Universidade Federal de Pernambuco

las4s e pelados

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Contest (1)

template.cpp 9 lines

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

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

.bashrc 2 lines

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

hash.sh 2 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
```

stressTest.sh 20 lines

```
P=code   #mude pro filename do codigo
Q=brute  #mude pro filename do brute [correto]
g++ ${P}.cpp -o sol -O2 || exit 1
g++ ${Q}.cpp -o brt -O2 || exit 1
g++ gen.cpp  -o gen -O2 || exit 1
for ((i = 1; ; i++)) do
  echo $i
  ./gen $i > in
  ./sol < in > out
  ./brt < in > out2
  if (! cmp -s out out2) then
    echo "--> entrada:"
    cat in
    echo "--> saida code:"
    cat out
    echo "--> saida brute:"
    cat out2
    break;
  fi
done
```

troubleshoot.txt 52 lines

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

Wrong answer:
Print your solution! Print debug output, as well.
Are you clearing all 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?
Confusing N and M, i and j, etc.?
Are you sure your algorithm works?
What special cases have you not thought of?
Are you sure the STL functions you use work as you think?
Add some assertions, maybe resubmit.
Create some testcases to run your algorithm on.
Go through the algorithm for a simple case.
Go through this list again.
Explain your algorithm to a teammate.
Ask the teammate to look at your code.
Go for a small walk, e.g. to the toilet.
Is your output format correct? (including whitespace)
Rewrite your solution from the start or let a teammate do it.

Runtime error:
Have you tested all corner cases locally?
Any uninitialized variables?
Are you reading or writing outside the range of any vector?
Any assertions that might fail?
Any possible division by 0? (mod 0 for example)
Any possible infinite recursion?
Invalidated pointers or iterators?
Are you using too much memory?
Debug with resubmits (e.g. remapped signals, see Various).

Time limit exceeded:
Do you have any possible infinite loops?
What is the complexity of your algorithm?
Are you copying a lot of unnecessary data? (References)
How big is the input and output? (consider scanf)
Avoid vector, map. (use arrays/unordered_map)
What do your teammates think about your algorithm?

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

Theoretical (2)

2.1 Mathematics

2.1.1 Recurrences

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

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

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

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

2.1.3 Geometry

Triangles

Side lengths: a, b, c

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

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

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

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

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

Length of bisector (divides angles in two):

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

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

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

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

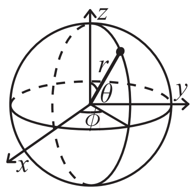
Quadrilaterals

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

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

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

Spherical coordinates



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

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.

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.

2.1.4 Derivatives/Integrals

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

Integration by parts:

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

2.1.5 Sums

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

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

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

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

2.1.6 Series

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

2.1.7 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) $\mu = \mathbb{E}(X) = \sum_x xp_X(x)$ and variance $\sigma^2 = V(X) = \mathbb{E}(X^2) - (\mathbb{E}(X))^2 = \sum_x (x - \mathbb{E}(X))^2 p_X(x)$ where σ is the standard deviation. If X is instead continuous it will have a probability density function $f_X(x)$ and the sums above will instead be integrals with $p_X(x)$ replaced by $f_X(x)$.

Expectation is linear:

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

For independent X and Y,

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

Binomial distribution

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

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

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

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

First success distribution

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

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

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

Poisson distribution

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

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

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

2.2 Combinatorial

2.2.1 Binomial Identities

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

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

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

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

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

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

2.2.2 Permutations

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

Cycles

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

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

Derangements

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

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

Burnside's lemma

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

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

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

2.2.3 Partitions and subsets

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	~2e5	~2e8

Lucas' Theorem

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

2.2.4 Sum of Binomials (FFT)

Goal: Given freq. array C, compute $Ans[k] = \sum_i C[i]\binom{i}{k}$ for all k. Rewrite: $Ans[k] = \frac{1}{k!}\sum_i (C[i]\cdot i!)\frac{1}{(i-k)!}$.

- Construct P where $P[i] = C[i]\cdot i!$
- Construct Q where $Q[i] = (i!)^{-1}$
- Reverse Q (to handle the $i-k$ subtraction).
- Multiply $R = NTT(P, Q)$.
- Result: $Ans[k] = R[k+|Q|-1]\cdot\frac{1}{k!}$.

2.2.5 General purpose numbers

Bernoulli numbers

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

Sums of powers:

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

Euler-Maclaurin formula for infinite sums:

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

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

Stirling numbers of the first kind

Number of permutations on n items with k cycles.

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

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

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. $\pi(j) > j$.

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

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

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

Stirling numbers of the second kind

Partitions of n distinct elements into exactly k groups.

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

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

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

Bell numbers

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

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

Labeled unrooted trees

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

Catalan numbers

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

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

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

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

2.3 Number Theory

2.3.1 Bézout's identity

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

$$ax + by = d$$

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

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

2.3.2 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 $\mathbb{Z}_2 \times \mathbb{Z}_{2^{a-2}}$.

2.3.3 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 $n < 1e10$, 6700 for $n < 1e12$, 200 000 for $n < 1e19$.

2.3.4 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)

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

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

2.3.5 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

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

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.

2.4 Graphs

2.4.1 Flows and Matching

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.

Kőnig'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:

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

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),

$$\text{Minimum Node-Disjoint Path Cover} = n - \text{Maximum Matching}.$$

The construction is as follows: for each vertex u, create a copy u'. Add an edge $u \to v'$ if there exists an edge $u \to v$ 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 $u \to v'$ corresponds to an edge $u \to v$ in the original DAG.
- Following these edges reconstructs all paths of the path cover.

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 $u \to v'$ 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.

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,

Minimum General Path Cover = Maximum Antichain.

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

2.4.2 Number of Spanning Trees

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

2.4.3 Erdős–Gallai theorem

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

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

2.4.4 Planar Graphs

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

2.5 Optimization tricks

2.5.1 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.

2.5.2 Pragmas

- `#pragma GCC optimize ("Ofast")` will make GCC auto-vectorize loops and optimizes floating points better.
- `#pragma GCC target ("avx2")` can double performance of vectorized code, but causes crashes on old machines.
- `#pragma GCC target("bmi,bmi2,popcnt,lzcnt")` improve bit operations.
- `#pragma GCC optimize("unroll-loops")` self explanatory.

2.6 Various

2.6.1 Master Theorem (Simple)

$T(n) = aT(n/b) + O(n^d)$. Compare a vs b^d:

- $a > b^d \implies O(n^{\log_b a})$ (Work at leaves dominates)
- $a = b^d \implies O(n^d \log n)$ (Work is uniform)
- $a < b^d \implies O(n^d)$ (Work at root dominates)

Data structures (3)

Bit.h

Description: *lower_bound* works the same as on vectors

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

5891da, 23 lines

```
8eb struct Bit {
406   vector<ll> bit;
1dd   Bit(int n) : bit(n + 1) {}
265   void update(int i, ll v) {
c38     for (i++; i < sz(bit); i += i & -i) bit[i] += v;
f21   }
74a   ll query(int i) {
b73     ll ret = 0;
71c     for (i++; i > 0; i -= i & -i) ret += bit[i];
edf     return ret;
e40   }
dc8   int lower_bound(ll v){ // min pos st sum[0, pos] >= v
bec     int pos = 0;
a40     for(int j=(1 << 23); j >= 1; j/=2){
3b1       if(pos+j < sz(bit) && bit[pos + j] < v){
b4e         pos += j;
18d         v -= bit[pos];
f6c       }
156     }
d75     return pos;
37b   }
589 };
```

Bit2d.h

Description: Points called on the update function NEED to be on the *pts* vector parameter on build.

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

"Bit.h" 5a98ac, 37 lines

```
9c0 struct Bit2d {
a37   vector<vector<int>> ys;
fe8   vector<Bit> bit;
543   vector<int> cmp_x;
425   Bit2d(){}
521   void put(int x, int y) {
005     for (x++; x < sz(ys); x += x & -x) ys[x].push_back(y);
f3c   }
ce0   int id(const vector<int> &v, int y) {
1e9     return (upper_bound(all(v), y) - v.begin()) - 1;
19a   }
7ff   void build(vector<pii> pts) {
3cb     sort(all(pts));
f99     for(auto p : pts) cmp_x.push_back(p.first);
9a7     cmp_x.erase(unique(all(cmp_x)), cmp_x.end());
f82     ys.resize(cmp_x.size() + 1);
94d     for(auto p : pts) put(id(cmp_x, p.first), p.second);
310     for(auto &v:ys)sort(all(v)), bit.emplace_back(sz(v));
a01   }
767   void update(int x, int y, int val){
f3f     x = id(cmp_x, x);
681     for(x++; x < sz(ys); x+= x&-x)
507       bit[x].update(id(ys[x], y), val);
c88   }
d95   int query(int x, int y){
f3f     x = id(cmp_x, x);
7c9     int ret = 0;
f32     for(x++; x > 0; x-= x&-x)
ea8       ret += bit[x].query(id(ys[x], y));
edf     return ret;
8f7   }
251   int query(int x1, int y1, int x2, int y2){
e4d     int a = query(x2, y2)-query(x2, y1-1);
7d1     return a-query(x1-1, y2)+query(x1-1, y1-1);
c33   }
5a9 };
```

LineContainer.h

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

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

8ec1c7, 32 lines

```
72c struct Line {
3e2   mutable ll k, m, p;
ca5   bool operator<(const Line& o) const { return k < o.k; }
abf   bool operator<(ll x) const { return p < x; }
7e3 };

781 struct LineContainer : multiset<Line, less<>> {
      // (for doubles, use inf = 1/.0, div(a,b) = a/b)
fd2   static const ll inf = LLONG_MAX;
33a   ll div(ll a, ll b) { // floored division
10f     return a / b - ((a ^ b) < 0 && a % b); }
a1c   bool isect(iterator x, iterator y) {
a95     if (y == end()) return x->p = inf, 0;
9cb     if (x->k == y->k) x->p = x->m > y->m ? inf : -inf;
591     else x->p = div(y->m - x->m, x->k - y->k);
870     return x->p >= y->p;
2fa   }
a0c   void add(ll k, ll m) {
116     auto z = insert({k, m, 0}), y = z++, x = y;
7b1     while (isect(y, z)) z = erase(z);
d94     if (x != begin() && isect(--x, y))
c07       isect(x, y = erase(y));
57d     while ((y = x) != begin() && (--x)->p >= y->p)
774       isect(x, erase(y));
086   }
4ad   ll query(ll x) {
229     assert(!empty());
7d1     auto l = *lower_bound(x);
96a     return l.k * x + l.m;
d21   }
577 };
```

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

fb7161, 44 lines

```
626 inline int64_t hilOrd(int x, int y, int pow, int rot) {
51a   if (pow == 0) return 0;
a6e   int hpow = 1 << (pow - 1);
```

```
01f   int seg = (x < hpow) ? ((y < hpow) ? 0 : 3) : ((y < hpow
    ) ? 1 : 2);
e08   seg = (seg + rot) & 3;
669   const int rotDelta[4] = { 3, 0, 0, 1 };
d0b   int nx = x & (x ^ hpow), ny = y & (y ^ hpow);
115   int nrot = (rot + rotDelta[seg]) & 3;
fba   int64_t sub = int64_t(1) << (2 * pow - 2);
65b   int64_t ans = seg * sub;
1ae   int64_t add = hilOrd(nx, ny, pow - 1, nrot);
ff7   ans += (seg == 1 || seg == 2) ? add : (sub - add - 1);
ba7   return ans;
ec4 }

670 struct Query {
738   int l, r, idx;
ce8   int64_t ord;
36f   Query(int l, int r, int idx) : l(l), r(r), idx(idx) {
6c4     ord = hilOrd(l, r, 21, 0);
926   }
847   bool operator < (const Query& other) const {
328     return ord < other.ord;
e05   }
315 };

240 vector<Query> queries;
4d5 int ans[ms];
566 void put(int x) {} // F
c29 void remove(int x) {} // F
64b int getAns() {}

1c1 void Mo() {
3d9   int l = 0, r = -1;
bfa   sort(queries.begin(), queries.end());
275   for (Query q : queries) {
482     while (l > q.l) put(--l);
fec     while (r < q.r) put(++r);
5b8     while (l < q.l) remove(l++);
9b5     while (r > q.r) remove(r--);
745     ans[q.idx] = getAns();
5a4   }
2a4 }
```

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: $\mathcal{O}\left(Q * (2 * N * N)^{\frac{1}{3}} * F\right)$ f8eda8, 55 lines

```
496 const int B = 2700;
247 struct MoUpdate {
670   struct Query {
fd6     int l, r, t, idx;
fc8     Query(int l, int r, int t, int idx)
8bf       : l(l), r(r), t(t), idx(idx) {}
f51     bool operator < (const Query& p) const {
f06       if (l / B != p.l / B) return l < p.l;
e80       if (r / B != p.r / B) return r < p.r;
d0c       return t < p.t;
673     }
bc2   };
f2f   struct Upd {
f25     int i, old, now;
f23     Upd(int i, int old, int now): i(i),old(old),now(now){}
c12   };

240   vector<Query> queries;
e2b   vector<Upd> updates;

ac5   void addQuery(int l, int r, int t, int idx) {
fc9     queries.push_back(Query(l, r, t, idx)); }
968   void addUpdate(int i, int old, int now) {
936     updates.push_back(Upd(i, old, now)); }

1aa   void add(int x) {} // F
598   void rem(int x) {} // F
64b   int getAns() {}
0d2   void update(int novo, int idx, int l, int r) {
2b9     if (l <= idx && idx <= r) rem(idx);
4ce     arr[idx] = novo;
ec1     if (l <= idx && idx <= r) add(idx);
100   }

63d   void solve() {
cb1     int l = 0, r = -1, t = 0;
bfa     sort(queries.begin(), queries.end());
275     for (Query q : queries) {
a95       while (l > q.l) add(--l);
875       while (r < q.r) add(++r);
8f6       while (l < q.l) rem(l++);
a38       while (r > q.r) rem(r--);
fda       while (t < q.t) {
df3         auto u = updates[t++];
285         update(u.now, u.i, l, r);
8a4       }
32a       while (t > q.t) {
d69         auto u = updates[--t];
ce2         update(u.old, u.i, l, r);
3bf       }
745       ans[q.idx] = getAns();
f06     }
b09   }
d3e };
```

MinQueue.h

40df8d, 19 lines

```
925 struct MQueue {
fdd     int tin, tout;
375     deque<pair<int, int>> dq;
1ce     MQueue() : tin(0), tout(0) {}
619     void push(int val) {
f0d         while (!dq.empty() && min(dq.back().first, val) ==
    val) dq.pop_back();
9c6         dq.push_back(pair(val, tin++));
769     }
42d     void pop() {
            // assert(!dq.empty());
48c         if (dq.front().second == tout) dq.pop_front();
470         tout++;
b0e     }
f46     int front() {
            // assert(!dq.empty());
651         return dq.front().first;
fa2     }
40d };
```

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: $\mathcal{O}(\log N)$ f609d9, 21 lines

```
5ae struct Tree {
ef4  typedef int T;
cbe  static constexpr T unit = INT_MIN;
e54  T f(T a, T b) { return max(a, b); } // (any associative
    fn)
6cd  vector<T> s; int n;
3d2  Tree(int n = 0, T def = unit) : s(2*n, def), n(n) {}
6a3  void update(int pos, T val) {
56a    for (s[pos += n] = val; pos /= 2;)
326      s[pos] = f(s[pos * 2], s[pos * 2 + 1]);
0e9  }
b4c  T query(int b, int e) { // query [b, e]
1a3    e++;
0f9    T ra = unit, rb = unit;
fbb    for (b += n, e += n; b < e; b /= 2, e /= 2) {
e83      if (b % 2) ra = f(ra, s[b++]);
064      if (e % 2) rb = f(s[--e], rb);
561    }
cb2    return f(ra, rb);
707  }
f60 };
```

OrderStatisticTree.h

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

Time: $\mathcal{O}(\log N)$ 782797, 17 lines

```
c4d #include <bits/extc++.h>
0d7 using namespace __gnu_pbds;

4fc template<class T>
c20 using Tree = tree<T, null_type, less<T>, rb_tree_tag,
3a1     tree_order_statistics_node_update>;

ad0 void example() {
c6f  Tree<int> t, t2; t.insert(8);
559  auto it = t.insert(10).first;
d28  assert(it == t.lower_bound(9));
969  assert(t.order_of_key(10) == 1);
d39  assert(t.order_of_key(11) == 2);
1b7  assert(*t.find_by_order(0) == 8);
a60  t.join(t2); // merge t2 into t
9ad }
```

PersistentSegTree.h

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

`roots = {0}, newRoot = update(roots.back(),...), roots.push(newRoot)` 58842f, 42 lines

```
b17 struct SegP {
709   static constexpr ll neut = 0;
bf2   struct Node {
aa3     ll v; // start with neutral value
74f     int l, r;
9ef     Node(ll v=neut, int l=0, int r=0) : v(v), l(l), r(r){}
945   };
38f   vector<Node> seg;
068   int n, CNT;
9ea   SegP(int _n, int upd): seg(20*(upd+_n)), n(_n), CNT(1){}
2ce   ll merge(ll a, ll b) { return a + b; }
c97   int update(int root, int pos, int val, int l, int r) {
ec9     int p = CNT++;
77a     seg[p] = seg[root];
893     if (l == r) {
00f       seg[p].v += val;
74e       return p;
3d7     }
ae0     int mid = (l + r) / 2;
8a3     if (pos <= mid){
aa8       seg[p].l = update(seg[p].l, pos, val, l, mid);
583     }else seg[p].r = update(seg[p].r,pos,val,mid+1,r);

