, in_v]$.
Usage: each g[u] must not contain the parent. call dfs_sz(), then dfs_hld(). Be careful about switching to 1-indexing.

430255, 12 lines

```
void dfs_sz(int u = 0) { sz[u] = 1;
  for(auto &v: g[u]) {
    dfs_sz(v); sz[u] += sz[v];
    if(sz[v] > sz[g[u][0]]) swap(v, g[u][0]);
  }
}
void dfs_hld(int u = 0) { in[u] = t++;
  for(auto v: g[u]) {
    nxt[v] = (v == g[u][0] ? nxt[u] : v);
    dfs_hld(v);
  } out[u] = t;
}
```

HLD-ruhan.h

Description: 0-based indexing, HLDSegTree refers to the type of the segment tree The segment tree must have update([l, r), +dx) and query([l, r)) methods.
Time: $\mathcal{O}\left((\log N)^2\right)$ (not sure about this, though).

a12c98, 59 lines

```
template<class T, class HLDSegTree>
class HLD {
  int n;
  V<int> par, heavy,level,root,tree_pos;
  HLDSegTree tree;
private:
  int dfs(const V<V<int>>& graph, int u);
  template<class BinOp>
  void process_path(int u, int v, BinOp op);
public:
  HLD(int n_, const V<V<int>>& graph) : n(n_),
      par(n), heavy(n, -1), level(n), root(n)
      , tree_pos(n), tree(n) {
    par[0] = -1;
    level[0] = 0;
    dfs(graph, 0);
    int ii = 0;
    for(int u = 0; u < n; u++) {
      if(par[u] != -1 && heavy[par[u]] == u)
          continue;
      for(int v = u; v != -1; v = heavy[v]) {
        root[v] = u;
        tree_pos[v] = ii++;
      }
    }
  }
  void update(int u, int v, T val) {
    process_path(u, v, [this, val](int l, int
        r) { tree.update(l, r, val); });
  }
  T query(int u, int v) {
    T res = T();
    process_path(u, v, [this, &res](int l, int
        r) { res += tree.query(l, r); });
    return res;
  }
};
template<class T, class HLDSegTree>
int HLD<T,HLDSegTree>::dfs(const V<V<int>>&
    graph, int u) {
  int cc = 1, max_sub = 0;
  for(int v : graph[u]) {
    if(v == par[u]) continue;
    par[v] = u;
    level[v] = level[u] + 1;
    int sub = dfs(graph, v);
    if(sub > max_sub) {
      max_sub = sub;
      heavy[u] = v;
    }
    cc += sub;
  }
  return cc;
}
template<class T, class HLDSegTree>
template<class BinOp>
void HLD<T, HLDSegTree>::process_path(int u,
    int v, BinOp op) {
  for(; root[u] != root[v]; v = par[root[v]])
      {
    if(level[root[u]] > level[root[v]]) swap
        (u, v);
    op(tree_pos[root[v]], tree_pos[v]);
    assert(v != -1);
  }
  if(level[u] > level[v]) swap(u, v);
  op(tree_pos[u], tree_pos[v]);
}
```

LinkCutTree.h

Description: Represents a forest of unrooted trees. You can add and remove edges (as long as the result is still a forest), and check whether two nodes are in the same tree.
Time: All operations take amortized $\mathcal{O}(\log N)$.

6b462, 90 lines

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

```
    if (p) p->fix();
    swap(pp, y->pp);
  }
  void splay() {
    for (pushFlip(); p; ) {
      if (p->p) p->p->pushFlip();
      p->pushFlip(); p->pushFlip();
      int c1 = up(), c2 = p->up();
      if (c2 == -1) p->rot(c1, 2);
      else p->p->rot(c2, c1 != c2);
    }
  }
  Node* first() {
    pushFlip();
    return c[0] ? c[0]->first() : (splay(),
        this);
  }
};

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

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

TreeBinarize.h

Description: Given a weighted tree in edge-listing representation, transforms it into a binary tree by adding at most $2n$ extra nodes.

Usage: call add_edge() for both directions to create the tree. Then call binarize(1). Will change n.

84b697, 31 lines

```
// N = 3 * max nodes, M = 2 * N
int n, o = 2;
int to[M],wgt[M],prv[M],nxt[M],lst[N],deg[N];

void add_edge (int u, int v, int w) {
  to[o] = v, wgt[o] = w, deg[v]++;
  prv[o] = lst[u], lst[u] = nxt[lst[u]] = o++;
}
void binarize (int u, int f = 0) {
  int d = deg[u] - 2 - (f != 0);
  if (d > 0) {
    int tmp_lst = (to[lst[u]] == f ? prv[lst[u
        ]] : lst[u]), x;
    for (int e = lst[u], at = n+d; at > n; ){
      x = prv[e];
      if (to[e] == f) { e = x; continue; }
      nxt[x] = nxt[e];
      nxt[e] ? prv[nxt[e]] = x : lst[u] = x;
      prv[e] = lst[at], nxt[e] = 0;
      lst[at] = nxt[lst[at]] = e, deg[at]++;
      to[e ^ 1] = at;
      if (e != tmp_lst) --at;
      e = x;
    }
    for (int i=1, p=u; i <= d; p = n + i++)
      add_edge(p, n + i, 0),
      add_edge(n + i, p, 0);
    n += d, deg[u] -= d + 1;
  }
  for (int e = lst[u]; e; e = prv[e])
    if (to[e] != f) binarize(to[e], u);
}
```

CentroidDecomp.h

Description: Divide and conquer on trees. Useful for solving problems regarding all pairs of paths. Simple modifications are needed to integrate TreeBinarize into this.

Usage: Just call decompose(1). ctp[u] = parent of u in ctree. cth[u] = height of u in ctree,
root has height = 1. dist[u][h] = original tree distance (u -> ctree ancestor of u at height h).

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

096de1, 24 lines

```
// H = __lg(N), reset: cth, ctp, dist
int sub[N], cth[N], ctp[N], dist[N][H + 1];
void dfs_siz (int u, int f) {
  sub[u] = 1;
  for (int v : g[u]) if (!cth[v] && v ^ f)
    dfs_siz(v, u), sub[u] += sub[v];
}
int fc (int u, int f, int lim) {
  for (int v : g[u]) if (!cth[v] && v ^ f &&
      sub[v] > lim) return fc(v, u, lim);
  return u;
}
void dfs_dist (int u, int f, int d, int h) {
  dist[u][h] = d;
  for (int v : g[u]) if (!cth[v] && v ^ f)
    dfs_dist(v, u, d + 1, h);
}
void decompose (int u, int f = 0, int h = 1) {
  dfs_siz(u, 0);
  u = fc(u, 0, sub[u] >> 1);
  dfs_dist(u, 0, 0, h);
  cth[u] = h, ctp[u] = f; // u now deleted
  for (int v : g[u]) if (!cth[v])
    decompose(v, u, h + 1);
}
```

Geometry (8)

8.1 Geometric primitives

Point.h

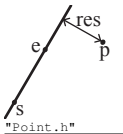
Description: Class to handle points in the plane. T can be e.g. double or long long. (Avoid int.)

ef0c0e, 29 lines

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

lineDistance.h

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

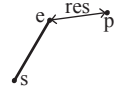


"Point.h" f6bf6b, 4 lines

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

SegmentDistance.h

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



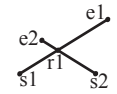
Usage: Point<double> a, b(2,2), p(1,1);
bool onSegment = segDist(a,b,p) < 1e-10;

"Point.h" 5c88f4, 6 lines

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

SegmentIntersection.h

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



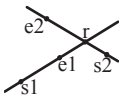
Usage: vector<P> inter = segInter(s1,e1,s2,e2);
if (sz(inter)==1)
cout << "segments intersect at " << inter[0] << endl;

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

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

lineIntersection.h

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



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

"Point.h" a01f81, 8 lines

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

sideOf.h

Description: Returns where p is as seen from s towards e. 1/0/-1 $\Leftrightarrow$ left/on line/right. If the optional argument eps is given 0 is returned if p is within distance eps from the line. P is supposed to be Point<T> where T is e.g. double or long long. It uses products in intermediate steps so watch out for overflow if using int or long long.
Usage: `bool left = sideOf(p1,p2,q)==1;`

"Point.h" 3af81c, 9 lines

```
template<class P>
int sideOf(P s, P e, P p) { return sgn(s.cross
    (e, p)); }

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

OnSegment.h

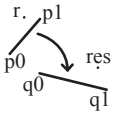
Description: Returns true iff p lies on the line segment from s to e. Use (segDist(s,e,p)<=epsilon) instead when using Point<double>.

"Point.h" c597e8, 3 lines

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

linearTransformation.h

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



"Point.h" 03a306, 6 lines

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

Angle.h

Description: A class for ordering angles (as represented by int points and a number of rotations around the origin). Useful for rotational sweeping. Sometimes also represents points or vectors.
Usage: `vector<Angle> v = {w[0], w[0].t360() ...}; // sorted`
`int j = 0; rep(i,0,n) { while (v[j] < v[i].t180()) ++j; }`
`// sweeps j such that (j-i) represents the number of positively oriented triangles with vertices at 0 and i`

0f0602, 35 lines

```
struct Angle {
  int x, y;
  int t;
  Angle(int x, int y, int t=0) : x(x), y(y), t
      (t) {}
  Angle operator-(Angle b) const { return {x-b
      .x, y-b.y, t}; }
  int half() const {
    assert(x || y);
    return y < 0 || (y == 0 && x < 0);
  }
  Angle t90() const { return {-y, x, t + (half
      () && x >= 0)}; }
  Angle t180() const { return {-x, -y, t +
      half()}; }
  Angle t360() const { return {x, y, t + 1}; }
};
bool operator<(Angle a, Angle b) {
  // add a.dist2() and b.dist2() to also
      compare distances
  return make_tuple(a.t, a.half(), a.y * (ll)b
      .x) <
      make_tuple(b.t, b.half(), a.x * (ll)b
          .y);
}

// Given two points, this calculates the
    smallest angle between
// them, i.e., the angle that covers the
    defined line segment.
pair<Angle, Angle> segmentAngles(Angle a,
    Angle b) {
  if (b < a) swap(a, b);
  return (b < a.t180() ?
          make_pair(a, b) : make_pair(b, a.
              t360()));
}
Angle operator+(Angle a, Angle b) { // point a
    + vector b
  Angle r(a.x + b.x, a.y + b.y, a.t);
  if (a.t180() < r) r.t--;
  return r.t180() < a ? r.t360() : r;
}
Angle angleDiff(Angle a, Angle b) { // angle b
    - angle a
  int tu = b.t - a.t; a.t = b.t;
  return {a.x*b.x + a.y*b.y, a.x*b.y - a.y*b.x
      , tu - (b < a)};
}
```

8.2 Circles

CircleIntersection.h

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

"Point.h" 84d6d3, 11 lines

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

CircleTangents.h

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

"Point.h" b0153d, 13 lines

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

CirclePolygonIntersection.h

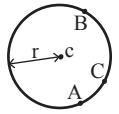
Description: Returns the area of the intersection of a circle with a ccw polygon.
Time: $\mathcal{O}(n)$

"../../content/geometry/Point.h" a1ee63, 19 lines

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

circumcircle.h

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



"Point.h" 1caa3a, 9 lines

```
typedef Point<double> P;
double ccRadius(const P& A, const P& B, const
    P& C) {
  return (B-A).dist()*(C-B).dist()*(A-C).dist
      ()/
      abs((B-A).cross(C-A))/2;
}
P ccCenter(const P& A, const P& B, const P& C)
    {
  P b = C-A, c = B-A;
```

```
  return A + (b*c.dist2()-c*b.dist2()).perp()/
      b.cross(c)/2;
}
```

