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las4s e pelados

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

Contest (1)

template.cpp8 lines

#include <bits/stdc++.h>
using namespace std;

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

.bashrc2 lines

alias c='g++ -Wall -Wconversion -Wfatal-errors -g -std=c++17 \\
-fsanitize=undefined,address'

hash.sh2 lines

bash hash.sh file.cpp l1 l2
sed -n \$2', '\$3' p' \$1 | sed '/^#w/d' | cpp -dD -P -
fpreprocessed | tr -d '[:space:]' | md5sum | cut -c-6

troubleshoot.txt52 lines

Pre-submit:
Write a few simple test cases if sample is not enough.
Are time limits close? If so, generate max cases.
Is the memory usage fine?
Could anything overflow?
Make sure to submit the right file.

Wrong answer:
Print your solution! Print debug output, as well.
Are you clearing all data structures between test cases?
Can your algorithm handle the whole range of input?
Read the full problem statement again.
Do you handle all corner cases correctly?
Have you understood the problem correctly?
Any uninitialized variables?
Any overflows?

1 Confusing N and M, i and j, etc.?
Are you sure your algorithm works?
What special cases have you not thought of?
1 Are you sure the STL functions you use work as you think?
Add some assertions, maybe resubmit.
2 Create some testcases to run your algorithm on.
Go through the algorithm for a simple case.
Go through this list again.
4 Explain your algorithm to a teammate.
Ask the teammate to look at your code.
Go for a small walk, e.g. to the toilet.
6 Is your output format correct? (including whitespace)
Rewrite your solution from the start or let a teammate do it.
7 Runtime error:
Have you tested all corner cases locally?
8 Any uninitialized variables?
Are you reading or writing outside the range of any vector?
Any assertions that might fail?
13 Any possible division by 0? (mod 0 for example)
Any possible infinite recursion?
Invalidated pointers or iterators?
19 Are you using too much memory?
Debug with resubmits (e.g. remapped signals, see Various).
20 Time limit exceeded:
Do you have any possible infinite loops?
What is the complexity of your algorithm?
Are you copying a lot of unnecessary data? (References)
How big is the input and output? (consider scanf)
Avoid vector, map. (use arrays/unordered_map)
What do your teammates think about your algorithm?

Memory limit exceeded:
What is the max amount of memory your algorithm should need?
Are you clearing all data structures between test cases?

Mathematics (2)

2.1 Recurrences

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

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

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

2.2 Trigonometry

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

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

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

where V, W are lengths of sides opposite angles v, w .
$$a \cos x + b \sin x = r \cos(x - \phi)$$
$$a \sin x + b \cos x = r \sin(x + \phi)$$

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

2.3 Geometry

2.3.1 Triangles

Side lengths: a, b, c
Semiperimeter: $p = \frac{a + b + c}{2}$
Area: $A = \sqrt{p(p - a)(p - b)(p - c)}$
Circumradius: $R = \frac{abc}{4A}$
Inradius: $r = \frac{A}{p}$
Length of median (divides triangle into two equal-area triangles):
 $m_a = \frac{1}{2} \sqrt{2b^2 + 2c^2 - a^2}$
Length of bisector (divides angles in two):

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

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

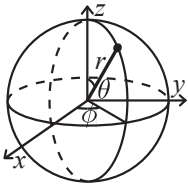
2.3.2 Quadrilaterals

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

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

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

2.3.3 Spherical coordinates



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

2.3.4 Pick’s Theorem

The area of a simple polygon whose vertices have integer coordinates is:

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

where I is the number of interior integer points, and B is the number of integer points in the border of the polygon.

2.3.5 Two Ears Theorem

Every simple polygon with more than 3 vertices has at least two non-overlapping ears (a ear is a vertex whose diagonal induced by its neighbors which lies strictly inside the polygon). Equivalently, every simple polygon can be triangulated.

2.4 Derivatives/Integrals

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

Integration by parts:

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

2.5 Sums

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

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

$$\sum_{i=0}^n ic^i = \frac{nc^{n+2} - (n+1)c^{n+1} + c}{(c-1)^2}, \quad c \neq 1$$

$$g_k(n) = \sum_{i=1}^n i^k = \frac{1}{k+1} \left(n^{k+1} + \sum_{j=1}^k \binom{k+1}{j+1} (-1)^{j+1} g_{k-j}(n) \right)$$

2.6 Series

$$\begin{aligned} e^x &= 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots, \quad (-\infty < x < \infty) \\ \ln(1+x) &= x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots, \quad (-1 < x \leq 1) \\ \sqrt{1+x} &= 1 + \frac{x}{2} - \frac{x^2}{8} + \frac{2x^3}{32} - \frac{5x^4}{128} + \dots, \quad (-1 \leq x \leq 1) \\ \sin x &= x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \dots, \quad (-\infty < x < \infty) \\ \cos x &= 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots, \quad (-\infty < x < \infty) \\ \sum_{i=0}^{\infty} ic^i &= \frac{c}{(1-c)^2}, \quad |c| < 1 \end{aligned}$$

2.7 Probability theory

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

Expectation is linear:

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

For independent X and Y ,

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

2.7.1 Discrete distributions

Binomial distribution

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

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

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

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

First success distribution

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

$$\begin{aligned} p(k) &= p(1-p)^{k-1}, \quad k = 1, 2, \dots \\ \mu &= \frac{1}{p}, \quad \sigma^2 = \frac{1-p}{p^2} \end{aligned}$$

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

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

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

Data structures (3)

Bit.h

d41d8c, 13 lines

```
d41 struct Bit {
d41     vector<int> bit;
d41     Bit(int n) : bit(n + 1) {}
d41     void update(int i, int v) {
d41         for (i++; i < sz(bit); i += i & -i) bit[i] += v;
d41     }
d41     int query(int i) {
d41         int ret = 0;
d41         for (i++; i > 0; i -= i & -i) ret += bit[i];
d41         return ret;
d41     }
d41 };
```

Bit2d.h

d41d8c, 37 lines

```
d41 struct Bit2d {
d41     vector<vector<int>> ys;
d41     vector<Bit> bit;
d41     vector<int> cmp_x;
d41     Bit2d(){}
d41     void put(int x, int y) {
d41         for (x++; x < sz(ys); x += x & -x) ys[x].push_back(y);
d41     }
d41     int id(const vector<int> &v, int y) {
d41         return (upper_bound(all(v), y) - v.begin()) - 1;
d41     }
d41     void build(vector<pii> pts) {
d41         sort(all(pts));
d41         for(auto p : pts) cmp_x.push_back(p.first);
d41         cmp_x.erase(unique(all(cmp_x)), cmp_x.end());
d41         ys.resize(cmp_x.size() + 1);
d41         for(auto p : pts) put(id(cmp_x, p.first), p.second);
d41         for(auto &v:ys) sort(all(v)), bit.emplace_back(sz(v));
d41     }
d41     void update(int x, int y, int val){
d41         x = id(cmp_x, x);
d41         for(x++; x < sz(ys); x+= x&-x)
d41             bit[x].update(id(ys[x], y), val);
d41     }
d41     int query(int x, int y){
d41         x = id(cmp_x, x);
d41         int ret = 0;
d41         for(x++; x > 0; x-= x&-x)
d41             ret += bit[x].query(id(ys[x], y));
d41         return ret;
d41     }
d41     int query(int x1, int y1, int x2, int y2){
d41         int a = query(x2, y2)-query(x2, y1-1);
```

```

d41         return a-query(x1-1, y2)+query(x1-1, y1-1);
d41     }
d41 };

```

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

d41d8c, 32 lines

```

d41 struct Line {
d41     mutable ll k, m, p;
d41     bool operator<(const Line& o) const { return k < o.k; }
d41     bool operator<(ll x) const { return p < x; }
d41 };

d41 struct LineContainer : multiset<Line, less<>> {
d41     // (for doubles, use inf = 1/.0, div(a,b) = a/b)
d41     static const ll inf = LLONG_MAX;
d41     ll div(ll a, ll b) { // floored division
d41         return a / b - ((a ^ b) < 0 && a % b); }
d41     bool isect(iterator x, iterator y) {
d41         if (y == end()) return x->p = inf, 0;
d41         if (x->k == y->k) x->p = x->m > y->m ? inf : -inf;
d41         else x->p = div(y->m - x->m, x->k - y->k);
d41         return x->p >= y->p;
d41     }
d41     void add(ll k, ll m) {
d41         auto z = insert({k, m, 0}), y = z++, x = y;
d41         while (isect(y, z)) z = erase(z);
d41         if (x != begin() && isect(--x, y))
d41             isect(x, y = erase(y));
d41         while ((y = x) != begin() && (--x)->p >= y->p)
d41             isect(x, erase(y));
d41     }
d41     ll query(ll x) {
d41         assert(!empty());
d41         auto l = *lower_bound(x);
d41         return l.k * x + l.m;
d41     }
d41 };

```

Mo.h

Description: For subtree queries, perform an Euler tour and map each node u to the interval $[tin[u], tin[u] + subtree_size[u] - 1]$. A subtree query becomes a range query over this interval.

For path queries between nodes U and V , Let U be the closest to the root. If V lies in U 's subtree, the path corresponds to the interval $[tin[U], tin[V]]$. Otherwise, the path corresponds to the interval $[min(tout[U], tout[V]), max(tin[U], tin[V])]$.

In both cases, nodes on the U - V path appear exactly once in the interval, while all other nodes appear either 0 or 2 times.

Usage: queries.push(Query(l, r, index of query)), intervals are $[l, r]$

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

d41d8c, 44 lines

```

d41 inline int64_t hilOrd(int x, int y, int pow, int rot) {
d41     if (pow == 0) return 0;
d41     int hpow = 1 << (pow - 1);
d41     int seg = (x < hpow) ? ((y < hpow) ? 0 : 3) : ((y < hpow
d41 ) ? 1 : 2);
d41     seg = (seg + rot) & 3;
d41     const int rotDelta[4] = { 3, 0, 0, 1 };
d41     int nx = x & (x ^ hpow), ny = y & (y ^ hpow);
d41     int nrot = (rot + rotDelta[seg]) & 3;
d41     int64_t sub = int64_t(1) << (2 * pow - 2);
d41     int64_t ans = seg * sub;
d41     int64_t add = hilOrd(nx, ny, pow - 1, nrot);
d41     ans += (seg == 1 || seg == 2) ? add : (sub - add - 1);

```

```

d41     return ans;
d41 }

d41 struct Query {
d41     int l, r, idx;
d41     int64_t ord;
d41     Query(int l, int r, int idx) : l(l), r(r), idx(idx) {
d41         ord = hilOrd(l, r, 21, 0);
d41     }
d41     bool operator < (const Query& other) const {
d41         return ord < other.ord;
d41     }
d41 };

d41 vector<Query> queries;
d41 int ans[ms];
d41 void put(int x) {} // F
d41 void remove(int x) {} // F
d41 int getAns() {}

d41 void Mo() {
d41     int l = 0, r = -1;
d41     sort(queries.begin(), queries.end());
d41     for (Query q : queries) {
d41         while (l > q.l) put(--l);
d41         while (r < q.r) put(++r);
d41         while (l < q.l) remove(l++);
d41         while (r > q.r) remove(r--);
d41         ans[q.idx] = getAns();
d41     }
d41 }

```

MoUpdate.h

Description: Block size should be around $(2 * N * N)^{\frac{1}{3}}$

Usage: intervals are $[l, r]$, addQuery(l, r, number of updates happened before this query, index of query), addUpdate(index of updated position, value before update, value after update)

Time: $\mathcal{O}(Q * (2 * N * N)^{\frac{1}{3}} * F)$

d41d8c, 55 lines

```

d41 const int B = 2700;
d41 struct MoUpdate {
d41     struct Query {
d41         int l, r, t, idx;
d41         Query(int l, int r, int t, int idx)
d41             : l(l), r(r), t(t), idx(idx) {}
d41         bool operator < (const Query& p) const {
d41             if (l / B != p.l / B) return l < p.l;
d41             if (r / B != p.r / B) return r < p.r;
d41             return t < p.t;
d41         }
d41     };
d41     struct Upd {
d41         int i, old, now;
d41         Upd(int i, int old, int now) : i(i), old(old), now(now) {}
d41     };

d41     vector<Query> queries;
d41     vector<Upd> updates;

d41     void addQuery(int l, int r, int t, int idx) {
d41         queries.push_back(Query(l, r, t, idx)); }
d41     void addUpdate(int i, int old, int now) {
d41         updates.push_back(Upd(i, old, now)); }

d41     void add(int x) {} // F
d41     void rem(int x) {} // F
d41     int getAns() {}

```

```

d41 void update(int novo, int idx, int l, int r) {
d41     if (l <= idx && idx <= r) rem(idx);
d41     arr[idx] = novo;
d41     if (l <= idx && idx <= r) add(idx);
d41 }

d41 void solve() {
d41     int l = 0, r = -1, t = 0;
d41     sort(queries.begin(), queries.end());
d41     for (Query q : queries) {
d41         while (l > q.l) add(--l);
d41         while (r < q.r) add(++r);
d41         while (l < q.l) rem(l++);
d41         while (r > q.r) rem(r--);
d41         while (t < q.t) {
d41             auto u = updates[t++];
d41             update(u.now, u.i, l, r);
d41         }
d41         while (t > q.t) {
d41             auto u = updates[--t];
d41             update(u.old, u.i, l, r);
d41         }
d41         ans[q.idx] = getAns();
d41     }
d41 }

```

SegmentTree.h

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

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

d41d8c, 21 lines

```

d41 struct Tree {
d41     typedef int T;
d41     static constexpr T unit = INT_MIN;
d41     T f(T a, T b) { return max(a, b); } // (any associative
d41 fn)
d41     vector<T> s; int n;
d41     Tree(int n = 0, T def = unit) : s(2*n, def), n(n) {}
d41     void update(int pos, T val) {
d41         for (s[pos += n] = val; pos /= 2;)
d41             s[pos] = f(s[pos * 2], s[pos * 2 + 1]);
d41     }
d41     T query(int b, int e) { // query [b, e]
d41         e++;
d41         T ra = unit, rb = unit;
d41         for (b += n, e += n; b < e; b /= 2, e /= 2) {
d41             if (b % 2) ra = f(ra, s[b++]);
d41             if (e % 2) rb = f(s[--e], rb);
d41         }
d41         return f(ra, rb);
d41     }
d41 };

```

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

d41d8c, 17 lines

```

d41 #include <bits/extc++.h>
d41 using namespace __gnu_pbds;

d41 template<class T>
d41 using Tree = tree<T, null_type, less<T>, rb_tree_tag,
d41     tree_order_statistics_node_update>;

d41 void example() {
d41     Tree<int> t, t2; t.insert(8);
d41     auto it = t.insert(10).first;

```

```
d41  assert(it == t.lower_bound(9));
d41  assert(t.order_of_key(10) == 1);
d41  assert(t.order_of_key(11) == 2);
d41  assert(*t.find_by_order(0) == 8);
d41  t.join(t2); // merge t2 into t
d41 }
```

PersistentSegTree.h

Usage: SegP(size of the segtree, number of updates)

```
roots = {0}, newRoot = update(roots.back(),...),
roots.push(newRoot)
```

d41d8c, 42 lines

```
d41  struct SegP {
d41      static constexpr ll neut = 0;
d41      struct Node {
d41          ll v; // start with neutral value
d41          int l, r;
d41          Node(ll v=neut, int l=0, int r=0) : v(v), l(l), r(r){}
d41      };
d41      vector<Node> seg;
d41      int n, CNT;
d41      SegP(int _n, int upd): seg(20*(upd+_n)), n(_n), CNT(1){}
d41      ll merge(ll a, ll b) { return a + b; }
d41      int update(int root, int pos, int val, int l, int r) {
d41          int p = CNT++;
d41          seg[p] = seg[root];
d41          if (l == r) {
d41              seg[p].v += val;
d41              return p;
d41          }
d41          int mid = (l + r) / 2;
d41          if (pos <= mid){
d41              seg[p].l = update(seg[p].l, pos, val, l, mid);
d41          }else seg[p].r = update(seg[p].r,pos,val,mid+1,r);
d41      }
```

```
        seg[p].v=merge(seg[seg[p].l].v, seg[seg[p].r].v);
        return p;
    }
    int query(int p, int L, int R, int l, int r) {
d41        if (l > R || r < L) return neut;
d41        if (L <= l && r <= R) return seg[p].v;
d41        int mid = (l + r) / 2;
d41        int left = query(seg[p].l, L, R, l, mid);
d41        int right = query(seg[p].r, L, R, mid + 1, r);
d41        return merge(left, right);
d41    }
d41    int update(int root, int pos, int val) {
d41        return update(root, pos, val, 0, n - 1);
d41    }
d41    int query(int root, int L, int R) {
d41        return query(root, L, R, 0, n - 1);
d41    }
d41 }
```

RMQ.h

Usage: RMQ rmq(values);

rmq.query(inclusive, inclusive);

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

d41d8c, 17 lines

```
d41  struct RMQ {
d41      vector<vector<int>>> dp;
d41      RMQ(const vector<int>& a) : dp(1, a) {
d41          for (int i = 1, pw = 1; pw*2 <= sz(a); pw*=2, i++) {
d41              dp.emplace_back(sz(a) - pw*2 + 1);
d41              for (int j = 0; j < sz(dp[i]); j++) {
d41                  dp[i][j] = min(dp[i-1][j], dp[i-1][j+pw]);
d41              }
d41          }
d41      }
```

```
    }
d41    int query(int l, int r) {
d41        assert(l <= r);
d41        int k = 31 - __builtin_clz(r - l + 1);
d41        return min(dp[k][l], dp[k][r - (1 << k) + 1]);
d41    }
d41 };
```

Numerical (4)

4.1 Polynomials and recurrences

Polynomial.h

d41d8c, 19 lines

```
d41  struct Poly {
d41      vector<double> a;
d41      double operator()(double x) const {
d41          double val = 0;
d41          for (int i = sz(a); i--;) (val *= x) += a[i];
d41          return val;
d41      }
d41      void diff() {
d41          rep(i,1,sz(a)) a[i-1] = i*a[i];
d41          a.pop_back();
d41      }
d41      void divroot(double x0) {
d41          double b = a.back(), c; a.back() = 0;
d41          for(int i=sz(a)-1; i--;)
d41              c = a[i], a[i] = a[i+1]*x0+b, b=c;
d41          a.pop_back();
d41      }
d41  };
```

PolyRoots.h

Description: Finds the real roots to a polynomial.