85a     seg[p].v=merge(seg[seg[p].l].v, seg[seg[p].r].v);
```

```
74e       return p;
a90     }
6a4     int query(int p, int L, int R, int l, int r) {
3c7       if (l > R || r < L) return neut;
c26       if (L <= l && r <= R) return seg[p].v;
ae0       int mid = (l + r) / 2;
864       int left = query(seg[p].l, L, R, l, mid);
195       int right = query(seg[p].r, L, R, mid + 1, r);
90a       return merge(left, right);
e77     }
304     int update(int root, int pos, int val) {
c68       return update(root, pos, val, 0, n - 1);
84e     }
7cc     int query(int root, int L, int R) {
a53       return query(root, L, R, 0, n - 1);
2f9     }
588   };
```

SegBeats.h

Description: In Segment Tree Beats, ‘lazy‘ does NOT mean ”updates still missing here”. The node already reflects all previous updates. Instead, ‘lazy‘ stores what must be propagated to the children before recursing. Always call ‘apply(l,r,p)‘ before descending. This node layout supports range add, range chmin and range chmax operations. Beats conditions:
break: MIN x: mx1 <= x ; MAX x: mi1 >= x
tag: MIN x: x > mx2 ; MAX x: x < mi2
Time: amortized $\mathcal{O}(\log^2 N)$, without range add $\mathcal{O}(\log N)$ fa8527, 47 lines

```
3c9   struct node{
45e     ll mx1, mx2, sum, lazy;
9e5     ll mi1, mi2;
faa     int cMax, cMin, tam;
db3     node(int x=0) : mx1(x),mx2(-inf),mi1(x),mi2(inf),
744                 cMax(1),cMin(1),tam(1),sum(x),lazy(0){}
b67     node(node a, node b){
4f5       sum = a.sum+b.sum, tam = a.tam+b.tam;
c60       lazy = 0;
15b       mx1 = max(a.mx1, b.mx1);
9ae       mx2 = max(a.mx2, b.mx2);
f62       if(a.mx1 != b.mx1) mx2 = max(mx2, min(a.mx1, b.mx1));
b60       cMax=(a.mx1==mx1 ? a.cMax:0)+(b.mx1==mx1 ? b.cMax:0);

09f       mi1 = min(a.mi1, b.mi1);
143       mi2 = min(a.mi2, b.mi2);
3bf       if(a.mi1 != b.mi1) mi2=min(mi2, max(a.mi1, b.mi1));
c18       cMin=(a.mi1==mi1 ? a.cMin:0)+(b.mi1==mi1 ? b.cMin:0);
23d     }
38d     void apply_sum(ll x){
2a1       mx1 += x, mx2 += x,mi1 += x, mi2 += x;
99b       sum += tam*x, lazy += x;
b5e     }
cf4     void apply_min(ll x){
e07       if(x >= mx1) return;
c44       sum -= (mx1 - x)*cMax;
be0       if(mi1 == mx1) mi1 = x;
8ef       if(mi2 == mx1) mi2 = x;
ea2       mx1 = x;
908     }
0c8     void apply_max(ll x){
e25       if(x <= mi1) return;
59e       sum -= (mi1 - x)*cMin;
4b1       if(mx1 == mi1) mx1 = x;
d69       if(mx2 == mi1) mx2 = x;
1ff       mi1 = x;
0e4     }
554   };
fdc   void apply(int l, int r, int p){
c8e     for(int i=2*p+1; i<=2*p+2; i++){
dbf       seg[i].apply_sum(st[p].lazy);
c90       seg[i].apply_min(st[p].mx1);
61a       seg[i].apply_max(st[p].mi1);
4b8     }
431     seg[p].lazy = 0;
dd0   }
```

RMQ.h

Usage: `RMQ rmq(values);`
`rmq.query(inclusive, inclusive);`
Time: $\mathcal{O}(|V|\log|V| + Q)$ bca062, 17 lines

```
76a   struct RMQ {
8ac     vector<vector<int>> dp;
dd1     RMQ(const vector<int>& a) : dp(1, a) {
71c       for (int i = 1, pw = 1; pw*2 <= sz(a); pw*=2, i++) {
394         dp.emplace_back(sz(a) - pw*2 + 1);
d17         for (int j = 0; j < sz(dp[i]); j++) {
dcc           dp[i][j] = min(dp[i-1][j], dp[i-1][j+pw]);
75a         }
b68       }
3e9     }
9e3     int query(int l, int r) {
658       assert(l <= r);
884       int k = 31 - __builtin_clz(r - l + 1);
1f9       return min(dp[k][l], dp[k][r - (1 << k) + 1]);
e21     }
bca   };
```

UnionFind.h

Description: Disjoint-set data structure with bipartite check 6d2739, 22 lines

```
146   struct Uf{
b54       vector<int> tam, ds, bi, c;
d2c       Uf(int n) : tam(n, 1), ds(n), bi(n, 1), c(n){
244           iota(all(ds), 0);
233       }
001       int find(int i){ return (i==ds[i] ? i : find(ds[i]));}
e5a       int color(int i){
300           return (i==ds[i] ? 0 : (c[i]^color(ds[i])));}
c3b       void merge(int a, int b){
8d0           int ca = color(a), cb = color(b);
605           a = find(a), b = find(b);
a89           if(a == b){
686               if(ca == cb) bi[a] = false;
505               return;
c08           }
226           if(tam[a] < tam[b]) swap(a, b);
1ac           ds[b] = a, tam[a] += tam[b];
27c           bi[a] = (bi[a] && bi[b]);
834           c[b] = (ca ^ cb ^ 1);
a70       }
6d2   };
```

UnionFindRollback.h

Description: Disjoint-set data structure with undo. If undo is not needed, skip st, time() and rollback().
Usage: `int t = uf.time(); ...; uf.rollback(t);`
Time: $\mathcal{O}(\log(N))$ d4405e, 23 lines

```
47a   struct RollbackUF {
f80    vector<int> e;
919       vector<pii> st;
f6f    RollbackUF(int n) : e(n, -1) {}
84b    int size(int x) { return -e[find(x)]; }
626    int find(int x) { return e[x] < 0 ? x : find(e[x]); }
49f    int time() { return sz(st); }
4db    void rollback(int t) {
314      for (int i = time(); i --> t;)
8d2       e[st[i].first] = st[i].second;
b04      st.resize(t);
30b    }
cf0    bool join(int a, int b) {
605      a = find(a), b = find(b);
5c2      if (a == b) return false;
745      if (e[a] > e[b]) swap(a, b);
bac      st.push_back({a, e[a]});
e6e      st.push_back({b, e[b]});
708      e[a] += e[b]; e[b] = a;
8a6      return true;
6c7    }
d44   };
```

Numerical (4)

4.1 Polynomials and recurrences

Polynomial.h c9b7b0, 19 lines

```
213   struct Poly {
3a1     vector<double> a;
9a5     double operator()(double x) const {
e3c       double val = 0;
d5c       for (int i = sz(a); i--;) (val *= x) += a[i];
d94       return val;
ae7     }
0ac     void diff() {
7b6       rep(i,1,sz(a)) a[i-1] = i*a[i];
468       a.pop_back();
afc     }
087     void divroot(double x0) {
898       double b = a.back(), c; a.back() = 0;
9cf       for(int i=sz(a)-1; i--;)
406         c = a[i], a[i] = a[i+1]*x0+b, b=c;
468       a.pop_back();
3f8     }
c9b   };
```

PolyRoots.h

Description: Finds the real roots to a polynomial.
Usage: `polyRoots({{2,-3,1}},-1e9,1e9) // solve x^2-3x+2 = 0`
Time: $\mathcal{O}(n^2 \log(1/\epsilon))$
"Polynomial.h" b00bfe, 24 lines

```
64a   vector<double> polyRoots(Poly p, double xmin, double xmax)
        {
853     if (sz(p.a) == 2) { return {-p.a[0]/p.a[1]}; }
539     vector<double> ret;
f55     Poly der = p;
c06     der.diff();
617     auto dr = polyRoots(der, xmin, xmax);
d85     dr.push_back(xmin-1);
12c     dr.push_back(xmax+1);
423     sort(all(dr));
b98     rep(i,0,sz(dr)-1) {
d85       double l = dr[i], h = dr[i+1];
ad1       bool sign = p(l) > 0;
b41       if (sign ^ (p(h) > 0)) {
03d         rep(it,0,60) { // while (h - l > 1e-8)
761           double m = (l + h) / 2, f = p(m);
0ac           if ((f <= 0) ^ sign) l = m;
193           else h = m;
b69         }
ff5         ret.push_back((l + h) / 2);
fc2       }
d15     }
edf     return ret;
b00   }
```

PolyInverse.h

2745a7, 18 lines

```
747 vector<ll> get_inverse(vector<ll> a) {
e4d   if (a.empty()) return {};
044   int Y = sz(a) - 1, n = 32 - __builtin_clz(Y);
ba5   n = (1 << n);
711   a.resize(n);
e3e   vector<ll> inv = { modpow(a[0], mod - 2) }, f, c;
a2b   inv.reserve(n);
599   for (int tam = 2; tam <= n; tam *= 2) {
d29     while (sz(f) < tam) f.push_back(a[sz(f)]);
fec     c = conv(f, inv);
757     rep(i, 0, tam) c[i] = (c[i] == 0 ? 0 : mod - c[i]);
df6     c[0] += (c[0] + 2 >= mod ? 2 - mod : 2);
f8b     inv = conv(inv, c);
118     inv.resize(tam);
9f4   }
531   return inv;
274 }
```

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

96548b, 21 lines

```
c10 vector<ll> berlekampMassey(vector<ll> s) {
ea1   int n = sz(s), L = 0, m = 0;
2a2   vector<ll> C(n), B(n), T;
2b3   C[0] = B[0] = 1;

d6f   ll b = 1;
36d   rep(i,0,n) { ++m;
b7f     ll d = s[i] % mod;
45a     rep(j,1,L+1) d = (d + C[j] * s[i - j]) % mod;
53a     if (!d) continue;
169     T = C; ll coef = d * modpow(b, mod-2) % mod;
2d1     rep(j,m,n) C[j] = (C[j] - coef * B[j - m]) % mod;
b6c     if (2 * L > i) continue;
dc3     L = i + 1 - L; B = T; b = d; m = 0;
8c2   }

51b   C.resize(L + 1); C.erase(C.begin());
e98   for (ll& x : C) x = (mod - x) % mod;
a91   return C;
965 }
```

LinearRecurrence.h

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

547b93, 27 lines

```
437 using Poly = vector<ll>;
2ef ll linearRec(Poly S, Poly tr, ll k) {
327   int n = sz(tr);

0e9   auto combine = [&](Poly a, Poly b) {
b1c     Poly res(n * 2 + 1);
5f7     rep(i,0,n+1) rep(j,0,n+1)
389       res[i + j] = (res[i + j] + a[i] * b[j]) % mod;
bdc     for (int i = 2 * n; i > n; --i) rep(j,0,n)
fc3       res[i-1-j] = (res[i-1-j] + res[i] * tr[j]) % mod;
b76     res.resize(n + 1);
b50     return res;
55c   };
bf8   Poly pol(n + 1), e(pol);
997   pol[0] = e[1] = 1;

e96   for (++k; k; k /= 2) {
491     if (k % 2) pol = combine(pol, e);
0d9     e = combine(e, e);
813   }

cd2   ll res = 0;
e8d   rep(i,0,n) res = (res + pol[i + 1] * S[i]) % mod;
b50   return res;
594 }
```

4.2 Matrices

SolveLinear.h

Description: If inv = 1, finds the inverse of the matrix eq and returns it as a flat vector
Time: $\mathcal{O}\left(\min(n,m)\, nm\right)$

2c134e, 52 lines

```
320 struct Gauss {
d6d   const double eps = 1e-9;
93d   vector<vector<double>> eq;
754   void addEquation(const vector<double>& e) {
503     eq.push_back(e); }
04f   pair<int, vector<double>> solve(int inv=0) {
214     int n = sz(eq), m = sz(eq[0]) - 1 + inv;
f9c     if(inv){
d33       rep(i, 0, n) eq[i].resize(2*n), eq[i][n+i] = 1;
2e2     }
3cb     vector<int> where(m, -1);
a73     for (int col = 0, row = 0; col < m && row < n; col++)
      {
f05       int sel = row;
53c       rep(i, row, n) {
664         if (abs(eq[i][col]) > abs(eq[sel][col])) sel = i;
e04       }
68b       if (abs(eq[sel][col]) < eps) continue;
3ad       rep(i, col, sz(eq[0])) swap(eq[sel][i], eq[row][i]);
2c3       where[col] = row;
dff       rep(i, 0, n) if (i != row) {
184         double c = eq[i][col] / eq[row][col];
7f1         rep(j, col, sz(eq[0])) eq[i][j] -= eq[row][j] * c;
17d       }
4ef       ++row;
9b8     }
f9c     if(inv){
208       vector<double> res;
fea       rep(i, 0, n) {
420         if (where[i] == -1) return {0, {}}; // Singular
3af         rep(j, n, 2*n)
f89           res.push_back(eq[where[i]][j] / eq[where[i]][i])
      ;
d81       }
3b1       return {1, res};
700     }

233     vector<double> ans(m, 0);
670     rep(i, 0, m) {
c19       if (where[i] != -1)
02c         ans[i] = eq[where[i]][m] / eq[where[i]][i];
5bb     }
fea     rep(i, 0, n) {
68c       double sum = 0;
5f8       rep(j, 0, m) {
f48         sum = sum + ans[j] * eq[i][j];
fa6       }
3c8       if(abs(sum - eq[i][m]) > eps)return {0, {}};
bf2     }
260     rep(i, 0, m) if (where[i] == -1) return {2, ans};
d4a     return {1, ans};
a95   }
2c1 };
```

SolveLinearBinary.h

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

28c946, 32 lines

```
e81 pair<int, bitset<M>> gauss(vector<bitset<M>> eq) {
579     int n = eq.size(), m = M - 1;
3cb     vector<int> where(m, -1);
a73     for(int col = 0, row = 0; col < m && row < n; col++){
dbb         rep(i,row,n)
926             if (eq[i][col]) {
c35                 swap(eq[i], eq[row]);
c2b                 break;
177             }
f4f         if (!eq[row][col]) continue;
2c3         where[col] = row;

fea         rep(i, 0, n) {
b60             if (i != row && eq[i][col]) eq[i] ^= eq[row];
981         }
4ef         ++row;
c74     }
7eb     bitset<M> ans;
670     rep(i,0,m) {
713         if (where[i] != -1) ans[i] = eq[where[i]][m];
691     }
fea     rep(i,0,n) {
e5c         int sum = (ans & eq[i]).count();
53f         sum %= 2;
36a         if (sum != eq[i][m]) return pair(0, bitset<M>());
29e     }
670     rep(i,0,m) {
be2         if (where[i] == -1) return pair(INF, ans);
958     }
280     return pair(1, ans);
28c }
```

XorGauss.h

5a1957, 30 lines

```
b94 struct XorGauss {
060     int N;
471     vector<ll> basis, who, mask;
47b     XorGauss(int N) : N(N), basis(N), who(N), mask(N) {}
        // if(ans & (1ll << j)) who[j] was used to form x
221     bool belong(ll x){
04b         ll ans = 0;
042         for(int i=N-1; i>=0; i--){
e13             if((x ^ basis[i]) < x){
4ec                 ans ^= mask[i];
6b0                 x ^= basis[i];
254             }
2ad         }
069         return (x == 0);
c26     }
397     void add(ll v, int idx) {
a4d         ll msk = 0;
042         for (int i = N - 1; i >= 0; i--) {
80f             if (!(v & (1ll << i))) continue;
bf3             if (basis[i] == 0) {
1c7                 basis[i] = v, who[i] = idx;
940                 mask[i] = (msk | (1ll << i));
505                 return;
bc8             }
00e             msk ^= mask[i];
647             v ^= basis[i];
25b         }
```

```
fcc       }
5a1   };
```

4.3 Fourier transforms

FastFourierTransform.h

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

773fcd, 44 lines

```
bcc  typedef complex<double> C;

7c0  void fft(vector<C>& a) {
a5b    int n = a.size(), L = 31 - __builtin_clz(n);
f82    static vector<complex<long double>> R(2, 1); // 10%
     faster if double
991    static vector<C> rt(2, 1);
ad8    for (static int k = 2; k < n; k *= 2) {
9d9      R.resize(n);
335      rt.resize(n);
411      auto x = polar(1.0L, acos(-1.0L) / k);
cdb      rep(i,k,2*k) rt[i] = R[i] = i&1 ? R[i/2] * x : R[i/2];
a8a    }
e66    vector<ll> rev(n);
dcb    rep(i,0,n) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
47b    rep(i,0,n) if (i < rev[i]) swap(a[i], a[rev[i]]);

d3f    for (int k = 1; k < n; k *= 2) {
cda      for (int i = 0; i < n; i += 2 * k) {
0c2        for (int j = 0; j < k; j++) {
30c          auto x = (double*)&rt[j + k];
ebe          auto y = (double*)&a[i + j + k];
15c          C z(x[0]*y[0] - x[1]*y[1], x[0]*y[1] + x[1]*y[0]);
20a          a[i + j + k] = a[i + j] - z;
1b0          a[i + j] += z;
b5b        }
1fe      }
fa0    }
b33  }

ccc  vector<ll> conv(const vector<ll>& a, const vector<ll>& b){
f88    if (a.empty() || b.empty()) return {};
920    vector<ll> res(sz(a) + sz(b) - 1);
441    int L = 32 - __builtin_clz(sz(res)), n = 1 << L;
060    vector<C> in(n), out(n);
b1a    copy(all(a), in.begin());
fef    rep(i,0,sz(b)) in[i].imag(b[i]);
21a    fft(in);
6fb    for (C& x : in) x *= x;
4d7    rep(i,0,n) out[i] = in[-i & (n - 1)] - conj(in[i]);
3d7    fft(out);
aa3    rep(i,0,sz(res)) res[i]=round(imag(out[i]) / (4 * n));
b50    return res;
7f4  }
```

FastFourierTransformMod.h

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

"FastFourierTransform.h" b82773, 23 lines