MinimumEnclosingCircle.h

Description: Computes the minimum circle that encloses a set of points.
Time: expected $\mathcal{O}(n)$

"circumcircle.h" 09dd0a, 17 lines

```
pair<P, double> mec(vector<P> ps) {
  shuffle(all(ps), mt19937(time(0)));
  P o = ps[0];
  double r = 0, EPS = 1 + 1e-8;
  rep(i,0,sz(ps)) if ((o - ps[i]).dist() > r *
       EPS) {
    o = ps[i], r = 0;
    rep(j,0,i) if ((o - ps[j]).dist() > r *
         EPS) {
      o = (ps[i] + ps[j]) / 2;
      r = (o - ps[i]).dist();
      rep(k,0,j) if ((o - ps[k]).dist() > r *
           EPS) {
        o = ccCenter(ps[i], ps[j], ps[k]);
        r = (o - ps[i]).dist();
      }
    }
  }
  return {o, r};
}
```

8.3 Polygons

InsidePolygon.h

Description: Returns true if p lies within the polygon. If strict is true, it returns false for points on the boundary. The algorithm uses products in intermediate steps so watch out for overflow.
Usage: `vector<P> v = {P{4,4}, P{1,2}, P{2,1}};`
`bool in = inPolygon(v, P{3, 3}, false);`
Time: $\mathcal{O}(n)$

"Point.h", "OnSegment.h", "SegmentDistance.h" 2bf504, 11 lines

```
template<class P>
bool inPolygon(vector<P> &p, P a, bool strict
    = true) {
  int cnt = 0, n = sz(p);
  rep(i,0,n) {
    P q = p[(i + 1) % n];
    if (onSegment(p[i], q, a)) return !strict;
    //or: if (segDist(p[i], q, a) <= eps)
        return !strict;
    cnt ^= ((a.y<p[i].y) - (a.y<q.y)) * a.
        cross(p[i], q) > 0;
  }
  return cnt;
}
```

PolygonArea.h

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

"Point.h" f12300, 6 lines

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

PolygonCenter.h

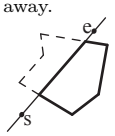
Description: Returns the center of mass for a polygon.
Time: $\mathcal{O}(n)$

"Point.h" 9706dc, 9 lines

```
typedef Point<double> P;
P polygonCenter(const vector<P>& v) {
  P res(0, 0); double A = 0;
  for (int i = 0, j = sz(v) - 1; i < sz(v); j
       = i++) {
    res = res + (v[i] + v[j]) * v[j].cross(v[i
        ]);
    A += v[j].cross(v[i]);
  }
  return res / A / 3;
}
```

PolygonCut.h

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



Usage: `vector<P> p = ...;`
`p = polygonCut(p, P(0,0), P(1,0));`

"Point.h", "lineIntersection.h" f2b7d4, 13 lines

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

ConvexHull.h

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

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

"Point.h" 310954, 13 lines

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

HullDiameter.h

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

"Point.h" c571b8, 12 lines

```
typedef Point<ll> P;
array<P, 2> hullDiameter(vector<P> S) {
  int n = sz(S), j = n < 2 ? 0 : 1;
  pair<ll, array<P, 2>> res({0, {S[0], S[0]}})
      ;
  rep(i,0,j)
    for (;; j = (j + 1) % n) {
      res = max(res, {(S[i] - S[j]).dist2(), {
          S[i], S[j]}});
      if ((S[(j + 1) % n] - S[j]).cross(S[i +
          1] - S[i]) >= 0)
        break;
    }
  return res.second;
}
```

PointInsideHull.h

Description: Determine whether a point t lies inside a convex hull (CCW order, with no collinear points). Returns true if point lies within the hull. If strict is true, points on the boundary aren't included.
Time: $\mathcal{O}(\log N)$

"Point.h", "sideOf.h", "OnSegment.h" 71446b, 14 lines

```
typedef Point<ll> P;

bool inHull(const vector<P>& l, P p, bool
    strict = true) {
  int a = 1, b = sz(l) - 1, r = !strict;
  if (sz(l) < 3) return r && onSegment(l[0], l
      .back(), p);
  if (sideOf(l[0], l[a], l[b]) > 0) swap(a, b)
      ;
  if (sideOf(l[0], l[a], p) >= r || sideOf(l
      [0], l[b], p)<= -r)
    return false;
  while (abs(a - b) > 1) {
    int c = (a + b) / 2;
    (sideOf(l[0], l[c], p) > 0 ? b : a) = c;
  }
  return sgn(l[a].cross(l[b], p)) < r;
}
```

LineHullIntersection.h

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

"Point.h" 7cf45b, 39 lines

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

#define cmpL(i) sgn(a.cross(poly[i], b))
template <class P>
array<int, 2> lineHull(P a, P b, vector<P>&
    poly) {
  int endA = extrVertex(poly, (a - b).perp());
  int endB = extrVertex(poly, (b - a).perp());
  if (cmpL(endA) < 0 || cmpL(endB) > 0)
    return {-1, -1};
  array<int, 2> res;
  rep(i,0,2) {
    int lo = endB, hi = endA, n = sz(poly);
    while ((lo + 1) % n != hi) {
      int m = ((lo + hi + (lo < hi ? 0 : n)) /
          2) % n;
      (cmpL(m) == cmpL(endB) ? lo : hi) = m;
    }
    res[i] = (lo + !cmpL(hi)) % n;
    swap(endA, endB);
  }
  if (res[0] == res[1]) return {res[0], -1};
  if (!cmpL(res[0]) && !cmpL(res[1]))
    switch ((res[0] - res[1] + sz(poly) + 1) %
        sz(poly)) {
      case 0: return {res[0], res[0]};
      case 2: return {res[1], res[1]};
    }
  return res;
}
```

8.4 Misc. Point Set Problems

ClosestPair.h

Description: Finds the closest pair of points.
Time: $\mathcal{O}(n \log n)$

"Point.h" ac41a6, 17 lines

```
typedef Point<ll> P;
pair<P, P> closest(vector<P> v) {
  assert(sz(v) > 1);
  set<P> S;
  sort(all(v), [](P a, P b) { return a.y < b.y
      ; });
  pair<ll, pair<P, P>> ret{LLONG_MAX, {P(), P
      ()}};
  int j = 0;
  for (P p : v) {
    P d{1 + (ll)sqrt(ret.first), 0};
```

```
    while (v[j].y <= p.y - d.x) S.erase(v[j
        ++]);
    auto lo = S.lower_bound(p - d), hi = S.
        upper_bound(p + d);
    for (; lo != hi; ++lo)
      ret = min(ret, {(*lo - p).dist2(), {*lo,
          p}});
    S.insert(p);
  }
  return ret.second;
}
```

kdTree.h

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

"Point.h" bac5b0, 63 lines

```
typedef long long T;
typedef Point<T> P;
const T INF = numeric_limits<T>::max();

bool on_x(const P& a, const P& b) { return a.x
    < b.x; }
bool on_y(const P& a, const P& b) { return a.y
    < b.y; }

struct Node {
  P pt; // if this is a leaf, the single point
      in it
  T x0 = INF, x1 = -INF, y0 = INF, y1 = -INF;
      // bounds
  Node *first = 0, *second = 0;

  T distance(const P& p) { // min squared
      distance to a point
    T x = (p.x < x0 ? x0 : p.x > x1 ? x1 : p.x
        );
    T y = (p.y < y0 ? y0 : p.y > y1 ? y1 : p.y
        );
    return (P(x,y) - p).dist2();
  }

  Node(vector<P>&& vp) : pt(vp[0]) {
    for (P p : vp) {
      x0 = min(x0, p.x); x1 = max(x1, p.x);
      y0 = min(y0, p.y); y1 = max(y1, p.y);
    }
    if (vp.size() > 1) {
      // split on x if width >= height (not
          ideal...)
      sort(all(vp), x1 - x0 >= y1 - y0 ? on_x
          : on_y);
      // divide by taking half the array for
          each child (not
      // best performance with many duplicates
          in the middle)
      int half = sz(vp)/2;
      first = new Node({vp.begin(), vp.begin()
          + half});
      second = new Node({vp.begin() + half, vp
          .end()});
    }
  }
};

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

  pair<T, P> search(Node *node, const P& p) {
    if (!node->first) {
      // uncomment if we should not find the
          point itself:
      // if (p == node->pt) return {INF, P()};
      return make_pair((p - node->pt).dist2(),
          node->pt);
    }

    Node *f = node->first, *s = node->second;
    T bfirst = f->distance(p), bsec = s->
        distance(p);
    if (bfirst > bsec) swap(bsec, bfirst),
        swap(f, s);

    // search closest side first, other side
        if needed
    auto best = search(f, p);
    if (bsec < best.first)
      best = min(best, search(s, p));
    return best;
  }

  // find nearest point to a point, and its
      squared distance
  // (requires an arbitrary operator< for
      Point)
  pair<T, P> nearest(const P& p) {
    return search(root, p);
  }
};
```

FastDelaunay.h

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

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

"Point.h" eefdf5, 88 lines

```
typedef Point<ll> P;
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 {
  Q rot, o; P p = arb; bool mark;
  P& F() { return r()->p; }
  Q& r() { return rot->rot; }
  Q prev() { return rot->o->rot; }
  Q next() { return r()->prev(); }
} *H;

bool circ(P p, P a, P b, P c) { // is p in the
    circumcircle?
  lll p2 = p.dist2(), A = a.dist2()-p2,
      B = b.dist2()-p2, C = c.dist2()-p2;
  return p.cross(a,b)*C + p.cross(b,c)*A + p.
      cross(c,a)*B > 0;
}
Q makeEdge(P orig, P dest) {
  Q r = H ? H : new Quad{new Quad{new Quad{new
      Quad{0}}}};
  H = r->o; r->r()->r() = r;
  rep(i,0,4) r = r->rot, r->p = arb, r->o = i
      & 1 ? r : r->r();
  r->p = orig; r->F() = dest;
  return r;
}
void splice(Q a, Q b) {
  swap(a->o->rot->o, b->o->rot->o); swap(a->o,
      b->o);
}
Q connect(Q a, Q b) {
  Q q = makeEdge(a->F(), b->p);
  splice(q, a->next());
  splice(q->r(), b);
  return q;
}

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

#define H(e) e->F(), e->p
#define valid(e) (e->F().cross(H(base)) > 0)
  Q A, B, ra, rb;
  int half = sz(s) / 2;
  tie(ra, A) = rec({all(s) - half});
  tie(B, rb) = rec({sz(s) - half + all(s)});
  while ((B->p.cross(H(A)) < 0 && (A = A->next
      ())) ||
         (A->p.cross(H(B)) > 0 && (B = B->r()
             ->o)));
  Q base = connect(B->r(), A);
  if (A->p == ra->p) ra = base->r();
  if (B->p == rb->p) rb = base;

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

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

Voronoi.h

Description: Not so fast Voronoi from FastDelaunay Assumes that there are no duplicate points and that not all points are on a single line. Each circumcircle contains none of the input points. Should work for doubles as well, but haven't checked This can be optimized to use much less memory if needed. Also manually fix BIG.