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

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

"Polynomial.h"

d41d8c, 24 lines

```
d41  vector<double> polyRoots(Poly p, double xmin, double xmax)
d41  {
d41      if (sz(p.a) == 2) { return {-p.a[0]/p.a[1]}; }
d41      vector<double> ret;
d41      Poly der = p;
d41      der.diff();
d41      auto dr = polyRoots(der, xmin, xmax);
d41      dr.push_back(xmin-1);
d41      dr.push_back(xmax+1);
d41      sort(all(dr));
d41      rep(i,0,sz(dr)-1) {
d41          double l = dr[i], h = dr[i+1];
d41          bool sign = p(l) > 0;
d41          if (sign ^ (p(h) > 0)) {
d41              rep(it,0,60) { // while (h - l > 1e-8)
d41                  double m = (l + h) / 2, f = p(m);
d41                  if ((f <= 0) ^ sign) l = m;
d41                  else h = m;
d41              }
d41              ret.push_back((l + h) / 2);
d41          }
d41      }
d41      return ret;
d41  }
```

BerlekampMassey.h

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

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

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

d41d8c, 21 lines

```
d41  vector<ll> berlekampMassey(vector<ll> s) {
d41      int n = sz(s), L = 0, m = 0;
d41      vector<ll> C(n), B(n), T;
d41      C[0] = B[0] = 1;
```

```

d41      ll b = 1;
d41      rep(i,0,n) { ++m;
d41          ll d = s[i] % mod;
d41          rep(j,1,L+1) d = (d + C[j] * s[i - j]) % mod;
d41          if (!d) continue;
d41          T = C; ll coef = d * modpow(b, mod-2) % mod;
d41          rep(j,m,n) C[j] = (C[j] - coef * B[j - m]) % mod;
d41          if (2 * L > i) continue;
d41          L = i + 1 - L; B = T; b = d; m = 0;
d41      }
```

```

d41      C.resize(L + 1); C.erase(C.begin());
d41      for (ll& x : C) x = (mod - x) % mod;
d41      return C;
d41 }
```

LinearRecurrence.h

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

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

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

d41d8c, 27 lines

```
d41  using Poly = vector<ll>;
d41  ll linearRec(Poly S, Poly tr, ll k) {
d41      int n = sz(tr);
```

```

d41      auto combine = [&](Poly a, Poly b) {
d41          Poly res(n * 2 + 1);
d41          rep(i,0,n+1) rep(j,0,n+1)
d41              res[i + j] = (res[i + j] + a[i] * b[j]) % mod;
d41          for (int i = 2 * n; i > n; --i) rep(j,0,n)
d41              res[i-1-j] = (res[i-1-j] + res[i] * tr[j]) % mod;
d41          res.resize(n + 1);
d41          return res;
d41      };
```

```

d41      Poly pol(n + 1), e(pol);
d41      pol[0] = e[1] = 1;
```

```

d41      for (++k; k; k /= 2) {
d41          if (k % 2) pol = combine(pol, e);
d41          e = combine(e, e);
d41      }
```

```

d41      ll res = 0;
d41      rep(i,0,n) res = (res + pol[i + 1] * S[i]) % mod;
d41      return res;
d41 }
```

4.2 Matrices

SolveLinearBinary.h

Time: $\mathcal{O}\left(\frac{\min(n,m)}{64}nm\right)$

d41d8c, 33 lines

```
d41  pair<int, bitset<M>> gauss(vector<bitset<M>> eq) {
d41      int n = eq.size(), m = M - 1;
d41      vector<int> where(m, -1);
```

```
d41 for(int col = 0, row = 0; col < m && row < n; col++){
d41     for (int i = row; i < n; i++)
d41         if (eq[i][col]) {
d41             swap(eq[i], eq[row]);
d41             break;
d41         }
d41     if (!eq[row][col]) continue;
d41     where[col] = row;

d41     for (int i = 0; i < n; i++) {
d41         if (i != row && eq[i][col]) eq[i] ^= eq[row];
d41     }
d41     ++row;
d41 }

d41 bitset<M> ans;
d41 for (int i = 0; i < m; i++) {
d41     if (where[i] != -1) ans[i] = eq[where[i]][m];
d41 }
d41 for (int i = 0; i < n; i++) {
d41     int sum = (ans & eq[i]).count();
d41     sum %= 2;
d41     if (sum != eq[i][m]) return pair(0, bitset<M>());
d41 }
d41 for (int i = 0; i < m; i++) {
d41     if (where[i] == -1) return pair(INF, ans);
d41 }
d41 return pair(1, ans);
d41 }
```

XorGauss.h

d41d8c, 30 lines

```
d41 struct XorGauss {
d41     int N;
d41     vector<ll> basis, who, mask;
d41     XorGauss(int N) : N(N), basis(N), who(N), mask(N) {}
d41     // if(ans & (1ll << j)) who[j] was used to form x
d41     bool belong(ll x){
d41         ll ans = 0;
d41         for(int i=N-1; i>=0; i--){
d41             if((x ^ basis[i]) < x){
d41                 ans ^= mask[i];
d41                 x ^= basis[i];
d41             }
d41         }
d41         return (x == 0);
d41     }
d41     void add(ll v, int idx) {
d41         ll msk = 0;
d41         for (int i = N - 1; i >= 0; i--) {
d41             if (!(v & (1ll << i))) continue;
d41             if (basis[i] == 0) {
d41                 basis[i] = v, who[i] = idx;
d41                 mask[i] = (msk | (1ll << i));
d41                 return;
d41             }
d41             msk ^= mask[i];
d41             v ^= basis[i];
d41         }
d41     }
d41 }
```

4.3 Fourier transforms

FastFourierTransform.h

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

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

```
d41 typedef complex<double> C;

d41 void fft(vector<C>& a) {
d41     int n = a.size(), L = 31 - __builtin_clz(n);
d41     static vector<complex<long double>> R(2, 1); // 10%
d41     faster if double
d41     static vector<C> rt(2, 1);
d41     for (static int k = 2; k < n; k *= 2) {
d41         R.resize(n);
d41         rt.resize(n);
d41         auto x = polar(1.0L, acos(-1.0L) / k);
d41         rep(i,k,2*k) rt[i] = R[i] = i&1 ? R[i/2] * x : R[i/2];
d41     }
d41     vector<ll> rev(n);
d41     rep(i,0,n) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
d41     rep(i,0,n) if (i < rev[i]) swap(a[i], a[rev[i]]);

d41     for (int k = 1; k < n; k *= 2) {
d41         for (int i = 0; i < n; i += 2 * k) {
d41             for (int j = 0; j < k; j++) {
d41                 auto x = (double*)&rt[j + k];
d41                 auto y = (double*)&a[i + j + k];
d41                 C z(x[0]*y[0] - x[1]*y[1], x[0]*y[1] + x[1]*y[0]);
d41                 a[i + j + k] = a[i + j] - z;
d41                 a[i + j] += z;
d41             }
d41         }
d41     }
d41 }
```

```
d41 vector<ll> conv(const vector<ll>& a, const vector<ll>& b){
d41     if (a.empty() || b.empty()) return {};
d41     vector<ll> res(sz(a) + sz(b) - 1);
d41     int L = 32 - __builtin_clz(sz(res)), n = 1 << L;
d41     vector<C> in(n), out(n);
d41     copy(all(a), in.begin());
d41     rep(i,0,sz(b)) in[i].imag(b[i]);
d41     fft(in);
d41     for (C& x : in) x *= x;
d41     rep(i,0,n) out[i] = in[-i & (n - 1)] - conj(in[i]);
d41     fft(out);
d41     rep(i,0,sz(res)) res[i]=round(imag(out[i]) / (4 * n));
d41     return res;
d41 }
```

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" d41d8c, 23 lines

```
d41 typedef vector<ll> vl;
d41 template<int M> vl convMod(const vl &a, const vl &b) {
d41     if (a.empty() || b.empty()) return {};
d41     vl res(sz(a) + sz(b) - 1);
d41     int B=32-__builtin_clz(sz(res)), n=1<<B,cut=int(sqrt(M));
d41     vector<C> L(n), R(n), outs(n), outl(n);
d41     rep(i,0,sz(a)) L[i] =C((int)a[i] / cut, (int)a[i] % cut);
d41     rep(i,0,sz(b)) R[i] =C((int)b[i] / cut, (int)b[i] % cut);
d41     fft(L), fft(R);
d41     rep(i,0,n) {
```

```
d41     int j = -i & (n - 1);
d41     outl[j] = (L[i] + conj(L[j])) * R[i] / (2.0 * n);
d41     outs[j] = (L[i] - conj(L[j])) * R[i] / (2.0 * n) / 1i;
d41 }
d41 fft(outl), fft(outs);
d41 rep(i,0,sz(res)) {
d41     ll av = ll(real(outl[i])+.5), cv =ll(imag(outs[i])+.5);
d41     ll bv = ll(imag(outl[i])+.5) + ll(real(outs[i])+.5);
d41     res[i] = ((av % M * cut + bv) % M * cut + cv) % M;
d41 }
d41 return res;
d41 }
```

NumberTheoreticTransform.h

Description: $\text{ntt}(a)$ 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. $\text{conv}(a, b) = c$, where $c[x] = \sum a[i]b[x-i]$. For manual convolution: NTT the inputs, multiply pointwise, divide by n , reverse(start+1, end), NTT back. Inputs must be in $[0, \text{mod})$.

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

d41d8c, 34 lines

```
d41 const int mod = 998244353, root = 62;
d41 typedef vector<ll> vl;
d41 void ntt(vl &a) {
d41     int n = sz(a), L = 31 - __builtin_clz(n);
d41     static vl rt(2, 1);
d41     for (static int k = 2, s = 2; k < n; k *= 2, s++) {
d41         rt.resize(n);
d41         ll z[] = {1, modpow(root, mod >> s)};
d41         rep(i,k,2*k) rt[i] = rt[i / 2] * z[i & 1] % mod;
d41     }
d41     vector<int> rev(n);
d41     rep(i,0,n) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
d41     rep(i,0,n) if (i < rev[i]) swap(a[i], a[rev[i]]);
d41     for (int k = 1; k < n; k *= 2)
d41         for (int i = 0; i < n; i += 2 * k) rep(j,0,k) {
d41             ll z = rt[j+k] * a[i+j+k] % mod, &ai = a[i+j];
d41             a[i + j + k] = ai - z + (z > ai ? mod : 0);
d41             ai += (ai + z >= mod ? z - mod : z);
d41         }
d41 }
d41 vl conv(const vl &a, const vl &b) {
d41     if (a.empty() || b.empty()) return {};
d41     int s = sz(a) + sz(b) - 1, B = 32 - __builtin_clz(s),
d41     n = 1 << B;
d41     int inv = modpow(n, mod - 2);
d41     vl L(a), R(b), out(n);
d41     L.resize(n), R.resize(n);
d41     ntt(L), ntt(R);
d41     rep(i,0,n)
d41         out[-i & (n - 1)] = (ll)L[i] * R[i] % mod * inv % mod;
d41     ntt(out);
d41     return {out.begin(), out.begin() + s};
d41 }
```

FWHT.h

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

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

d41d8c, 20 lines

```
d41 void FST(vector<ll>& a, bool inv) {
d41     for (int n = sz(a), step = 1; step < n; step *= 2) {
d41         for (int i = 0; i < n; i += 2 * step) {
d41             for (int j = i; j < i + step; j++) {
d41                 ll& u = a[j], &v = a[j + step];
```



```
d41 tie(u, v) =
d41 inv ? pair(v - u, u) : pair(v, u + v); // AND
d41 inv ? pair(v, u - v) : pair(u + v, u); // OR
d41 pair(u + v, u - v); // XOR
d41 }
d41 }
d41 }
d41 if(inv) for(ll& x : a) x /= sz(a); // XOR only
d41 }
d41 vector<ll> conv(vector<ll> a, vector<ll> b) {
d41 FST(a, 0); FST(b, 0);
d41 for(int i = 0; i < sz(a); i++) a[i]*=b[i];
d41 FST(a, 1); return a;
d41 }
```

Number theory (5)

5.1 Modular arithmetic

ModInverse.h

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

d41d8c, 5 lines

```
d41 const ll mod = 1000000007, LIM = 200000;
d41 inv[1] = 1;
d41 for(int i=2; i<LIM; i++)
d41 inv[i] = mod - (mod / i) * inv[mod % i] % mod;
```

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

d41d8c, 12 lines

```
d41 typedef unsigned long long ull;
d41 ull modmul(ull a, ull b, ull M) {
d41 ll ret = a * b - M * ull(1.L / M * a * b);
d41 return ret + M * (ret < 0) - M * (ret >= (ll)M);
d41 }
d41 ull modpow(ull b, ull e, ull mod) {
d41 ull ans = 1;
d41 for (; e; b = modmul(b, b, mod), e /= 2)
d41 if (e & 1) ans = modmul(ans, b, mod);
d41 return ans;
d41 }
```

DiscreteLog.h

Description: Returns the smallest x such that $a^x \bmod m = b \bmod m$. If no such x exists, returns -1 .

Time: $\mathcal{O}(\sqrt{m}) \cdot \log(\sqrt{m})$

d41d8c, 32 lines

```
d41 int solve(int a, int b, int m) {
d41 a %= m, b %= m;
d41 if (a == 0) return (b ? -1 : 1);
d41 // caso gcd(a, m) > 1
d41 int k = 1, add = 0, g;
d41 while ((g = gcd(a, m)) > 1) {
d41 if (b == k) return add;
d41 if (b % g) return -1;
d41 b /= g, m /= g, ++add;
d41 k = (k * 111 * a / g) % m;
d41 }

d41 int sq = sqrt(m) + 1;
d41 int big = 1;
d41 for (int i = 0; i < sq; i++) big = (111 * big * a) % m
;

d41 vector<pii> vals;
d41 for (int q = 0, cur = b; q <= sq; q++) {
```

```
d41 vals.push_back({ cur, q });
d41 cur = (111 * cur * a) % m;
d41 }
d41 sort(all(vals));
d41 for (int p = 1, cur = k; p <= sq; p++) {
d41 cur = (111 * cur * big) % m;
d41 auto it = lower_bound(all(vals), pair(cur, INF));
d41 if (it != vals.begin() && (--it)->first == cur) {
d41 return sq * p - it->second + add;
d41 }
d41 }
d41 return -1;
d41 }
```

DiscreteRoot.h

Description: Returns x such that $x^k \bmod m = a \bmod m$. If no such x exists, returns -1 .