```
192  typedef vector<ll> vl;
3fe  template<int M> vl convMod(const vl &a, const vl &b) {
f88   if (a.empty() || b.empty()) return {};
19d   vl res(sz(a) + sz(b) - 1);
a6f   int B=32-__builtin_clz(sz(res)), n=1<<B,cut=int(sqrt(M));
3dd   vector<C> L(n), R(n), outs(n), outl(n);
a1d   rep(i,0,sz(a)) L[i] =C((int)a[i] / cut, (int)a[i] % cut);
97d   rep(i,0,sz(b)) R[i] =C((int)b[i] / cut, (int)b[i] % cut);
5d5   fft(L), fft(R);
fea   rep(i,0,n) {
39d     int j = -i & (n - 1);
65e     outl[j] = (L[i] + conj(L[j])) * R[i] / (2.0 * n);
91a     outs[j] = (L[i] - conj(L[j])) * R[i] / (2.0 * n) / 1i;
cb3   }
d08   fft(outl), fft(outs);
35e   rep(i,0,sz(res)) {
351     ll av = ll(real(outl[i])+.5), cv =ll(imag(outs[i])+.5);
988     ll bv = ll(imag(outl[i])+.5) + ll(real(outs[i])+.5);
6a3     res[i] = ((av % M * cut + bv) % M * cut + cv) % M;
58f   }
b50   return res;
c1f  }
```

NumberTheoreticTransform.h

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

84c11e, 34 lines

```
376  const int mod = 998244353, root = 62;
192  typedef vector<ll> vl;
8ec  void ntt(vl &a) {
6ae   int n = sz(a), L = 31 - __builtin_clz(n);
7c9   static vl rt(2, 1);
8ee   for (static int k = 2, s = 2; k < n; k *= 2, s++) {
335     rt.resize(n);
d43     ll z[] = {1, modpow(root, mod >> s)};
8e7     rep(i,k,2*k) rt[i] = rt[i / 2] * z[i & 1] % mod;
f39   }
808   vector<int> rev(n);
dcb   rep(i,0,n) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
47b   rep(i,0,n) if (i < rev[i]) swap(a[i], a[rev[i]]);
657   for (int k = 1; k < n; k *= 2)
2cb     for (int i = 0; i < n; i += 2 * k) rep(j,0,k) {
86e       ll z = rt[j+k] * a[i+j+k] % mod, &ai = a[i+j];
598       a[i + j + k] = ai - z + (z > ai ? mod : 0);
589       ai += (ai + z >= mod ? z - mod : z);
9a8     }
de9  }
08f  vl conv(const vl &a, const vl &b) {
f88   if (a.empty() || b.empty()) return {};
f51   int s = sz(a) + sz(b) - 1, B = 32 - __builtin_clz(s),
570       n = 1 << B;
9ef   int inv = modpow(n, mod - 2);
e4c   vl L(a), R(b), out(n);
6b4   L.resize(n), R.resize(n);
d9e   ntt(L), ntt(R);
dfc   rep(i,0,n)
0db     out[-i & (n - 1)] = (ll)L[i] * R[i] % mod * inv % mod;
ec9   ntt(out);
c20   return {out.begin(), out.begin() + s};
387  }
```

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

124c14, 20 lines

```
5ad  void FST(vector<ll>& a, bool inv) {
a9d    for (int n = sz(a), step = 1; step < n; step *= 2) {
5bd      for (int i = 0; i < n; i += 2 * step) {
4ee        for (int j = i; j < i + step; j++) {
2fe          ll& u = a[j], &v = a[j + step];
c6f          tie(u, v) =
2d3          inv ? pair(v - u, u) : pair(v, u + v); // AND
aba          inv ? pair(v, u - v) : pair(u + v, u); // OR
a5a          pair(u + v, u - v);  // XOR
0b4        }
fb4      }
cd3    }
c9b    if(inv) for(ll& x : a) x /= sz(a); // XOR only
075  }
eb2  vector<ll> conv(vector<ll> a, vector<ll> b) {
595    FST(a, 0); FST(b, 0);
2dd    for (int i = 0; i < sz(a); i++) a[i]*=b[i];
062    FST(a, 1); return a;
7bf  }
```

Number theory (5)

5.1 Modular arithmetic

ModInverse.h

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

c375f5, 5 lines

```
88a  const ll mod = 1000000007, LIM = 200000;
0f2  inv[1] = 1;
379  for(int i=2; i<LIM; i++)
86c      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`

bbbd8f, 12 lines

```
f4c  typedef unsigned long long ull;
f85  ull modmul(ull a, ull b, ull M) {
2dd   ll ret = a * b - M * ull(1.L / M * a * b);
964   return ret + M * (ret < 0) - M * (ret >= (ll)M);
e93  }
4f6  ull modpow(ull b, ull e, ull mod) {
c1a   ull ans = 1;
a18   for (; e; b = modmul(b, b, mod), e /= 2)
9e8     if (e & 1) ans = modmul(ans, b, mod);
ba7   return ans;
100  }
```

ModPow.h

b83e45, 9 lines

```
e2e  const ll mod = 1000000007; // faster if const

9d8  ll modpow(ll b, ll e) {
d54   ll ans = 1;
36e   for (; e; b = b * b % mod, e /= 2)
b46     if (e & 1) ans = ans * b % mod;
ba7   return ans;
d1e  }
```

ModSqrt.h

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

"ModPow.h" 19a793, 25 lines

```
a77  ll sqrt(ll a, ll p) {
5de   a %= p; if (a < 0) a += p;
```

```
b47   if (a == 0) return 0;
5c6   assert(modpow(a, (p-1)/2, p) == 1); // else no solution
a75   if (p % 4 == 3) return modpow(a, (p+1)/4, p);
      // a^(n+3)/8 or 2^(n+3)/8 * 2^(n-1)/4 works if p % 8 == 5
b94   ll s = p - 1, n = 2;
ee5   int r = 0, m;
084   while (s % 2 == 0)
082     ++r, s /= 2;
eaa   while (modpow(n, (p - 1) / 2, p) != p - 1) ++n;
0c3   ll x = modpow(a, (s + 1) / 2, p);
b74   ll b = modpow(a, s, p), g = modpow(n, s, p);
1af   for (;; r = m) {
4fd     ll t = b;
713     for (m = 0; m < r && t != 1; ++m)
c58       t = t * t % p;
ae0     if (m == 0) return x;
20e     ll gs = modpow(g, 1LL << (r - m - 1), p);
fba     g = gs * gs % p;
4fb     x = x * gs % p;
c5c     b = b * g % p;
e3a   }
19a }
```

DiscreteLog.h

Description: Returns the smallest x such that $a^x \bmod m = b \bmod m$. If no such x exists, returns -1.
Time: O(sqrt(m) * log(sqrt(m)))

2f126b, 32 lines

```
758 int solve(int a, int b, int m) {
a6e     a %= m, b %= m;
ec4     if (a == 0) return (b ? -1 : 1);
        // caso gcd(a, m) > 1
6af     int k = 1, add = 0, g;
553     while ((g = gcd(a, m)) > 1) {
d90         if (b == k) return add;
642         if (b % g) return -1;
92a         b /= g, m /= g, ++add;
803         k = (k * 1ll * a / g) % m;
8a0     }

16c     int sq = sqrt(m) + 1;
b51     int big = 1;
4e1     for (int i = 0; i < sq; i++) big = (1ll * big * a) % m
    ;

053     vector<pii> vals;
3c2     for (int q = 0, cur = b; q <= sq; q++) {
b53         vals.push_back({ cur, q });
b50         cur = (1ll * cur * a) % m;
837     }
62b     sort(all(vals));
90c     for (int p = 1, cur = k; p <= sq; p++) {
5d3         cur = (1ll * cur * big) % m;
958         auto it = lower_bound(all(vals), pair(cur, INF));
721         if (it != vals.begin() && (--it)->first == cur) {
a30             return sq * p - it->second + add;
6fe         }
f22     }
daa     return -1;
2f1 }
```

DiscreteRoot.h

Description: Returns x such that $x^k \bmod m = a \bmod m$. If no such x exists, returns -1.
Time: O(sqrt(m) * log(sqrt(m)))

"PrimitiveRoot.h", "DiscreteLog.h" 1d582e, 11 lines

```
    // Discrete Root

27c ll discreteRoot(ll k, ll a, ll m) {
738     ll g = primitiveRoot(m);
58b     ll y = discreteLog(fexp(g, k, m), a, m);
f31     if (y == -1) return y;
a58     return fexp(g, y, m);
1d5 }
```

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 $a^b \mod c$.

"ModMulLL.h" 66fe73, 13 lines

```
da4 bool isPrime(ull n) {
c16  if (n < 2 || n % 6 % 4 != 1) return (n | 1) == 3;
062  ull A[] = {2, 325, 9375, 28178, 450775, 9780504, 17952650
    22};
ae0  ull s = __builtin_ctzll(n-1), d = n >> s;
e80  for (ull a : A) {   // ^ count trailing zeroes
6b4    ull p = modpow(a%n, d, n), i = s;
274    while (p != 1 && p != n - 1 && a % n && i--)
c77      p = modmul(p, p, n);
e28    if (p != n-1 && i != s) return 0;
edf  }
6a5  return 1;
66f }
```

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" da0c7c, 19 lines

```
7eb ull pollard(ull n) {
222  ull x = 0, y = 0, t = 30, prd = 2, i = 1, q;
5f5  auto f = [&](ull x) { return modmul(x, x, n) + i; };
f51  while (t++ % 40 || gcd(prd, n) == 1) {
be9    if (x == y) x = ++i, y = f(x);
70f    if ((q = modmul(prd, max(x,y) - min(x,y), n))) prd = q;
b78    x = f(x), y = f(f(y));
bf8  }
002  return gcd(prd, n);
d1b }
591 vector<ull> factor(ull n) {
1b9  if (n == 1) return {};
6b5  if (isPrime(n)) return {n};
bc6  ull x = pollard(n);
52a  auto l = factor(x), r = factor(n / x);
7af  l.insert(l.end(), all(r));
792  return l;
d54 }
```

PrimitiveRoot.h

18a01e, 15 lines

```
    //is n primitive root of p ?
ad0 bool test(ll x, ll p) {
a56     ll m = p - 1;
845     for (ll i = 2; i * i <= m; ++i) if (!(m % i)) {
e64         if (modpow(x, i, p) == 1) return false;
599         if (modpow(x, m / i, p) == 1) return false;
53a     }
8a6     return true;
c4e }
    //find the smallest primitive root for p
220 ll search(ll p) {
1bf     for (ll i = 2; i < p; i++) if (test(i, p)) return i;
daa     return -1;
a3c }
```

5.3 Divisibility

Euclid.h

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

33ba8f, 6 lines

```
c22 ll euclid(ll a, ll b, ll &x, ll &y) {
1ee  if (!b) return x = 1, y = 0, a;
e3d  ll d = euclid(b, a % b, y, x);
0a4  return y -= a/b * x, d;
33b }
```

CRT.h

ba1a4a, 25 lines

```
bc9 ll modinverse(ll a, ll b, ll s0 = 1, ll s1 = 0) {
a76   return !b ? s0 : modinverse(b, a % b, s1, s0 - s1 * (a /
     b)); }

d8b ll mul(ll a, ll b, ll m) {
a6f   return (((__int128_t)a*b)%m + m)%m;
0bc }

28d struct Equation {
4c5   ll mod, ans;
08f   bool valid;
145   Equation(ll a, ll m) { mod = m, ans = a, valid = true; }
0fc   Equation() { valid = false; }
4d3   Equation(Equation a, Equation b) {
515     valid = false;
1a0     if (!a.valid || !b.valid) return;
85c     ll g = gcd(a.mod, b.mod);
44d     if ((a.ans - b.ans) % g != 0) return;
af0     valid = true;
b98     mod = a.mod * (b.mod / g);
81a     ll x = mul(a.mod, modinverse(a.mod, b.mod), mod);
38a     ans = a.ans + mul(x, (b.ans - a.ans) / g, mod);
c4c     ans = (ans % mod + mod) % mod;
6f5   }
f48 };
```

DivisionTrick.h

02aebb, 15 lines

```
7f1 void floor_ranges(int n) {
79c     for (int l = 1, r; l <= n; l = r + 1) {
746         r = n / (n / l);
            // floor(n/y) has the same value for y in [l..r]
5bf     }
eee }
678 void ceil_ranges(int n) {
79c     for (int l = 1, r; l <= n; l = r + 1) {
d47         int x = (n + l - 1) / l;
374         if (x == 1) r = n;
21b         else r = (n - 1) / (x - 1);
            // ceil(n/y) has the same value for y in [l..r]
06c     }
57c }
```

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 $n = p_1^{k_1} p_2^{k_2} \ldots p_r^{k_r}$ then $\phi(n) = (p_1 - 1)p_1^{k_1 - 1} \ldots (p_r - 1)p_r^{k_r - 1}$. $\phi(n) = n \cdot \prod_{p|n}(1 - 1/p)$.
$\sum_{d|n} \phi(d) = n$, $\sum_{1 \leq k \leq n, \gcd(k,n)=1} k = n\phi(n)/2, n > 1$
Euler's thm: a, n coprime $\Rightarrow a^{\phi(n)} \equiv 1 \pmod n$.
Euler's thm (generalized): a, m arbitrary, $n \geq \log_2 m \Rightarrow a^n \equiv a^{\phi(m)+(n \bmod \phi(m))} \pmod m$.

e58bf0, 6 lines

```
d08 void calculatePhi() {
265  for(int i=0; i<LIM; i++) phi[i] = i&1 ? i : i/2;
c83  for (int i = 3; i < LIM; i += 2) if(phi[i] == i)
dc2    for (int j = i; j < LIM; j += i) phi[j] -= phi[j] / i;
e58 }
```

Combinatorial (6)

PartitionSolver.h

e50fb7, 61 lines

```
d38 template<const int N>
182 struct PartitionSolver {
4ce   vector<vector<int>> part, to, from;
621   PartitionSolver() {
a9d     vector<int> a;
1ed     part.push_back(a);
77f     gen(1, N, a);
796     sort(all(part));
ed4     to.assign(sz(part), vector<int>(N + 1, -1));
9a5     from = to;
ddd     for (int i = 0; i < sz(part); i++) {
a93       int sum = 0;
87f       auto arr = part[i];
bca       for (auto x : arr) sum += x;
4fa       to[i][0] = i;
615       from[i][0] = i;
afc       for (int j = 1; j + sum <= N; j++) {
123         arr = part[i];
9d6         arr.push_back(j);
ceb         sort(all(arr));
d02         to[i][j] = getIndex(arr);
942         from[to[i][j]][j] = i;
20d       }
bef     }
283   }

810   int size() const { return sz(part); }
9ee   int getIndex(const vector<int>& arr) const {
168     return lower_bound(all(part), arr) - part.begin(); }
b49   int add(int id, int num) const { return to[id][num]; }
944   int rem(int id, int num) const { return from[id][num]; }
168   vector<int> getPartition(int id) const {
37b     return part[id]; }

1ba   void gen(int i, int sum, vector<int>& a) {
a05     if (i > sum) { return; }
726     a.push_back(i);
1ed     part.push_back(a);
278     gen(i, sum - i, a);
468     a.pop_back();
48f     gen(i + 1, sum, a);
537   }
f4f };

    // Number of partitions for all integers <= n
75c vector<ll> partitionNumber(int n) {
d9c   vector<ll> ans(n + 1, 0);
82f   ans[0] = 1;
78a   for (int i = 1; i <= n; i++) {
87f     for (int j = 1; j * (3 * j + 1) / 2 <= i; j++) {
b6b       ll here = ans[i - j * (3 * j + 1) / 2];
c91       ans[i] = (ans[i] + (j & 1 ? here : -here));
365     }
7c6     for (int j = 1; j * (3 * j - 1) / 2 <= i; j++) {
a1a       ll here = ans[i - j * (3 * j - 1) / 2];
c91       ans[i] = (ans[i] + (j & 1 ? here : -here));
162     }
4a3   }
ba7   return ans;
08b }
```

Graph (7)

7.1 Fundamentals

BellmanFord.h

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

529834, 24 lines

```
f5e const ll inf = LLONG_MAX;
83a struct Ed { int a, b, w, s() { return a < b ? a : -a; }};
9ac struct Node { ll dist = inf; int prev = -1; };

6fc void bell(vector<Node>& nodes, vector<Ed>& eds, int s) {
97b  nodes[s].dist = 0;
eb9  sort(all(eds), [](Ed a, Ed b) { return a.s() < b.s(); });

74e  int lim = sz(nodes) / 2 + 2; // /3+100 with shuffled vertices
c5a  rep(i,0,lim) for (Ed ed : eds) {
905    Node cur = nodes[ed.a], &dest = nodes[ed.b];
d7d    if (abs(cur.dist) == inf) continue;
6ab    ll d = cur.dist + ed.w;
6ec    if (d < dest.dist) {
956      dest.prev = ed.a;
4c2      dest.dist = (i < lim-1 ? d : -inf);
452    }
75a  }
ced  rep(i,0,lim) for (Ed e : eds) {
3ab    if (nodes[e.a].dist == -inf)
5ff      nodes[e.b].dist = -inf;
1d7  }
166 }
```

FloydWarshall.h

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

531245, 13 lines

```
964 const ll inf = 1LL << 62;
914 void floydWarshall(vector<vector<ll>>& m) {
e9d  int n = sz(m);
831  rep(i,0,n) m[i][i] = min(m[i][i], 0LL);
99d  rep(k,0,n) rep(i,0,n) rep(j,0,n)
19b    if (m[i][k] != inf && m[k][j] != inf) {
6e8      auto newDist = max(m[i][k] + m[k][j], -inf);
e89      m[i][j] = min(m[i][j], newDist);
f38    }
a69  rep(k,0,n) if (m[k][k] < 0) rep(i,0,n) rep(j,0,n)
ffd    if (m[i][k] != inf && m[k][j] != inf) m[i][j] = -inf;
f12 }
```

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: $\mathcal{O}\left(\min(m\sqrt{m},\ mn^{2/3})\right)$.
- 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.