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

"FastDelaunay.h" a1e388, 66 lines

```
struct voronoi_graph {
 using P = Point<ll>;
 using Pd = Point<double>;

 const double BIG = 1e8;

 static Pd promote (P p) { return Pd(p.x, p.y)
     ; }

 vector<tuple<P,P,P>> nodes;
 vector<vector<tuple<pair<P,P>, int, Pd>>> adj
     ;
 // ((A, B), v, Direction)
 // the edge, when extended to a line, is the
      perpendicular bisector of the segment
     AB
 // v is the index of the adjacent node. it
     is -1 if the edge goes to infty
 // circumcenter(node) + Direction gives us
     the other vertex

 voronoi_graph (const vector<P>& pts) {
  auto t = delaunay::triangulate(pts);
  assert (sz(t) % 3 == 0);
  nodes.resize(sz(t) / 3);
  for (int i = 0; i < sz(t); i += 3)
   nodes[i / 3] = {t[i], t[i+1], t[i+2]};
  sort(all(nodes));
  adj.resize(sz(nodes));

  vector<pair<pair<P,P>, tuple<P,P,P>>>
      delaunay_edges;
  delaunay_edges.reserve(sz(t));
  for (int i = 0; i < sz(t); i += 3) {
   for (int j = i; j < i + 3; j++)
    for (int k = j + 1; k < i + 3; k++)
     delaunay_edges.emplace_back(pair(min(t[j
         ], t[k]), max(t[j], t[k])), tuple(t[i
         ], t[i+1], t[i+2]));
  }
  sort(all(delaunay_edges));

  for (int i = 0; i < sz(delaunay_edges); i++)
      {
   const int x = lower_bound(all(nodes),
       delaunay_edges[i].second) - nodes.begin
       ();
   auto [a,b,c] = delaunay_edges[i].second;
```

```
  if (c == delaunay_edges[i].first.first || c
       == delaunay_edges[i].first.second)
   swap(b, c);
  if (c == delaunay_edges[i].first.first || c
       == delaunay_edges[i].first.second)
   swap(a, c);
  if (c == delaunay_edges[i].first.first || c
       == delaunay_edges[i].first.second)
   assert (false);

  if (i+1 < sz(delaunay_edges) &&
      delaunay_edges[i+1].first ==
      delaunay_edges[i].first) {
   const int y = lower_bound(all(nodes),
       delaunay_edges[i+1].second) - nodes.
       begin();
   auto dir = get_vertex(y) - get_vertex(x);
   adj[x].emplace_back(delaunay_edges[i].
       first, y, dir);
   adj[y].emplace_back(delaunay_edges[i].
       first, x, dir * (-1.0));
  } else if (i == 0 || delaunay_edges[i-1].
      first != delaunay_edges[i].first) {
   bool out = (a - c).dot(b - c) < 0;
   auto dir = ((promote(a + b) / 2.0) -
       get_vertex(x)) * (out ? -1.0 : 1.0);
   adj[x].emplace_back(delaunay_edges[i].
       first, -1, dir * BIG);
  }
 }
}

Pd get_vertex (int i) {
 auto [a, b, c] = nodes[i];
 return ccCenter(promote(a), promote(b),
     promote(c));
}

pair<Pd,Pd> get_edge (int i, int j) {
 const Pd vi = get_vertex(i);
 return {vi, vi + get<2>(adj[i][j])};
}
};
```

hplane-cpalg.h

Description: Half plane intersection in O(n log n). The direction of the plane is ccw of pq vector in Halfplane struct. Usage: Status:

2e310c, 75 lines

```
const long double eps = 1e-9, inf = 1e9;

struct Point {
    long double x, y;
    explicit Point(long double x = 0, long
        double y = 0) : x(x), y(y) {}
    friend Point operator+(const Point &p,
        const Point &q) { return Point(p.x + q
        .x, p.y + q.y); }
    friend Point operator-(const Point &p,
        const Point &q) { return Point(p.x - q
        .x, p.y - q.y); }
    friend Point operator*(const Point &p,
        const long double &k) { return Point(p
        .x * k, p.y * k); }
    friend long double dot(const Point &p,
        const Point &q) { return p.x * q.x + p
        .y * q.y; }
    friend long double cross(const Point &p,
        const Point &q) { return p.x * q.y - p
        .y * q.x; }
};

struct Halfplane {
    Point p, pq;
    long double angle;
    Halfplane() {}
    Halfplane(const Point &a, const Point &b)
        : p(a), pq(b - a) {
        angle = atan2l(pq.y, pq.x);
    }
    bool out(const Point &r) { return cross(pq
        , r - p) < -eps; }
    bool operator<(const Halfplane &e) const {
         return angle < e.angle; }
    friend Point inter(const Halfplane &s,
        const Halfplane &t) {
        long double alpha = cross((t.p - s.p),
            t.pq) / cross(s.pq, t.pq);
        return s.p + (s.pq * alpha);
    }
};

vector<Point> hp_intersect(vector<Halfplane> &
    H) {

    Point box[4] = {Point(inf, inf), Point(-
        inf, inf), Point(-inf, -inf),
                    Point(inf, -inf)};

    for (int i = 0; i < 4; i++) {
        Halfplane aux(box[i], box[(i + 1) %
            4]);
        H.push_back(aux);
    }

    sort(H.begin(), H.end());
    deque<Halfplane> dq;
    int len = 0;
    for (int i = 0; i < int(H.size()); i++) {
        while (len > 1 && H[i].out(inter(dq[
            len - 1], dq[len - 2]))) {
            dq.pop_back(); --len;
        }
        while (len > 1 && H[i].out(inter(dq
            [0], dq[1]))) {
            dq.pop_front(); --len;
        }
        if (len > 0 && fabsl(cross(H[i].pq, dq
            [len - 1].pq)) < eps) {
            if (dot(H[i].pq, dq[len - 1].pq) <
                0.0)
                return vector<Point>();
            if (H[i].out(dq[len - 1].p)) {
                dq.pop_back();
                --len;
            } else
                continue;
        }
        dq.push_back(H[i]);
        ++len;
    }
    while (len > 2 && dq[0].out(inter(dq[len -
        1], dq[len - 2]))) {
        dq.pop_back(); --len;
    }
    while (len > 2 && dq[len - 1].out(inter(dq
        [0], dq[1]))) {
        dq.pop_front(); --len;
    }
    if (len < 3)
        return vector<Point>();
    vector<Point> ret(len);
    for (int i = 0; i + 1 < len; i++) {
        ret[i] = inter(dq[i], dq[i + 1]);
    }
    ret.back() = inter(dq[len - 1], dq[0]);
    return ret;
}
```

8.5 3D

PolyhedronVolume.h

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

3058c3, 6 lines

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

Point3D.h

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

8058ae, 32 lines

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

3dHull.h

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

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

"Point3D.h" 5b45fc, 49 lines

```
typedef Point3D<double> P3;

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

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

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

  rep(i,4,sz(A)) {
    rep(j,0,sz(FS)) {
      F f = FS[j];
      if(f.q.dot(A[i]) > f.q.dot(A[f.a])) {
        E(a,b).rem(f.c);
        E(a,c).rem(f.b);
        E(b,c).rem(f.a);
        swap(FS[j--], FS.back());
        FS.pop_back();
      }
    }
    int nw = sz(FS);
    rep(j,0,nw) {
      F f = FS[j];
#define C(a, b, c) if (E(a,b).cnt() != 2) mf(f
     .a, f.b, i, f.c);
      C(a, b, c); C(a, c, b); C(b, c, a);
    }
```

```
  }
  for (F& it : FS) if ((A[it.b] - A[it.a]).
      cross(
    A[it.c] - A[it.a]).dot(it.q) <= 0) swap(it
        .c, it.b);
  return FS;
};
```