Time: $\mathcal{O}(\sqrt{m}) \cdot \log(\sqrt{m})$

"PrimitiveRoot.h", "DiscreteLog.h" d41d8c, 11 lines

// Discrete Root

```
d41 ll discreteRoot(ll k, ll a, ll m) {
d41 ll g = primitiveRoot(m);
d41 ll y = discreteLog(fexp(g, k, m), a, m);
d41 if (y == -1) return y;
d41 return fexp(g, y, m);
d41 }
```

5.2 Primality

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" d41d8c, 13 lines

```
d41 bool isPrime(ull n) {
d41 if (n < 2 || n % 6 % 4 != 1) return (n | 1) == 3;
d41 ull A[] = {2, 325, 9375, 28178, 450775, 9780504, 17952650
d41 22};
d41 ull s = __builtin_ctzll(n-1), d = n >> s;
d41 for (ull a : A) { // ^ count trailing zeroes
d41 ull p = modpow(a%n, d, n), i = s;
d41 while (p != 1 && p != n - 1 && a % n && i--)
d41 p = modmul(p, p, n);
d41 if (p != n-1 && i != s) return 0;
d41 }
d41 return 1;
d41 }
```

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" d41d8c, 19 lines

```
d41 ull pollard(ull n) {
d41 ull x = 0, y = 0, t = 30, prd = 2, i = 1, q;
d41 auto f = [&](ull x) { return modmul(x, x, n) + i; };
d41 while (t++ % 40 || gcd(prd, n) == 1) {
d41 if (x == y) x = ++i, y = f(x);
d41 if ((q = modmul(prd, max(x,y) - min(x,y), n))) prd = q;
d41 x = f(x), y = f(f(y));
d41 }
d41 return gcd(prd, n);
d41 }

d41 vector<ull> factor(ull n) {
d41 if (n == 1) return {};
d41 if (isPrime(n)) return {n};
```

```
d41 ull x = pollard(n);
d41 auto l = factor(x), r = factor(n / x);
d41 l.insert(l.end(), all(r));
d41 return l;
d41 }
```

PrimitiveRoot.h

d41d8c, 15 lines

```
//is n primitive root of p ?
d41 bool test(ll x, ll p) {
d41 ll m = p - 1;
d41 for (ll i = 2; i * i <= m; ++i) if (!(m % i)) {
d41 if (modpow(x, i, p) == 1) return false;
d41 if (modpow(x, m / i, p) == 1) return false;
d41 }
d41 return true;
d41 }

//find the smallest primitive root for p
d41 ll search(ll p) {
d41 for (ll i = 2; i < p; i++) if (test(i, p)) return i;
d41 return -1;
d41 }
```

5.3 Divisibility

Euclid.h

Description: Find x, y such that $Ax + By = \gcd(A, B)$. If $\gcd(A, B) = 1$, then $x = A^{-1} \bmod B$ and $y = B^{-1} \bmod A$.

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

d41d8c, 6 lines

```
d41 tuple<ll, ll, ll> ext_gcd(ll a, ll b) {
d41 if (!a) return { b, 0, 1 };
d41 auto [g, x, y] = ext_gcd(b % a, a);
d41 return { g, y - b / a * x, x };
d41 }
```

CRT.h

d41d8c, 32 lines

```
d41 ll modinverse(ll a, ll b, ll s0 = 1, ll s1 = 0) {
d41 return !b ? s0 : modinverse(b, a % b, s1, s0 - s1 * (a / b)); }

d41 ll mul(ll a, ll b, ll m) {
d41 ll q = (long double)a * (long double)b / (long double)m;
d41 ll r = a * b - q * m;
d41 return (r + m) % m;
d41 }
```

```
d41 struct Equation {
d41 ll mod, ans;
d41 bool valid;
d41 Equation(ll a, ll m) { mod = m, ans = a, valid = true; }
d41 Equation() { valid = false; }
d41 Equation(Equation a, Equation b) {
d41 if (!a.valid || !b.valid) {
d41 valid = false;
d41 return;
d41 }
d41 ll g = gcd(a.mod, b.mod);
d41 if ((a.ans - b.ans) % g != 0) {
d41 valid = false;
d41 return;
d41 }
d41 valid = true;
d41 mod = a.mod * (b.mod / g);
d41 ll x = mul(a.mod, modinverse(a.mod, b.mod), mod);
d41 ans = a.ans + mul(x, (b.ans - a.ans) / g, mod);
d41 ans = (ans % mod + mod) % mod;
d41 }
d41 };
```

DivisionTrick.h

d41d8c, 15 lines

```
d41 void floor_ranges(int n) {
d41     for (int l = 1, r; l <= n; l = r + 1) {
d41         r = n / (n / l);
           // floor(n/y) has the same value for y in [l..r]
d41     }
d41 }
d41 void ceil_ranges(int n) {
d41     for (int l = 1, r; l <= n; l = r + 1) {
d41         int x = (n + l - 1) / l;
d41         if (x == 1) r = n;
d41         else r = (n - 1) / (x - 1);
           // ceil(n/y) has the same value for y in [l..r]
d41     }
d41 }
```

5.3.1 Bézout’s identity

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

$ax + by = d$

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

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

Phi.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 $\Rightarrow a^{\phi(n)} \equiv 1 \pmod n$.

Euler’s thm (generalized): a, m arbitrary, $n \geq \log_2 m \Rightarrow a^n \equiv a^{\phi(m)+(n \bmod \phi(m))} \pmod m$.

d41d8c, 6 lines

```
d41 void calculatePhi() {
d41     for(int i=0; i<LIM; i++) phi[i] = i&1 ? i : i/2;
d41     for (int i = 3; i < LIM; i += 2) if(phi[i] == i)
d41         for (int j = i; j < LIM; j += i) phi[j] -= phi[j] / i;
d41 }
```

5.4 Primes

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

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

5.5 Estimates

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

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

5.6 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:

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

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

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

5.7 Theorems

Goldbach’s conjecture: Every even integer $n > 2$ can be written as $n = a + b$ with a, b prime.

Legendre’s conjecture: There is always at least one prime between n^2 and $(n + 1)^2$.

Lagrange’s four-square theorem: Every positive integer can be written as

$$n = a^2 + b^2 + c^2 + d^2.$$

Zeckendorf’s theorem: Every integer $n \geq 1$ has a unique representation as a sum of non-consecutive Fibonacci numbers:

$$n = F_{i_1} + F_{i_2} + \cdots + F_{i_k}, \quad i_j - i_{j+1} \geq 2.$$

Euclid’s formula (primitive Pythagorean triples): The Pythagorean triples are uniquely generated by

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

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

Wilson’s theorem: n is prime iff

$$(n - 1)! \equiv -1 \pmod n.$$

Chicken McNugget theorem: For coprime n, m , the largest integer not representable as $an + bm$ (with $a, b \geq 0$) is

$$nm - n - m.$$

There are $\frac{(n-1)(m-1)}{2}$ non-representable integers, and for each pair $(k, nm - n - m - k)$ exactly one is representable.

Combinatorial (6)

6.1 Binomial Identities

$$\binom{n-1}{k} - \binom{n-1}{k-1} = \frac{n-2k}{k} \binom{n}{k} \qquad \binom{n}{h} \binom{n-h}{k} = \binom{n}{k} \binom{n-k}{h}$$

$$\sum_{k=0}^n k \binom{n}{k} = n2^{n-1} \qquad \sum_{k=0}^n k^2 \binom{n}{k} = (n + n^2)2^{n-2}$$

$$\sum_{j=0}^k \binom{m}{j} \binom{n-m}{k-j} = \binom{n}{k} \qquad \sum_{j=0}^m \binom{m}{j}^2 = \binom{2m}{m}$$

$$\sum_{m=0}^n \binom{m}{j} \binom{n-m}{k-j} = \binom{n+1}{k+1} \qquad \sum_{m=0}^n \binom{m}{k} = \binom{n+1}{k+1}$$

$$\sum_{r=0}^m \binom{n+r}{r} = \binom{n+m+1}{m} \qquad \sum_{k=0}^n \binom{n-k}{k} = \text{Fib}(n + 1)$$

$$\sum_{k=0}^n \binom{r}{k} \binom{s}{n-k} = \binom{r+s}{n}$$

6.2 Permutations

6.2.1 Factorial

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

6.2.2 Cycles

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

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

6.2.3 Derangements

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

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

6.2.4 Burnside’s lemma

Counts the number of distinct colorings of an object under symmetry.

$$\frac{1}{|G|} \sum_{g \in G} k^{\text{cyc}(g)},$$

where G is the symmetry group, k the number of colors, and $\text{cyc}(g)$ the number of cycles induced by g .

Example: number of ways to color a necklace with n beads using k colors (rotations only):

$$g(n) = \frac{1}{n} \sum_{i=0}^{n-1} k^{(\gcd(n,i))}$$

where rotation i shifts the necklace by i positions.

6.3 Partitions and subsets

6.3.1 Partition function

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

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

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

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

PartitionSolver.h

d41d8c, 61 lines

```
d41  template<const int N>
d41  struct PartitionSolver {
d41      vector<vector<int>>> part, to, from;
d41      PartitionSolver() {
d41          vector<int> a;
d41          part.push_back(a);
d41          gen(1, N, a);
d41          sort(all(part));
d41          to.assign(sz(part), vector<int>(N + 1, -1));
d41          from = to;
d41          for (int i = 0; i < sz(part); i++) {
d41              int sum = 0;
d41              auto arr = part[i];
d41              for (auto x : arr) sum += x;
d41              to[i][0] = i;
d41              from[i][0] = i;
d41              for (int j = 1; j + sum <= N; j++) {
d41                  arr = part[i];
d41                  arr.push_back(j);
d41                  sort(all(arr));
d41                  to[i][j] = getIndex(arr);
d41                  from[to[i][j]][j] = i;
d41              }
d41          }
d41      }
d41
d41      int size() const { return sz(part); }
d41      int getIndex(const vector<int>& arr) const {
d41          return lower_bound(all(part), arr) - part.begin(); }
d41      int add(int id, int num) const { return to[id][num]; }
d41      int rem(int id, int num) const { return from[id][num]; }
d41      vector<int> getPartition(int id) const {
d41          return part[id]; }
d41
d41      void gen(int i, int sum, vector<int>& a) {
d41          if (i > sum) { return; }
d41          a.push_back(i);
d41          part.push_back(a);
d41          gen(i, sum - i, a);
d41          a.pop_back();
d41          gen(i + 1, sum, a);
d41      }
d41  };
d41
d41  // Number of partitions for all integers <= n
d41  vector<ll> partitionNumber(int n) {
d41      vector<ll> ans(n + 1, 0);
d41      ans[0] = 1;
d41      for (int i = 1; i <= n; i++) {
d41          for (int j = 1; j * (3 * j + 1) / 2 <= i; j++) {
d41              ll here = ans[i - j * (3 * j + 1) / 2];
```

```
d41      ans[i] = (ans[i] + (j & 1 ? here : -here));
d41      }
d41      for (int j = 1; j * (3 * j - 1) / 2 <= i; j++) {
d41          ll here = ans[i - j * (3 * j - 1) / 2];
d41          ans[i] = (ans[i] + (j & 1 ? here : -here));
d41      }
d41      return ans;
d41  }
```

6.3.2 Lucas' Theorem

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

6.4 General purpose numbers

6.4.1 Bernoulli numbers

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

Sums of powers:

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

Euler-Maclaurin formula for infinite sums:

$$\sum_{i=m}^\infty f(i) = \int_m^\infty f(x)dx - \sum_{k=1}^\infty \frac{B_k}{k!} f^{(k-1)}(m)$$

$$\approx \int_m^\infty f(x)dx + \frac{f(m)}{2} - \frac{f'(m)}{12} + \frac{f'''(m)}{720} + O(f^{(5)}(m))$$

6.4.2 Stirling numbers of the first kind

Number of permutations on n items with k cycles.

$$c(n, k) = c(n - 1, k - 1) + (n - 1)c(n - 1, k), \, c(0, 0) = 1$$

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

$$c(8, k) = 8, 0, 5040, 13068, 13132, 6769, 1960, 322, 28, 1$$

$$c(n, 2) = 0, 0, 1, 3, 11, 50, 274, 1764, 13068, 109584, \dots$$

6.4.3 Eulerian numbers

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

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

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

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

6.4.4 Stirling numbers of the second kind

Partitions of n distinct elements into exactly k groups.

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

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

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

6.4.5 Bell numbers

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

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

6.4.6 Labeled unrooted trees

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

6.4.7 Catalan numbers

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

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

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

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

Graph (7)

7.1 Fundamentals

BellmanFord.h

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

d41d8c, 24 lines

```
d41  const ll inf = LLONG_MAX;
d41  struct Ed { int a, b, w, s() { return a < b ? a : -a; }};
d41  struct Node { ll dist = inf; int prev = -1; };
d41
d41  void bell(vector<Node>& nodes, vector<Ed>& eds, int s) {
d41      nodes[s].dist = 0;
d41      sort(all(eds), [](Ed a, Ed b) { return a.s() < b.s(); });
d41
d41      int lim = sz(nodes) / 2 + 2; // /3+100 with shuffled
d41      vertices
d41      for(int i=0; i<lim; i++) for (Ed ed : eds) {
d41          Node cur = nodes[ed.a], &dest = nodes[ed.b];
d41          if (abs(cur.dist) == inf) continue;
d41          ll d = cur.dist + ed.w;
```

```

d41     if (d < dest.dist) {
d41         dest.prev = ed.a;
d41         dest.dist = (i < lim-1 ? d : -inf);
d41     }
d41 }
d41 for(int i=0; i<lim; i++) for (Ed e : eds) {
d41     if (nodes[e.a].dist == -inf)
d41         nodes[e.b].dist = -inf;
d41 }
d41 }

```

FloydWarshall.h

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

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

d41d8c, 20 lines

```

d41 void floydWarshall(vector<vector<ll>>& m) {
d41     int n = sz(m);
d41     for(int i=0; i<n; i++) m[i][i] = min(m[i][i], 0LL);
d41     for(int k=0; k<n; k++)
d41         for(int i=0; i<n; i++)
d41             for(int j=0; j<n; j++)
d41                 if (m[i][k] != inf && m[k][j] != inf) {
d41                     auto newDist = max(m[i][k] + m[k][j], -inf);
d41                     m[i][j] = min(m[i][j], newDist);
d41                 }
d41 }

d41 for(int k=0; k<n; k++)
d41     if (m[k][k] < 0)
d41         for(int i=0; i<n; i++)
d41             for(int j=0; j<n; j++)
d41                 if (m[i][k] != inf && m[k][j] != inf) {
d41                     m[i][j] = -inf;
d41                 }
d41 }

```

7.2 Network flow and Matching

Dinic.h

Time: - $\mathcal{O}(\min(m \cdot \text{max_flow}, n^2 m))$.

- For graphs with unit capacities: $\mathcal{O}(\min(m\sqrt{m}, mn^{2/3}))$.

- If every vertex has in-degree 1 or out-degree 1: $\mathcal{O}(m\sqrt{n})$.