892d6e, 56 lines

```
14d struct Dinic {
61f   const bool scaling = false;
206   int lim;
670   struct edge {
c63     int to, rev;
a14     ll cap, flow;
7f9     bool res;
6dd     edge(int to_, ll cap_, int rev_, bool res_)
a94       : to(to_), cap(cap_), rev(rev_), flow(0), res(res_){}
477   };

002   vector<vector<edge>> g;
216   vector<int> lev, beg;
a71   ll F;
63f   Dinic(int n) : g(n), lev(n), beg(n), F(0) {}

0c5   void add(int a, int b, ll c, ll other = 0) {
de2     g[a].emplace_back(b, c, sz(g[b]), false);
fa5     g[b].emplace_back(a, other, sz(g[a])-1, true);
14f   }
123   bool bfs(int s, int t) {
e59     fill(all(lev), -1);
4e7     fill(all(beg), 0);
0a4           lev[s] = 0;
8b2     queue<int> q; q.push(s);
647     while (sz(q)) {
be1       int u = q.front(); q.pop();
bd9       for (auto& i : g[u]) {
dbc         if (lev[i.to] != -1 or (i.flow == i.cap)) continue;
b4f         if (scaling and i.cap - i.flow < lim) continue;
185         lev[i.to] = lev[u] + 1;
8ca         q.push(i.to);
f97       }
b1b     }
0de     return lev[t] != -1;
310   }
1dc   ll dfs(int v, int s, ll f = INF) {
50b     if (!f or v == s) return f;
84d     for (int& i = beg[v]; i < sz(g[v]); i++) {
027       auto& e = g[v][i];
206       if (lev[e.to] != lev[v] + 1) continue;
a30       ll foi = dfs(e.to, s, min(f, e.cap - e.flow));
749       if (!foi) continue;
3c5       e.flow += foi, g[e.to][e.rev].flow -= foi;
45c       return foi;
e08     }
bb3     return 0;
b98   }
2b4   ll maxFlow(int s, int t) {
a86     for (lim = scaling ? (1<<30) : 1; lim; lim /= 2)
69c       while (bfs(s, t)) while (ll ff = dfs(s, t)) F += ff;
4ff     return F;
6c8   }
0fe      bool inCut(int u){ return lev[u] != -1; }
892 };
```

LowerBoundFlow.h

Description: Calculates maximum flow with lower/upper bounds on edges. Returns -1 if no feasible flow exists. add(a, b, l, r) adds edge $a \to b$ where flow f must satisfy $l \le f \le r$. add(a, b, c) adds edge $a \to b$ with capacity c (implies $0 \le f \le c$). Same complexity as Dinic.

"Dinic.h" 756539, 36 lines

```
0ca struct lb_max_flow : Dinic {
96f   vector<ll> d;
be9   lb_max_flow(int n) : Dinic(n + 2), d(n, 0) {}
b12   void add(int a, int b, int l, int r) {
c97     d[a] -= l;
f1b     d[b] += l;
cb6     Dinic::add(a, b, r - l);
989   }
```

```
087   void add(int a, int b, int c) {
610     Dinic::add(a, b, c);
330   }
7a1   bool has_circulation() {
ac0     int n = sz(d);
854     ll cost = 0;
fea     rep(i, 0, n){
c69       if (d[i] > 0) {
f56         cost += d[i];
4f6         Dinic::add(n, i, d[i]);
551       } else if (d[i] < 0) {
bd2         Dinic::add(i, n+1, -d[i]);
bd9       }
a13     }

9f2     return (Dinic::maxFlow(n, n+1) == cost);
cc6   }
7bd   bool has_flow(int src, int snk) {
eda     Dinic::add(snk, src, INF);
e40     return has_circulation();
4aa   }
4eb   ll max_flow(int src, int snk) {
ee8     if (!has_flow(src, snk)) return -1;
99c     Dinic::F = 0;
703     return Dinic::maxFlow(src, snk);
0bb   }
756 };
```

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. 6f4fae, 95 lines

```
c4d #include <bits/extc++.h>

9f4 const ll INF = numeric_limits<ll>::max() / 4;

6f3 struct MCMF {
670   struct edge {
ede     int from, to, rev;
e20     ll cap, cost, flow;
092   };
060   int N;
091   vector<vector<edge>> ed;
a83   vector<int> seen, vis;
0ec   vector<ll> dist, pi;
c45   vector<edge*> par;

2cc   MCMF(int N) : N(N), ed(N), seen(N), vis(N),
dc7     dist(N), pi(N), par(N) {}

6f3   void addEdge(int from, int to, ll cap, ll cost) {
ad8     if (from == to || cap == 0) return;
1af     ed[from].push_back(edge{from,to,sz(ed[to]),cap,cost,0
    });
700     ed[to].push_back(edge{to,from,sz(ed[from])-1,0,-cost,0
    });
dad   }

975   void path(int s) {
7d4     fill(all(seen), 0);
04e     fill(all(dist), INF);
a93     dist[s] = 0;
841     ll di;
937     __gnu_pbds::priority_queue<pair<ll, int>> q;
9fb     vector<decltype(q)::point_iterator> its(N);
23b     q.push({ 0, s });
14d     while (!q.empty()) {
eda       s = q.top().second; q.pop();
2af       seen[s] = 1; di = dist[s] + pi[s];
6bd       for (edge& e : ed[s]) {
d20         if (!seen[e.to]) {
f1f           ll val = di - pi[e.to] + e.cost;
f3c           if(e.cap - e.flow > 0 && val < dist[e.to]){
0c7             dist[e.to] = val;
fb6             par[e.to] = &e;
22d             if (its[e.to] == q.end()) {
aac               its[e.to] = q.push({-dist[e.to], e.to});
388             }
6f8             else q.modify(its[e.to], {-dist[e.to], e.to});
80b           }
fce         }
013       }
e16     }
faa     for (int i = 0; i < N; i++) {
0ef       pi[i] = min(pi[i] + dist[i], INF);
ded     }
17b   }

310   pair<ll, ll> maxflow(int s, int t) {
923     setpi(s, t);
3d3     ll totflow = 0, totcost = 0;
8dd     while (path(s), seen[t]) {
535       ll fl = INF;
733       for (edge* x = par[t]; x; x = par[x->from]) {
8ed         fl = min(fl, x->cap - x->flow);
ddf       }
f9f       totflow += fl;
733       for (edge* x = par[t]; x; x = par[x->from]) {
10b         x->flow += fl;
e58         ed[x->to][x->rev].flow -= fl;
3bf       }
219     }
faa     for (int i = 0; i < N; i++) {
a18       for (edge& e : ed[i]) {
7a0         totcost += e.cost * e.flow;
774       }
a06     }
17e     return { totflow, totcost / 2 };
411   }

      // If some costs can be negative, call this before
           maxflow:
eda   void setpi(int s, int t) {
3ef     fill(all(pi), INF);
156     pi[s] = 0;
45c     int it = N, ch = 1;
aa3     ll v;
5e8     while (ch-- && it--) {
faa       for (int i = 0; i < N; i++) {
c9b         if (pi[i] != INF)
fb0           for (edge& e : ed[i]) if (e.cap)
257             if((v= pi[i] + e.cost)< pi[e.to])
a43               pi[e.to] = v, ch = 1;
d0b       }
250     }
38b     assert(it >= 0); // negative cost cycle
545   }
f1d };
```

PushRelabel.h

Description: Push-relabel using the highest label selection rule and the gap heuristic. Quite fast in practice. To obtain the actual flow, look at positive values only.
Time: $\mathcal{O}\left(V^2\sqrt{E}\right)$ a7bbd5, 55 lines

```
49f struct PushRelabel {
e9b   struct Edge {
548     int dest, back;
e00     ll f, c;
571   };
ed3   vector<vector<Edge>> g;
51c   vector<ll> ec;
658   vector<Edge*> cur;
b08   vector<vector<int>> hs;
4d4   vector<int> H;
4e1   PushRelabel(int n) : g(n), ec(n), cur(n), hs(2*n), H(n){}

b1c   void addEdge(int s, int t, ll cap, ll rcap=0) {
50b     if (s == t) return;
cc8     g[s].push_back({t, sz(g[t]), 0, cap});
2aa     g[t].push_back({s, sz(g[s])-1, 0, rcap});
817   }

359   void addFlow(Edge& e, ll f) {
759     Edge &back = g[e.dest][e.back];
f7e     if (!ec[e.dest] && f) hs[H[e.dest]].push_back(e.dest);
d2e     e.f += f; e.c -= f; ec[e.dest] += f;
c47     back.f -= f; back.c += f; ec[back.dest] -= f;
340   }
0e0   ll calc(int s, int t) {
f00     int v = sz(g); H[s] = v; ec[t] = 1;
fbb     vector<int> co(2*v); co[0] = v-1;
e20     for(int i=0; i<v; i++) cur[i] = g[i].data();
8c2     for (Edge& e : g[s]) addFlow(e, e.c);

604     for (int hi = 0;;) {
ae9       while (hs[hi].empty()) if (!hi--) return -ec[s];
c6f       int u = hs[hi].back(); hs[hi].pop_back();
a3e       while (ec[u] > 0)  // discharge u
457         if (cur[u] == g[u].data() + sz(g[u])) {
e94           H[u] = 1e9;
5fa           for (Edge& e : g[u]){
256             if (e.c && H[u] > H[e.dest]+1)
740               H[u] = H[e.dest]+1, cur[u] = &e;
88f           }
f04           if (++co[H[u]], !--co[hi] && hi < v){
10d             for(int i=0; i<v; i++){
4be               if (hi < H[i] && H[i] < v)
021                 --co[H[i]], H[i] = v + 1;
a21             }
cc1           }
3a2           hi = H[u];
b6b         } else if (cur[u]->c && H[u] == H[cur[u]->dest]+1){
779           addFlow(*cur[u], min(ec[u], cur[u]->c));
e91         }else ++cur[u];
4d7     }
b65   }
385   bool inCut(int a) { return H[a] >= sz(g); }
a7b };
```

Blossom.h

Description: Max matching on general Graph. $mate[i]$ = match of i
Time: $\mathcal{O}\left(N^3\right)$ 21cc7b, 56 lines

```
40f vector<int> Blossom(vector<vector<int>>& g) {
10a     int n = sz(g), timer = -1;
f55     vector<int> mate(n, -1),label(n),par(n),orig(n),aux(n,
      -1),q;

060     auto lca = [&](int x, int y) {
7b8         for (timer++; ; swap(x, y)) {
583             if (x == -1) continue;
```

```
4be              if (aux[x] == timer) return x;
90d              aux[x] = timer;
fb4              x=(mate[x] == -1 ? -1 : orig[par[mate[x]]]);
f6a          }
aba      };
be4      auto blossom = [&](int v, int w, int a) {
509          while (orig[v] != a) {
721              par[v] = w; w = mate[v];
1e2              if(label[w] == 1) label[w] = 0,q.push_back(w);
8c7              orig[v] = orig[w] = a;
3d0              v = par[w];
eae          }
068      };
a0f      auto aug = [&](int v) {
8c8          while (v != -1) {
86a              int pv = par[v], nv = mate[pv];
941              mate[v] = pv; mate[pv] = v; v = nv;
ba8          }
54c      };
9f9      auto bfs = [&](int root) {
be5          fill(all(label), -1);
652          iota(all(orig), 0);
4b6          q.clear();
594          label[root] = 0; q.push_back(root);
a43          rep(i, 0, sz(q)) {
4c1              int v = q[i];
5aa              for (auto x : g[v]) {
464                  if (label[x] == -1) {
73a                      label[x] = 1; par[x] = v;
1bd                      if (mate[x] == -1) return aug(x), 1;
8d9                      label[mate[x]] = 0;
de3                      q.push_back(mate[x]);
641                  }
018                  else if(!label[x] && orig[v] != orig[x]){
37f                      int a = lca(orig[v], orig[x]);
f12                      blossom(x, v, a);
183                      blossom(v, x, a);
405                  }
ab5              }
9e2          }
bb3          return 0;
139      };
         // Time halves if you start with (any) maximal matching.
fea      rep(i, 0, n) {
698          if (mate[i] == -1) bfs(i);
7b5      }
568      return mate;
21c  }
```

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: $\mathcal{O}\left(\sqrt{V}E\right)$

c4f2f2, 46 lines

```
725  struct HopcroftKarp {
e40      vector<int> g, l, r;
959      int ans;
b82      HopcroftKarp(int n, int m, vector<pii> e)
aa0           : g(sz(e)), l(n, -1), r(m, -1), ans(0) {
bb0          shuffle(all(e), rng);
322          vector<int> deg(n + 1);
235          for (auto& [x, y] : e) deg[x]++;
b4a          rep(i, 1, n+1) deg[i] += deg[i - 1];
85a          for (auto& [x, y] : e) g[--deg[x]] = y;

5ae          vector<int> q(n);
667          while (true) {
661              vector<int> a(n, -1), p(n, -1);
6bb              int t = 0;
fea              rep(i, 0, n){
4b1                  if (l[i] == -1) {
b53                      q[t++] = a[i] = p[i] = i;
4b6                  }
62e              }
a15              bool match = false;
edb              rep(i, 0, t){
912                  int x = q[i];
08c                  if (~l[a[x]]) continue;
0ba                  rep(j, deg[x], deg[x+1]) {
360                      int y = g[j];
89a                      if (r[y] == -1) {
d3b                          while (~y) {
ee7                              r[y] = x;
dbb                              swap(l[x], y);
2a5                              x = p[x];
ebf                          }
6aa                          match = true, ans++;
c2b                          break;
b54                      }
f06                      if (p[r[y]] == -1) {
a74                          q[t++] = y = r[y];
d11                          p[y] = x, a[y] = a[x];
9ef                      }
e8a                  }
0ab              }
984              if (!match) break;
bc5          }
6ec      }
c4f  };
```

WeightedMatching.h

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

4a75d2, 41 lines

```
d57  pair<ll, vector<int>> hunga(const vector<vector<ll>>& a) {
c04      if (a.empty()) return { 0, {} };
1a9      int n = sz(a) + 1, m = sz(a[0]) + 1;
fc8      vector<ll> u(n), v(m), p(m);
5bd      vector<int> ans(n - 1);
6f5      for (int i = 1; i < n; i++) {
8c9          p[0] = i;
625          int j0 = 0;
91d          vector<ll> dist(m, LLONG_MAX), pre(m, -1);
910          vector<bool> done(m + 1);
016          do {
781              done[j0] = true;
507              ll i0 = p[j0], j1 = -1, delta = LLONG_MAX;
b84              for (int j = 1; j < m; j++) {
10a                  if (!done[j]) {
ed6                      ll cur = a[i0-1][j-1] - u[i0] - v[j];
607                      if (cur < dist[j])
29f                          dist[j] = cur, pre[j] = j0;
172                      if(dist[j] < delta)
4ab                          delta = dist[j], j1 = j;
103                  }
bb2              }
891              for (int j = 0; j < m; j++) {
7a9                  if (done[j])
3bc                      u[p[j]] += delta, v[j] -= delta;
202                  else dist[j] -= delta;
11a              }
e73              assert(j1 != -1);
6d4              j0 = j1;
ac1          } while (p[j0]);
4b9          while (j0) {
196              int j1 = pre[j0];
0c1              p[j0] = p[j1], j0 = j1;
f55          }
193      }
b84      for (int j = 1; j < m; j++) {
eb3          if (p[j]) ans[p[j] - 1] = j - 1;
c9a      }
def      return { -v[0], ans }; // min cost
4a7  }
```

GlobalMinCut.h

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

8b0e19, 22 lines

```
192  pair<int, vi> globalMinCut(vector<vi> mat) {
afa   pair<int, vi> best = {INT_MAX, {}};
755   int n = sz(mat);
91d   vector<vi> co(n);
d0f   rep(i,0,n) co[i] = {i};
488   rep(ph,1,n) {
2e9     vi w = mat[0];
e44     size_t s = 0, t = 0;
694     rep(it,0,n-ph) { // O(V^2) -> O(E log V) with prio. queue
d6e       w[t] = INT_MIN;
a5f       s = t, t = max_element(all(w)) - w.begin();
d39       rep(i,0,n) w[i] += mat[t][i];
ec9     }
3df     best = min(best, {w[t] - mat[t][t], co[t]});
096     co[s].insert(co[s].end(), all(co[t]));
959     rep(i,0,n) mat[s][i] += mat[t][i];
984     rep(i,0,n) mat[i][s] = mat[s][i];
5dd     mat[0][t] = INT_MIN;
ca0   }
f26   return best;
8b0  }
```