sphericalDistance.h

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

611f07, 8 lines

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

warsawGeo3D.h

Description: 3D geometry

c53353, 336 lines

```
using LD = long double;
const LD kEps = 1e-9;
const LD kPi = acosl(-1);
LD Sq(LD x) { return x * x; }
struct Point {
  LD x, y;
  Point() {}
  Point(LD a, LD b) : x(a), y(b) {}
  Point(const Point& a) : Point(a.x, a.y) {}
  void operator=(const Point &a) { x = a.x; y
      = a.y; }
  Point operator+(const Point &a) const {
      Point p(x + a.x, y + a.y); return p; }
  Point operator-(const Point &a) const {
      Point p(x - a.x, y - a.y); return p; }
  Point operator*(LD a) const { Point p(x * a,
       y * a); return p; }
  Point operator/(LD a) const { assert(abs(a)
      > kEps); Point p(x / a, y / a); return p
      ; }
  Point &operator+=(const Point &a) { x += a.x
      ; y += a.y; return *this; }
  Point &operator-=(const Point &a) { x -= a.x
      ; y -= a.y; return *this; }
  LD CrossProd(const Point &a) const { return
      x * a.y - y * a.x; }
  LD CrossProd(Point a, Point b) const { a -=
      *this; b -= *this; return a.CrossProd(b)
      ; }
};
struct Line {
  Point p[2];
  Line(Point a, Point b) { p[0] = a; p[1] = b;
      }
  Point &operator[](int a) { return p[a]; }
};
struct P3 {
  LD x, y, z;
  P3 operator+(P3 a) { P3 p{x + a.x, y + a.y,
      z + a.z}; return p; }
  P3 operator-(P3 a) { P3 p{x - a.x, y - a.y,
      z - a.z}; return p; }
  P3 operator*(LD a) { P3 p{x * a, y * a, z *
      a}; return p; }
  P3 operator/(LD a) { assert(a > kEps); P3 p{
      x / a, y / a, z / a}; return p; }
  P3 &operator+=(P3 a) { x += a.x; y += a.y; z
       += a.z; return *this; }
  P3 &operator-=(P3 a) { x -= a.x; y -= a.y; z
       -= a.z; return *this; }
  P3 &operator*=(LD a) { x *= a; y *= a; z *=
      a; return *this; }
  P3 &operator/=(LD a) { assert(a > kEps); x
      /= a; y /= a; z /= a; return *this; }
  LD &operator[](int a) {
    if (a == 0) return x;
    if (a == 1) return y;
    return z;
  }
  bool IsZero() { return abs(x) < kEps && abs(
      y) < kEps && abs(z) < kEps; }
  LD DotProd(P3 a) { return x * a.x + y * a.y
      + z * a.z; }
  LD Norm() { return sqrt(x * x + y * y + z *
      z); }
  LD SqNorm() { return x * x + y * y + z * z;
      }
  void NormalizeSelf() { *this /= Norm(); }
  P3 Normalize() {
    P3 res(*this); res.NormalizeSelf();
    return res;
  }
  LD Dis(P3 a) { return (*this - a).Norm(); }
  pair<LD, LD> SphericalAngles() {
    return {atan2(z, sqrt(x * x + y * y)),
        atan2(y, x)};
  }
  LD Area(P3 p) { return Norm() * p.Norm() *
      sin(Angle(p)) / 2; }
  LD Angle(P3 p) {
    LD a = Norm();
    LD b = p.Norm();
    LD c = Dis(p);
    return acos((a * a + b * b - c * c) / (2 *
        a * b));
  }
  LD Angle(P3 p, P3 q) { return p.Angle(q); }
  P3 CrossProd(P3 p) {
    P3 q(*this);
    return {q[1] * p[2] - q[2] * p[1], q[2] *
        p[0] - q[0] * p[2],
            q[0] * p[1] - q[1] * p[0]};
  }
  bool LexCmp(P3 &a, const P3 &b) {
    if (abs(a.x - b.x) > kEps) return a.x < b.
        x;
    if (abs(a.y - b.y) > kEps) return a.y < b.
        y;
    return a.z < b.z;
  }
};
struct Line3 {
  P3 p[2];
  P3 &operator[](int a) { return p[a]; }
  friend ostream &operator<<(ostream &out,
      Line3 m);
};
struct Plane {
  P3 p[3];
  P3 &operator[](int a) { return p[a]; }
  P3 GetNormal() {
    P3 cross = (p[1] - p[0]).CrossProd(p[2] -
        p[0]);
    return cross.Normalize();
  }
  void GetPlaneEq(LD &A, LD &B, LD &C, LD &D)
      {
    P3 normal = GetNormal();
    A = normal[0];
    B = normal[1];
    C = normal[2];
    D = normal.DotProd(p[0]);
    assert(abs(D - normal.DotProd(p[1])) <
        kEps);
    assert(abs(D - normal.DotProd(p[2])) <
        kEps);
  }
  vector<P3> GetOrthonormalBase() {
    P3 normal = GetNormal();
    P3 cand = {-normal.y, normal.x, 0};
    if (abs(cand.x) < kEps && abs(cand.y) <
        kEps) {
      cand = {0, -normal.z, normal.y};
    }
    cand.NormalizeSelf();
    P3 third = Plane{P3{0, 0, 0}, normal, cand
        }.GetNormal();
    assert(abs(normal.DotProd(cand)) < kEps &&
           abs(normal.DotProd(third)) < kEps
               &&
           abs(cand.DotProd(third)) < kEps);
    return {normal, cand, third};
  }
};
struct Circle3 {
  Plane pl; P3 o; LD r;
};
struct Sphere {
  P3 o;
  LD r;
};
// angle PQR
LD Angle(P3 P, P3 Q, P3 R) { return (P - Q).
    Angle(R - Q); }
P3 ProjPtToLine3(P3 p, Line3 l) { // ok
  P3 diff = l[1] - l[0];
  diff.NormalizeSelf();
  return l[0] + diff * (p - l[0]).DotProd(diff
      );
}
LD DisPtLine3(P3 p, Line3 l) { // ok
  //  LD area = Area(p, l[0], l[1]); LD dis1 =
      2 * area / l[0].Dis(l[1]);
  LD dis2 = p.Dis(ProjPtToLine3(p, l)); //
      assert(abs(dis1 - dis2) < kEps);
  return dis2;
}
LD DisPtPlane(P3 p, Plane pl) {
  P3 normal = pl.GetNormal();
  return abs(normal.DotProd(p - pl[0]));
}
P3 ProjPtToPlane(P3 p, Plane pl) {
  P3 normal = pl.GetNormal();
  return p - normal * normal.DotProd(p - pl
      [0]);
}
bool PtBelongToLine3(P3 p, Line3 l) { return
    DisPtLine3(p, l) < kEps; }
bool Lines3Equal(Line3 p, Line3 l) {
  return PtBelongToLine3(p[0], l) &&
      PtBelongToLine3(p[1], l);
}
bool PtBelongToPlane(P3 p, Plane pl) { return
    DisPtPlane(p, pl) < kEps; }
Point PlanePtTo2D(Plane pl, P3 p) { // ok
  assert(PtBelongToPlane(p, pl));
  vector<P3> base = pl.GetOrthonormalBase();
  P3 control{0, 0, 0};
  REP(tr, 3) { control += base[tr] * p.DotProd
      (base[tr]); }
  assert(PtBelongToPlane(pl[0] + base[1], pl))
      ;
  assert(PtBelongToPlane(pl[0] + base[2], pl))
      ;
  assert((p - control).IsZero());
  return {p.DotProd(base[1]), p.DotProd(base
      [2])};
}
Line PlaneLineTo2D(Plane pl, Line3 l) {
  return {PlanePtTo2D(pl, l[0]), PlanePtTo2D(
      pl, l[1])};
}
P3 PlanePtTo3D(Plane pl, Point p) { // ok
  vector<P3> base = pl.GetOrthonormalBase();
  return base[0] * base[0].DotProd(pl[0]) +
      base[1] * p.x + base[2] * p.y;
}
Line3 PlaneLineTo3D(Plane pl, Line l) {
  return {PlanePtTo3D(pl, l[0]), PlanePtTo3D(
      pl, l[1])};
}
Line3 ProjLineToPlane(Line3 l, Plane pl) { //
    ok
  return {ProjPtToPlane(l[0], pl),
      ProjPtToPlane(l[1], pl)};
}
bool Line3BelongToPlane(Line3 l, Plane pl) {
  return PtBelongToPlane(l[0], pl) &&
      PtBelongToPlane(l[1], pl);
}
LD Det(P3 a, P3 b, P3 d) { // ok
  P3 pts[3] = {a, b, d};
  LD res = 0;
  for (int sign : {-1, 1}) {
    REP(st_col, 3) {
      int c = st_col;
      LD prod = 1;
      REP(r, 3) {
        prod *= pts[r][c];
        c = (c + sign + 3) % 3;
      }
      res += sign * prod;
    }
  }
  return res;
}
LD Area(P3 p, P3 q, P3 r) {
  q -= p; r -= p;
  return q.Area(r);
}
vector<Point> InterLineLine(Line &a, Line &b)
    { // working fine
```

```
  Point vec_a = a[1] - a[0];
  Point vec_b1 = b[1] - a[0];
  Point vec_b0 = b[0] - a[0];
  LD tr_area = vec_b1.CrossProd(vec_b0);
  LD quad_area = vec_b1.CrossProd(vec_a) +
      vec_a.CrossProd(vec_b0);
  if (abs(quad_area) < kEps) { // parallel or
      coinciding
    if (abs(b[0].CrossProd(b[1], a[0])) < kEps
        ) {
      return {a[0], a[1]};
    } else return {};
  }
  return {a[0] + vec_a * (tr_area / quad_area)
      };
}
vector<P3> InterLineLine(Line3 k, Line3 l) {
  if (Lines3Equal(k, l)) return {k[0], k[1]};
  if (PtBelongToLine3(l[0], k)) return {l[0]};
  Plane pl{l[0], k[0], k[1]};
  if (!PtBelongToPlane(l[1], pl)) return {};
  Line k2 = PlaneLineTo2D(pl, k);
  Line l2 = PlaneLineTo2D(pl, l);
  vector<Point> inter = InterLineLine(k2, l2);
  vector<P3> res;
  for (auto P : inter) res.push_back(
      PlanePtTo3D(pl, P));
  return res;
}
LD DisLineLine(Line3 l, Line3 k) { // ok
  Plane together{l[0], l[1], l[0] + k[1] - k
      [0]}; // parallel FIXME
  Line3 proj = ProjLineToPlane(k, together);
  P3 inter = (InterLineLine(l, proj))[0];
  P3 on_k_inter = k[0] + inter - proj[0];
  return inter.Dis(on_k_inter);
}
Plane ParallelPlane(Plane pl, P3 A) { // plane
     parallel to pl going through A
  P3 diff = A - ProjPtToPlane(A, pl);
  return {pl[0] + diff, pl[1] + diff, pl[2] +
      diff};
}
// image of B in rotation wrt line passing
     through origin s.t. A1->A2
// implemented in more general case with
     similarity instead of rotation
P3 RotateAccordingly(P3 A1, P3 A2, P3 B1) { //
     ok
  Plane pl{A1, A2, {0, 0, 0}};
  Point A12 = PlanePtTo2D(pl, A1);
  Point A22 = PlanePtTo2D(pl, A2);
  complex<LD> rat = complex<LD>(A22.x, A22.y)
      / complex<LD>(A12.x, A12.y);
  Plane plb = ParallelPlane(pl, B1);
  Point B2 = PlanePtTo2D(plb, B1);
  complex<LD> Brot = rat * complex<LD>(B2.x,
      B2.y);
  return PlanePtTo3D(plb, {Brot.real(), Brot.
      imag()});
}
vector<Circle3> InterSpherePlane(Sphere s,
    Plane pl) { // ok
  P3 proj = ProjPtToPlane(s.o, pl);
  LD dis = s.o.Dis(proj);
  if (dis > s.r + kEps) return {};
  if (dis > s.r - kEps) return {{pl, proj, 0}}
      ; // is it best choice?
  return {{pl, proj, sqrt(s.r * s.r - dis *
      dis)}};
}
bool PtBelongToSphere(Sphere s, P3 p) { return
     abs(s.r - s.o.Dis(p)) < kEps; }
struct PointS { // just for conversion
    purposes, probably toEucl suffices
  LD lat, lon;
  P3 toEucl() { return P3{cos(lat) * cos(lon),
      cos(lat) * sin(lon), sin(lat)}; }
  PointS(P3 p) {
    p.NormalizeSelf();
    lat = asin(p.z);
    lon = acos(p.y / cos(lat));
  }
};
LD DistS(P3 a, P3 b) { return atan2l(b.
    CrossProd(a).Norm(), a.DotProd(b)); }
struct CircleS {
  P3 o; // center of circle on sphere
  LD r; // arc len
  LD area() const { return 2 * kPi * (1 - cos(
      r)); }
};
CircleS From3(P3 a, P3 b, P3 c) { // any three
     different points
  int tmp = 1;
  if ((a - b).Norm() > (c - b).Norm()) {
    swap(a, c); tmp = -tmp;
  }
  if ((b - c).Norm() > (a - c).Norm()) {
    swap(a, b); tmp = -tmp;
  }
  P3 v = (c - b).CrossProd(b - a);
  v = v * (tmp / v.Norm());
  return CircleS{v, DistS(a, v)};
}
CircleS From2(P3 a, P3 b) { // neither the
    same nor the opposite
  P3 mid = (a + b) / 2;
  mid = mid / mid.Norm();
  return From3(a, mid, b);
}
LD SphAngle(P3 A, P3 B, P3 C) { // angle at A,
     no two points opposite
  LD a = B.DotProd(C);
  LD b = C.DotProd(A);
  LD c = A.DotProd(B);
  return acos((b - a * c) / sqrt((1 - Sq(a)) *
      (1 - Sq(c))));
}
LD TriangleArea(P3 A, P3 B, P3 C) { // no two
    poins opposite
  LD a = SphAngle(C, A, B);
  LD b = SphAngle(A, B, C);
  LD c = SphAngle(B, C, A);
  return a + b + c - kPi;
}
vector<P3> IntersectionS(CircleS c1, CircleS
    c2) {
  P3 n = c2.o.CrossProd(c1.o), w = c2.o * cos(
      c1.r) - c1.o * cos(c2.r);
  LD d = n.SqNorm();
  if (d < kEps) return {}; // parallel circles
      (can fully overlap)
  LD a = w.SqNorm() / d;
  vector<P3> res;
  if (a >= 1 + kEps) return res;
  P3 u = n.CrossProd(w) / d;
  if (a > 1 - kEps) {
    res.push_back(u);
    return res;
  }
  LD h = sqrt((1 - a) / d);
  res.push_back(u + n * h);
  res.push_back(u - n * h);
  return res;
}
bool Eq(LD a, LD b) { return abs(a - b) < kEps
    ; }
vector<P3> intersect(Sphere a, Sphere b,
    Sphere c) { // Does not work for 3
    colinear centers
  vector<P3> res; // Bardzo podejrzana funkcja
      .
  P3 ex, ey, ez;
  LD r1 = a.r, r2 = b.r, r3 = c.r, d, cnd_x =
      0, i, j;
  ex = (b.o - a.o).Normalize();
  i = ex.DotProd(c.o - a.o);
  ey = ((c.o - a.o) - ex * i).Normalize();
  ez = ex.CrossProd(ey);
  d = (b.o - a.o).Norm();
  j = ey.DotProd(c.o - a.o);
  bool cnd = 0;
  if (Eq(r2, d - r1)) {
    cnd_x = +r1; cnd = 1;
  }
  if (Eq(r2, d + r1)) {
    cnd_x = -r1; cnd = 1;
  }
  if (!cnd && (r2 < d - r1 || r2 > d + r1))
      return res;
  if (cnd) {
    if (Eq(Sq(r3), (Sq(cnd_x - i) + Sq(j))))
      res.push_back(P3{cnd_x, LD(0), LD(0)});
  } else {
    LD x = (Sq(r1) - Sq(r2) + Sq(d)) / (2 * d)
        ;
    LD y = (Sq(r1) - Sq(r3) + Sq(i) + Sq(j)) /
        (2 * j) - (i / j) * x;
    LD u = Sq(r1) - Sq(x) - Sq(y);
    if (u >= -kEps) {
      LD z = sqrtl(max(LD(0), u));
      res.push_back(P3{x, y, z});
      if (abs(z) > kEps) res.push_back(P3{x, y
          , -z});
    }
  }
  for (auto &it : res) it = a.o + ex * it[0] +
      ey * it[1] + ez * it[2];
  return res;
}
```