- With capacity scaling: $\mathcal{O}(nm \log(\text{MAXCAP}))$ with high constant factor.

d41d8c, 96 lines

```

d41 struct Dinic {
d41     const bool scaling = false;
d41     int lim;
d41     struct edge {
d41         int to, rev;
d41         ll cap, flow;
d41         bool res;
d41     };
d41     edge(int to_, int cap_, int rev_, bool res_)
d41         : to(to_), cap(cap_), rev(rev_), flow(0), res(res_) {}
d41 };

d41 vector<vector<edge>> g;
d41 vector<int> lev, beg;
d41 ll F;
d41 Dinic(int n) : g(n), lev(n), beg(n), F(0) {}

d41 void add(int a, int b, ll c, ll other = 0) {
d41     g[a].emplace_back(b, c, g[b].size(), false);
d41     g[b].emplace_back(a, other, g[a].size()-1, true);
d41 }

d41 bool bfs(int s, int t) {
d41     fill(all(lev), -1);

```

```

d41     fill(all(beg), 0);
d41     lev[s] = 0;
d41     queue<int> q; q.push(s);
d41     while (q.size()) {
d41         int u = q.front(); q.pop();
d41         for (auto& i : g[u]) {
d41             if (lev[i.to] != -1 or (i.flow == i.cap)) continue;
d41             if (scaling and i.cap - i.flow < lim) continue;
d41             lev[i.to] = lev[u] + 1;
d41             q.push(i.to);
d41         }
d41     }
d41     return lev[t] != -1;
d41 }

d41 ll dfs(int v, int s, ll f = INF) {
d41     if (!f or v == s) return f;
d41     for (int& i = beg[v]; i < g[v].size(); i++) {
d41         auto& e = g[v][i];
d41         if (lev[e.to] != lev[v] + 1) continue;
d41         ll foi = dfs(e.to, s, min(f, e.cap - e.flow));
d41         if (!foi) continue;
d41         e.flow += foi, g[e.to][e.rev].flow -= foi;
d41         return foi;
d41     }
d41     return 0;
d41 }

d41 ll maxFlow(int s, int t) {
d41     for (lim = scaling ? (1<<30) : 1; lim; lim /= 2)
d41         while (bfs(s, t)) while (ll ff = dfs(s, t)) F += ff;
d41     return F;
d41 }

d41 bool inCut(int u) { return lev[u] != -1; }
d41 };

```

MinCost.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. If graph is a DAG pi can be calculated with DP instead of Bellman ford.

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

d41d8c, 95 lines

```

d41 #include <bits/extc++.h>

d41 const ll INF = numeric_limits<ll>::max() / 4;

d41 struct MCMF {
d41     struct edge {
d41         int from, to, rev;
d41         ll cap, cost, flow;
d41     };
d41     int N;
d41     vector<vector<edge>> ed;
d41     vector<int> seen, vis;
d41     vector<ll> dist, pi;
d41     vector<edge*> par;

d41     MCMF(int N) : N(N), ed(N), seen(N), vis(N),
d41         dist(N), pi(N), par(N) {}

d41     void addEdge(int from, int to, ll cap, ll cost) {
d41         if (from == to || cap == 0) return;
d41         ed[from].push_back(edge{from, to, sz(ed[to]), cap, cost, 0});
d41         ed[to].push_back(edge{to, from, sz(ed[from])-1, 0, -cost, 0});
d41     }

d41     void path(int s) {
d41         fill(all(seen), 0);

```

```

d41     fill(all(dist), INF);
d41     dist[s] = 0;
d41     ll di;
d41     __gnu_pbds::priority_queue<pair<ll, int>> q;
d41     vector<decltype(q)::point_iterator> its(N);
d41     q.push({ 0, s });

d41     while (!q.empty()) {
d41         s = q.top().second; q.pop();
d41         seen[s] = 1; di = dist[s] + pi[s];
d41         for (edge& e : ed[s]) {
d41             if (!seen[e.to]) {
d41                 ll val = di - pi[e.to] + e.cost;
d41                 if (e.cap - e.flow > 0 && val < dist[e.to]) {
d41                     dist[e.to] = val;
d41                     par[e.to] = &e;
d41                     if (its[e.to] == q.end()) {
d41                         its[e.to] = q.push({-dist[e.to], e.to});
d41                     } else q.modify(its[e.to], {-dist[e.to], e.to});
d41                 }
d41             }
d41         }
d41     }

d41     for (int i = 0; i < N; i++) {
d41         pi[i] = min(pi[i] + dist[i], INF);
d41     }
d41 }

d41 pair<ll, ll> maxflow(int s, int t) {
d41     setpi(s, t);
d41     ll totflow = 0, totcost = 0;
d41     while (path(s), seen[t]) {
d41         ll fl = INF;
d41         for (edge* x = par[t]; x; x = par[x->from]) {
d41             fl = min(fl, x->cap - x->flow);
d41         }
d41         totflow += fl;
d41         for (edge* x = par[t]; x; x = par[x->from]) {
d41             x->flow += fl;
d41             ed[x->to][x->rev].flow -= fl;
d41         }
d41     }
d41     for (int i = 0; i < N; i++) {
d41         for (edge& e : ed[i]) {
d41             totcost += e.cost * e.flow;
d41         }
d41     }
d41     return { totflow, totcost / 2 };
d41 }

// If some costs can be negative, call this before
// maxflow:
d41 void setpi(int s, int t) {
d41     fill(all(pi), INF);
d41     pi[s] = 0;
d41     int it = N, ch = 1;
d41     ll v;
d41     while (ch-- && it--) {
d41         for (int i = 0; i < N; i++) {
d41             if (pi[i] != INF)
d41                 for (edge& e : ed[i]) if (e.cap)
d41                     if ((v = pi[i] + e.cost) < pi[e.to])
d41                         pi[e.to] = v, ch = 1;
d41         }
d41     }
d41     assert(it >= 0); // negative cost cycle
d41 }

```

PushRelabel.h

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

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

d41d8c, 55 lines

```
d41 struct PushRelabel {
d41     struct Edge {
d41         int dest, back;
d41         ll f, c;
d41     };
d41     vector<vector<Edge>> g;
d41     vector<ll> ec;
d41     vector<Edge*> cur;
d41     vector<vector<int>> hs;
d41     vector<int> H;
d41     PushRelabel(int n) : g(n), ec(n), cur(n), hs(2*n), H(n) {}

d41     void addEdge(int s, int t, ll cap, ll rcap=0) {
d41         if (s == t) return;
d41         g[s].push_back({t, sz(g[t]), 0, cap});
d41         g[t].push_back({s, sz(g[s])-1, 0, rcap});
d41     }

d41     void addFlow(Edge& e, ll f) {
d41         Edge &back = g[e.dest][e.back];
d41         if (!ec[e.dest] && f) hs[H[e.dest]].push_back(e.dest);
d41         e.f += f; e.c -= f; ec[e.dest] += f;
d41         back.f -= f; back.c += f; ec[back.dest] -= f;
d41     }

d41     ll calc(int s, int t) {
d41         int v = sz(g); H[s] = v; ec[t] = 1;
d41         vector<int> co(2*v); co[0] = v-1;
d41         for(int i=0; i<v; i++) cur[i] = g[i].data();
d41         for (Edge& e : g[s]) addFlow(e, e.c);

d41         for (int hi = 0;;) {
d41             while (hs[hi].empty()) if (!hi--) return -ec[s];
d41             int u = hs[hi].back(); hs[hi].pop_back();
d41             while (ec[u] > 0) // discharge u
d41                 if (cur[u] == g[u].data() + sz(g[u])) {
d41                     H[u] = 1e9;
d41                     for (Edge& e : g[u]){
d41                         if (e.c && H[u] > H[e.dest]+1)
d41                             H[u] = H[e.dest]+1, cur[u] = &e;
d41                     }
d41                     if (++co[H[u]], !--co[hi] && hi < v){
d41                         for(int i=0; i<v; i++){
d41                             if (hi < H[i] && H[i] < v)
d41                                 --co[H[i]], H[i] = v + 1;
d41                         }
d41                         hi = H[u];
d41                     }
d41                     else if (cur[u]->c && H[u] == H[cur[u]->dest]+1){
d41                         addFlow(*cur[u], min(ec[u], cur[u]->c));
d41                     }else ++cur[u];
d41                 }
d41             }
d41             hi = H[u];
d41             if (cur[u]->c && H[u] == H[cur[u]->dest]+1){
d41                 addFlow(*cur[u], min(ec[u], cur[u]->c));
d41             }else ++cur[u];
d41         }
d41     }

d41     bool inCut(int a) { return H[a] >= sz(g); }
d41 };
```

Blossom.h

Description: Max matching on general Graph. $mate[i]$ = match of i

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

d41d8c, 56 lines

```
d41 vector<int> Blossom(vector<vector<int>>& g) {
d41     int n = sz(g), timer = -1;
d41     vector<int> mate(n, -1), label(n), par(n), orig(n), aux(n,
```

```
d41     auto lca = [&](int x, int y) {
d41         for (timer++; ; swap(x, y)) {
d41             if (x == -1) continue;
d41             if (aux[x] == timer) return x;
d41             aux[x] = timer;
d41             x=(mate[x] == -1 ? -1 : orig[par[mate[x]]]);
d41         }
d41     };
d41     auto blossom = [&](int v, int w, int a) {
d41         while (orig[v] != a) {
d41             par[v] = w; w = mate[v];
d41             if (label[w] == 1) label[w] = 0, q.push_back(w);
d41             orig[v] = orig[w] = a;
d41             v = par[w];
d41         }
d41     };
d41     auto aug = [&](int v) {
d41         while (v != -1) {
d41             int pv = par[v], nv = mate[pv];
d41             mate[v] = pv; mate[pv] = v; v = nv;
d41         }
d41     };
d41     auto bfs = [&](int root) {
d41         fill(all(label), -1);
d41         iota(all(orig), 0);
d41         q.clear();
d41         label[root] = 0; q.push_back(root);
d41         for (int i = 0; i < sz(q); i++) {
d41             int v = q[i];
d41             for (auto x : g[v]) {
d41                 if (label[x] == -1) {
d41                     label[x] = 1; par[x] = v;
d41                     if (mate[x] == -1) return aug(x), 1;
d41                     label[mate[x]] = 0;
d41                     q.push_back(mate[x]);
d41                 }
d41                 else if (!label[x] && orig[v] != orig[x]){
d41                     int a = lca(orig[v], orig[x]);
d41                     blossom(x, v, a);
d41                     blossom(v, x, a);
d41                 }
d41             }
d41         }
d41         return 0;
d41     };
d41     // Time halves if you start with (any) maximal
d41     // matching.
d41     for (int i = 0; i < n; i++) {
d41         if (mate[i] == -1) bfs(i);
d41     }
d41     return mate;
d41 };
```

HopcroftKarp.h

Description: ans is the size of the max matching.

The match of x is $l[x]$

Usage: HopcroftKarp(|X|, |Y|, edges(x, y))

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

d41d8c, 46 lines

```
d41 struct HopcroftKarp {
d41     vector<int> g, l, r;
d41     int ans;
d41     HopcroftKarp(int n, int m, vector<pair<int, int>> e)
d41         : g(e.size()), l(n, -1), r(m, -1), ans(0) {
d41         shuffle(e.begin(), e.end(), rng);
d41         vector<int> deg(n + 1);
d41         for (auto& [x, y] : e) deg[x]++;
d41         for (int i = 1; i <= n; i++) deg[i] += deg[i - 1];
```

```
d41         for (auto& [x, y] : e) g[--deg[x]] = y;
```

```
d41     vector<int> q(n);
d41     while (true) {
d41         vector<int> a(n, -1), p(n, -1);
d41         int t = 0;
d41         for (int i = 0; i < n; i++) {
d41             if (l[i] == -1) {
d41                 q[t++] = a[i] = p[i] = i;
d41             }
d41         }
d41         bool match = false;
d41         for (int i = 0; i < t; i++) {
d41             int x = q[i];
d41             if (!l[a[x]]) continue;
d41             for (int j = deg[x]; j < deg[x + 1]; j++)
d41                 {
d41                     int y = g[j];
d41                     if (r[y] == -1) {
d41                         while (!y) {
d41                             r[y] = x;
d41                             swap(l[x], y);
d41                             x = p[x];
d41                         }
d41                         match = true, ans++;
d41                         break;
d41                     }
d41                     if (p[r[y]] == -1) {
d41                         q[t++] = y = r[y];
d41                         p[y] = x, a[y] = a[x];
d41                     }
d41                 }
d41             }
d41             if (!match) break;
d41         }
d41     }
d41 };
```

WeightedMatching.h

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

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

d41d8c, 41 lines

```
d41 pair<ll, vector<int>> hunga(const vector<vector<ll>>& a) {
d41     if (a.empty()) return { 0, {} };
d41     int n = sz(a) + 1, m = sz(a[0]) + 1;
d41     vector<ll> u(n), v(m), p(m);
d41     vector<int> ans(n - 1);
d41     for (int i = 1; i < n; i++) {
d41         p[0] = i;
d41         int j0 = 0;
d41         vector<ll> dist(m, LLONG_MAX), pre(m, -1);
d41         vector<bool> done(m + 1);
d41         do {
d41             done[j0] = true;
d41             ll i0 = p[j0], j1 = -1, delta = LLONG_MAX;
d41             for (int j = 1; j < m; j++) {
d41                 if (!done[j]) {
d41                     ll cur = a[i0-1][j-1] - u[i0] - v[j];
d41                     if (cur < dist[j])
d41                         dist[j] = cur, pre[j] = j0;
d41                     if (dist[j] < delta)
d41                         delta = dist[j], j1 = j;
d41                 }
d41             }
d41             for (int j = 0; j < m; j++) {
```

```

d41         if (done[j])
d41             u[p[j]] += delta, v[j] -= delta;
d41         else dist[j] -= delta;
d41     }
d41     assert(j1 != -1);
d41     j0 = j1;
d41 } while (p[j0]);
d41 while (j0) {
d41     int j1 = pre[j0];
d41     p[j0] = p[j1], j0 = j1;
d41 }
d41 }
d41 for (int j = 1; j < m; j++) {
d41     if (p[j]) ans[p[j] - 1] = j - 1;
d41 }
d41 return { -v[0], ans }; // min cost
d41 }
```

7.2.1 Hall's Theorem

In bipartite graphs, there exists a perfect matching covering the entire side X if and only if for every subset $Y \subseteq X$,

$$|Y| \leq |N(Y)|,$$

where $N(Y)$ denotes the set of neighbors of Y .

7.2.2 König's Theorem

In a bipartite graph, the size of a Minimum Vertex Cover is equal to the size of a Maximum Matching. A Minimum Vertex Cover is a minimum set of vertices such that every edge of the graph has at least one endpoint in the set.

As a consequence,

$$n - \text{Maximum Matching} = \text{Maximum Independent Set},$$

where a Maximum Independent Set is the largest set of vertices with no edges between them.

Recovering the Minimum Vertex Cover Given a maximum matching in a bipartite graph (X, Y) :

- Construct the residual graph by orienting:
 - non-matching edges from X to Y ;
 - matching edges from Y to X .
- Perform a BFS or DFS starting from all free (unmatched) vertices in X .
- Let Z_X be the set of reachable vertices in X , and Z_Y the set of reachable vertices in Y .

The Minimum Vertex Cover is given by:

$$(X \setminus Z_X) \cup Z_Y.$$

7.2.3 Node-Disjoint Path Cover

A node-disjoint path cover is a set of paths such that each vertex belongs to exactly one path.

In a directed acyclic graph (DAG),

Minimum Node-Disjoint Path Cover = n – Maximum Matching.

The construction is as follows: for each vertex u , create a copy u' . Add an edge $u \rightarrow v'$ if there exists an edge $u \rightarrow v$ in the original graph.

Recovering the Paths

- Vertices that do not appear as destinations in the matching are starting points of paths.
- Each matching edge $u \rightarrow v'$ corresponds to an edge $u \rightarrow v$ in the original DAG.
- Following these edges reconstructs all paths of the path cover.

7.2.4 General Path Cover

A general path cover is a path cover where a vertex may belong to more than one path.

In a DAG, the construction is similar to the node-disjoint case, but an edge $u \rightarrow v'$ exists if there is a path from u to v in the original graph.

Recovering the Cover The vertices can be grouped according to the edges used in the matching to form the path cover.

7.2.5 Dilworth's Theorem

An antichain is a set of vertices such that there is no path between any pair of vertices in the set.

In a directed acyclic graph,

$$\text{Minimum General Path Cover} = \text{Maximum Antichain}.$$

Recovering a Maximum Antichain Given a minimum general path cover, selecting one vertex from each path produces a maximum antichain.