7.3 DFS algorithms

Bridges.h

1fa56b, 24 lines

```
cd9  vector<int> g[ms];
9e4  int low[ms], tin[ms], vis[ms], t;

403  void dfs(int u = 0, int p = -1) {
b9c      vis[u] = true;
b4a      low[u] = tin[u] = t++;
7b9      for (auto v : g[u]) {
730          if (v == p) continue;
c84          if (vis[v]) {
34f              low[u] = min(low[u], tin[v]);
728          }
4e6          else {
95e              dfs(v, u);
ab6              low[u] = min(low[u], low[v]);
                 // if (low[v] >= tin[u] && p != -1), U is an articulation point
975              if (low[v] > tin[u]) {
                     // edge from U to V is a bridge
4b8              }
                 // children++
862          }
677      }
         // if(children > 1 && p == -1) root is an articulation point
30c  }
```

BridgeOnline.h

Description: Maintains bridges and 2-edge-connected components (2-ECC) incrementally. `ds[0]` tracks Connected Components (CC). `ds[1]` tracks 2-ECCs. Nodes u, v are in the same 2-ECC iff `dsfind(u, 1) == dsfind(v, 1)`. `g` stores the spanning forest edges (edges that were bridges when added). An edge $(u, v) \in g$ is a current bridge iff `dsfind(u, 1) != dsfind(v, 1)`. `bridges` tracks the total count of active bridges. Use `init()` before starting.
Time: Amortized $\mathcal{O}(\log N)$ ef24c8, 75 lines

```
4dd int bridges;
801 int ds[2][ms], sz[2][ms];
87b int h[ms], pai[ms], old[ms];
cd9 vector<int> g[ms];

ca2 void init() {
786     bridges = 0;
f0d     rep(i, 0, ms) {
a4e         g[i].clear(), h[i] = 0;
606         ds[0][i] = ds[1][i] = i;
8f3         sz[0][i] = sz[1][i] = 1;
4a6     }
c1e }

243 int dsfind(int j, int i) {
7fa     if(j == ds[i][j]) return ds[i][j];
db7     return ds[i][j] = dsfind(ds[i][j], i);
4a4 }

b55 void dfs(int u, int p, int l) {
40d     h[u] = l;
49e     pai[u] = p;
a32     old[u] = dsfind(u, 1);
4d5     for (int v : g[u]) {
730         if (v == p) continue;
0c5         dfs(v, u, l + 1);
11d     }
f2e }

94c void updateNodes(int u, int p) {
840     if (old[u] == old[p]) {
dc4         ds[1][u] = ds[1][p];
574     }
e79     else ds[1][u] = u;
4d5     for (int v : g[u]) {
730         if (v == p) continue;
01c         updateNodes(v, u);
42a     }
329 }

814 void mergeTrees(int a, int b) {
cbf     bridges++;
5cb     int iniA = a, iniB = b;
19d     a = dsfind(a, 0), b = dsfind(b, 0);
834     if (sz[0][a] < sz[0][b]) swap(a, b), swap(iniA, iniB);
e14     dfs(iniB, iniA, h[iniA] + 1);
376     old[iniA] = -1;
ee0     updateNodes(iniB, iniA);
86b     ds[0][b] = a;
013     sz[0][a] += sz[0][b];
c9a }

416 void removeBridges(int a, int b) {
532     a = dsfind(a, 1), b = dsfind(b, 1);
984     while (a != b) {
e7a         bridges--;
54b         if (h[a] < h[b]) swap(a, b);
            // ponte entre (a, pai[a]) deixou de existir
9f6         ds[1][a] = dsfind(pai[a], 1);
e40         a = ds[1][a];
cda     }
a78 }

02b void addEdge(int a, int b) {
7b9     if (dsfind(a, 0) == dsfind(b, 0)) {
69d         removeBridges(a, b);
221     }
4e6     else {
            // nova ponte entre (a, b)
025         g[a].push_back(b);
3e9         g[b].push_back(a);
f8e         mergeTrees(a, b);
447     }
e57 }
```

BlockCutTree.h

Description: Constructs the Block-Cut Tree, which is a bipartite graph with blocks (maximal 2-vertex-connected components) on one side and articulation points on the other. Works for disconnected graphs. Tree size is $\leq 2N$. Be careful with self loops and multi edges. `art[i]`: number of new components created by removing i (AP if ≥ 1). `blocks[i]`, `edgblocks[i]`: vertices/edges of block i. `tree[i]`: the tree node index corresponding to block i. `pos[i]`: the tree node index corresponding to vertex i.
Time: $\mathcal{O}(N + M)$ e55ab0, 66 lines

```
d10 struct block_cut_tree {
d8e  vector<vector<int>> g, blocks, tree;
43b  vector<vector<pair<int, int>>> edgblocks;
4ce  stack<int> s;
6c0  stack<pair<int, int>> s2;
2bb  vector<int> id, art, pos;

763  block_cut_tree(vector<vector<int>> g_) : g(g_) {
625    int n = sz(g);
37a    id.resize(n, -1), art.resize(n), pos.resize(n);
6f2    build();
246  }

df6  int dfs(int i, int& t, int p = -1) {
cf0    int lo = id[i] = t++;
18e    s.push(i);

827    if (p != -1) s2.emplace(i, p);
43f    for (int j : g[i])
6bf            if (j != p and id[j] != -1) s2.emplace(i, j);

cac    for (int j : g[i]) if (j != p) {
9a3      if (id[j] == -1) {
121        int val = dfs(j, t, i);
0c3        lo = min(lo, val);

588        if (val >= id[i]) {
66a          art[i]++;
483          blocks.emplace_back(1, i);
110          while (blocks.back().back() != j)
138            blocks.back().push_back(s.top()), s.pop();

128          edgblocks.emplace_back(1, s2.top()), s2.pop();
904          while (edgblocks.back().back() != pii(j, i))
bce            edgblocks.back().push_back(s2.top()), s2.pop();
041        }
38c      }
328      else lo = min(lo, id[j]);
5b6    }
924    if (p == -1) {
2db            if(art[i]) art[i]--;
4e6            else{
483                blocks.emplace_back(1, i);
433                edgblocks.emplace_back();
333            }
384        }
253    return lo;
6d7  }

0a8  void build() {
6bb    int t = 0;
c80    rep(i, 0, sz(g)) if(id[i] == -1) dfs(i, t, -1);
de0    tree.resize(sz(blocks));
008    rep(i, 0, sz(g)) if (art[i])
b9a      pos[i] = sz(tree), tree.emplace_back();

05c    rep(i, 0, sz(blocks)) for (int j : blocks[i]) {
403      if (!art[j]) pos[j] = i;
4e6      else {
49d                tree[i].push_back(pos[j]);
9a7                tree[pos[j]].push_back(i);
01e            }
27c    }
5a7  }
e55 };
```

DominatorTree.h

Description: Builds the Dominator Tree of a directed graph rooted at `root`. Node u dominates v if every path from `root` to v passes through u. The immediate dominator of v is the unique dominator closest to v (excluding v). Returns a vector `par` where `par[u]` is the parent of u in the tree. Roots and unreachable nodes satisfy `par[u] = u`.
Time: $\mathcal{O}(M \log N)$ 8c4613, 55 lines

```
3db struct dominator_tree {
577  int n, t;
324  vector<vector<int>> g, rg, bucket;
7f3  vector<int> arr, par, rev, sdom, dom, ds, lbl;

226  dominator_tree(int n) : n(n),t(0),g(n),rg(n),bucket(n),
7a1    arr(n,-1),par(n),rev(n),sdom(n),dom(n),ds(n),lbl(n) {}

c2b  void add_edge(int u, int v) { g[u].push_back(v); }

315  void dfs(int u) {
12e    arr[u] = t;
64f    rev[t] = u;
bad    lbl[t] = sdom[t] = ds[t] = t;
c82     t++;
6f1    for (int w : g[u]) {
0c2      if (arr[w] == -1) {
8c6        dfs(w);
81a        par[arr[w]] = arr[u];
869      }
f8e      rg[arr[w]].push_back(arr[u]);
93a    }
b04  }
792  int find(int u, int x=0) {
9fe    if (u == ds[u]) return x ? -1 : u;
41f    int v = find(ds[u], x+1);
388    if (v < 0) return u;
b30    if(sdom[lbl[ds[u]]] < sdom[lbl[u]]) lbl[u]= lbl[ds[u]];
300    ds[u] = v;
784    return x ? v : lbl[u];
a59  }

46f  vector<int> run(int root) {
14e    dfs(root);
b81    iota(all(dom), 0);
da8    for (int i=t-1; i>=0; i--) {
76c      for(int w : rg[i]) sdom[i] = min(sdom[i],sdom[find(w)
   ]);
c94      if (i) bucket[sdom[i]].push_back(i);
```

```
3b2       for (int w : bucket[i]) {
46a         int v = find(w);
ae4         if (sdom[v] == sdom[w]) dom[w] = sdom[w];
41c         else dom[w] = v;
1e6       }
fd8       if (i > 1) ds[i] = par[i];
b9e     }
e8f     rep(i, 1, t) {
7d7       if (dom[i] != sdom[i]) dom[i] = dom[dom[i]];
32d     }
af8     vector<int> par(n);
2c2     iota(all(par), 0);
533     rep(i, 0, t) par[rev[i]] = rev[dom[i]];
148     return par;
900   }
8c4 };
```

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.

a3ed13, 27 lines

```
b4a vector<pii> eulerPath(const vector<vector<pii>>& g, int
    nedges, int src) {
625     int n = sz(g);
b47     vector<int> deg(n, 0), its(n, 0), used(nedges + 1, 0);
a42     vector<pii> s = { {src, -1} };
        //deg[src]++; //to allow paths, not only circuits
a5f     vector<pii> ret;
980     while (!s.empty()) {
d0b         int u = s.back().first, &it = its[u];
c45         if (it == sz(g[u])) {
5e3             ret.push_back(s.back());
342             s.pop_back();
5e2             continue;
8e8         }
f7f         auto& [nxt, id] = g[u][it++];
b25         if (!used[id]) {
e48             deg[u]--, deg[nxt]++;
029             used[id] = 1;
e1c             s.push_back({ nxt, id });
777         }
388     }
8d8     for (int x : deg) {
518         if (x < 0 || sz(ret) != (nedges + 1)) return {};
26e     }
969     reverse(ret.begin(), ret.end());
edf     return ret;
a3e }
```

SCC.h

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

008ff2, 36 lines

```
bf0 struct SCC {
dab     int n, ncomp;
0e3     vector<vector<int>> g, inv;
829     vector<int> comp, vis, stk;
8b6     SCC(){}
471     SCC(int n)
464         : n(n),ncomp(0),g(n),inv(n),comp(n, -1),vis(n){}

315     void dfs(int u) {
150         vis[u] = 1;
a35         for (int v : g[u]) if (!vis[v]) dfs(v);
967         stk.push_back(u);
37b     }
f20     void dfs_inv(int u) {
62c         comp[u] = ncomp;
3a5         for (int v : inv[u]) {
df4             if (comp[v] == -1) dfs_inv(v);
0a0         }
984     }
63d     void solve() {
603         for (int i = 0; i < n; i++) {
b65             if (!vis[i]) dfs(i);
358         }
340         reverse(all(stk));
49b         for (int u : stk) {
9ef             if (comp[u] != -1) continue;
672             dfs_inv(u);
a8f             ncomp++;
ecb         }
ef8     }
010     void add_edge(int a, int b) {
025         g[a].push_back(b);
a6a         inv[b].push_back(a);
1ec     }
008 };
```

TwoSat.h

Usage: not A = ~A

"SCC.h" c8b989, 37 lines

```
d9d struct TwoSat{
1a8  int n;
3c9  SCC scc;
7c7  vector<int> value;
425  vector<pii> e;
e2c  TwoSat(int n) : n(n){}
6c0  bool solve(){
b36    value.resize(n);
8cc    scc = SCC(2*n);
1f3    for(auto &x : e) scc.add_edge(x.first, x.second);
7f9    scc.solve();
3df    for(int i=0; i<2*n; i++)
f83      if(scc.comp[i] == scc.comp[i^1]) return false;
830    for(int i=0; i<n; i++)
733      value[i] = scc.comp[id(i)] > scc.comp[id(~i)];
8a6    return true;
949  }
a0a  void atMostOne(vector<int> &li){
615    if(sz(li) <= 1) return;
da9    int cur = ~li[0];
b25    for(int i = 2; i < sz(li); i++) {
abb      int next = n++;
e0a      addOr(cur, ~li[i]);
f26      addOr(cur, next);
7ba      addOr(~li[i], next);
072      cur = ~next;
e3d    }
921    addOr(cur, ~li[1]);
bbb  }
41b  int id(int v) { return v < 0 ? (~v) * 2 ^ 1 : v * 2; }
276  void add(int a, int b) { e.push_back({id(a), id(b)}); }
bc7  void addOr(int a, int b) { add(~a, b); add(~b, a); }
671  void addImp(int a, int b) { addOr(~a, b); }
d9d  void addEqual(int a, int b){ addOr(a, ~b); addOr(~a, b);
    }
ec3  void isFalse(int a) { addImp(a, ~a); }
c8b };
```

7.4 Coloring

EdgeColoring.h

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

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

e210e2, 32 lines

```
f41 vi edgeColoring(int N, vector<pii> eds) {
727   vi cc(N + 1), ret(sz(eds)), fan(N), free(N), loc;
10d   for (pii e : eds) ++cc[e.first], ++cc[e.second];
e2f   int u, v, ncols = *max_element(all(cc)) + 1;
fda   vector<vi> adj(N, vi(ncols, -1));
6ec   for (pii e : eds) {
119     tie(u, v) = e;
e51     fan[0] = v;
0f4     loc.assign(ncols, 0);
696     int at = u, end = u, d, c = free[u], ind = 0, i = 0;
3b2     while (d = free[v], !loc[d] && (v = adj[u][d]) != -1)
3e1       loc[d] = ++ind, cc[ind] = d, fan[ind] = v;
01e     cc[loc[d]] = c;
997     for (int cd = d; at != -1; cd ^= c ^ d, at = adj[at][cd
    ])
4ff       swap(adj[at][cd], adj[end = at][cd ^ c ^ d]);
79f     while (adj[fan[i]][d] != -1) {
a9f       int left = fan[i], right = fan[++i], e = cc[i];
99b       adj[u][e] = left;
ccb       adj[left][e] = u;
f7e       adj[right][e] = -1;
d99       free[right] = e;
316     }
dfd     adj[u][d] = fan[i];
c45     adj[fan[i]][d] = u;
0e1     for (int y : {fan[0], u, end})
3fa       for (int& z = free[y] = 0; adj[y][z] != -1; z++);
fdc   }
29d   rep(i,0,sz(eds))
961     for (tie(u, v) = eds[i]; adj[u][ret[i]] != v;) ++ret[i
    ];
edf   return ret;
e21 }
```

7.5 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.

2eeaf4, 53 lines

```
db9 using vb = vector<bitset<200>>;
c7d struct Maxclique {
24e  double limit=0.025, pk=0;
c04  struct Vertex { int i, d=0; };
547  using vv = vector<Vertex>;
d44  vb e;
df7  vv V;
e5c  vector<vector<int>> C;
497  vector<int> qmax, q, S, old;
fe3  void init(vv& r) {
fd3    for (auto& v : r) v.d = 0;
583    for (auto& v : r) for (auto j : r) v.d += e[v.i][j.i];
0f1    sort(all(r), [](auto a, auto b) { return a.d > b.d; });
c43    int mxD = r[0].d;
3f8    for(int i=0; i<sz(r); i++) r[i].d = min(i, mxD) + 1;
526  }
bc8  void expand(vv& R, int lev = 1) {
ac1    S[lev] += S[lev - 1] - old[lev];
92c    old[lev] = S[lev - 1];
d18    while (sz(R)) {
3fd      if (sz(q) + R.back().d <= sz(qmax)) return;
d62      q.push_back(R.back().i);
f28      vv T;
7fb      for(auto v : R)
740        if (e[R.back().i][v.i]) T.push_back({v.i});
```

```
d21       if (sz(T)) {
eea         if (S[lev]++ / ++pk < limit) init(T);
457         int j = 0, mxk = 1, mnk = max(sz(qmax)-sz(q)+1, 1);
9bc         C[1].clear(), C[2].clear();
969         for (auto v : T) {
bfe           int k = 1;
8f5           auto f = [&](int i) { return e[v.i][i]; };
5c6           while (any_of(all(C[k]), f)) k++;
782           if (k > mxk) mxk = k, C[mxk + 1].clear();
18a           if (k < mnk) T[j++].i = v.i;
0e6           C[k].push_back(v.i);
322         }
238         if (j > 0) T[j - 1].d = 0;
d2f         for(int k=mnk; k<mxk + 1; k++){
5bf                     for (int i : C[k])
361                 T[j].i = i, T[j++].d = k;
9dc                 }
22d         expand(T, lev + 1);
61f       } else if (sz(q) > sz(qmax)) qmax = q;
c81       q.pop_back(), R.pop_back();
3e0     }
81d   }
b2d   vector<int> maxClique(){ init(V),expand(V); return qmax;}
b40   Maxclique(vb conn) : e(conn),C(sz(e)+1),S(sz(C)),old(S){
01d     for(int i=0; i<sz(e); i++) V.push_back({i});
b60   }
534 };
```

MaximalCliques.h

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

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

b0d5b1, 13 lines

```
753 typedef bitset<128> B;
044 template<class F>
6a9 void cliques(vector<B>& eds, F f, B P = ~B(), B X={}, B R
    ={}) {
9bb   if (!P.any()) { if (!X.any()) f(R); return; }
a8e   auto q = (P | X)._Find_first();
cd1   auto cands = P & ~eds[q];
3d7   rep(i,0,sz(eds)) if (cands[i]) {
a75     R[i] = 1;
e78     cliques(eds, f, P & eds[i], X & eds[i], R);
bb6     R[i] = P[i] = 0; X[i] = 1;
181   }
c9d }
```