Strings (9)

KMP.h

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

d4375c, 16 lines

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

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

Zfunc.h

Description: z[i] computes the length of the longest common prefix of s[i:] and s, except z[0] = 0. (abacaba -> 0010301)
Time: $\mathcal{O}(n)$

ee09e2, 12 lines

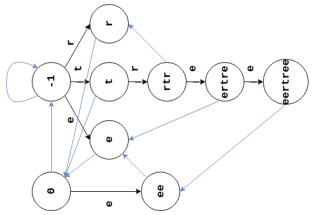
```
vi Z(const string& S) {
  vi z(sz(S));
  int l = -1, r = -1;
  rep(i,1,sz(S)) {
    z[i] = i >= r ? 0 : min(r - i, z[i - l]);
    while (i + z[i] < sz(S) && S[i + z[i]] ==
        S[z[i]])
      z[i]++;
    if (i + z[i] > r)
      l = i, r = i + z[i];
  }
  return z;
}
```

Manacher.h

Description: For each position in a string, computes p[0][i] = half length of longest even palindrome around pos i, p[1][i] = longest odd (half rounded down).
Time: $\mathcal{O}(N)$

e7ad79, 13 lines

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



PalindromicTree.h

Description: Makes a trie of $\mathcal{O}(|S|)$ vertices containing all distinct palindromes of a string. Suffix links give the longest proper suffix/prefix of that palindrome which is also a palindrome.
Usage: S := 1-indexed string. append characters 1-by-1.
After adding the ith character, ptr points to the node containing
the longest palindrome ending at i. Change ALPHA, ID() as problem requires.
Time: $\mathcal{O}(|S|)$

13f2cf, 36 lines

```
const int ALPHA = 26;
struct PalindromicTree {
  struct node {
    int to[ALPHA];
    int link, len;
    node(int a=0, int b=0) : link(a), len(b) {
      memset(to, 0, sizeof to);
  } };
  V<node> T; int ptr;
  int ID(char x) { return x - 'a'; }
  void init() {
    T.clear(); ptr = 1;
    T.emplace_back(0, -1); // 0=Odd root
    T.emplace_back(0, 0);  // 1=Evn root
  }
  void append(int i, string &s) {
    while (s[i - T[ptr].len - 1] != s[i])
      ptr = T[ptr].link;

    int id = ID(s[i]);
    // if node already exists, return
    if (T[ptr].to[id]) return void(ptr = T[ptr
        ].to[id]);
    int tmp = T[ptr].link;
    while (s[i - T[tmp].len - 1] != s[i])
      tmp = T[tmp].link;

    int newlink = T[ptr].len == -1 ? 1 : T[tmp
        ].to[id];

    // ptr is the parent of this new node
    T.emplace_back(newlink, T[ptr].len + 2);

    // Now shift ptr to the newly created node
    T[ptr].to[id] = sz(T) - 1;
    ptr = sz(T) - 1;
  }
};
```

MinRotation.h

Description: Finds the lexicographically smallest rotation of a string.
Usage: rotate(v.begin(), v.begin()+minRotation(v), v.end());
Time: $\mathcal{O}(N)$

d07a42, 8 lines

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

SuffixArray.h

Description: Builds suffix array for a string. sa[i] is the starting index of the suffix which is i'th in the sorted suffix array. The returned vector is of size $n+1$, and sa[0] = n. lcp[i] = lcp(sa[i], sa[i-1]), lcp[0] = 0. The input string must not contain any nul chars.
Time: $\mathcal{O}(n \log n)$

635552, 22 lines

```
struct SuffixArray {
  vi sa, lcp; // passing V<int> also works
  SuffixArray(string s, int lim=256) {
    s.push_back(0); int n = sz(s), k = 0, a,b;
    vi x(all(s)), y(n), ws(max(n, lim));
    sa = lcp = y, iota(all(sa), 0);
    for (int j = 0, p = 0; p < n; j = max(1, j
        * 2), lim = p) {
      p = j, iota(all(y), n - j);
      rep(i,0,n) if(sa[i]>=j) y[p++]=sa[i]-j;
      fill(all(ws), 0);
      rep(i,0,n) ws[x[i]]++;
      rep(i,1,lim) ws[i] += ws[i - 1];
for(int i = n; i--;) sa[--ws[x[y[i]]]] = y[i];
      swap(x, y), p = 1, x[sa[0]] = 0;
      rep(i,1,n) a=sa[i-1], b=sa[i], x[b] =
        (y[a]==y[b] && y[a+j] == y[b+j]) ? p-1
            : p++;
    }
    for (int i=0,j; i<n-1; lcp[x[i++]]=k)
      for (k && k--, j = sa[x[i] - 1];
          s[i + k] == s[j + k]; k++);
  } // loop with no body, wrong indentation
};
```

SuffixTree.h

Description: Ukkonen's algorithm for online suffix tree construction. Each node contains indices [l, r) into the string, and a list of child nodes. Suffixes are given by traversals of this tree, joining [l, r) substrings. The root is 0 (has l = -1, r = 0), non-existent children are -1. To get a complete tree, append a dummy symbol – otherwise it may contain an incomplete path (still useful for substring matching, though).
Time: $\mathcal{O}(26N)$

ca8d4d, 50 lines

```
struct SuffixTree { // N ~ 2*maxlen+10
  enum { N = 200010, ALP = 26 };
  int toi(char c) { return c - 'a'; }
  string a; // v = cur node, q = cur position
int t[N][ALP],l[N],r[N],p[N],s[N],v=0,q=0,m=2;

  void ukkadd(int i, int c) { suff:
    if (r[v]<=q) {
      if (t[v][c]==-1) { t[v][c]=m;  l[m]=i;
        p[m++]=v; v=s[v]; q=r[v]; goto suff; }
      v=t[v][c]; q=l[v];
    }
    if (q==-1 || c==toi(a[q])) q++; else {
      l[m+1]=i;  p[m+1]=m;  l[m]=l[v]; r[m]=q;
      p[m]=p[v];  t[m][c]=m+1;
      t[m][toi(a[q])] = v;
      l[v]=q;  p[v]=m;
      t[p[m]][toi(a[l[m]])] = m;
      v=s[p[m]];  q=l[m];
      while (q<r[m]) { v=t[v][toi(a[q])];  q+=
          r[v]-l[v]; }
      if (q==r[m])  s[m]=v;  else s[m]=m+2;
      q=r[v]-(q-r[m]);  m+=2;  goto suff;
    }
  }
  SuffixTree(string a) : a(a) {
    fill(r,r+N,sz(a));
    memset(s, 0, sizeof s);
    memset(t, -1, sizeof t);
    fill(t[1],t[1]+ALP,0);
    s[0] = 1; l[0] = l[1] = -1; r[0] = r[1] =
        p[0] = p[1] = 0;
    rep(i,0,sz(a)) ukkadd(i, toi(a[i]));
  }
  // example: find longest common substring (
      uses ALP = 28)
  pii best;
  int lcs(int node, int i1, int i2, int olen)
      {
    if (l[node]<=i1 && i1<r[node]) return 1;
    if (l[node]<=i2 && i2<r[node]) return 2;
    int mask = 0, len = node ? olen + (r[node]
        - l[node]) : 0;
    rep(c,0,ALP) if (t[node][c] != -1)
      mask |= lcs(t[node][c], i1, i2, len);
    if (mask == 3)
      best = max(best, {len, r[node] - len});
    return mask;
  }
  static pii LCS(string s, string t) {
    SuffixTree st(s + (char)('z' + 1) + t + (
        char)('z' + 2));
    st.lcs(0, sz(s), sz(s) + 1 + sz(t), 0);
    return st.best;
  }
};
```

Hashing.h

Description: Static hashing for 0-indexed string. Intervals are $[l, r]$.

82983c, 20 lines

```
template<const ll M, const ll B>
struct Hashing {
  int n; V<ll> h, pw;
  Hashing(const string &s) : n(sz(s)),h(n+1),
      pw(n+1) {
    pw[0] = 1; // ^^ s is 0 indexed
    for (int i = 1; i <= n; ++i)
      pw[i] = (pw[i-1] * B) % M,
      h[i] = (h[i-1] * B + s[i-1]) % M;
  }
  ll eval(int l, int r) { // assert(l <= r);
    return (h[r+1] - ((h[l] * pw[r-l+1])%M) +
        M)%M;
} };
struct Double_Hash {
  using H1 = Hashing<916969619, 101>;
  using H2 = Hashing<285646799, 103>;
  H1 h1; H2 h2;
  Double_Hash(const string &s):h1(s),h2(s){}
  pii eval(int l, int r)
    { return {h1.eval(l,r), h2.eval(l,r)}; }
};
```

HashingDynamic.h

Description: Hashing with point updates on string (0-indexed). upd(i, x): s[i] += x. Intervals are $[l, r]$.
Time: $\mathcal{O}(n \log n)$

c51931, 33 lines

```
template<const ll M, const ll B>
struct Dynamic_Hashing {
  int n; V<ll> h, pw;
  void upd(int pos, int c_add) {
    if (c_add < 0) c_add = (c_add + M) % M;
    for (int i = ++pos; i <= n; i += i&-i)
      h[i] = (h[i]+c_add *1LL* pw[i - pos])%M;
  }
  ll get(int pos, int r = 0) {
    for (int i = ++pos, j = 0; i; i -= i&-i) {
      r = (r + h[i] * 1LL * pw[j]) % M;
      j += i&-i;
    } return r;
  }
  Dynamic_Hashing(const string &s) : n(sz(s)),
      h(n+1), pw(n+1) {
    pw[0] = 1; // ^^ s is 0 indexed
    for (int i = 1; i <= n; ++i) pw[i] = (pw[i
        -1] * 1LL * B) % M;
    for (int i = 0; i < n; ++i) upd(i, s[i]);
  }
  ll eval(int l, int r) { // assert(l <= r);
    return (get(r) - ((get(l-1) * 1LL * pw[r-l
        +1]) % M) + M) % M;
} };
struct Double_Dynamic {
  using DH1 = Dynamic_Hashing<916969619, 571>;
  using DH2 = Dynamic_Hashing<285646799, 953>;
  DH1 h1; DH2 h2;
  Double_Dynamic(const string &s) : h1(s), h2(
      s) {}
  void upd(int pos, int c_add) {
    h1.upd(pos, c_add);
    h2.upd(pos, c_add);
  } pll eval(int l, int r)
    { return {h1.eval(l,r), h2.eval(l,r)}; }
};
```