7.3 DFS algorithms

Bridges.h

```

d41 vector<int> g[ms];
d41 int low[ms], tin[ms], vis[ms], t;

d41 void dfs(int u = 0, int p = -1) {
d41     vis[u] = true;
d41     low[u] = tin[u] = t++;
d41     for (auto v : g[u]) {
d41         if (v == p) continue;
```

```

d41         if (vis[v]) {
d41             low[u] = min(low[u], tin[v]);
d41         }
d41         else {
d41             dfs(v, u);
d41             low[u] = min(low[u], low[v]);
d41             // if (low[v] >= tin[u] && p != -1), U is an
d41                 articulation point
d41             if (low[v] > tin[u]) {
d41                 // edge from U to V is a bridge
d41             }
d41             // children++
d41         }
d41     }
d41     // if(children > 1 && p == -1) root is an articulation
d41         point
d41 }
```

EulerPath.h

Description: Receives as input graph(node, edge index), number of edges and source. Returns list of node, index of edge he came from, if path/circuit does not exists returns empty list.

```

d41d8c, 27 lines
d41 vector<pii> eulerPath(const vector<vector<pii>>& g, int
d41     nedges, int src) {
d41     int n = sz(g);
d41     vector<int> deg(n, 0), its(n, 0), used(nedges + 1, 0);
d41     vector<pii> s = { {src, -1} };
d41     //deg[src]++; //to allow paths, not only circuits
d41     vector<pii> ret;
d41     while (!s.empty()) {
d41         int u = s.back().first, &it = its[u];
d41         if (it == sz(g[u])) {
d41             ret.push_back(s.back());
d41             s.pop_back();
d41             continue;
d41         }
d41         auto& [nxt, id] = g[u][it++];
d41         if (!used[id]) {
d41             deg[u]--, deg[nxt]++;
d41             used[id] = 1;
d41             s.push_back({ nxt, id });
d41         }
d41     }
d41     for (int x : deg) {
d41         if (x < 0 || sz(ret) != (nedges + 1)) return {};
d41     }
d41     reverse(ret.begin(), ret.end());
d41     return ret;
d41 }
```

SCC.h

Description: Kosaraju algorithm for calculating strongly connected components. Components are ordered in topological order.

```

d41d8c, 36 lines
d41 struct SCC {
d41     int n, ncomp;
d41     vector<vector<int>> g, inv;
d41     vector<int> comp, vis, stk;
d41     SCC() {}
d41     SCC(int n)
d41         : n(n), ncomp(0), g(n), inv(n), comp(n, -1), vis(n) {}

d41     void dfs(int u) {
d41         vis[u] = 1;
d41         for (int v : g[u]) if (!vis[v]) dfs(v);
d41         stk.push_back(u);
d41     }
d41     void dfs_inv(int u) {
```

```

d41      comp[u] = ncomp;
d41      for (int v : inv[u]) {
d41          if (comp[v] == -1) dfs_inv(v);
d41      }
d41  }
d41  void solve() {
d41      for (int i = 0; i < n; i++) {
d41          if (!vis[i]) dfs(i);
d41      }
d41      reverse(all(stk));
d41      for (int u : stk) {
d41          if (comp[u] != -1) continue;
d41          dfs_inv(u);
d41          ncomp++;
d41      }
d41  }
d41  void add_edge(int a, int b) {
d41      g[a].push_back(b);
d41      inv[b].push_back(a);
d41  }
d41 };

```

Twosat.h

Usage: not A = ~A

"scc.h" d41d8c, 37 lines

```

d41 struct TwoSat{
d41     int n;
d41     SCC scc;
d41     vector<int> value;
d41     vector<pii> e;
d41     TwoSat(int n) : n(n){}
d41     bool solve(){
d41         value.resize(n);
d41         scc = SCC(2*n);
d41         for(auto &x : e) scc.add_edge(x.first, x.second);
d41         scc.solve();
d41         for(int i=0; i<2*n; i++)
d41             if(scc.comp[i] == scc.comp[i^1]) return false;
d41         for(int i=0; i<n; i++)
d41             value[i] = scc.comp[id(i)] > scc.comp[id(~i)];
d41         return true;
d41     }
d41     void atMostOne(vector<int> &li){
d41         if(sz(li) <= 1) return;
d41         int cur = ~li[0];
d41         for(int i = 2; i < sz(li); i++) {
d41             int next = n++;
d41             addOr(cur, ~li[i]);
d41             addOr(cur, next);
d41             addOr(~li[i], next);
d41             cur = ~next;
d41         }
d41         addOr(cur, ~li[1]);
d41     }
d41     int id(int v) { return v < 0 ? (~v) * 2 ^ 1 : v * 2; }
d41     void add(int a, int b) { e.push_back({id(a), id(b)}); }
d41     void addOr(int a, int b) { add(~a, b); add(~b, a); }
d41     void addImp(int a, int b) { addOr(~a, b); }
d41     void addEqual(int a, int b){ addOr(a, ~b); addOr(~a, b); }
d41 }
d41 void isFalse(int a) { addImp(a, ~a); }
d41 };

```

7.4 Heuristics

MaxClique.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.

d41d8c, 53 lines

```

d41 using vb = vector<bitset<200>>;
d41 struct Maxclique {
d41     double limit=0.025, pk=0;
d41     struct Vertex { int i, d=0; };
d41     using vv = vector<Vertex>;
d41     vb e;
d41     vv V;
d41     vector<vector<int>>> C;
d41     vector<int> qmax, q, S, old;
d41     void init(vv& r) {
d41         for (auto& v : r) v.d = 0;
d41         for (auto& v : r) for (auto j : r) v.d += e[v.i][j.i];
d41         sort(all(r), [](auto a, auto b) { return a.d > b.d; });
d41         int mxD = r[0].d;
d41         for(int i=0; i<sz(r); i++) r[i].d = min(i, mxD) + 1;
d41     }
d41     void expand(vv& R, int lev = 1) {
d41         S[lev] += S[lev - 1] - old[lev];
d41         old[lev] = S[lev - 1];
d41         while (sz(R)) {
d41             if (sz(q) + R.back().d <= sz(qmax)) return;
d41             q.push_back(R.back().i);
d41             vv T;
d41             for(auto v : R)
d41                 if (e[R.back().i][v.i]) T.push_back({v.i});
d41             if (sz(T)) {
d41                 if (S[lev]++ / ++pk < limit) init(T);
d41                 int j = 0, mxk = 1, mnk = max(sz(qmax)-sz(q)+1, 1);
d41                 C[1].clear(), C[2].clear();
d41                 for (auto v : T) {
d41                     int k = 1;
d41                     auto f = [&](int i) { return e[v.i][i]; };
d41                     while (any_of(all(C[k]), f)) k++;
d41                     if (k > mxk) mxk = k, C[mxk + 1].clear();
d41                     if (k < mnk) T[j++].i = v.i;
d41                     C[k].push_back(v.i);
d41                 }
d41                 if (j > 0) T[j - 1].d = 0;
d41                 for(int k=mnk; k<mxk + 1; k++){
d41                     for (int i : C[k])
d41                         T[j].i = i, T[j++].d = k;
d41                 }
d41                 expand(T, lev + 1);
d41             } else if (sz(q) > sz(qmax)) qmax = q;
d41             q.pop_back(), R.pop_back();
d41         }
d41     }
d41     vector<int> maxClique(){ init(V), expand(V); return qmax; }
d41     Maxclique(vb conn) : e(conn), C(sz(e)+1), S(sz(C)), old(S) {
d41         for(int i=0; i<sz(e); i++) V.push_back({i});
d41     }
d41 };

```

7.5 Trees

Centroid.h

Description: Call decomp(0) to solve, marked array should be initially set to zero.

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

d41d8c, 27 lines

```

d41 int tam[ms], marked[ms];

d41 int calc_tam(int u, int p) {
d41     tam[u] = 1;
d41     for (int v : g[u]) {
d41         if (v != p && !marked[v]) tam[u] += calc_tam(v, u);
d41     }

```

```

d41     return tam[u];
d41 }

d41 int get_centroid(int u, int p, int tot) {
d41     for (int v : g[u]) {
d41         if (v != p && !marked[v] && (tam[v] > (tot / 2)))
d41             return get_centroid(v, u, tot);
d41     }
d41     return u;
d41 }
// Cent is a child of P in the centroid tree
d41 void decomp(int u, int p = -1) {
d41     calc_tam(u, -1);
d41     int cent = get_centroid(u, -1, tam[u]);
d41     marked[cent] = 1;
d41     for (int v : g[cent]) {
d41         if (!marked[v]) decomp(v, cent);
d41     }
d41 }

```

HLD.h

Description: If values are stored on edges, set EDGE = true and store each edge's value at the endpoint farther from the root (the deeper node).

rp[i] is the representative (head) of the heavy path containing node i: it is the node in that chain that is closest to the root.

d41d8c, 51 lines

```

d41 template<bool EDGE> struct HLD {
d41     int n, t;
d41     vector<vector<int>>> g;
d41     vector<int> pai, rp, tam, pos, val, arr;
d41     Seg seg;
d41     HLD(int n, vector<vector<int>>>& g, vector<int>& val)
d41         : n(n), t(0), g(g), pai(n), rp(n), tam(n, 1),
d41           pos(n), val(val), arr(n) {
d41         calc_tam(0, -1);
d41         dfs(0, -1);
d41         seg.build(arr);
d41     }

d41     int calc_tam(int u, int p) {
d41         pai[u] = p;
d41         for (int& v : g[u]) {
d41             if (v == p) continue;
d41             tam[u] += calc_tam(v, u);
d41             if(tam[v] > tam[g[u][0]] || g[u][0] == p)
d41                 swap(g[u][0], v);
d41         }
d41         return tam[u];
d41     }

d41     void dfs(int u, int p) {
d41         pos[u] = t++;
d41         arr[pos[u]] = val[u];
d41         for (int v : g[u]) {
d41             if (v == p) continue;
d41             rp[v] = (v == g[u][0] ? rp[u] : v);
d41             dfs(v, u);
d41         }
d41     }

d41     int query(int a, int b) { // query on the path from a
to b
d41         int ans = 0; // neutral value
d41         while (rp[a] != rp[b]) {
d41             if (pos[a] < pos[b]) swap(a, b);
d41             ans = max(ans, seg.query(pos[rp[a]], pos[a]));
d41             a = pai[rp[a]];
d41         }
d41         if(pos[a] > pos[b]) swap(a, b);

```



```
d41      ans = max(ans, seg.query(pos[a] + EDGE, pos[b]));
d41      return ans;
d41  }

d41  void update(int a, int x) {
d41      seg.update(pos[a], x);
d41  }
d41 }
```

LCA.h
Description: LCA algorithm using binary lifting, *is_ancestor(a,b)* returns true if *a* is an ancestral of *b* and false otherwise.
Time: $\mathcal{O}(N \log N)$

d41d8c, 26 lines

```
d41  int tin[MAXN], tout[MAXN], timer=0;
d41  int up[MAXN][BITS];
d41  void dfs(int u, int p){
d41      tin[u] = timer++; up[u][0] = p;
d41      for (int i=1; i<BITS; i++) {
d41          up[u][i] = up[up[u][i-1]][i-1];
d41      }
d41      for (int v: g[u]) if (v != p) dfs(v, u);
d41      tout[u] = timer;
d41  }

d41  bool is_ancestor(int u, int v){
d41      return (tin[u] <= tin[v] && tout[u] >= tout[v]);
d41  }

d41  int lca(int u, int v){
d41      if (is_ancestor(u, v)) return u;
d41      if (is_ancestor(v, u)) return v;
d41      for (int i=BITS-1; i>=0; i--) {
d41          if (up[u][i] && !is_ancestor(up[u][i], v)) {
d41              u = up[u][i];
d41          }
d41      }
d41      return up[u][0];
d41  }
```

VirtualTree.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. *virt[u]* is the adjacency list of the virtual tree: it stores pairs (*v*, *dist*), where *v* is a neighbor of *u* in the virtual tree and *dist* is the distance between *u* and *v* in the original tree.
Time: $\mathcal{O}(|S| \log |S|)$

"LCA.h" d41d8c, 24 lines

```
d41  vector<pair<int, int>> virt[ms];

d41  void build_virt(vector<int>& v) {
d41      auto cmp = [&](int i, int j){ return tin[i] < tin[j]; };
d41      sort(all(v), cmp);
d41      for (int i = 0, n = sz(v); i + 1 < n; i++)
d41          v.push_back(lca(v[i], v[i + 1]));
d41      sort(all(v), cmp);
d41      v.erase(unique(all(v)), v.end());
d41      stack<int> st;
d41      for (auto u : v) {
d41          if (st.empty()) {
d41              st.push(u);
d41          }
d41          else {
d41              while(sz(st) && !is_ancestor(st.top(), u)) st.pop();
d41              int p = st.top();
d41              virt[p].emplace_back(u, abs(lvl[u] - lvl[p]));
d41              virt[u].emplace_back(p, abs(lvl[u] - lvl[p]));
d41              st.push(u);
d41          }
d41      }
```

```
d41  }
d41 }
```

7.6 Math

7.6.1 Number of Spanning Trees

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

7.6.2 Erdős–Gallai theorem

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

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

7.7 Planar Graphs

If *G* has *k* connected components, then $n - m + f = k + 1$.

Geometry (8)

8.1 Geometric primitives

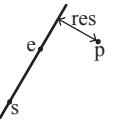
Point.h d41d8c, 29 lines

```
d41  template <class T> int sgn(T x) { return (x > 0) - (x < 0)
d41  ; }
d41  template<class T>
d41  struct Point {
d41      typedef Point P;
d41      T x, y;
d41      explicit Point(T x=0, T y=0) : x(x), y(y) {}
d41      bool operator<(P p) const { return tie(x,y) < tie(p.x,p.y)
d41      }; }
d41      bool operator==(P p) const { return tie(x,y)==tie(p.x,p.y)
d41      }; }
d41      P operator+(P p) const { return P(x+p.x, y+p.y); }
d41      P operator-(P p) const { return P(x-p.x, y-p.y); }
d41      P operator*(T d) const { return P(x*d, y*d); }
d41      P operator/(T d) const { return P(x/d, y/d); }
d41      T dot(P p) const { return x*p.x + y*p.y; }
d41      T cross(P p) const { return x*p.y - y*p.x; }
d41      T cross(P a, P b) const { return (a-*this).cross(b-*this)
d41      ; }
d41      T dist2() const { return x*x + y*y; }
d41      double dist() const { return sqrt((double)dist2()); }
d41      // angle to x-axis in interval [-pi, pi]
d41      double angle() const { return atan2(y, x); }
d41      P unit() const { return *this/dist(); } // makes dist()=1
d41      P perp() const { return P(-y, x); } // rotates +90
d41      degrees
d41      P normal() const { return perp().unit(); }
d41      // returns point rotated 'a' radians ccw around the
d41      origin
d41      P rotate(double a) const {
d41          return P(x*cos(a)-y*sin(a),x*sin(a)+y*cos(a)); }
```

d41d8c, 5 lines

```
d41  friend ostream& operator<<(ostream& os, P p) {
d41      return os << "(" << p.x << ", " << p.y << ")"; }
d41  };

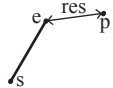
lineDistance.h
Description:
Returns the signed distance between point p and the line
containing points a and b. Positive value on left side and negative
on right as seen from a towards b. a==b gives nan. P is sup-
posed to be Point<T> or Point3D<T> where T is e.g. double
or long long. It uses products 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
```



SegmentDistance.h

d41d8c, 7 lines

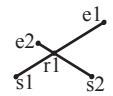
```
d41  typedef Point<double> P;
d41  double segDist(P& s, P& e, P& p) {
d41      if (s==e) return (p-s).dist();
d41      auto d = (e-s).dist2(), t = min(d,max(.0, (p-s).dot(e-s)))
d41      ;
d41      return ((p-s)*d-(e-s)*t).dist()/d;
d41  }
```



SegmentIntersection.h

d41d8c, 14 lines

```
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 in-
tersection 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"
```



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" d41d8c, 9 lines

```
d41 template<class P>
d41 pair<int, P> lineInter(P s1, P e1, P s2, P e2) {
d41     auto d = (e1 - s1).cross(e2 - s2);
d41     if (d == 0) // if parallel
d41         return {(s1.cross(e1, s2) == 0), P(0, 0)};
d41     auto p = s2.cross(e1, e2), q = s2.cross(e2, s1);
d41     return {1, (s1 * p + e1 * q) / d};
d41 }
```

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" d41d8c, 10 lines

```
d41 template<class P>
d41 int sideOf(P s, P e, P p) { return sgn(s.cross(e, p)); }
```

```
d41 template<class P>
d41 int sideOf(const P& s, const P& e, const P& p, double eps)
d41 {
d41     auto a = (e-s).cross(p-s);
d41     double l = (e-s).dist()*eps;
d41     return (a > l) - (a < -l);
d41 }
```

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" d41d8c, 4 lines

```
d41 template<class P> bool onSegment(P s, P e, P p) {
d41     return p.cross(s, e) == 0 && (s - p).dot(e - p) <= 0;
d41 }
```