7.6 Trees

Centroid.h

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

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

b73755, 27 lines

```
6b6 int tam[ms], marked[ms];

2a1 int calc_tam(int u, int p) {
5d1   tam[u] = 1;
4d5   for (int v : g[u]) {
5ea     if (v != p && !marked[v]) tam[u] += calc_tam(v, u);
d09   }
f95   return tam[u];
d5d }

5fb int get_centroid(int u, int p, int tot) {
4d5   for (int v : g[u]) {
38c     if (v != p && !marked[v] && (tam[v] > (tot / 2)))
32c       return get_centroid(v, u, tot);
b6c   }
03f   return u;
0c7 }
    // Cent is a child of P in the centroid tree
179 void decomp(int u, int p = -1) {
308   calc_tam(u, -1);
bd4   int cent = get_centroid(u, -1, tam[u]);
83d   marked[cent] = 1;
9f1   for (int v : g[cent]) {
c6e     if (!marked[v]) decomp(v, cent);
194   }
dc1 }
```

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.

a129d6, 51 lines

```
5f2 template<bool EDGE> struct HLD {
577     int n, t;
789     vector<vector<int>> g;
003     vector<int> pai, rp, tam, pos, val, arr;
f1e     Seg seg;
bcf     HLD(int n, vector<vector<int>>& g, vector<int>& val)
ac9         : n(n), t(0), g(g), pai(n), rp(n), tam(n, 1),
616           pos(n), val(val), arr(n) {
f80         calc_tam(0, -1);
c91         dfs(0, -1);
d14         seg.build(arr);
a43     }

2a1     int calc_tam(int u, int p) {
49e         pai[u] = p;
704         for (int& v : g[u]) {
730             if (v == p) continue;
2e4             tam[u] += calc_tam(v, u);
2d5             if(tam[v] > tam[g[u][0]] || g[u][0] == p)
a7f                 swap(g[u][0], v);
0a3         }
f95         return tam[u];
c19     }

fb6     void dfs(int u, int p) {
4c8         pos[u] = t++;
d7b         arr[pos[u]] = val[u];
4d5         for (int v : g[u]) {
730             if (v == p) continue;
84d             rp[v] = (v == g[u][0] ? rp[u] : v);
95e             dfs(v, u);
42d         }
de1     }

4ea     int query(int a, int b) { // query on the path from a
    to b
1a4         int ans = 0; // neutral value
34d         while (rp[a] != rp[b]) {
aa1             if (pos[a] < pos[b]) swap(a, b);
9a5             ans = max(ans, seg.query(pos[rp[a]], pos[a]));
677             a = pai[rp[a]];
ebd         }
9bc         if(pos[a] > pos[b]) swap(a, b);
0f8         ans = max(ans, seg.query(pos[a] + EDGE, pos[b]));
ba7         return ans;
e8a     }

534     void update(int a, int x) {
e5e         seg.update(pos[a], x);
5db     }
a12 };
```

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

db7791, 26 lines

```
67e int tin[MAXN], tout[MAXN], timer=0;
768 int up[MAXN][BITS];
fb6 void dfs(int u, int p){
545     tin[u] = timer++, up[u][0] = p;
532     for (int i=1; i<BITS; i++) {
88a         up[u][i] = up[up[u][i-1]][i-1];
4a0     }
712     for (int v: g[u]) if (v != p) dfs(v, u);
4f8     tout[u] = timer;
4a1 }

f31 bool is_ancestor(int u, int v){
d34     return (tin[u] <= tin[v] && tout[u] >= tout[v]);
f9f }

310 int lca(int u, int v){
bd5     if (is_ancestor(u, v)) return u;
6fc     if (is_ancestor(v, u)) return v;
3c3     for (int i=BITS-1; i>=0; i--) {
3a3         if (up[u][i] && !is_ancestor(up[u][i], v)) {
c3f             u = up[u][i];
49e         }
dc4     }
c15     return up[u][0];
001 }
```

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" 11157a, 24 lines

```
0b1 vector<pair<int, int>> virt[ms];

d0c void build_virt(vector<int>& v) {
078   auto cmp = [&](int i, int j){ return tin[i] < tin[j]; };
b84   sort(all(v), cmp);
1ee   for (int i = 0, n = sz(v);i + 1 < n; i++)
4cf     v.push_back(lca(v[i], v[i + 1]));
b84   sort(all(v), cmp);
64f   v.erase(unique(all(v)), v.end());
7b4   stack<int> st;
3a7   for (auto u : v) {
c53     if (st.empty()) {
4a6       st.push(u);
e82     }
4e6     else {
7eb       while(sz(st) && !is_ancestor(st.top(), u)) st.pop();
88b       int p = st.top();
bfa       virt[p].emplace_back(u, abs(lvl[u] - lvl[p]));
0a5       virt[u].emplace_back(p, abs(lvl[u] - lvl[p]));
4a6       st.push(u);
92c     }
f46   }
c83 }
```

DirectedMST.h

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

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

"../data-structures/UnionFindRollback.h" 39e620, 61 lines

```
030 struct Edge { int a, b; ll w; };
bf2 struct Node {
25f  Edge key;
c17  Node *l, *r;
981  ll delta;
a9c  void prop() {
6f9   key.w += delta;
d2d   if (l) l->delta += delta;
d86   if (r) r->delta += delta;
978   delta = 0;
0d3  }
866  Edge top() { prop(); return key; }
ab4 };
3eb Node *merge(Node *a, Node *b) {
b9f  if (!a || !b) return a ?: b;
626  a->prop(), b->prop();
dc2  if (a->key.w > b->key.w) swap(a, b);
485  swap(a->l, (a->r = merge(b, a->r)));
3f5  return a;
c51 }
7bb void pop(Node*& a) { a->prop(); a = merge(a->l, a->r); }

002 pair<ll, vi> dmst(int n, int r, vector<Edge>& g) {
8df  RollbackUF uf(n);
3f8  vector<Node*> heap(n);
563  for (Edge e : g) heap[e.b] = merge(heap[e.b], new Node{e
    });
cd2  ll res = 0;
517  vi seen(n, -1), path(n), par(n);
559  seen[r] = r;
dd6  vector<Edge> Q(n), in(n, {-1,-1}), comp;
111  deque<tuple<int, int, vector<Edge>>> cycs;
328  rep(s,0,n) {
3cb   int u = s, qi = 0, w;
a0a   while (seen[u] < 0) {
572    if (!heap[u]) return {-1,{}};
ebe    Edge e = heap[u]->top();
5ed    heap[u]->delta -= e.w, pop(heap[u]);
952    Q[qi] = e, path[qi++] = u, seen[u] = s;
d56    res += e.w, u = uf.find(e.a);
9e2    if (seen[u] == s) {
28d     Node* cyc = 0;
cab     int end = qi, time = uf.time();
f38     do cyc = merge(cyc, heap[w = path[--qi]]);
4f9     while (uf.join(u, w));
562     u = uf.find(u), heap[u] = cyc, seen[u] = -1;
c06     cycs.push_front({u, time, {&Q[qi], &Q[end]}});
00a    }
c8f   }
068   rep(i,0,qi) in[uf.find(Q[i].b)] = Q[i];
fa3  }

e41  for (auto& [u,t,comp] : cycs) { // restore sol (optional)
36c   uf.rollback(t);
1d0   Edge inEdge = in[u];
251   for (auto& e : comp) in[uf.find(e.b)] = e;
56d   in[uf.find(inEdge.b)] = inEdge;
4f9  }
427  rep(i,0,n) par[i] = in[i].a;
efb  return {res, par};
efa }
```

Geometry (8)

8.1 Geometric primitives

Point.h

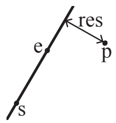
Description: Class to handle points in the plane. T can be e.g. double or long long. (Avoid int.)

47ec0a, 29 lines

```
48b template <class T> int sgn(T x) { return (x > 0) - (x < 0)
    ; }
4fc template<class T>
f26 struct Point {
ea4  typedef Point P;
645  T x, y;
ea6  explicit Point(T x=0, T y=0) : x(x), y(y) {}
0d0  bool operator<(P p) const { return tie(x,y) < tie(p.x,p.y
    ); }
ec7  bool operator==(P p) const { return tie(x,y)==tie(p.x,p.y
    ); }
279  P operator+(P p) const { return P(x+p.x, y+p.y); }
40d  P operator-(P p) const { return P(x-p.x, y-p.y); }
e03  P operator*(T d) const { return P(x*d, y*d); }
0b9  P operator/(T d) const { return P(x/d, y/d); }
57b  T dot(P p) const { return x*p.x + y*p.y; }
460  T cross(P p) const { return x*p.y - y*p.x; }
b3f  T cross(P a, P b) const { return (a-*this).cross(b-*this)
    ; }
f68  T dist2() const { return x*x + y*y; }
18b  double dist() const { return sqrt((double)dist2()); }
     // angle to x-axis in interval [-pi, pi]
907  double angle() const { return atan2(y, x); }
d06  P unit() const { return *this/dist(); } // makes dist()=1
200  P perp() const { return P(-y, x); } // rotates +90
    degrees
852  P normal() const { return perp().unit(); }
     // returns point rotated 'a' radians ccw around the
         origin
f23  P rotate(double a) const {
482   return P(x*cos(a)-y*sin(a),x*sin(a)+y*cos(a)); }
902  friend ostream& operator<<(ostream& os, P p) {
9a9   return os << "(" << p.x << "," << p.y << ")"; }
d2d };
```

lineDistance.h

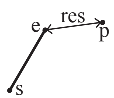
Description:
Returns the signed distance between point p and the line containing points a and b. Positive value on left side and negative on right as seen from a towards b. a==b gives nan. P is supposed to be Point<T> or Point3D<T> where T is e.g. double or long long. It uses products in intermediate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



"Point.h" f6bf6b, 5 lines

```
7dc template<class P>
2ff double lineDist(const P& a, const P& b, const P& p) {
e07  return (double)(b-a).cross(p-a)/(b-a).dist();
008 }
```

SegmentDistance.h



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

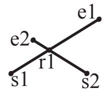
Usage: `Point<double> a, b(2,2), p(1,1);`
`bool onSegment = segDist(a,b,p) < 1e-10;`

"Point.h" 5c88f4, 7 lines

```
626 typedef Point<double> P;
929 double segDist(P& s, P& e, P& p) {
a44  if (s==e) return (p-s).dist();
f81  auto d = (e-s).dist2(), t = min(d,max(.0,(p-s).dot(e-s)))
    ;
2c1  return ((p-s)*d-(e-s)*t).dist()/d;
ae7 }
```

SegmentIntersection.h

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



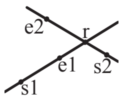
Usage: `vector<P> inter = segInter(s1,e1,s2,e2);`
`if (sz(inter)==1)`
`cout << "segments intersect at " << inter[0] << endl;`

"Point.h", "OnSegment.h" 9d57f2, 14 lines

```
dae template<class P> vector<P> segInter(P a, P b, P c, P d) {
0b6  auto oa = c.cross(d, a), ob = c.cross(d, b),
318       oc = a.cross(b, c), od = a.cross(b, d);
     // Checks if intersection is single non-endpoint point.
914  if (sgn(oa) * sgn(ob) < 0 && sgn(oc) * sgn(od) < 0)
e5b   return {(a * ob - b * oa) / (ob - oa)};
4c1  set<P> s;
ccb  if (onSegment(c, d, a)) s.insert(a);
0ad  if (onSegment(c, d, b)) s.insert(b);
3d8  if (onSegment(a, b, c)) s.insert(c);
2fa  if (onSegment(a, b, d)) s.insert(d);
a35  return {all(s)};
9d5 }
```

lineIntersection.h

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



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

"Point.h" a01f81, 9 lines

```
7dc template<class P>
0bf pair<int, P> lineInter(P s1, P e1, P s2, P e2) {
14f  auto d = (e1 - s1).cross(e2 - s2);
8cc  if (d == 0) // if parallel
d99   return {-(s1.cross(e1, s2) == 0), P(0, 0)};
f6b  auto p = s2.cross(e1, e2), q = s2.cross(e2, s1);
9b8  return {1, (s1 * p + e1 * q) / d};
472 }
```

sideOf.h

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

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

"Point.h" 3af81c, 10 lines

```
7dc template<class P>
70b int sideOf(P s, P e, P p) { return sgn(s.cross(e, p)); }

7dc template<class P>
```

```
b5e int sideOf(const P& s, const P& e, const P& p, double eps) {
79e   auto a = (e-s).cross(p-s);
653   double l = (e-s).dist()*eps;
c32   return (a > l) - (a < -l);
33f }
```

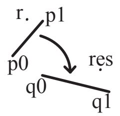
OnSegment.h

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

"Point.h" c597e8, 4 lines

```
514 template<class P> bool onSegment(P s, P e, P p) {
5fb   return p.cross(s, e) == 0 && (s - p).dot(e - p) <= 0;
c59 }
```

linearTransformation.h



Description:

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

"Point.h" 03a306, 7 lines

```
626 typedef Point<double> P;
664 P linearTransformation(const P& p0, const P& p1,
f06     const P& q0, const P& q1, const P& r) {
99f   P dp = p1-p0, dq = q1-q0, num(dp.cross(dq), dp.dot(dq));
0aa   return q0 + P((r-p0).cross(num), (r-p0).dot(num))/dp.dist2();
45e }
```

LineProjectionReflection.h

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

"Point.h" b5562d, 6 lines

```
7dc template<class P>
981 P lineProj(P a, P b, P p, bool refl=false) {
de3   P v = b - a;
3fc   return p - v.perp()*(1+refl)*v.cross(p-a)/v.dist2();
4b7 }
```

Angle.h

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

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

0f0602, 36 lines

```
755 struct Angle {
e91   int x, y;
8bd   int t;
5ac   Angle(int x, int y, int t=0) : x(x), y(y), t(t) {}
de8   Angle operator-(Angle b) const { return {x-b.x, y-b.y, t}; }
3cd   int half() const {
840     assert(x || y);
aa4     return y < 0 || (y == 0 && x < 0);
c93   }
dfc   Angle t90() const { return {-y, x, t + (half() && x >= 0)}; }
726   Angle t180() const { return {-x, -y, t + half()}; }
925   Angle t360() const { return {x, y, t + 1}; }
e25 };
a92 bool operator<(Angle a, Angle b) {
      // add a.dist2() and b.dist2() to also compare distances
ea7   return make_tuple(a.t, a.half(), a.y * (ll)b.x) <
05f          make_tuple(b.t, b.half(), a.x * (ll)b.y);
ce5 }

    // Given two points, this calculates the smallest angle between
    // them, i.e., the angle that covers the defined line segment.
908 pair<Angle, Angle> segmentAngles(Angle a, Angle b) {
ee4   if (b < a) swap(a, b);
423   return (b < a.t180() ?
c35           make_pair(a, b) : make_pair(b, a.t360()));
5ea }
784 Angle operator+(Angle a, Angle b) { // point a + vector b
eb1   Angle r(a.x + b.x, a.y + b.y, a.t);
8ca   if (a.t180() < r) r.t--;
d9f   return r.t180() < a ? r.t360() : r;
3d8 }
106 Angle angleDiff(Angle a, Angle b) { // angle b - angle a
125   int tu = b.t - a.t; a.t = b.t;
e63   return {a.x*b.x + a.y*b.y, a.x*b.y - a.y*b.x, tu - (b < a)};
ba3 }
```

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" cf24a8, 72 lines

```
984 using ld = long double;
207 using P = Point<ld>;

533 struct Hp { // Half plane struct
      // 'p' is a passing point of the line and 'pq' is the direction vector of the line.
812   P p, pq;
d29   ld angle;

b93   Hp() {}
65d   Hp(const P& a, const P& b) : p(a), pq(b - a) {
0e3     angle = atan2l(pq.y, pq.x);
2ff   }
8ce   bool out(const P& r) { return pq.cross(r - p) < -eps; }
d36   bool operator < (const Hp& e) const {
1dd     return angle < e.angle;
44e   }
ea9   friend P inter(const Hp& s, const Hp& t) {
020     ld alpha = (t.p - s.p).cross(t.pq) / s.pq.cross(t.pq);
93b     return s.p + (s.pq * alpha);
825   }
b46 };

fa5 vector<P> hp_intersect(vector<Hp>& H) {
12f   P box[4] = { P(inf, inf), P(-inf, inf),
9c8                P(-inf, -inf), P(inf, -inf) };

1cd   for(int i = 0; i<4; i++) {
1a8     Hp aux(box[i], box[(i+1) % 4]);
d82     H.push_back(aux);
560   }
f1a   sort(all(H));
6c5   deque<Hp> dq;
486   int len = 0;
908   for(int i = 0; i < sz(H); i++) {
3fb     while(len>1 && H[i].out(inter(dq[len-1], dq[len-2]))){
c70       dq.pop_back();
654       --len;
a31     }
757     while (len > 1 && H[i].out(inter(dq[0], dq[1]))){
c68       dq.pop_front();
654       --len;
1eb     }
a5a     if(len && fabsl(H[i].pq.cross(dq[len-1].pq)) < eps){
25f       if (H[i].pq.dot(dq[len-1].pq) < 0.0)
282         return vector<P>();
e7b       if (H[i].out(dq[len-1].p)) {
c70         dq.pop_back();
654         --len;
2dc       }
64e       else continue;
9a0     }
fc2     dq.push_back(H[i]);
250     ++len;
8ed   }

337   while(len> 2 && dq[0].out(inter(dq[len-1], dq[len-2]))){
c70     dq.pop_back();
654     --len;
faa   }
81e   while (len > 2 && dq[len-1].out(inter(dq[0], dq[1]))){
c68     dq.pop_front();
654     --len;
694   }
1a3   if (len < 3) return vector<P>();
7e7   vector<P> ret(len);
cc7   for(int i = 0; i+1 < len; i++) {
01e     ret[i] = inter(dq[i], dq[i+1]);
00f   }
4fd   ret.back() = inter(dq[len-1], dq[0]);
edf   return ret;
deb }
```