AhoCorasick-arman.h

Usage: insert strings first (0-indexed). Then call prepare to use everything. link = suffix link. to[ch] = trie transition. jump[ch] = aho transition to ch using links.
Time: $\mathcal{O}(AL)$

36fabb, 35 lines

```
const int L = 5000; // Total no of characters
const int A = 10; // Alphabet size

struct Aho_Corasick {
  struct Node {
    bool end_flag;
    int par, pch, to[A], link, jump[A];
    Node() {
      par = link = end_flag = 0;
      memset(to, 0, sizeof to);
      memset(jump, 0, sizeof jump);
    }
  }; Node t[L]; int at;
  Aho_Corasick() { at = 0; }

  void insert(string &s) {
    int u = 0;
    for (auto ch : s) {
      int &v = t[u].to[ch - '0'];
      if (!v) v = ++at;
      t[v].par = u; t[v].pch = ch - '0'; u=v;
    } t[u].end_flag = true;
  }
  void prepare() {
    for(queue<int>q({0});!q.empty();q.pop()){
      int u = q.front(), w = t[u].link;
      for (int ch = 0; ch < A; ++ch) {
        int v = t[u].to[ch];
        if (v) {
          t[v].link = t[w].jump[ch];
```

```
        q.push(v);
      }
      t[u].jump[ch] = v ? v : t[w].jump[ch];
  } } }
}aho;
```

Various (10)

Random.h

Description: Nice uniform real/int distribution wrapper

24d233, 9 lines

```
mt19937 rng(chrono::steady_clock::now().
    time_since_epoch().count());
// use mt19937_64 for long long
uniform_int_distribution<int> dist1(lo, hi);
uniform_real_distribution<> dist2(lo, hi);
// Usage
#define rand(l,r) uniform_int_distribution<ll
    >(l, r)(rng_64)
int val = rng(), val3 = dist1(rng);
ll val2 = rng_64(); double val4 = dist2(rng);
shuffle(vec.begin(), vec.end(), rng);
```

10.1 Intervals

IntervalContainer.h

Description: Add and remove intervals from a set of disjoint intervals. Will merge the added interval with any overlapping intervals in the set when adding. Intervals are [inclusive, exclusive).
Time: $\mathcal{O}(\log N)$

edce47, 23 lines

```
set<pii>::iterator addInterval(set<pii>& is,
    int L, int R) {
  if (L == R) return is.end();
  auto it=is.lower_bound({L, R}), before=it;
  while (it != is.end() && it->first <= R) {
    R = max(R, it->second);
    before = it = is.erase(it);
  }
  if (it != is.begin() && (--it)->second >= L)
      {
    L = min(L, it->first);
    R = max(R, it->second);
    is.erase(it);
  }
  return is.insert(before, {L,R});
}

void removeInterval(set<pii>& is,int L,int R){
  if (L == R) return;
  auto it = addInterval(is, L, R);
  auto r2 = it->second;
  if (it->first == L) is.erase(it);
  else (int&)it->second = L;
  if (R != r2) is.emplace(R, r2);
}
```

IntervalCover.h

Description: Compute indices of smallest set of intervals covering another interval. Intervals should be [inclusive, exclusive). To support [inclusive, inclusive], change (A) to add `|| R.empty()`. Returns empty set on failure (or if G is empty).
Time: $\mathcal{O}(N \log N)$

9e9d8d, 18 lines

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

ConstantIntervals.h

Description: Split a monotone function on [from, to) into a minimal set of half-open intervals on which it has the same value. Runs a callback g for each such interval.
Usage: `constantIntervals(0, sz(v), [&](int x){return v[x];}, [&](int lo, int hi, T val){...});`
Time: $\mathcal{O}\left(k \log \frac{n}{k}\right)$

753a4c, 19 lines

```
template<class F, class G, class T>
void rec(int from, int to, F& f, G& g, int& i,
      T& p, T q) {
  if (p == q) return;
  if (from == to) {
    g(i, to, p);
    i = to; p = q;
  } else {
    int mid = (from + to) >> 1;
    rec(from, mid, f, g, i, p, f(mid));
    rec(mid+1, to, f, g, i, p, q);
  }
}
template<class F, class G>
void constantIntervals(int from, int to, F f,
    G g) {
  if (to <= from) return;
  int i = from; auto p = f(i), q = f(to-1);
  rec(from, to-1, f, g, i, p, q);
  g(i, to, q);
}
```

10.2 Misc. algorithms

LIS.h

Description: Compute indices for the longest increasing subsequence.
Time: $\mathcal{O}(N \log N)$

2932a0, 17 lines

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

FastKnapsack.h

Description: Given N non-negative integer weights w and a non-negative target t, computes the maximum S <= t such that S is the sum of some subset of the weights.
Time: $\mathcal{O}(N \max(w_i))$

b20ccc, 16 lines

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

10.3 Dynamic programming

KnuthDP.h

Description: When doing DP on intervals: $a[i][j] = \min_{i<k<j}(a[i][k] + a[k][j]) + f(i,j)$, where the (minimal) optimal k increases with both i and j, one can solve intervals in increasing order of length, and search $k = p[i][j]$ for $a[i][j]$ only between $p[i][j-1]$ and $p[i+1][j]$. This is known as Knuth DP. Sufficient criteria for this are if $f(b,c) \le f(a,d)$ and $f(a,c) + f(b,d) \le f(a,d) + f(b,c)$ for all $a \le b \le c \le d$. Consider also: LineContainer (ch. Data structures), monotone queues, ternary search.
Time: $\mathcal{O}\left(N^2\right)$

DivideAndConquerDP.h

Description: Given $a[i] = \min_{lo(i) \le k < hi(i)}(f(i,k))$ where the (minimal) optimal k increases with i, computes $a[i]$ for $i = L..R-1$.
Time: $\mathcal{O}\left((N + (hi - lo)) \log N\right)$

d38d2b, 18 lines

```
struct DP { // Modify at will:
  int lo(int ind) { return 0; }
  int hi(int ind) { return ind; }
  ll f(int ind, int k) { return dp[ind][k]; }
  void store(int ind, int k, ll v) { res[ind]
      = pii(k, v); }

  void rec(int L, int R, int LO, int HI) {
    if (L >= R) return;
    int mid = (L + R) >> 1;
    pair<ll, int> best(LLONG_MAX, LO);
    rep(k, max(LO,lo(mid)), min(HI,hi(mid)))
      best = min(best, make_pair(f(mid, k), k)
          );
    store(mid, best.second, best.first);
    rec(L, mid, LO, best.second+1);
    rec(mid+1, R, best.second, HI);
  }
  void solve(int L, int R) { rec(L, R, INT_MIN
      , INT_MAX); }
};
```

10.4 Debugging tricks

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

10.5 Optimization tricks

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

10.5.1 Bit hacks

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

10.5.2 Pragmas

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

FastMod.h

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

751a02, 8 lines

```
typedef unsigned long long ull;
```

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

FastInput.h

Description: Read an integer from stdin. Usage requires your program to pipe in input from file.
Usage: `./a.out < input.txt`
Time: About 5x as fast as cin/scanf.

7b3c70, 15 lines

```
inline char gc() { // like getchar()
  static char buf[1 << 16];
  static size_t bc, be;
  if (bc >= be) {
    buf[0] = 0, bc = 0;
    be = fread(buf, 1, sizeof(buf), stdin);
  } return buf[bc++]; // returns 0 on EOF
}
int readInt() {
  int a, c;
  while ((a = gc()) < 40);
  if (a == '-') return -readInt();
  while ((c = gc()) >= 48) a = a*10+c-480;
  return a - 48;
}
```

BumpAllocator.h

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

745db2, 8 lines

```
// Either globally or in a single class:
static char buf[450 << 20];
void* operator new(size_t s) {
  static size_t i = sizeof buf;
  assert(s < i);
  return (void*)&buf[i -= s];
}
void operator delete(void*) {}
```

SmallPtr.h

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

"BumpAllocator.h" 2dd6c9, 10 lines

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

BumpAllocatorSTL.h

Description: BumpAllocator for STL containers.

Usage: `vector<vector<int, small<int>>> ed(N);`

bb66d4, 14 lines

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

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

Unrolling.h

5e0f99, 14 lines

```
#define F {...; ++i;}
int i = from;
while (i&3 && i < to) F // for alignment, if
    needed
while (i + 4 <= to) { F F F F }
while (i < to) F

int n32 = n / 32;
while (n32--) {
#define F(i) a[i] = a[i] == x ? y : a[i];
#define FP(i) F(i+0) F(i+1) F(i+2) F(i+3)
  FP(0); FP(4); FP(8); FP(12);
  FP(16); FP(20); FP(24); FP(28);
  a += 32;
}
```