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" d41d8c, 7 lines

```
d41 typedef Point<double> P;
d41 P linearTransformation(const P& p0, const P& p1,
d41     const P& q0, const P& q1, const P& r) {
d41     P dp = p1-p0, dq = q1-q0, num(dp.cross(dq), dp.dot(dq));
d41     return q0 + P((r-p0).cross(num), (r-p0).dot(num))/dp.dist
d41         2();
d41 }
```

LineProjectionReflection.h

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

"Point.h" d41d8c, 6 lines

```
d41 template<class P>
d41 P lineProj(P a, P b, P p, bool refl=false) {
d41     P v = b - a;
d41     return p - v.perp()*(1+refl)*v.cross(p-a)/v.dist2();
d41 }
```

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

d41d8c, 36 lines

```
d41 struct Angle {
d41     int x, y;
d41     int t;
d41     Angle(int x, int y, int t=0) : x(x), y(y), t(t) {}
d41     Angle operator-(Angle b) const { return {x-b.x, y-b.y, t
d41         }; }
d41     int half() const {
d41         assert(x || y);
d41         return y < 0 || (y == 0 && x < 0);
d41     }
d41     Angle t90() const { return {-y, x, t + (half() && x >= 0)
d41         }; }
d41     Angle t180() const { return {-x, -y, t + half()}; }
d41     Angle t360() const { return {x, y, t + 1}; }
d41 };
d41 bool operator<(Angle a, Angle b) {
d41     // add a.dist2() and b.dist2() to also compare distances
d41     return make_tuple(a.t, a.half(), a.y * (11)b.x) <
d41         make_tuple(b.t, b.half(), a.x * (11)b.y);
d41 }
```

// Given two points, this calculates the smallest angle
between
// them, i.e., the angle that covers the defined line
segment.

```
d41 pair<Angle, Angle> segmentAngles(Angle a, Angle b) {
d41     if (b < a) swap(a, b);
d41     return (b < a.t180() ?
d41         make_pair(a, b) : make_pair(b, a.t360()));
d41 }
d41 Angle operator+(Angle a, Angle b) { // point a + vector b
d41     Angle r(a.x + b.x, a.y + b.y, a.t);
d41     if (a.t180() < r) r.t--;
d41     return r.t180() < a ? r.t360() : r;
d41 }
d41 Angle angleDiff(Angle a, Angle b) { // angle b - angle a
d41     int tu = b.t - a.t; a.t = b.t;
d41     return {a.x*b.x + a.y*b.y, a.x*b.y - a.y*b.x, tu - (b < a
d41         )};
d41 }
```

HalfPlane.h

Description: Computes the intersection of a set of half-planes. Half-planes are sorted by angle and processed with a deque, removing redundant or conflicting constraints. Parallel half-planes are handled explicitly. Returns the convex polygon of the intersection, or empty if infeasible.

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

"Point.h" d41d8c, 72 lines

```
d41 using ld = long double;
d41 using P = Point<ld>;
```

```
d41 struct Hp { // Half plane struct
d41     // 'p' is a passing point of the line and 'pq' is the
d41     direction vector of the line.
```

```
d41     P p, pq;
d41     ld angle;
```

```
d41     Hp() {}
d41     Hp(const P& a, const P& b) : p(a), pq(b - a) {
d41         angle = atan21(pq.y, pq.x);
d41     }
d41     bool out(const P& r) { return pq.cross(r - p) < -eps; }
d41     bool operator < (const Hp& e) const {
d41         return angle < e.angle;
d41     }
d41     friend P inter(const Hp& s, const Hp& t) {
d41         ld alpha = (t.p - s.p).cross(t.pq) / s.pq.cross(t.pq);
d41         return s.p + (s.pq * alpha);
d41     }
d41     };
```

```
d41 vector<P> hp_intersect(vector<Hp>& H) {
d41     P box[4] = { P(-inf, inf), P(-inf, -inf),
d41         P(-inf, -inf), P(inf, -inf) };
```

```
d41     for(int i = 0; i < 4; i++) {
d41         Hp aux(box[i], box[(i+1) % 4]);
d41         H.push_back(aux);
d41     }
d41     sort(all(H));
d41     deque<Hp> dq;
d41     int len = 0;
d41     for(int i = 0; i < sz(H); i++) {
d41         while(len > 1 && H[i].out(inter(dq[len-1], dq[len-2]])) {
d41             dq.pop_back();
d41             --len;
d41         }
d41         while (len > 1 && H[i].out(inter(dq[0], dq[1]])) {
d41             dq.pop_front();
d41             --len;
d41         }
d41         if(len && fabs1(H[i].pq.cross(dq[len-1].pq)) < eps) {
d41             if (H[i].pq.dot(dq[len-1].pq) < 0.0)
d41                 return vector<P>();
d41             if (H[i].out(dq[len-1].p)) {
d41                 dq.pop_back();
d41                 --len;
d41             }
d41             else continue;
d41         }
d41         dq.push_back(H[i]);
d41         ++len;
d41     }
```

```
d41     while(len > 2 && dq[0].out(inter(dq[len-1], dq[len-2]])) {
d41         dq.pop_back();
d41         --len;
d41     }
d41     while (len > 2 && dq[len-1].out(inter(dq[0], dq[1]])) {
d41         dq.pop_front();
d41         --len;
d41     }
d41     if (len < 3) return vector<P>();
d41     vector<P> ret(len);
d41     for(int i = 0; i+1 < len; i++) {
d41         ret[i] = inter(dq[i], dq[i+1]);
```

```

d41 }
d41 ret.back() = inter(dq[len-1], dq[0]);
d41 return ret;
d41 }

```

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" d41d8c, 12 lines
d41 typedef Point<double> P;
d41 bool circleInter(P a,P b,double r1,double r2,pair<P, P>*
out) {
d41 if (a == b) { assert(r1 != r2); return false; }
d41 P vec = b - a;
d41 double d2 = vec.dist2(), sum = r1+r2, dif = r1-r2;
d41 double p = (d2 + r1*r1 - r2*r2)/(d2*2), h2 = r1*r1 - p*p*
d2;
d41 if (sum*sum < d2 || dif*dif > d2) return false;
d41 P mid = a + vec*p, per = vec.perp() * sqrt(fmax(0, h2) /
d2);
d41 *out = {mid + per, mid - per};
d41 return true;
d41 }

```

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" d41d8c, 14 lines
d41 template<class P>
d41 vector<pair<P, P>> tangents(P c1, double r1, P c2, double
r2) {
d41 P d = c2 - c1;
d41 double dr = r1 - r2, d2 = d.dist2(), h2 = d2 - dr * dr;
d41 if (d2 == 0 || h2 < 0) return {};
d41 vector<pair<P, P>> out;
d41 for (double sign : {-1, 1}) {
d41 P v = (d * dr + d.perp() * sqrt(h2) * sign) / d2;
d41 out.push_back({c1 + v * r1, c2 + v * r2});
d41 }
d41 if (h2 == 0) out.pop_back();
d41 return out;
d41 }

```

CircleLine.h

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

```

"Point.h" d41d8c, 10 lines
d41 template<class P>
d41 vector<P> circleLine(P c, double r, P a, P b) {
d41 P ab = b - a, p = a + ab * (c-a).dot(ab) / ab.dist2();
d41 double s = a.cross(b, c), h2 = r*r - s*s / ab.dist2();
d41 if (h2 < 0) return {};
d41 if (h2 == 0) return {p};
d41 P h = ab.unit() * sqrt(h2);
d41 return {p - h, p + h};
d41 }

```

CirclePolygonIntersection.h

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

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

```

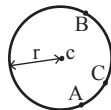
"../content/geometry/Point.h" d41d8c, 20 lines
d41 typedef Point<double> P;
d41 #define arg(p, q) atan2(p.cross(q), p.dot(q))
d41 double circlePoly(P c, double r, vector<P> ps) {
d41 auto tri = [&](P p, P q) {
d41 auto r2 = r * r / 2;
d41 P d = q - p;
d41 auto a = d.dot(p)/d.dist2(), b = (p.dist2()-r*r)/d.dist
2();
d41 auto det = a * a - b;
d41 if (det <= 0) return arg(p, q) * r2;
d41 auto s = max(0., -a-sqrt(det)), t = min(1., -a+sqrt(det
));
d41 if (t < 0 || 1 <= s) return arg(p, q) * r2;
d41 P u = p + d * s, v = q + d * (t-1);
d41 return arg(p,u) * r2 + u.cross(v)/2 + arg(v,q) * r2;
d41 };
d41 auto sum = 0.0;
d41 rep(i,0,sz(ps))
d41 sum += tri(ps[i] - c, ps[(i + 1) % sz(ps)] - c);
d41 return sum;
d41 }

```

circumcircle.h

Description:

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



```

"Point.h" d41d8c, 10 lines
d41 typedef Point<double> P;
d41 double ccRadius(const P& A, const P& B, const P& C) {
d41 return (B-A).dist()*(C-B).dist()*(A-C).dist()/
d41 abs((B-A).cross(C-A))/2;
d41 }
d41 P ccCenter(const P& A, const P& B, const P& C) {
d41 P b = C-A, c = B-A;
d41 return A + (b*c.dist2()-c*b.dist2()).perp()/b.cross(c)/2;
d41 }

```

MinimumEnclosingCircle.h

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

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

```

"circumcircle.h" d41d8c, 18 lines
d41 pair<P, double> mec(vector<P> ps) {
d41 shuffle(all(ps), mt19937(time(0)));
d41 P o = ps[0];
d41 double r = 0, EPS = 1 + 1e-8;
d41 rep(i,0,sz(ps)) if ((o - ps[i]).dist() > r * EPS) {
d41 o = ps[i], r = 0;
d41 rep(j,0,i) if ((o - ps[j]).dist() > r * EPS) {
d41 o = (ps[i] + ps[j]) / 2;
d41 r = (o - ps[i]).dist();
d41 rep(k,0,j) if ((o - ps[k]).dist() > r * EPS) {
d41 o = ccCenter(ps[i], ps[j], ps[k]);
d41 r = (o - ps[i]).dist();
d41 }
d41 }
d41 }
d41 return {o, r};
d41 }

```

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" d41d8c, 12 lines
d41 template<class P>
d41 bool inPolygon(vector<P> &p, P a, bool strict = true) {
d41 int cnt = 0, n = sz(p);
d41 rep(i,0,n) {
d41 P q = p[(i + 1) % n];
d41 if (onSegment(p[i], q, a)) return !strict;
d41 //or: if (segDist(p[i], q, a) <= eps) return !strict;
d41 cnt ^= ((a.y<p[i].y) - (a.y<q.y)) * a.cross(p[i], q) >
0;
d41 }
d41 return cnt;
d41 }

```

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" d41d8c, 7 lines
d41 template<class T>
d41 T polygonArea2(vector<Point<T>>& v) {
d41 T a = v.back().cross(v[0]);
d41 rep(i,0,sz(v)-1) a += v[i].cross(v[i+1]);
d41 return a;
d41 }

```

PolygonCenter.h

Description: Returns the center of mass for a polygon.

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

```

"Point.h" d41d8c, 10 lines
d41 typedef Point<double> P;
d41 P polygonCenter(const vector<P>& v) {
d41 P res(0, 0); double A = 0;
d41 for (int i = 0, j = sz(v) - 1; i < sz(v); j = i++) {
d41 res = res + (v[i] + v[j]) * v[j].cross(v[i]);
d41 A += v[j].cross(v[i]);
d41 }
d41 return res / A / 3;
d41 }

```

PolygonCut.h

Description:

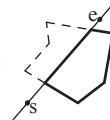
Returns a vector with the vertices of a polygon with everything to the left of the line going from s to e cut away.

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

```

"Point.h" d41d8c, 14 lines
d41 typedef Point<double> P;
d41 vector<P> polygonCut(const vector<P>& poly, P s, P e) {
d41 vector<P> res;
d41 rep(i,0,sz(poly)) {
d41 P cur = poly[i], prev = i ? poly[i-1] : poly.back();
d41 auto a = s.cross(e, cur), b = s.cross(e, prev);
d41 if ((a < 0) != (b < 0))
d41 res.push_back(cur + (prev - cur) * (a / (a - b)));
d41 if (a < 0)
d41 res.push_back(cur);
d41 }
d41 return res;
d41 }

```



PolygonUnion.h

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

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

```
"Point.h", "sideOf.h"
d41d8c, 34 lines

d41 typedef Point<double> P;
d41 double rat(P a, P b) { return sgn(b.x) ? a.x/b.x : a.y/b.y; }
d41 double polyUnion(vector<vector<P>>& poly) {
d41     double ret = 0;
d41     rep(i,0,sz(poly)) rep(v,0,sz(poly[i])) {
d41         P A = poly[i][v], B = poly[i][(v + 1) % sz(poly[i])];
d41         vector<pair<double, int>> segs = {{0, 0}, {1, 0}};
d41         rep(j,0,sz(poly)) if (i != j) {
d41             rep(u,0,sz(poly[j])) {
d41                 P C = poly[j][u], D = poly[j][(u + 1) % sz(poly[j])];
d41             }
d41             int sc = sideOf(A, B, C), sd = sideOf(A, B, D);
d41             if (sc != sd) {
d41                 double sa = C.cross(D, A), sb = C.cross(D, B);
d41                 if (min(sc, sd) < 0)
d41                     segs.emplace_back(sa / (sa - sb), sgn(sc - sd));
d41             } else if (!sc && !sd && j < i && sgn((B-A).dot(D-C)) > 0) {
d41                 segs.emplace_back(rat(C - A, B - A), 1);
d41                 segs.emplace_back(rat(D - A, B - A), -1);
d41             }
d41         }
d41     }
d41     sort(all(segs));
d41     for (auto& s : segs) s.first = min(max(s.first, 0.0), 1.0);
d41     double sum = 0;
d41     int cnt = segs[0].second;
d41     rep(j,1,sz(segs)) {
d41         if (!cnt) sum += segs[j].first - segs[j - 1].first;
d41         cnt += segs[j].second;
d41     }
d41     ret += A.cross(B) * sum;
d41 }
d41 return ret / 2;
d41 }
```

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. If you want to keep the collinear points in the convex hull, change the comparison to $h[t - 2].cross(h[t - 1], p) < 0$ and the size of the vector h to $2 * sz(pts) + 1$.