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" ba7267, 12 lines

```
626 typedef Point<double> P;
27f bool circleInter(P a,P b,double r1,double r2,pair<P, P>* out) {
b48   if (a == b) { assert(r1 != r2); return false; }
f30   P vec = b - a;
6c8   double d2 = vec.dist2(), sum = r1+r2, dif = r1-r2;
c28   double p = (d2 + r1*r1 - r2*r2)/(d2*2), h2 = r1*r1 - p*p*d2;
5b0   if (sum*sum < d2 || dif*dif > d2) return false;
84d   P mid = a + vec*p, per = vec.perp() * sqrt(fmax(0, h2) / d2);
21e   *out = {mid + per, mid - per};
8a6   return true;
170 }
```

CircleTangents.h

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

"Point.h" b0153d, 14 lines

```
7dc template<class P>
3a5 vector<pair<P, P>> tangents(P c1, double r1, P c2, double r2) {
c0b   P d = c2 - c1;
```

```
432   double dr = r1 - r2, d2 = d.dist2(), h2 = d2 - dr * dr;
018   if (d2 == 0 || h2 < 0)  return {};
c14   vector<pair<P, P>> out;
092   for (double sign : {-1, 1}) {
2ad     P v = (d * dr + d.perp() * sqrt(h2) * sign) / d2;
2e3     out.push_back({c1 + v * r1, c2 + v * r2});
e25   }
b21   if (h2 == 0) out.pop_back();
fe8   return out;
483 }
```

CircleLine.h

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

"Point.h" e0cfba, 10 lines

```
7dc template<class P>
195 vector<P> circleLine(P c, double r, P a, P b) {
33b   P ab = b - a, p = a + ab * (c-a).dot(ab) / ab.dist2();
55a   double s = a.cross(b, c), h2 = r*r - s*s / ab.dist2();
3e4   if (h2 < 0) return {};
071   if (h2 == 0) return {p};
7cd   P h = ab.unit() * sqrt(h2);
d65   return {p - h, p + h};
59a }
```

CirclePolygonIntersection.h

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

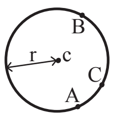
"../../content/geometry/Point.h" 19add1, 20 lines

```
626 typedef Point<double> P;
361 #define arg(p, q) atan2(p.cross(q), p.dot(q))
bb9 double circlePoly(P c, double r, vector<P> ps) {
6d1   auto tri = [&](P p, P q) {
c9c     auto r2 = r * r / 2;
291     P d = q - p;
127     auto a = d.dot(p)/d.dist2(), b = (p.dist2()-r*r)/d.dist
    2();
eea     auto det = a * a - b;
691     if (det <= 0) return arg(p, q) * r2;
f43     auto s = max(0., -a-sqrt(det)), t = min(1., -a+sqrt(det
    ));
aba     if (t < 0 || 1 <= s) return arg(p, q) * r2;
57f     P u = p + d * s, v = q + d * (t-1);
8c0     return arg(p,u) * r2 + u.cross(v)/2 + arg(v,q) * r2;
a52   };
bef   auto sum = 0.0;
8f4   rep(i,0,sz(ps))
3b7     sum += tri(ps[i] - c, ps[(i + 1) % sz(ps)] - c);
e66   return sum;
f08 }
```

circumcircle.h

Description:

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



"Point.h" 1caa3a, 10 lines

```
626 typedef Point<double> P;
510 double ccRadius(const P& A, const P& B, const P& C) {
14b   return (B-A).dist()*(C-B).dist()*(A-C).dist()/
f73       abs((B-A).cross(C-A))/2;
607 }
c0d P ccCenter(const P& A, const P& B, const P& C) {
28a   P b = C-A, c = B-A;
680   return A + (b*c.dist2()-c*b.dist2()).perp()/b.cross(c)/2;
793 }
```

MinimumEnclosingCircle.h

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

"circumcircle.h" 09dd0a, 18 lines

```
a28 pair<P, double> mec(vector<P> ps) {
4da   shuffle(all(ps), mt19937(time(0)));
f6a   P o = ps[0];
328   double r = 0, EPS = 1 + 1e-8;
2be   rep(i,0,sz(ps)) if ((o - ps[i]).dist() > r * EPS) {
5cc     o = ps[i], r = 0;
4da     rep(j,0,i) if ((o - ps[j]).dist() > r * EPS) {
a30       o = (ps[i] + ps[j]) / 2;
6f7       r = (o - ps[i]).dist();
102       rep(k,0,j) if ((o - ps[k]).dist() > r * EPS) {
fa9         o = ccCenter(ps[i], ps[j], ps[k]);
6f7         r = (o - ps[i]).dist();
648       }
7b0     }
dcf   }
645   return {o, r};
09d }
```

8.3 Polygons

InsidePolygon.h

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

"Point.h", "OnSegment.h", "SegmentDistance.h" 2bf504, 12 lines

```
7dc template<class P>
0cc bool inPolygon(vector<P> &p, P a, bool strict = true) {
8b7   int cnt = 0, n = sz(p);
fea   rep(i,0,n) {
444     P q = p[(i + 1) % n];
cbd     if (onSegment(p[i], q, a)) return !strict;
        //or: if (segDist(p[i], q, a) <= eps) return !strict;
007     cnt ^= ((a.y<p[i].y) - (a.y<q.y)) * a.cross(p[i], q) >
    0;
1b9   }
70a   return cnt;
c72 }
```

PolygonArea.h

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

"Point.h" f12300, 7 lines

```
4fc template<class T>
a51 T polygonArea2(vector<Point<T>>& v) {
2f8   T a = v.back().cross(v[0]);
06e   rep(i,0,sz(v)-1) a += v[i].cross(v[i+1]);
3f5   return a;
693 }
```

PolygonCenter.h

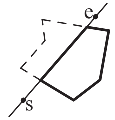
Description: Returns the center of mass for a polygon.
Time: $\mathcal{O}(n)$

"Point.h" 9706dc, 10 lines

```
626 typedef Point<double> P;
6d9 P polygonCenter(const vector<P>& v) {
f9f   P res(0, 0); double A = 0;
70b   for (int i = 0, j = sz(v) - 1; i < sz(v); j = i++) {
346     res = res + (v[i] + v[j]) * v[j].cross(v[i]);
3ea     A += v[j].cross(v[i]);
307   }
33c   return res / A / 3;
0d0 }
```

PolygonCut.h

Description:



Returns a vector with the vertices of a polygon with everything to the left of the line going from s to e cut away.
Usage: `vector<P> p = ...;`
`p = polygonCut(p, P(0,0), P(1,0));`

"Point.h" d07181, 14 lines

```
626 typedef Point<double> P;
37d vector<P> polygonCut(const vector<P>& poly, P s, P e) {
fe2   vector<P> res;
d48   rep(i,0,sz(poly)) {
21c     P cur = poly[i], prev = i ? poly[i-1] : poly.back();
c5f     auto a = s.cross(e, cur), b = s.cross(e, prev);
2dc     if ((a < 0) != (b < 0))
380       res.push_back(cur + (prev - cur) * (a / (a - b)));
c5c     if (a < 0)
a5f       res.push_back(cur);
757   }
b50   return res;
42c }
```

PolygonUnion.h

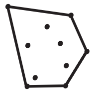
Description: Calculates the area of the union of n polygons (not necessarily convex). The points within each polygon must be given in CCW order. (Epsilon checks may optionally be added to sideOf/sgn, but shouldn't be needed.)
Time: $\mathcal{O}(N^2)$, where N is the total number of points

"Point.h", "sideOf.h" 3931c6, 34 lines

```
626 typedef Point<double> P;
142 double rat(P a, P b) { return sgn(b.x) ? a.x/b.x : a.y/b.y
    ; }
61d double polyUnion(vector<vector<P>>& poly) {
499   double ret = 0;
9af   rep(i,0,sz(poly)) rep(v,0,sz(poly[i])) {
9c8     P A = poly[i][v], B = poly[i][(v + 1) % sz(poly[i])];
05c     vector<pair<double, int>> segs = {{0, 0}, {1, 0}};
cbd     rep(j,0,sz(poly)) if (i != j) {
cc1       rep(u,0,sz(poly[j])) {
418         P C = poly[j][u], D = poly[j][(u + 1) % sz(poly[j])
    ];
688         int sc = sideOf(A, B, C), sd = sideOf(A, B, D);
68b         if (sc != sd) {
295           double sa = C.cross(D, A), sb = C.cross(D, B);
e90           if (min(sc, sd) < 0)
dac             segs.emplace_back(sa / (sa - sb), sgn(sc - sd))
    ;
cf7         } else if (!sc && !sd && j<i && sgn((B-A).dot(D-C))
    >0){
5b4           segs.emplace_back(rat(C - A, B - A), 1);
e96           segs.emplace_back(rat(D - A, B - A), -1);
313         }
0d1       }
fdc     }
861     sort(all(segs));
153     for (auto& s : segs) s.first = min(max(s.first, 0.0), 1
    .0);
68c     double sum = 0;
723     int cnt = segs[0].second;
067     rep(j,1,sz(segs)) {
081       if (!cnt) sum += segs[j].first - segs[j - 1].first;
6e9       cnt += segs[j].second;
f58     }
```

```
320     ret += A.cross(B) * sum;
191   }
ad6   return ret / 2;
6e8 }
```

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" 310954, 14 lines

```
2c0 typedef Point<ll> P;
f16 vector<P> convexHull(vector<P> pts) {
f78   if (sz(pts) <= 1) return pts;
3cb   sort(all(pts));
abf   vector<P> h(sz(pts)+1);
573   int s = 0, t = 0;
628   for (int it = 2; it--; s = --t, reverse(all(pts)))
4eb     for (P p : pts) {
3da       while (t >= s + 2 && h[t-2].cross(h[t-1], p) <= 0) t--;
f39       h[t++] = p;
bf0     }
036   return {h.begin(), h.begin() + t - (t == 2 && h[0] == h[1])};
ec8 }
```

HullDiameter.h

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

"Point.h" c571b8, 13 lines

```
2c0 typedef Point<ll> P;
d31 array<P, 2> hullDiameter(vector<P> S) {
e79   int n = sz(S), j = n < 2 ? 0 : 1;
354   pair<ll, array<P, 2>> res({0, {S[0], S[0]}});
e4d   rep(i,0,j)
42e     for (;; j = (j + 1) % n) {
ca1       res = max(res, {(S[i] - S[j]).dist2(), {S[i], S[j]}});
be8       if ((S[(j + 1) % n] - S[j]).cross(S[i + 1] - S[i]) >= 0)
c2b         break;
56c     }
3f2   return res.second;
5f7 }
```

PointInsideHull.h

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

"Point.h", "sideOf.h", "OnSegment.h" 71446b, 15 lines

```
2c0 typedef Point<ll> P;

2d4 bool inHull(const vector<P>& l, P p, bool strict = true) {
d44   int a = 1, b = sz(l) - 1, r = !strict;
5cc   if (sz(l) < 3) return r && onSegment(l[0], l.back(), p);
6bc   if (sideOf(l[0], l[a], l[b]) > 0) swap(a, b);
456   if (sideOf(l[0], l[a], p) >= r || sideOf(l[0], l[b], p)<= -r)
d1f     return false;
48a   while (abs(a - b) > 1) {
4f7     int c = (a + b) / 2;
ac8     (sideOf(l[0], l[c], p) > 0 ? b : a) = c;
b26   }
06f   return sgn(l[a].cross(l[b], p)) < r;
c74 }
```

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

"Point.h" 7cf45b, 40 lines

```
530 #define cmp(i,j) sgn(dir.perp().cross(poly[(i)%n]-poly[(j)%n]))
f84 #define extr(i) cmp(i + 1, i) >= 0 && cmp(i, i - 1 + n) < 0
e7e template <class P> int extrVertex(vector<P>& poly, P dir) {
747   int n = sz(poly), lo = 0, hi = n;
fdf   if (extr(0)) return 0;
3d1   while (lo + 1 < hi) {
591     int m = (lo + hi) / 2;
855     if (extr(m)) return m;
c0c     int ls = cmp(lo + 1, lo), ms = cmp(m + 1, m);
f48     (ls < ms || (ls == ms && ls == cmp(lo, m)) ? hi : lo) = m;
68a   }
253   return lo;
7f0 }

8e0 #define cmpL(i) sgn(a.cross(poly[i], b))
7dc template <class P>
ec4 array<int, 2> lineHull(P a, P b, vector<P>& poly) {
409   int endA = extrVertex(poly, (a - b).perp());
761   int endB = extrVertex(poly, (b - a).perp());
1a8   if (cmpL(endA) < 0 || cmpL(endB) > 0)
423     return {-1, -1};
649   array<int, 2> res;
f4b   rep(i,0,2) {
234     int lo = endB, hi = endA, n = sz(poly);
c2d     while ((lo + 1) % n != hi) {
57e       int m = ((lo + hi + (lo < hi ? 0 : n)) / 2) % n;
7f6       (cmpL(m) == cmpL(endB) ? lo : hi) = m;
525     }
7dd     res[i] = (lo + !cmpL(hi)) % n;
356     swap(endA, endB);
c05   }
e00   if (res[0] == res[1]) return {res[0], -1};
3d1   if (!cmpL(res[0]) && !cmpL(res[1]))
959     switch ((res[0] - res[1] + sz(poly) + 1) % sz(poly)) {
3f3       case 0: return {res[0], res[0]};
223       case 2: return {res[1], res[1]};
8fa     }
b50   return res;
36f }
```

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" 664d67, 24 lines

```
780 using P = Point<ll>;
89f vector<P> minkowski(vector<P> p, vector<P> q) {
a8e   auto fix = [](vector<P>& A) {
bec     int pos = 0;
2bb     for (int i = 1; i < sz(A); i++) {
609       if(A[i].y < A[pos].y || (A[i].y == A[pos].y && A[i].x < A[pos].x))
e4c         pos = i;
f76     }
703     rotate(A.begin(), A.begin() + pos, A.end());
9e5     A.push_back(A[0]), A.push_back(A[1]);
236   };
889   fix(p), fix(q);
db6   vector<P> result;
692   int i = 0, j = 0;
98a   while (i < sz(p) - 2 || j < sz(q) - 2) {
942     result.push_back(p[i] + q[j]);
3bd     auto cross = (p[i + 1] - p[i]).cross(q[j + 1] - q[j]);
c3c     if (cross >= 0 && i < sz(p) - 2) i++;
f33     if (cross <= 0 && j < sz(q) - 2) j++;
801   }
dc8   return result;
2f9 }
```

Extreme.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" 70b181, 26 lines

```
780 using P = Point<ll>;
c88 int extreme(vector<P> &pol, const function<bool(P, P)>& cmp) {
b1c   int n = pol.size();
4a2   auto extr = [&](int i, bool& cur_dir) {
22a     cur_dir = cmp(pol[(i+1)%n], pol[i]);
61a     return !cur_dir and !cmp(pol[(i+n-1)%n], pol[i]);
364   };
63d   bool last_dir, cur_dir;
a0d   if (extr(0, last_dir)) return 0;
993   int l = 0, r = n;
ead   while (l+1 < r) {
ee4     int m = (l+r)/2;
f29     if (extr(m, cur_dir)) return m;
44a     bool rel_dir = cmp(pol[m], pol[l]);
b18     if ((!last_dir and cur_dir) or
261         (last_dir == cur_dir and rel_dir == cur_dir)) {
8a6       l = m;
1f1       last_dir = cur_dir;
94a     } else r = m;
606   }
792   return l;
985 }
cad int max_dot(vector<P> &pol, P v) {
a98   return extreme([&](P p, P q) { return p.dot(v) > q.dot(v); });
27e }
```

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", "Extreme.h" dcf85f, 11 lines

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

08d bool ccw(P p, P q, P r) {
```

```
274   return (q-p).cross(r-q) > 0;
0f3 }
826 pair<int, int> tangents(vector<P> &pol, P p) {
ae2     auto L = [&](P q, P r) { return ccw(p, r, q); };
98c     auto R = [&](P q, P r) { return ccw(p, q, r); };
861     return {extreme(pol, L), extreme(pol, R)};
3dc }
```

8.4 Misc. Point Set Problems

ClosestPair.h

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

"Point.h" ac41a6, 18 lines

```
2c0 typedef Point<ll> P;
24b pair<P, P> closest(vector<P> v) {
7f9  assert(sz(v) > 1);
7f7  set<P> S;
879  sort(all(v), [](P a, P b) { return a.y < b.y; });
571  pair<ll, pair<P, P>> ret{LLONG_MAX, {P(), P()}};
eec  int j = 0;
813  for (P p : v) {
3fb    P d{1 + (ll)sqrt(ret.first), 0};
8be    while (v[j].y <= p.y - d.x) S.erase(v[j++]);
a5a    auto lo = S.lower_bound(p - d), hi = S.upper_bound(p +
    d);
c77    for (; lo != hi; ++lo)
113      ret = min(ret, {(*lo - p).dist2(), {*lo, p}});
8aa    S.insert(p);
5b0  }
70d  return ret.second;
bf2 }
```

ManhattanMST.h

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

"Point.h" df6f59, 24 lines