Polynomial-shohag.h

e69b89, 542 lines

```
const int N = 3e5 + 9, mod = 998244353;

struct base {
  double x, y;
  base() { x = y = 0; }
  base(double x, double y): x(x), y(y) { }
};
inline base operator + (base a, base b) {
    return base(a.x + b.x, a.y + b.y); }
inline base operator - (base a, base b) {
    return base(a.x - b.x, a.y - b.y); }
inline base operator * (base a, base b) {
    return base(a.x * b.x - a.y * b.y, a.x * b
    .y + a.y * b.x); }
inline base conj(base a) { return base(a.x, -a
    .y); }
int lim = 1;
vector<base> roots = {{0, 0}, {1, 0}};
vector<int> rev = {0, 1};
const double PI = acosl(-1.0);
void ensure_base(int p) {
  if(p <= lim) return;
  rev.resize(1 << p);
  for(int i = 0; i < (1 << p); i++) rev[i] = (
      rev[i >> 1] >> 1) + ((i & 1) << (p -
      1));
  roots.resize(1 << p);
  while(lim < p) {
    double angle = 2 * PI / (1 << (lim + 1));
    for(int i = 1 << (lim - 1); i < (1 << lim)
        ; i++) {
      roots[i << 1] = roots[i];
      double angle_i = angle * (2 * i + 1 - (1
          << lim));
      roots[(i << 1) + 1] = base(cos(angle_i),
          sin(angle_i));
    }
    lim++;
  }
}
void fft(vector<base> &a, int n = -1) {
  if(n == -1) n = a.size();
  assert((n & (n - 1)) == 0);
  int zeros = __builtin_ctz(n);
  ensure_base(zeros);
  int shift = lim - zeros;
  for(int i = 0; i < n; i++) if(i < (rev[i] >>
      shift)) swap(a[i], a[rev[i] >> shift]);
  for(int k = 1; k < n; k <<= 1) {
    for(int i = 0; i < n; i += 2 * k) {
      for(int j = 0; j < k; j++) {
        base z = a[i + j + k] * roots[j + k];
        a[i + j + k] = a[i + j] - z;
        a[i + j] = a[i + j] + z;
      }
    }
  }
}
//eq = 0: 4 FFTs in total. eq = 1: 3 FFTs in
    total
vector<int> multiply(vector<int> &a, vector<
    int> &b, int eq = 0) {
  int need = a.size() + b.size() - 1;
  int p = 0;
  while((1 << p) < need) p++;
  ensure_base(p);
  int sz = 1 << p;
  vector<base> A, B;
  if(sz > (int)A.size()) A.resize(sz);
  for(int i = 0; i < (int)a.size(); i++) {
    int x = (a[i] % mod + mod) % mod;
    A[i] = base(x & ((1 << 15) - 1), x >> 15);
  }
  fill(A.begin() + a.size(), A.begin() + sz,
      base{0, 0});
  fft(A, sz);
  if(sz > (int)B.size()) B.resize(sz);
  if(eq) copy(A.begin(), A.begin() + sz, B.
      begin());
  else {
    for(int i = 0; i < (int)b.size(); i++) {
      int x = (b[i] % mod + mod) % mod;
      B[i] = base(x & ((1 << 15) - 1), x >>
          15);
    }
    fill(B.begin() + b.size(), B.begin() + sz,
        base{0, 0});
    fft(B, sz);
  }
  double ratio = 0.25 / sz;
  base r2(0,  - 1), r3(ratio, 0), r4(0,  -
      ratio), r5(0, 1);
  for(int i = 0; i <= (sz >> 1); i++) {
    int j = (sz - i) & (sz - 1);
    base a1 = (A[i] + conj(A[j])), a2 = (A[i]
        - conj(A[j])) * r2;
    base b1 = (B[i] + conj(B[j])) * r3, b2 = (
        B[i] - conj(B[j])) * r4;
    if(i != j) {
      base c1 = (A[j] + conj(A[i])), c2 = (A[j
          ] - conj(A[i])) * r2;
      base d1 = (B[j] + conj(B[i])) * r3, d2 =
          (B[j] - conj(B[i])) * r4;
      A[i] = c1 * d1 + c2 * d2 * r5;
      B[i] = c1 * d2 + c2 * d1;
    }
    A[j] = a1 * b1 + a2 * b2 * r5;
    B[j] = a1 * b2 + a2 * b1;
  }
  fft(A, sz); fft(B, sz);
  vector<int> res(need);
  for(int i = 0; i < need; i++) {
    long long aa = A[i].x + 0.5;
    long long bb = B[i].x + 0.5;
    long long cc = A[i].y + 0.5;
    res[i] = (aa + ((bb % mod) << 15) + ((cc %
        mod) << 30))%mod;
  }
  return res;
}
template <int32_t MOD>
struct modint {
  int32_t value;
  modint() = default;
  modint(int32_t value_) : value(value_) {}
  inline modint<MOD> operator + (modint<MOD>
      other) const { int32_t c = this->value +
      other.value; return modint<MOD>(c >=
      MOD ? c - MOD : c); }
  inline modint<MOD> operator - (modint<MOD>
      other) const { int32_t c = this->value -
      other.value; return modint<MOD>(c <
      0 ? c + MOD : c); }
  inline modint<MOD> operator * (modint<MOD>
      other) const { int32_t c = (int64_t)this
      ->value * other.value % MOD; return
      modint<MOD>(c < 0 ? c + MOD : c); }
  inline modint<MOD> & operator += (modint<MOD
      > other) { this->value += other.value;
      if (this->value >= MOD) this->value -=
      MOD; return *this; }
  inline modint<MOD> & operator -= (modint<MOD
      > other) { this->value -= other.value;
      if (this->value <    0) this->value +=
      MOD; return *this; }
  inline modint<MOD> & operator *= (modint<MOD
      > other) { this->value = (int64_t)this->
      value * other.value % MOD; if (this->
      value < 0) this->value += MOD; return *
      this; }
  inline modint<MOD> operator - () const {
      return modint<MOD>(this->value ? MOD -
      this->value : 0); }
  modint<MOD> pow(uint64_t k) const {
    modint<MOD> x = *this, y = 1;
    for (; k; k >>= 1) {
      if (k & 1) y *= x;
      x *= x;
    }
    return y;
  }
  modint sqrt() const {
    if (value == 0) return 0;
    if (MOD == 2) return 1;
    if (pow((MOD - 1) >> 1) == MOD - 1)
        return 0; // does not exist, it should
        be -1, but kept as 0 for this program
    unsigned int Q = MOD - 1, M = 0, i;
    modint zQ; while (!(Q & 1)) Q >>= 1, M++;
    for (int z = 1;; z++) {
```

```
      if (modint(z).pow((MOD - 1) >> 1) == MOD
          - 1) {
        zQ = modint(z).pow(Q); break;
      }
    }
    modint t = pow(Q), R = pow((Q + 1) >> 1),
        r;
    while (true) {
      if (t == 1) { r = R; break; }
      for (i = 1; modint(t).pow(1 << i) != 1;
          i++);
      modint b = modint(zQ).pow(1 << (M - 1 -
          i));
      M = i, zQ = b * b, t = t * zQ, R = R * b
          ;
    }
    return min(r, - r + MOD);
  }
  modint<MOD> inv() const { return pow(MOD -
      2); }  // MOD must be a prime
  inline modint<MOD> operator /  (modint<MOD>
      other) const { return *this *  other.inv
      (); }
  inline modint<MOD> operator /= (modint<MOD>
      other)       { return *this *= other.inv
      (); }
  inline bool operator == (modint<MOD> other)
      const { return value == other.value; }
  inline bool operator != (modint<MOD> other)
      const { return value != other.value; }
  inline bool operator < (modint<MOD> other)
      const { return value < other.value; }
  inline bool operator > (modint<MOD> other)
      const { return value > other.value; }
};
template <int32_t MOD> modint<MOD> operator *
    (int64_t value, modint<MOD> n) { return
    modint<MOD>(value) * n; }
template <int32_t MOD> modint<MOD> operator *
    (int32_t value, modint<MOD> n) { return
    modint<MOD>(value % MOD) * n; }
template <int32_t MOD> ostream & operator << (
    ostream & out, modint<MOD> n) { return out
     << n.value; }

using mint = modint<mod>;
struct poly {
  vector<mint> a;
  inline void normalize() {
    while((int)a.size() && a.back() == 0) a.
        pop_back();
  }
  template<class...Args> poly(Args...args): a(
      args...) { }
  poly(const initializer_list<mint> &x): a(x.
      begin(), x.end()) { }
  int size() const { return (int)a.size(); }
  inline mint coef(const int i) const { return
      (i < a.size() && i >= 0) ? a[i]: mint
      (0); }
  mint operator[](const int i) const { return
      (i < a.size() && i >= 0) ? a[i]: mint(0)
      ; } //Beware!! p[i] = k won't change the
       value of p.a[i]
  bool is_zero() const {
    for (int i = 0; i < size(); i++) if (a[i]
        != 0) return 0;
    return 1;
  }
  poly operator + (const poly &x) const {
    int n = max(size(), x.size());
    vector<mint> ans(n);
    for(int i = 0; i < n; i++) ans[i] = coef(i
        ) + x.coef(i);
    while ((int)ans.size() && ans.back() == 0)
        ans.pop_back();
    return ans;
  }
  poly operator - (const poly &x) const {
    int n = max(size(), x.size());
    vector<mint> ans(n);
    for(int i = 0; i < n; i++) ans[i] = coef(i
        ) - x.coef(i);
    while ((int)ans.size() && ans.back() == 0)
        ans.pop_back();
    return ans;
  }
  poly operator * (const poly& b) const {
    if(is_zero() || b.is_zero()) return {};
    vector<int> A, B;
    for(auto x: a) A.push_back(x.value);
    for(auto x: b.a) B.push_back(x.value);
    auto res = multiply(A, B, (A == B));
    vector<mint> ans;
    for(auto x: res) ans.push_back(mint(x));
    while ((int)ans.size() && ans.back() == 0)
        ans.pop_back();
    return ans;
  }
  poly operator * (const mint& x) const {
    int n = size();
    vector<mint> ans(n);
    for(int i = 0; i < n; i++) ans[i] = a[i] *
        x;
    return ans;
  }
  poly operator / (const mint &x) const{
      return (*this) * x.inv(); }
  poly& operator += (const poly &x) { return *
      this = (*this) + x; }
  poly& operator -= (const poly &x) { return *
      this = (*this) - x; }
  poly& operator *= (const poly &x) { return *
      this = (*this) * x; }
  poly& operator *= (const mint &x) { return *
      this = (*this) * x; }
  poly& operator /= (const mint &x) { return *
      this = (*this) / x; }
  poly mod_xk(int k) const { return {a.begin()
      , a.begin() + min(k, size())}; } //
      modulo by x^k
  poly mul_xk(int k) const { // multiply by x^
      k
    poly ans(*this);
    ans.a.insert(ans.a.begin(), k, 0);
    return ans;
  }
  poly div_xk(int k) const { // divide by x^k
    return vector<mint>(a.begin() + min(k, (
        int)a.size()), a.end());
  }
  poly substr(int l, int r) const { // return
      mod_xk(r).div_xk(l)
    l = min(l, size());
    r = min(r, size());
    return vector<mint>(a.begin() + l, a.begin
        () + r);
  }
  poly reverse_it(int n, bool rev = 0) const {
       // reverses and leaves only n terms
    poly ans(*this);
    if(rev) { // if rev = 1 then tail goes to
        head
      ans.a.resize(max(n, (int)ans.a.size()));
    }
    reverse(ans.a.begin(), ans.a.end());
    return ans.mod_xk(n);
  }
  poly differentiate() const {
    int n = size(); vector<mint> ans(n);
    for(int i = 1; i < size(); i++) ans[i - 1]
        = coef(i) * i;
    return ans;
  }
  poly integrate() const {
    int n = size(); vector<mint> ans(n + 1);
    for(int i = 0; i < size(); i++) ans[i + 1]
        = coef(i) / (i + 1);
    return ans;
  }
  poly inverse(int n) const {  // 1 / p(x) % x
      ^n, O(nlogn)
    assert(!is_zero()); assert(a[0] != 0);
    poly ans{mint(1) / a[0]};
    for(int i = 1; i < n; i *= 2) {