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

```
"Point.h"
d41d8c, 14 lines

d41 typedef Point<ll> P;
d41 vector<P> convexHull(vector<P> pts) {
d41     if (sz(pts) <= 1) return pts;
d41     sort(all(pts));
d41     vector<P> h(sz(pts)+1);
d41     int s = 0, t = 0;
d41     for (int it = 2; it--; s = --t, reverse(all(pts)))
d41         for (P p : pts) {
d41             while (t >= s + 2 && h[t-2].cross(h[t-1], p) <= 0) t--;
d41             h[t++] = p;
d41         }
```



```
d41 return {h.begin(), h.begin() + t - (t == 2 && h[0] == h[1])};
d41 }
```

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"
d41d8c, 13 lines

d41 typedef Point<ll> P;
d41 array<P, 2> hullDiameter(vector<P> S) {
d41     int n = sz(S), j = n < 2 ? 0 : 1;
d41     pair<ll, array<P, 2>> res({0, {S[0], S[0]}});
d41     rep(i,0,j)
d41         for (; j = (j + 1) % n) {
d41             res = max(res, {(S[i] - S[j]).dist2(), {S[i], S[j]}});
d41         }
d41     if ((S[(j + 1) % n] - S[j]).cross(S[i + 1] - S[i]) >= 0)
d41         break;
d41     }
d41     return res.second;
d41 }
```

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"
d41d8c, 15 lines

d41 typedef Point<ll> P;

d41 bool inHull(const vector<P>& l, P p, bool strict = true) {
d41     int a = 1, b = sz(l) - 1, r = !strict;
d41     if (sz(l) < 3) return r && onSegment(l[0], l.back(), p);
d41     if (sideOf(l[0], l[a], l[b]) > 0) swap(a, b);
d41     if (sideOf(l[0], l[a], p) >= r || sideOf(l[0], l[b], p) <= -r)
d41         return false;
d41     while (abs(a - b) > 1) {
d41         int c = (a + b) / 2;
d41         (sideOf(l[0], l[c], p) > 0 ? b : a) = c;
d41     }
d41     return sgn(l[a].cross(l[b], p)) < r;
d41 }
```

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"
d41d8c, 40 lines

d41 #define cmp(i,j) sgn(dir.perp().cross(poly[(i)%n]-poly[(j)%n]))
d41 #define extr(i) cmp(i + 1, i) >= 0 && cmp(i, i - 1 + n) < 0
d41 template <class P> int extrVertex(vector<P>& poly, P dir) {
d41     int n = sz(poly), lo = 0, hi = n;
d41     if (extr(0)) return 0;
d41     while (lo + 1 < hi) {
d41         int m = (lo + hi) / 2;
```

```
d41     if (extr(m)) return m;
d41     int ls = cmp(lo + 1, lo), ms = cmp(m + 1, m);
d41     (ls < ms || (ls == ms && ls == cmp(lo, m)) ? hi : lo) = m;
d41 }
d41 return lo;
d41 }
```

```
d41 #define cmpL(i) sgn(a.cross(poly[i], b))
d41 template <class P>
d41 array<int, 2> lineHull(P a, P b, vector<P>& poly) {
d41     int endA = extrVertex(poly, (a - b).perp());
d41     int endB = extrVertex(poly, (b - a).perp());
d41     if (cmpL(endA) < 0 || cmpL(endB) > 0)
d41         return {-1, -1};
d41     array<int, 2> res;
d41     rep(i,0,2) {
d41         int lo = endB, hi = endA, n = sz(poly);
d41         while ((lo + 1) % n != hi) {
d41             int m = ((lo + hi + (lo < hi ? 0 : n)) / 2) % n;
d41             (cmpL(m) == cmpL(endB) ? lo : hi) = m;
d41         }
d41         res[i] = (lo + !cmpL(hi)) % n;
d41         swap(endA, endB);
d41     }
d41     if (res[0] == res[1]) return {res[0], -1};
d41     if (!cmpL(res[0]) && !cmpL(res[1]))
d41         switch ((res[0] - res[1] + sz(poly) + 1) % sz(poly)) {
d41             case 0: return {res[0], res[0]};
d41             case 2: return {res[1], res[1]};
d41         }
d41     return res;
d41 }
```

Minkowski.h

Description: Computes the Minkowski sum of two convex polygons. Polygons must be convex and given in CCW order. Returns the vertices of the Minkowski sum polygon in CCW order.

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

```
"Point.h"
d41d8c, 24 lines

d41 using P = Point<ll>;

d41 vector<P> minkowski(vector<P> p, vector<P> q) {
d41     auto fix = [](vector<P>& A) {
d41         int pos = 0;
d41         for (int i = 1; i < sz(A); i++) {
d41             if (A[i].y < A[pos].y || (A[i].y == A[pos].y && A[i].x < A[pos].x))
d41                 pos = i;
d41         }
d41         rotate(A.begin(), A.begin() + pos, A.end());
d41         A.push_back(A[0]), A.push_back(A[1]);
d41     };
d41     fix(p), fix(q);
d41     vector<P> result;
d41     int i = 0, j = 0;
d41     while (i < sz(p) - 2 || j < sz(q) - 2) {
d41         result.push_back(p[i] + q[j]);
d41         auto cross = (p[i + 1] - p[i]).cross(q[j + 1] - q[j]);
d41         if (cross >= 0 && i < sz(p) - 2) i++;
d41         if (cross <= 0 && j < sz(q) - 2) j++;
d41     }
d41     return result;
d41 }
```


Extremeh.h

Description: Finds an extreme vertex of a convex polygon according to a unimodal comparator. The comparator defines a total order along the polygon (given in CCW order).

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

"Point.h" d41d8c, 26 lines

```
d41 using P = Point<ll>;
d41 int extreme(vector<P> &pol, const function<bool(P, P)>&
    cmp) {
d41     int n = pol.size();
d41     auto extr = [&](int i, bool& cur_dir) {
d41         cur_dir = cmp(pol[(i+1)%n], pol[i]);
d41         return !cur_dir and !cmp(pol[(i+n-1)%n], pol[i]);
d41     };
d41     bool last_dir, cur_dir;
d41     if (extr(0, last_dir)) return 0;
d41     int l = 0, r = n;
d41     while (l+1 < r) {
d41         int m = (l+r)/2;
d41         if (extr(m, cur_dir)) return m;
d41         bool rel_dir = cmp(pol[m], pol[l]);
d41         if ((!last_dir and cur_dir) or
d41             (last_dir == cur_dir and rel_dir == cur_dir)) {
d41             l = m;
d41             last_dir = cur_dir;
d41         } else r = m;
d41     }
d41     return l;
d41 }
d41 int max_dot(vector<P> &pol, P v) {
d41     return extreme([&](P p, P q) { return p.dot(v) > q.dot(v)
    }); };
d41 }
```

Tangents.h

Description: Finds the left and right tangent points from an external point p to a convex polygon given in CCW order. A tangent point is a vertex where the segment p->v touches the polygon without intersecting its interior, defining the limits of visibility from p. Returns the indices of the left and right tangent vertices.

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

"Point.h", "Extremeh.h" d41d8c, 11 lines

```
d41 using P = Point<ll>;

d41 bool ccw(P p, P q, P r) {
d41     return (q-p).cross(r-q) > 0;
d41 }

d41 pair<int, int> tangents(vector<P> &pol, P p) {
d41     auto L = [&](P q, P r) { return ccw(p, r, q); };
d41     auto R = [&](P q, P r) { return ccw(p, q, r); };
d41     return {extreme(pol, L), extreme(pol, R)};
d41 }
```

8.4 Misc. Point Set Problems

ClosestPair.h

Description: Finds the closest pair of points.

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

"Point.h" d41d8c, 18 lines

```
d41 typedef Point<ll> P;
d41 pair<P, P> closest(vector<P> v) {
d41     assert(sz(v) > 1);
d41     set<P> S;
d41     sort(all(v), [](P a, P b) { return a.y < b.y; });
d41     pair<ll, pair<P, P>> ret{LLONG_MAX, {P(), P()}};
d41     int j = 0;
d41     for (P p : v) {
d41         P d{1 + (ll)sqrt(ret.first), 0};
```

```
d41         while (v[j].y <= p.y - d.x) S.erase(v[j++]);
d41         auto lo = S.lower_bound(p - d), hi = S.upper_bound(p +
    d);
d41         for (; lo != hi; ++lo)
d41             ret = min(ret, {( *lo - p).dist2(), { *lo, p } });
d41         S.insert(p);
d41     }
d41     return ret.second;
d41 }
```

ManhattanMST.h

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

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

"Point.h" d41d8c, 24 lines

```
d41 typedef Point<int> P;
d41 vector<array<int, 3>> manhattanMST(vector<P> ps) {
d41     vi id(sz(ps));
d41     iota(all(id), 0);
d41     vector<array<int, 3>> edges;
d41     rep(k, 0, 4) {
d41         sort(all(id), [&](int i, int j) {
d41             return (ps[i]-ps[j]).x < (ps[j]-ps[i]).y; });
d41         map<int, int> sweep;
d41         for (int i : id) {
d41             for (auto it = sweep.lower_bound(-ps[i].y);
d41                 it != sweep.end(); sweep.erase(it++)) {
d41                 int j = it->second;
d41                 P d = ps[i] - ps[j];
d41                 if (d.y > d.x) break;
d41                 edges.push_back({d.y + d.x, i, j});
d41             }
d41             sweep[-ps[i].y] = i;
d41         }
d41         for (P& p : ps) if (k & 1) p.x = -p.x; else swap(p.x, p
    .y);
d41     }
d41     return edges;
d41 }
```

kdTree.h

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

"Point.h" d41d8c, 64 lines

```
d41 typedef long long T;
d41 typedef Point<T> P;
d41 const T INF = numeric_limits<T>::max();

d41 bool on_x(const P& a, const P& b) { return a.x < b.x; }
d41 bool on_y(const P& a, const P& b) { return a.y < b.y; }

d41 struct Node {
d41     P pt; // if this is a leaf, the single point in it
d41     T x0 = INF, x1 = -INF, y0 = INF, y1 = -INF; // bounds
d41     Node *first = 0, *second = 0;

d41     T distance(const P& p) { // min squared distance to a
    point
d41         T x = (p.x < x0 ? x0 : p.x > x1 ? x1 : p.x);
d41         T y = (p.y < y0 ? y0 : p.y > y1 ? y1 : p.y);
d41         return (P(x,y) - p).dist2();
d41     }

d41     Node(vector<P>&& vp) : pt(vp[0]) {
d41         for (P p : vp) {
d41             x0 = min(x0, p.x); x1 = max(x1, p.x);
d41             y0 = min(y0, p.y); y1 = max(y1, p.y);
```

```
d41         }
d41         if (vp.size() > 1) {
d41             // split on x if width >= height (not ideal...)
d41             sort(all(vp), x1 - x0 >= y1 - y0 ? on_x : on_y);
d41             // divide by taking half the array for each child (
    not
d41             // best performance with many duplicates in the
    middle)
d41             int half = sz(vp)/2;
d41             first = new Node({vp.begin(), vp.begin() + half});
d41             second = new Node({vp.begin() + half, vp.end()});
d41         }
d41     };

d41 struct KDTree {
d41     Node* root;
d41     KDTree(const vector<P>& vp) : root(new Node({all(vp)}))
    {}

d41     pair<T, P> search(Node *node, const P& p) {
d41         if (!node->first) {
d41             // uncomment if we should not find the point itself:
d41             // if (p == node->pt) return {INF, P()};
d41             return make_pair((p - node->pt).dist2(), node->pt);
d41         }

d41         Node *f = node->first, *s = node->second;
d41         T bfirst = f->distance(p), bsec = s->distance(p);
d41         if (bfirst > bsec) swap(bsec, bfirst), swap(f, s);

d41         // search closest side first, other side if needed
d41         auto best = search(f, p);
d41         if (bsec < best.first)
d41             best = min(best, search(s, p));
d41         return best;
d41     }

d41     // find nearest point to a point, and its squared
d41     // distance
d41     // (requires an arbitrary operator< for Point)
d41     pair<T, P> nearest(const P& p) {
d41         return search(root, p);
d41     }
d41     };
```

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 $\{t[0][0], t[0][1], t[0][2], t[1][0], \dots\}$, all counter-clockwise.

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

"Point.h" d41d8c, 89 lines

```
d41 typedef Point<ll> P;
d41 typedef struct Quad* Q;
d41 typedef __int128_t ll1; // (can be ll if coords are < 2e4)
d41 P arb(LLONG_MAX, LLONG_MAX); // not equal to any other
    point

d41 struct Quad {
d41     Q rot, o; P p = arb; bool mark;
d41     P& F() { return r()->p; }
d41     Q& r() { return rot->rot; }
d41     Q prev() { return rot->o->rot; }
d41     Q next() { return r()->prev(); }
d41     } *H;
```



```

d41 bool circ(P p, P a, P b, P c) { // is p in the
    circumcircle?
d41 lll p2 = p.dist2(), A = a.dist2()-p2,
d41 B = b.dist2()-p2, C = c.dist2()-p2;
d41 return p.cross(a,b)*C + p.cross(b,c)*A + p.cross(c,a)*B >
    0;
d41 }
d41 Q makeEdge(P orig, P dest) {
d41 Q r = H ? H : new Quad{new Quad{new Quad{0}}}};
d41 H = r->o; r->r()->r() = r;
d41 rep(i,0,4) r = r->rot, r->p = arb, r->o = i & 1 ? r : r->
    r();
d41 r->p = orig; r->F() = dest;
d41 return r;
d41 }
d41 void splice(Q a, Q b) {
d41 swap(a->o->rot->o, b->o->rot->o); swap(a->o, b->o);
d41 }
d41 Q connect(Q a, Q b) {
d41 Q q = makeEdge(a->F(), b->p);
d41 splice(q, a->next());
d41 splice(q->r(), b);
d41 return q;
d41 }

d41 pair<Q,Q> rec(const vector<P>& s) {
d41 if (sz(s) <= 3) {
d41 Q a = makeEdge(s[0], s[1]), b = makeEdge(s[1], s.back()
    );
d41 if (sz(s) == 2) return { a, a->r() };
d41 splice(a->r(), b);
d41 auto side = s[0].cross(s[1], s[2]);
d41 Q c = side ? connect(b, a) : 0;
d41 return {side < 0 ? c->r() : a, side < 0 ? c : b->r() };
d41 }

d41 #define H(e) e->F(), e->p
d41 #define valid(e) (e->F().cross(H(base)) > 0)
d41 Q A, B, ra, rb;
d41 int half = sz(s) / 2;
d41 tie(ra, A) = rec({all(s) - half});
d41 tie(B, rb) = rec({sz(s) - half + all(s)});
d41 while ((B->p.cross(H(A)) < 0 && (A = A->next())) ||
d41 (A->p.cross(H(B)) > 0 && (B = B->r()->o)));
d41 Q base = connect(B->r(), A);
d41 if (A->p == ra->p) ra = base->r();
d41 if (B->p == rb->p) rb = base;

d41 #define DEL(e, init, dir) Q e = init->dir; if (valid(e)) \
d41 while (circ(e->dir->F(), H(base), e->F())) { \
d41 Q t = e->dir; \
d41 splice(e, e->prev()); \
d41 splice(e->r(), e->r()->prev()); \
d41 e->o = H; H = e; e = t; \
d41 }
d41 for (;;) {
d41 DEL(LC, base->r(), o); DEL(RC, base, prev());
d41 if (!valid(LC) && !valid(RC)) break;
d41 if (!valid(LC) || (valid(RC) && circ(H(RC), H(LC))))
d41 base = connect(RC, base->r());
d41 else
d41 base = connect(base->r(), LC->r());
d41 }
d41 return { ra, rb };
d41 }

d41 vector<P> triangulate(vector<P> pts) {
d41 sort(all(pts)); assert(unique(all(pts)) == pts.end());
d41 if (sz(pts) < 2) return {};

```

```

d41 Q e = rec(pts).first;
d41 vector<Q> q = {e};
d41 int qi = 0;
d41 while (e->o->F().cross(e->F(), e->p) < 0) e = e->o;
d41 #define ADD { Q c = e; do { c->mark = 1; pts.push_back(c->
    p); \
d41 q.push_back(c->r()); c = c->next(); } while (c != e); }
d41 ADD; pts.clear();
d41 while (qi < sz(q)) if (!(e = q[qi++])->mark) ADD;
d41 return pts;
d41 }

```

8.5 3D

PolyhedronVolume.h

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

d41d8c, 7 lines

```

d41 template<class V, class L>
d41 double signedPolyVolume(const V& p, const L& trilst) {
d41 double v = 0;
d41 for (auto i : trilst) v += p[i.a].cross(p[i.b]).dot(p[i.
    c]);
d41 return v / 6;
d41 }

```

Point3D.h

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

d41d8c, 33 lines

```

d41 template<class T> struct Point3D {
d41 typedef Point3D P;
d41 typedef const P& R;
d41 T x, y, z;
d41 explicit Point3D(T x=0, T y=0, T z=0) : x(x), y(y), z(z)
    {}
d41 bool operator<(R p) const {
d41 return tie(x, y, z) < tie(p.x, p.y, p.z); }
d41 bool operator==(R p) const {
d41 return tie(x, y, z) == tie(p.x, p.y, p.z); }
d41 P operator+(R p) const { return P(x+p.x, y+p.y, z+p.z); }
d41 P operator-(R p) const { return P(x-p.x, y-p.y, z-p.z); }
d41 P operator*(T d) const { return P(x*d, y*d, z*d); }
d41 P operator/(T d) const { return P(x/d, y/d, z/d); }
d41 T dot(R p) const { return x*p.x + y*p.y + z*p.z; }
d41 P cross(R p) const {
d41 return P(y*p.z - z*p.y, z*p.x - x*p.z, x*p.y - y*p.x);
d41 }
d41 T dist2() const { return x*x + y*y + z*z; }
d41 double dist() const { return sqrt((double)dist2()); }
d41 //Azimuthal angle (longitude) to x-axis in interval [-pi,
    pi]
d41 double phi() const { return atan2(y, x); }
d41 //Zenith angle (latitude) to the z-axis in interval [0,
    pi]
d41 double theta() const { return atan2(sqrt(x*x+y*y),z); }
d41 P unit() const { return *this/(T)dist(); } //makes dist()
    =1
d41 //returns unit vector normal to *this and p
d41 P normal(P p) const { return cross(p).unit(); }
d41 //returns point rotated 'angle' radians ccw around axis
d41 P rotate(double angle, P axis) const {
d41 double s = sin(angle), c = cos(angle); P u = axis.unit
    ();
d41 return u*dot(u)*(1-c) + (*this)*c - cross(u)*s;
d41 }
d41 };

```

3dHull.h

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

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

"Point3D.h" d41d8c, 50 lines