      ans = (ans * mint(2) - ans * ans *
          mod_xk(2 * i)).mod_xk(2 * i);
    }
    return ans.mod_xk(n);
  }
  pair<poly, poly> divmod_slow(const poly &b)
      const { // when divisor or quotient is
      small
    vector<mint> A(a);
    vector<mint> ans;
    while(A.size() >= b.a.size()) {
      ans.push_back(A.back() / b.a.back());
      if(ans.back() != mint(0)) {
        for(size_t i = 0; i < b.a.size(); i++)
            {
          A[A.size() - i - 1] -= ans.back() *
              b.a[b.a.size() - i - 1];
        }
      }
      A.pop_back();
    }
    reverse(ans.begin(), ans.end());
    return {ans, A};
  }
  pair<poly, poly> divmod(const poly &b) const
       { // returns quotient and remainder of
      a mod b
    if(size() < b.size()) return {poly{0}, *
        this};
    int d = size() - b.size();
    if(min(d, b.size()) < 250) return
        divmod_slow(b);
    poly D = (reverse_it(d + 1) * b.reverse_it
        (d + 1).inverse(d + 1)).mod_xk(d + 1).
        reverse_it(d + 1, 1);
    return {D, *this - (D * b)};
  }
  poly operator / (const poly &t) const {
      return divmod(t).first;}
  poly operator % (const poly &t) const {
      return divmod(t).second;}
  poly& operator /= (const poly &t) {return *
      this = divmod(t).first;}
  poly& operator %= (const poly &t) {return *
      this = divmod(t).second;}
  poly log(int n) const { //ln p(x) mod x^n
    assert(a[0] == 1);
    return (differentiate().mod_xk(n) *
        inverse(n)).integrate().mod_xk(n);
  }
  poly exp(int n) const { //e ^ p(x) mod x^n
    if(is_zero()) return {1};
    assert(a[0] == 0);
    poly ans({1});
    int i = 1;
    while(i < n) {
      poly C = ans.log(2 * i).div_xk(i) -
          substr(i, 2 * i);
      ans -= (ans * C).mod_xk(i).mul_xk(i);
      i *= 2;
    }
    return ans.mod_xk(n);
  }
  //better for small k, k < 100000
  poly pow(int k, int n) const { // p(x)^k mod
      x^n
    if(is_zero()) return *this;
    poly ans({1}), b = mod_xk(n);
    while(k) {
      if(k & 1) ans = (ans * b).mod_xk(n);
      b = (b * b).mod_xk(n);
      k >>= 1;
    }
    return ans;
  }
  int leading_xk() const { //minimum i such
      that C[i] > 0
    if(is_zero()) return 1000000000;
    int res = 0; while(a[res] == 0) res++;
    return res;
  }
  //better for k > 100000
  poly pow2(int k, int n) const { // p(x)^k
      mod x^n
    if(is_zero()) return *this;
    int i = leading_xk();
    mint j = a[i];
    poly t = div_xk(i) / j;
    poly ans = (t.log(n) * mint(k)).exp(n);
    if (1LL * i * k > n) ans = {0};
    else ans = ans.mul_xk(i * k).mod_xk(n);
    ans *= (j.pow(k));
    return ans;
  }
  // if the poly is not zero but the result is
       zero, then no solution
  poly sqrt(int n) const {
    if ((*this)[0] == mint(0)) {
      for (int i = 1; i < size(); i++) {
        if ((*this)[i] != mint(0)) {
          if (i & 1) return {};
          if (n - i / 2 <= 0) break;
          return div_xk(i).sqrt(n - i / 2).
              mul_xk(i / 2);
        }
      }
      return {};
    }
    mint s = (*this)[0].sqrt();
    if (s == 0)  return {};
```

```
  poly y = *this / (*this)[0];
  poly ret({1});
  mint inv2 = mint(1) / 2;
  for (int i = 1; i < n; i <<= 1) {
    ret = (ret + y.mod_xk(i << 1) * ret.
        inverse(i << 1)) * inv2;
  }
  return ret.mod_xk(n) * s;
}
poly root(int n, int k = 2) const { //kth
    root of p(x) mod x^n
  if(is_zero()) return *this;
  if (k == 1) return mod_xk(n);
  assert(a[0] == 1);
  poly q({1});
  for(int i = 1; i < n; i <<= 1){
    if(k == 2) q += mod_xk(2 * i) * q.
        inverse(2 * i);
    else q = q * mint(k - 1) + mod_xk(2 * i)
         * q.inverse(2 * i).pow(k - 1, 2 * i
        );
    q = q.mod_xk(2 * i) / mint(k);
  }
  return q.mod_xk(n);
}
poly mulx(mint x) { //component-wise
    multiplication with x^k
  mint cur = 1; poly ans(*this);
  for(int i = 0; i < size(); i++) ans.a[i]
      *= cur, cur *= x;
  return ans;
}
poly mulx_sq(mint x) { //component-wise
    multiplication with x^{k^2}
  mint cur = x, total = 1, xx = x * x; poly
      ans(*this);
  for(int i = 0; i < size(); i++) ans.a[i]
      *= total, total *= cur, cur *= xx;
  return ans;
}
vector<mint> chirpz_even(mint z, int n) { //
    P(1), P(z^2), P(z^4), ..., P(z^2(n-1))
  int m = size() - 1;
  if(is_zero()) return vector<mint>(n, 0);
  vector<mint> vv(m + n);
  mint iz = z.inv(), zz = iz * iz, cur = iz,
       total = 1;
  for(int i = 0; i <= max(n - 1, m); i++) {
    if(i <= m) vv[m - i] = total;
    if(i < n) vv[m + i] = total;
    total *= cur; cur *= zz;
  }
  poly w = (mulx_sq(z) * vv).substr(m, m + n
      ).mulx_sq(z);
  vector<mint> ans(n);
  for(int i = 0; i < n; i++) ans[i] = w[i];
  return ans;
}
//O(nlogn)
vector<mint> chirpz(mint z, int n) { //P(1),
    P(z), P(z^2), ..., P(z^(n-1))
  auto even = chirpz_even(z, (n + 1) / 2);
  auto odd = mulx(z).chirpz_even(z, n / 2);
  vector<mint> ans(n);
  for(int i = 0; i < n / 2; i++) {
    ans[2 * i] = even[i];
    ans[2 * i + 1] = odd[i];
  }
  if(n % 2 == 1) ans[n - 1] = even.back();
  return ans;
}
poly shift_it(int m, vector<poly> &pw) {
  if (size() <= 1) return *this;
  while (m >= size()) m /= 2;
  poly q(a.begin() + m, a.end());
  return q.shift_it(m, pw) * pw[m] + mod_xk(
      m).shift_it(m, pw);
};
//n log(n)
poly shift(mint a) { //p(x + a)
  int n = size();
  if (n == 1) return *this;
  vector<poly> pw(n);
  pw[0] = poly({1});
  pw[1] = poly({a, 1});
  int i = 2;
  for (; i < n; i *= 2) pw[i] = pw[i / 2] *
      pw[i / 2];
  return shift_it(i, pw);
}
mint eval(mint x) { // evaluates in single
    point x
  mint ans(0);
  for(int i = size() - 1; i >= 0; i--) {
    ans *= x;
    ans += a[i];
  }
  return ans;
}
// p(g(x))
// O(n^2 logn)
poly composition_brute(poly g, int deg){
  int n = size();
  poly c(deg, 0), pw({1});
  for (int i = 0; i < min(deg, n); i++){
    int d = min(deg, (int)pw.size());
    for (int j = 0; j < d; j++){
      c.a[j] += coef(i) * pw[j];
    }
    pw *= g;
    if (pw.size() > deg) pw.a.resize(deg);
  }
  return c;
}
// p(g(x))
// O(nlogn * sqrt(nlogn))
poly composition(poly g, int deg) {
  int n = size();
  int k = 1;
  while (k * k <= n) k++;
  k--;
  int d = n / k;
  if (k * d < n) d++;
  vector<poly> pw(k + 3, poly({1}));
  for(int i = 1; i <= k + 2; i++) {
    pw[i] = pw[i - 1] * g;
    if (pw[i].size() > deg) pw[i].a.resize(
        deg);
  }
  vector<poly> fi(k, poly(deg, 0));
  for (int i = 0; i < k; i++) {
    for (int j = 0; j < d; j++) {
      int idx = i * d + j;
      if (idx >= n) break;
      int sz = min(fi[i].size(), pw[j].size
          ());
      for (int t = 0; t < sz; t++) {
        fi[i].a[t] += pw[j][t] * coef(idx);
      }
    }
  }
  poly ret(deg, 0), gd({1});
  for (int i = 0; i < k; i++){
    fi[i] = fi[i] * gd;
    int sz = min((int)ret.size(), (int)fi[i
        ].size());
    for (int j = 0; j < sz; j++) ret.a[j] +=
        fi[i][j];
    gd = gd * pw[d];
    if (gd.size() > deg) gd.a.resize(deg);
  }
  return ret;
}
poly build(vector<poly> &ans, int v, int l,
    int r, vector<mint> &vec) { //builds
    evaluation tree for (x-a1)(x-a2)...(x-an
    )
  if(l == r) return ans[v] = poly({-vec[l],
      1});
  int mid = l + r >> 1;
  return ans[v] = build(ans, 2 * v, l, mid,
      vec) * build(ans, 2 * v + 1, mid + 1,
      r, vec);
}
vector<mint> eval(vector<poly> &tree, int v,
    int l, int r, vector<mint> &vec) { //
    auxiliary evaluation function
  if(l == r) return {eval(vec[l])};
  if (size() < 400) {
    vector<mint> ans(r - l + 1, 0);
    for (int i = l; i <= r; i++) ans[i - l]
        = eval(vec[i]);
    return ans;
  }
  int mid = l + r >> 1;
  auto A = (*this % tree[2 * v]).eval(tree,
      2 * v, l, mid, vec);
  auto B = (*this % tree[2 * v + 1]).eval(
      tree, 2 * v + 1, mid + 1, r, vec);
  A.insert(A.end(), B.begin(), B.end());
  return A;
}
//O(nlog^2n)
vector<mint> eval(vector<mint> x) {//
    evaluate polynomial in (x_0, ..., x_n-1)
  int n = x.size();
  if(is_zero()) return vector<mint>(n, mint
      (0));
  vector<poly> tree(4 * n);
  build(tree, 1, 0, n - 1, x);
  return eval(tree, 1, 0, n - 1, x);
}
poly interpolate(vector<poly> &tree, int v,
    int l, int r, int ly, int ry, vector<
    mint> &y) { //auxiliary interpolation
    function
  if(l == r) return {y[ly] / a[0]};
  int mid = l + r >> 1;
  int midy = ly + ry >> 1;
  auto A = (*this % tree[2 * v]).interpolate
      (tree, 2 * v, l, mid, ly, midy, y);
  auto B = (*this % tree[2 * v + 1]).
      interpolate(tree, 2 * v + 1, mid + 1,
      r, midy + 1, ry, y);
  return A * tree[2 * v + 1] + B * tree[2 *
      v];
}
};
//O(nlog^2n)
poly interpolate(vector<mint> x, vector<mint>
    y) { //interpolates minimum polynomial
    from (xi, yi) pairs
  int n = x.size(); assert(n == (int)y.size())
      ;//assert(all x are distinct)
  vector<poly> tree(4 * n);
  poly tmp({1});
  return tmp.build(tree, 1, 0, n - 1, x).
      differentiate().interpolate(tree, 1, 0,
      n - 1, 0, n - 1, y);
}
//O(a.size() * b.size())
//if gcd.size() - 1 = number of common roots
    between a and b
poly gcd(poly a, poly b) {
  return b.is_zero()? a : gcd(b, a % b);
}
//Let ra_0, ..., ra_n be the roots of A and
    rb_0, ..., rb_m be the roots of B
//resultant = A(rb_0) * ... A(rb_m). It is 0
    iif there is a common root between A and B
//O(a.size() * b.size())
mint resultant(poly a, poly b) { //computes
    resultant of a and b, assert(!a.is_zero())
  if(b.is_zero() || a.is_zero()) return 0;
  else if(b.size() == 1) return b.a.back().pow
      ((int)a.size() - 1);
  else {
    int pw = (int)a.size() - 1;
    a %= b;
    pw -= (int)a.size() - 1;
    mint mul = b.a.back().pow(pw) * mint(((b.
        size() - 1) & (a.size() - 1) & 1) ? -1
        : 1);
    mint ans = resultant(b, a);
    return ans * mul;
  }
}
int32_t main() {
  ios_base::sync_with_stdio(0);
  cin.tie(0);
  int n, m; cin >> n >> m;
  vector<mint> a, b;
  a.resize(m + 1);
  a[0] = 1;
  for(int i = 1; i <= n; i++) {
    int x; cin >> x;
    if (x <= m) a[x] = -4;
  }
  b = poly(a).root(m + 1).a;
  if (b.size() == 1) {
    for(int i = 1; i <= m; i++) cout << 0 << '
        \n';
    return 0;
  }
  b[0] += 1;
  a = poly(b).inverse(m + 1).a;
  a.resize(m + 1);
  for(int i = 1; i <= m; i++) cout << a[i] * 2
      << '\n';
  return 0;
}
// https://codeforces.com/problemset/problem
    /438/E
```