```

d41 typedef Point3D<double> P3;

d41 struct PR {
d41 void ins(int x) { (a == -1 ? a : b) = x; }
d41 void rem(int x) { (a == x ? a : b) = -1; }
d41 int cnt() { return (a != -1) + (b != -1); }
d41 int a, b;
d41 };

d41 struct F { P3 q; int a, b, c; };

d41 vector<F> hull3d(const vector<P3>& A) {
d41 assert(sz(A) >= 4);
d41 vector<vector<PR>> E(sz(A), vector<PR>(sz(A), {-1, -1}));
d41 #define E(x,y) E[f.x][f.y]
d41 vector<F> FS;
d41 auto mf = [&](int i, int j, int k, int l) {
d41 P3 q = (A[j] - A[i]).cross((A[k] - A[i]));
d41 if (q.dot(A[l]) > q.dot(A[i]))
d41 q = q * -1;
d41 F f{q, i, j, k};
d41 E(a,b).ins(k); E(a,c).ins(j); E(b,c).ins(i);
d41 FS.push_back(f);
d41 };
d41 rep(i,0,4) rep(j,i+1,4) rep(k,j+1,4)
d41 mf(i, j, k, 6 - i - j - k);

d41 rep(i,4,sz(A)) {
d41 rep(j,0,sz(FS)) {
d41 F f = FS[j];
d41 if (f.q.dot(A[i]) > f.q.dot(A[f.a])) {
d41 E(a,b).rem(f.c);
d41 E(a,c).rem(f.b);
d41 E(b,c).rem(f.a);
d41 swap(FS[j-1], FS.back());
d41 FS.pop_back();
d41 }
d41 int nw = sz(FS);
d41 rep(j,0,nw) {
d41 F f = FS[j];
d41 #define C(a, b, c) if (E(a,b).cnt() != 2) mf(f.a, f.b, i,
    f.c);
d41 C(a, b, c); C(a, c, b); C(b, c, a);
d41 }
d41 }
d41 for (F& it : FS) if ((A[it.b] - A[it.a]).cross(
d41 A[it.c] - A[it.a]).dot(it.q) <= 0) swap(it.c, it.b);
d41 return FS;
d41 };

```

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.

d41d8c, 9 lines

```

d41 double sphericalDistance(double f1, double t1,
d41 double f2, double t2, double radius) {

```

```
d41 double dx = sin(t2)*cos(f2) - sin(t1)*cos(f1);
d41 double dy = sin(t2)*sin(f2) - sin(t1)*sin(f1);
d41 double dz = cos(t2) - cos(t1);
d41 double d = sqrt(dx*dx + dy*dy + dz*dz);
d41 return radius*2*asin(d/2);
d41 }
```

Strings (9)

AhoCorasick.h

d41d8c, 46 lines

```
d41 int trie[ms][sigma], fail[ms], terminal[ms], superfail[ms];
d41 bool present[ms];
d41 int z = 1;
```

```
d41 int val(char c) { return c - 'a'; }
```

```
d41 void add(string& p) {
d41     int cur = 0;
d41     for (int i = 0; i < (int)p.size(); i++) {
d41         int& nxt = trie[cur][val(p[i])];
d41         if (nxt == 0) nxt = z++;
d41         cur = nxt;
d41     }
d41     present[cur] = true;
d41     terminal[cur]++;
d41 }
```

```
d41 void build() {
d41     queue<int> q;
d41     for (q.push(0); !q.empty(); q.pop()) {
d41         int on = q.front();
d41         for (int i = 0; i < sigma; i++) {
d41             int& to = trie[on][i];
d41             int f = (on == 0 ? 0 : trie[fail[on]][i]);
d41             int sf = (present[f] ? f : superfail[f]);
d41             if (!to) {
d41                 to = f;
d41             }
d41             else {
d41                 fail[to] = f;
d41                 superfail[to] = sf;
d41                 // merge infos (ex: terminal[to] +=
d41                     terminal[f])
d41                 q.push(to);
d41             }
d41         }
d41     }
d41 }
```

```
d41 void search(string& s) {
d41     int cur = 0;
d41     for (char c : s) {
d41         cur = trie[cur][val(c)];
d41         // process infos on current node (ex: ocurrences
d41             += terminal[cur])
d41     }
d41 }
```

Hash.h

Description: C can also be random, operator is $[l, r]$

```
d41 using ull = uint64_t;
d41 struct H {
d41     ull x; H(ull x = 0) : x(x) {}
d41     H operator+(H o) { return x + o.x + (x + o.x < x); }
d41     H operator-(H o) { return *this + ~o.x; }
```

```
d41     H operator*(H o) {
d41         auto m = (__uint128_t)x * o.x;
d41         return H((ull)m) + (ull)(m >> 64);
d41     }
d41     ull get() const { return x + !~x; }
d41     bool operator==(H o) const { return get() == o.get(); }
d41     bool operator<(H o) const { return get() < o.get(); }
d41 };
d41 static const H C = (1l)1e11 + 3;
d41 struct Hash {
d41     vector<H> h, pw;
d41     Hash(string& str) : h(str.size()), pw(str.size()) {
d41         pw[0] = 1, h[0] = str[0];
d41         for (int i = 1; i < str.size(); i++) {
d41             h[i] = h[i - 1] * C + str[i];
d41             pw[i] = pw[i - 1] * C;
d41         }
d41     }
d41     H operator()(int l, int r) {
d41         return h[r] - (l ? h[l - 1] * pw[r - l + 1] : 0);
d41     }
d41 };
```

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).

```
d41 vector<int> pi(const string& s) {
d41     vector<int> p(sz(s));
d41     for (int i = 1; i < sz(s); i++) {
d41         int g = p[i-1];
d41         while (g && s[i] != s[g]) g = p[g-1];
d41         p[i] = g + (s[i] == s[g]);
d41     }
d41     return p;
d41 }
```

KmpAutomaton.h

Description: $go[i][j]$ = length of the longest prefix of s that is a suffix of $s[0..i]$ followed by the letter j (i.e., the next matched prefix length if, at state i , we read letter j).

```
d41 int go[ms][sigma];
d41 int val(char c) { return c - 'a'; }
d41 void automaton(string& s) {
d41     for (int i = 0; i < sigma; i++)
d41         go[0][i] = (i == val(s[0]));
d41
d41     for (int i = 1, bdr = 0; i <= (int)s.size(); i++) {
d41         for (int j = 0; j < sigma; j++) {
d41             go[i][j] = go[bdr][j];
d41         }
d41         if (i < (int)s.size()) {
d41             go[i][val(s[i])] = i + 1;
d41             bdr = go[bdr][val(s[i])];
d41         }
d41     }
d41 }
```

Manacher.h

Description: $p[0][i + 1]$ is the length of matches of even length palindrome, starting from $[i, i + 1]$.
 $p[1][i]$ is the length of matches of odd length palindrome, starting from $[i, i]$.
(abaxx -> p[0] = 00001)
(abaxx -> p[1] = 01000)

```
d41 array<vector<int>, 2> manacher(const string& s) {
d41     int n = sz(s);
```

```
d41     array<vector<int>, 2> p={vector<int>(n+1),vector<int>(n
d41         )};
d41     for (int z = 0; z < 2; z++) {
d41         for (int i = 0, l = 0, r = 0; i < n; i++) {
d41             int t = r - i + !z;
d41             if (i < r) p[z][i] = min(t, p[z][l + t]);
d41             int L = i - p[z][i], R = i + p[z][i] - !z;
d41             while(L >= 1 && R+1 < n && s[L-1] == s[R+1]){
d41                 p[z][i]++, L--, R++;
d41             }
d41             if (R > r) l = L, r = R;
d41         }
d41     }
d41     return p;
d41 }
```

MinRotation.h

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

```
d41 int minRotation(string s) {
d41     int a = 0, N = s.size(); s += s;
d41     for (int b = 0; b < N; b++) {
d41         for (int k = 0; k < N; k++) {
d41             if (a+k == b || s[a+k] < s[b+k]) {
d41                 b += max(0, k-1);
d41                 break;
d41             }
d41             if (s[a+k] > s[b+k]) { a = b; break; }
d41         }
d41     }
d41     return a;
d41 }
```

SuffixArray.h

Description: $lcp[i]$ is the length of the longest common prefix between the suffixes $s[sa[i]..n - 1]$ and $s[sa[i - 1]..n - 1]$.
If we concatenate multiple strings using separator characters, the separator that appears furthest to the right must be the smallest character in the alphabet.

```
d41 struct SuffixArray {
d41     vector<int> sa, lcp;
d41     SuffixArray(string s, int lim=256) {
d41         s.push_back('$');
d41         int n = sz(s), k = 0, a, b;
d41         vector<int> x(all(s)), y(n), ws(max(n, lim));
d41         sa = lcp = y, iota(all(sa), 0);
d41         for(int j = 0, p = 0; p < n; j= max(1, j*2), lim = p) {
d41             p = j, iota(all(y), n - j);
d41             for(int i=0; i<n; i++){
d41                 if (sa[i] >= j) y[p++] = sa[i] - j;
d41             }
d41             fill(all(ws), 0);
d41             for(int i=0; i<n; i++) ws[x[i]]++;
d41             for(int i=1; i<lim; i++) ws[i] += ws[i - 1];
d41             for (int i = n; i--;) sa[--ws[x[y[i]]]] = y[i];
d41             swap(x, y), p = 1, x[sa[0]] = 0;
d41             for(int i=1; i<n; i++){
d41                 a = sa[i - 1], b = sa[i];
d41                 x[b] = p-1;
d41                 if(y[a] != y[b] || y[a+j] != y[b+j]) x[b] = p++;
d41             }
d41         }
d41         for (int i = 0, j; i < n - 1; lcp[x[i++]] = k)
d41             for (k && k--, j = sa[x[i] - 1];
d41                 s[i + k] == s[j + k]; k++);
d41         sa = vector<int>(sa.begin() + 1, sa.end());
```

```
d41 lcp = vector<int>(lcp.begin() + 1, lcp.end());
d41 }
d41 };
```

Zfunc.h

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

d41d8c, 13 lines

```
d41 vector<int> ZFunc(const string& s) {
d41     int n = sz(s), a = 0, b = 0;
d41     vector<int> z(n, 0);
d41     if (!z.empty()) z[0] = 0;
d41     for (int i = 1; i < n; i++) {
d41         int end = i;
d41         if (i < b) end = min(i + z[i - a], b);
d41         while (end < n && s[end] == s[end - i]) ++end;
d41         z[i] = end - i; if (end > b) a = i, b = end;
d41     }
d41     return z;
d41 }
```

Various (10)

10.1 Misc. algorithms

Dates.h

Description: dateToInt converts Gregorian date to integer (Julian day number). intToDate converts integer (Julian day number) to Gregorian date: month/day/year. intToDay converts Julian day number to day of the week

d41d8c, 23 lines

```
d41 string day[] = { "Mon", "Tue", "Wed", "Thu", "Fri", "Sat",
d41 "Sun" };
d41 int dateToInt(int m, int d, int y) {
d41     return
d41         1461 * (y + 4800 + (m - 14) / 12) / 4 +
d41         367 * (m - 2 - (m - 14) / 12 * 12) / 12 -
d41         3 * ((y + 4900 + (m - 14) / 12) / 100) / 4 +
d41         d - 32075;
d41 }
d41 void intToDate(int jd, int& m, int& d, int& y) {
d41     int x, n, i, j;
d41     x = jd + 68569;
d41     n = 4 * x / 146097;
d41     x -= (146097 * n + 3) / 4;
d41     i = (4000 * (x + 1)) / 1461001;
d41     x -= 1461 * i / 4 - 31;
d41     j = 80 * x / 2447;
d41     d = x - 2447 * j / 80;
d41     x = j / 11;
d41     m = j + 2 - 12 * x;
d41     y = 100 * (n - 49) + i + x;
d41 }
d41 string intToDay(int jd) { return day[jd % 7]; }
```

MultisetHash.h

d41d8c, 8 lines

```
d41 ull hashify(ull sum) {
d41     sum += FIXED_RANDOM;
d41     sum += 0x9e3779b97f4a7c15;
d41     sum = (sum ^ (sum >> 30)) * 0xbf58476d1ce4e5b9;
d41     sum = (sum ^ (sum >> 27)) * 0x94d049bb133111eb;
d41     return sum ^ (sum >> 31);
d41 }
```

Rand.h

d41d8c, 3 lines

```
d41 mt19937 rng(chrono::steady_clock::now().time_since_epoch()
d41 .count());
```

```
// -64
d41 int uniform(int l, int r) { // [l, r]
d41     uniform_int_distribution<int> uid(l, r);
d41     return uid(rng);
d41 }
```

10.2 Dynamic programming

KnuthDP.h

Description: When doing DP on intervals: $dp[i][j] = \min_{i < k < j} (dp[i][k] + dp[k][j]) + f(i, j)$, where the (minimal) optimal k increases with both i and j . This is known as Knuth DP. Sufficient criteria for this are if $f(b, c) \leq f(a, d)$ and $f(a, c) + f(b, d) \leq f(a, d) + f(b, c)$ for all $a \leq b \leq c \leq d$. Another sufficient criteria is: $opt[i][j - 1] \leq opt[i][j] \leq opt[i + 1][j]$

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

d41d8c, 22 lines

```
d41 ll knuth() {
d41     memset(opt, -1, sizeof opt);
d41     for (int i=n-1; i>=0; i--){
d41         dp[i][i] = 0; // base case
d41         opt[i][i] = i;
d41         for (int j=i+1; j<n; j++){
d41             int optL = (!j ? 0 : opt[i][j-1]);
d41             int optR = (~opt[i+1][j] ? opt[i+1][j] : n-1);
d41             ll cst = cost(i, j);
d41             dp[i][j] = INF;
d41             optL = max(i, optL), optR = min(j-1, optR);
d41             for (int k=optL; k<=optR; k++){
d41                 ll now = dp[i][k] + dp[k+1][j] + cst;
d41                 if (now <= dp[i][j]){
d41                     dp[i][j] = now;
d41                     opt[i][j] = k;
d41                 }
d41             }
d41         }
d41     }
d41 }
```

DivideAndConquerDP.h

Description: Divide and Conquer DP maintaining cost, can be used when $opt[i][j] \leq opt[i][j + 1]$. In this code everything is 1-based. Memory can be optimized by keeping only the last row

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

d41d8c, 42 lines

```
d41 void add(int idx) {}
d41 void rem(int idx) {}

d41 void deC(int i, int l, int r, int optL, int optR) {
d41     if (l > r) return;
d41     int j = (l + r) / 2;
d41     for (int k = r; k > j; k--) rem(k);
d41     int opt = optL;
d41     for (int k = optL; k <= min(optR, j); k++) {
d41         // cost = cost[k, j]
d41         int val = dp[i - 1][k - 1] + cost;
d41         if (val < dp[i][j]) {
d41             dp[i][j] = val;
d41             opt = k;
d41         }
d41         rem(k);
d41     }
d41     for (int k = min(optR, j); k >= optL; k--) add(k);
d41     rem(j);
d41     deC(i, l, j - 1, optL, opt);

d41     for (int k = j; k <= r; k++) add(k);
d41     for (int k = optL; k < opt; k++) rem(k);
d41     deC(i, j + 1, r, opt, optR);
}
```

```
d41     for (int k = optL; k < opt; k++) add(k);
d41 }

d41 int solve(int N, int M) { // 1-based
d41     for (int i = 0; i <= M; i++) {
d41         for (int j = 0; j <= N; j++){
d41             dp[i][j] = inf; // base case
d41         }
d41     }
d41     cost = 0; // neutral value
d41     for (int i = 1; i <= N; i++) add(i);
d41     for (int i = 1; i <= M; i++) {
d41         deC(i, 1, N, 1, N);
d41     }
d41     return dp[M][N];
d41 }
```

10.3 Optimization tricks

10.3.1 Bit hacks

- for (int x = m; x; x = (x - 1)&m) { ... } loops over all subset masks of m (except 0).
- 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.

10.3.2 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 target ("bmi,bmi2,popcnt,lzcnt") improve bit operations.
- #pragma GCC optimize ("unroll-loops") self explanatory.