```
bbe typedef Point<int> P;
ea9 vector<array<int, 3>> manhattanMST(vector<P> ps) {
850  vi id(sz(ps));
27c  iota(all(id), 0);
8c1  vector<array<int, 3>> edges;
8de  rep(k,0,4) {
1dd    sort(all(id), [&](int i, int j) {
02b         return (ps[i]-ps[j]).x < (ps[j]-ps[i]).y;});
702    map<int, int> sweep;
1e2    for (int i : id) {
84d      for (auto it = sweep.lower_bound(-ps[i].y);
904                it != sweep.end(); sweep.erase(it++)) {
61d        int j = it->second;
6f3        P d = ps[i] - ps[j];
d18        if (d.y > d.x) break;
537        edges.push_back({d.y + d.x, i, j});
271      }
923      sweep[-ps[i].y] = i;
e69    }
4eb    for (P& p : ps) if (k & 1) p.x = -p.x; else swap(p.x, p
    .y);
a11  }
da2  return edges;
a11 }
```

kdTree.h

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

"Point.h" bac5b0, 64 lines

```
9a6 typedef long long T;
293 typedef Point<T> P;
305 const T INF = numeric_limits<T>::max();

173 bool on_x(const P& a, const P& b) { return a.x < b.x; }
0bd bool on_y(const P& a, const P& b) { return a.y < b.y; }

bf2 struct Node {
975  P pt; // if this is a leaf, the single point in it
877  T x0 = INF, x1 = -INF, y0 = INF, y1 = -INF; // bounds
a23  Node *first = 0, *second = 0;

86a  T distance(const P& p) { // min squared distance to a
    point
28b    T x = (p.x < x0 ? x0 : p.x > x1 ? x1 : p.x);
88e    T y = (p.y < y0 ? y0 : p.y > y1 ? y1 : p.y);
d98    return (P(x,y) - p).dist2();
ca4  }

d97  Node(vector<P>&& vp) : pt(vp[0]) {
741    for (P p : vp) {
ad3      x0 = min(x0, p.x); x1 = max(x1, p.x);
e5d      y0 = min(y0, p.y); y1 = max(y1, p.y);
310    }
994    if (vp.size() > 1) {
       // split on x if width >= height (not ideal...)
9b7      sort(all(vp), x1 - x0 >= y1 - y0 ? on_x : on_y);
       // divide by taking half the array for each child (
           not
       // best performance with many duplicates in the
           middle)
0f9      int half = sz(vp)/2;
48e      first = new Node({vp.begin(), vp.begin() + half});
902      second = new Node({vp.begin() + half, vp.end()});
66e    }
204  }
a77 };

dad struct KDTree {
95f  Node* root;
c30  KDTree(const vector<P>& vp) : root(new Node({all(vp)}))
    {}

113  pair<T, P> search(Node *node, const P& p) {
ec4    if (!node->first) {
         // uncomment if we should not find the point itself:
         // if (p == node->pt) return {INF, P()};
47e      return make_pair((p - node->pt).dist2(), node->pt);
119    }

ea4    Node *f = node->first, *s = node->second;
d40    T bfirst = f->distance(p), bsec = s->distance(p);
a16    if (bfirst > bsec) swap(bsec, bfirst), swap(f, s);

       // search closest side first, other side if needed
86c    auto best = search(f, p);
314    if (bsec < best.first)
509      best = min(best, search(s, p));
f26    return best;
74c  }

     // find nearest point to a point, and its squared
          distance
     // (requires an arbitrary operator< for Point)
9b6  pair<T, P> nearest(const P& p) {
195    return search(root, p);
94c  }
6f5 };
```

FastDelaunay.h

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

"Point.h" eefdf5, 89 lines

```
2c0 typedef Point<ll> P;
806 typedef struct Quad* Q;
449 typedef __int128_t lll; // (can be ll if coords are < 2e4)
59b P arb(LLONG_MAX,LLONG_MAX); // not equal to any other
    point

070 struct Quad {
461  Q rot, o; P p = arb; bool mark;
b38  P& F() { return r()->p; }
23a  Q& r() { return rot->rot; }
f4f  Q prev() { return rot->o->rot; }
57e  Q next() { return r()->prev(); }
180 } *H;

d15 bool circ(P p, P a, P b, P c) { // is p in the
    circumcircle?
4b4  lll p2 = p.dist2(), A = a.dist2()-p2,
ffa      B = b.dist2()-p2, C = c.dist2()-p2;
59a  return p.cross(a,b)*C + p.cross(b,c)*A + p.cross(c,a)*B >
    0;
6af }
00a Q makeEdge(P orig, P dest) {
bdf  Q r = H ? H : new Quad{new Quad{new Quad{new Quad{0}}}};
516  H = r->o; r->r()->r() = r;
2c3  rep(i,0,4) r = r->rot, r->p = arb, r->o = i & 1 ? r : r->
    r();
ed2  r->p = orig; r->F() = dest;
4c1  return r;
b3b }
d8d void splice(Q a, Q b) {
686  swap(a->o->rot->o, b->o->rot->o); swap(a->o, b->o);
86c }
e92 Q connect(Q a, Q b) {
fc2  Q q = makeEdge(a->F(), b->p);
6e6  splice(q, a->next());
642  splice(q->r(), b);
bef  return q;
4a4 }

196 pair<Q,Q> rec(const vector<P>& s) {
e63  if (sz(s) <= 3) {
4a0    Q a = makeEdge(s[0], s[1]), b = makeEdge(s[1], s.back()
    );
2ba    if (sz(s) == 2) return { a, a->r() };
19e    splice(a->r(), b);
5f8    auto side = s[0].cross(s[1], s[2]);
b9f    Q c = side ? connect(b, a) : 0;
3d8    return {side < 0 ? c->r() : a, side < 0 ? c : b->r() };
c9e  }

5ef #define H(e) e->F(), e->p
c98 #define valid(e) (e->F().cross(H(base)) > 0)
a3e  Q A, B, ra, rb;
f5e  int half = sz(s) / 2;
391  tie(ra, A) = rec({all(s) - half});
d9b  tie(B, rb) = rec({sz(s) - half + all(s)});
f80  while ((B->p.cross(H(A)) < 0 && (A = A->next())) ||
b08         (A->p.cross(H(B)) > 0 && (B = B->r()->o)));
76d  Q base = connect(B->r(), A);
87f  if (A->p == ra->p) ra = base->r();
b58  if (B->p == rb->p) rb = base;
```

```
3e6 #define DEL(e, init, dir) Q e = init->dir; if (valid(e)) \
f02     while (circ(e->dir->F(), H(base), e->F())) { \
936       Q t = e->dir; \
6d3       splice(e, e->prev()); \
16e       splice(e->r(), e->r()->prev()); \
d47       e->o = H; H = e; e = t; \
a2e     }
1de   for (;;) {
eaa     DEL(LC, base->r(), o);  DEL(RC, base, prev());
6fa     if (!valid(LC) && !valid(RC)) break;
e09     if (!valid(LC) || (valid(RC) && circ(H(RC), H(LC))))
b74       base = connect(RC, base->r());
295     else
271       base = connect(base->r(), LC->r());
fcf   }
345   return { ra, rb };
7cf }

da1 vector<P> triangulate(vector<P> pts) {
af6   sort(all(pts));  assert(unique(all(pts)) == pts.end());
e00   if (sz(pts) < 2) return {};
235   Q e = rec(pts).first;
50c   vector<Q> q = {e};
6c1   int qi = 0;
7a5   while (e->o->F().cross(e->F(), e->p) < 0) e = e->o;
806 #define ADD { Q c = e; do { c->mark = 1; pts.push_back(c->p); \
43e   q.push_back(c->r()); c = c->next(); } while (c != e); }
9d6   ADD; pts.clear();
b58   while (qi < sz(q)) if (!(e = q[qi++])->mark) ADD;
a42   return pts;
a02 }
```

8.5 3D

PolyhedronVolume.h

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

3058c3, 7 lines

```
f9c template<class V, class L>
cb3 double signedPolyVolume(const V& p, const L& trilist) {
9e8   double v = 0;
b72   for (auto i : trilist) v += p[i.a].cross(p[i.b]).dot(p[i.c]);
fb8   return v / 6;
fca }
```

Point3D.h

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

8058ae, 33 lines

```
f10 template<class T> struct Point3D {
f07   typedef Point3D P;
d0e   typedef const P& R;
329   T x, y, z;
cf2   explicit Point3D(T x=0, T y=0, T z=0) : x(x), y(y), z(z){}
803   bool operator<(R p) const {
8ee     return tie(x, y, z) < tie(p.x, p.y, p.z); }
236   bool operator==(R p) const {
bd6     return tie(x, y, z) == tie(p.x, p.y, p.z); }
9ae   P operator+(R p) const { return P(x+p.x, y+p.y, z+p.z); }
54a   P operator-(R p) const { return P(x-p.x, y-p.y, z-p.z); }
743   P operator*(T d) const { return P(x*d, y*d, z*d); }
17b   P operator/(T d) const { return P(x/d, y/d, z/d); }
e49   T dot(R p) const { return x*p.x + y*p.y + z*p.z; }
270   P cross(R p) const {
923     return P(y*p.z - z*p.y, z*p.x - x*p.z, x*p.y - y*p.x);
a77   }
b70   T dist2() const { return x*x + y*y + z*z; }
18b   double dist() const { return sqrt((double)dist2()); }
      //Azimuthal angle (longitude) to x-axis in interval [-pi, pi]
3d6   double phi() const { return atan2(y, x); }
      //Zenith angle (latitude) to the z-axis in interval [0, pi]
0fa   double theta() const { return atan2(sqrt(x*x+y*y),z); }
55e   P unit() const { return *this/(T)dist(); } //makes dist()=1
      //returns unit vector normal to *this and p
685   P normal(P p) const { return cross(p).unit(); }
      //returns point rotated 'angle' radians ccw around axis
c67   P rotate(double angle, P axis) const {
7cd     double s = sin(angle), c = cos(angle); P u = axis.unit();
6b7     return u*dot(u)*(1-c) + (*this)*c - cross(u)*s;
73a   }
805 };
```

3dHull.h

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

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

"Point3D.h" 5b45fc, 50 lines

```
b8e typedef Point3D<double> P3;

9ce struct PR {
1fc   void ins(int x) { (a == -1 ? a : b) = x; }
82f   void rem(int x) { (a == x ? a : b) = -1; }
2ad   int cnt() { return (a != -1) + (b != -1); }
ba2   int a, b;
cf7 };

5e4 struct F { P3 q; int a, b, c; };

b6d vector<F> hull3d(const vector<P3>& A) {
cd9   assert(sz(A) >= 4);
ec1   vector<vector<PR>> E(sz(A), vector<PR>(sz(A), {-1, -1}));
394 #define E(x,y) E[f.x][f.y]
afe   vector<F> FS;
9e0   auto mf = [&](int i, int j, int k, int l) {
2ce     P3 q = (A[j] - A[i]).cross((A[k] - A[i]));
fa1     if (q.dot(A[l]) > q.dot(A[i]))
eaa       q = q * -1;
f22     F f{q, i, j, k};
ee5     E(a,b).ins(k); E(a,c).ins(j); E(b,c).ins(i);
471     FS.push_back(f);
d73   };
30c   rep(i,0,4) rep(j,i+1,4) rep(k,j+1,4)
047     mf(i, j, k, 6 - i - j - k);

3ef   rep(i,4,sz(A)) {
3b5     rep(j,0,sz(FS)) {
068       F f = FS[j];
04f       if(f.q.dot(A[i]) > f.q.dot(A[f.a])) {
412         E(a,b).rem(f.c);
b61         E(a,c).rem(f.b);
e5c         E(b,c).rem(f.a);
8d5         swap(FS[j--], FS.back());
eef         FS.pop_back();
5cd       }
220     }
97f     int nw = sz(FS);
c63     rep(j,0,nw) {
068       F f = FS[j];
561 #define C(a, b, c) if (E(a,b).cnt() != 2) mf(f.a, f.b, i, f.c);
3da       C(a, b, c); C(a, c, b); C(b, c, a);
248     }
472   }
864   for (F& it : FS) if ((A[it.b] - A[it.a]).cross(
770     A[it.c] - A[it.a]).dot(it.q) <= 0) swap(it.c, it.b);
311   return FS;
be2 };
```

sphericalDistance.h

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

611f07, 9 lines

```
c5f double sphericalDistance(double f1, double t1,
3e8     double f2, double t2, double radius) {
284   double dx = sin(t2)*cos(f2) - sin(t1)*cos(f1);
277   double dy = sin(t2)*sin(f2) - sin(t1)*sin(f1);
c7e   double dz = cos(t2) - cos(t1);
c09   double d = sqrt(dx*dx + dy*dy + dz*dz);
154   return radius*2*asin(d/2);
4fa }
```

Strings (9)

AhoCorasick.h

95b3e7, 46 lines

```
c2e int trie[ms][sigma], fail[ms], terminal[ms], superfail[ms];
1e1 bool present[ms];
965 int z = 1;

ca3 int val(char c) { return c - 'a'; }

f97 void add(string& p) {
b3d     int cur = 0;
b4b     for (int i = 0; i < (int)p.size(); i++) {
9e4         int& nxt = trie[cur][val(p[i])];
b6e         if (nxt == 0) nxt = z++;
1bc         cur = nxt;
a92     }
c0e     present[cur] = true;
b07     terminal[cur]++;
6aa }

0a8 void build() {
26a     queue<int> q;
f47     for (q.push(0); !q.empty(); q.pop()) {
fb5         int on = q.front();
0b2         for (int i = 0; i < sigma; i++) {
df1             int& to = trie[on][i];
279             int f = (on == 0 ? 0 : trie[fail[on]][i]);
de7             int sf = (present[f] ? f : superfail[f]);
24d             if (!to) {
c4e                 to = f;
6fd             }
4e6             else {
3ef                 fail[to] = f;
b86                 superfail[to] = sf;
                    // merge infos (ex: terminal[to] += terminal[f])
91b                 q.push(to);
692             }
bff         }
```

```
e61         }
b89     }

54e     void search(string& s) {
b3d         int cur = 0;
b4f         for (char c : s) {
3ba             cur = trie[cur][val(c)];
                // process infos on current node (ex: ocurrences
                    += terminal[cur])
5ac         }
d1b     }
```

Hash.h

Description: C can also be random, operator is $[l, r]$ 79e7f5, 28 lines

```
541 using ull = uint64_t;
54d struct H {
858     ull x; H(ull x = 0) : x(x) {}
c9b     H operator+(H o) { return x + o.x + (x + o.x < x); }
5cd     H operator-(H o) { return *this + ~o.x; }
167     H operator*(H o) {
2f3         auto m = (__uint128_t)x * o.x;
540         return H((ull)m) + (ull)(m >> 64);
681     }
bf2     ull get() const { return x + !~x; }
03c     bool operator==(H o) const{ return get() == o.get();}
0ab     bool operator<(H o) const{ return get() < o.get();}
bf6 };
862 static const H C = (ll)1e11 + 3;
61c struct Hash {
2f2     vector<H> h, pw;
1df     Hash(string& str) : h(str.size()), pw(str.size()) {
9bc         pw[0] = 1, h[0] = str[0];
1c5         for (int i = 1; i < str.size(); i++) {
90a             h[i] = h[i - 1] * C + str[i];
b3c             pw[i] = pw[i - 1] * C;
57e         }
f1b     }
75e     H operator()(int l, int r) {
91f         return h[r] - (l ? h[l - 1] * pw[r - l + 1] : 0);
9cf     }
c36 };
```

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). c7cf15, 10 lines

```
a56 vector<int> pi(const string& s) {
627     vector<int> p(sz(s));
edb     for(int i = 1; i < sz(s); i++) {
052         int g = p[i-1];
6c0         while (g && s[i] != s[g]) g = p[g-1];
7cf         p[i] = g + (s[i] == s[g]);
a2e     }
74e     return p;
c7c }
```

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). 8833cb, 17 lines

```
ab6 int go[ms][sigma];
ca3 int val(char c) { return c - 'a'; }
8cf void automaton(string& s) {
3cc     for (int i = 0; i < sigma; i++)
48d         go[0][i] = (i == val(s[0]));

8cc     for (int i = 1, bdr = 0; i <= (int)s.size(); i++) {
782         for (int j = 0; j < sigma; j++) {
6ef             go[i][j] = go[bdr][j];
87c         }
f8d         if (i < (int)s.size()) {
02f             go[i][val(s[i])] = i + 1;
364             bdr = go[bdr][val(s[i])];
63b         }
d7e     }
0c5 }
```

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) 7dfe41, 17 lines

```
aa9 array<vector<int>, 2> manacher(const string& s) {
f89     int n = sz(s);
ca1     array<vector<int>,2> p={vector<int>(n+1),vector<int>(n
        )};
6b7     for (int z = 0; z < 2; z++) {
22c         for (int i = 0, l = 0, r = 0; i < n; i++) {
24e             int t = r - i + !z;
e70             if (i < r) p[z][i] = min(t, p[z][l + t]);
fff             int L = i - p[z][i], R = i + p[z][i] - !z;
40c             while(L >= 1 && R+1 < n && s[L-1] == s[R+1]){
895                 p[z][i]++, L--, R++;
48e             }
f28             if (R > r) l = L, r = R;
e05         }
7a3     }
74e     return p;
7df }
```

MinRotation.h

Description: Finds the lexicographically smallest rotation of a string.
Usage: `rotate(s.begin(), s.begin()+minRotation(s), s.end());`
Time: $\mathcal{O}(N)$ 19c4ce, 14 lines

```
5fa int minRotation(string s) {
a3e     int a = 0, N = s.size(); s += s;
239     for (int b = 0; b < N; b++) {
e0d         for (int k = 0; k < N; k++) {
32f             if (a+k == b || s[a+k] < s[b+k]) {
313                 b += max(0, k-1);
c2b                 break;
873             }
068             if (s[a+k] > s[b+k]) { a = b; break; }
9b5         }
193     }
3f5     return a;
19c }
```

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. 048424, 31 lines

```
3f4 struct SuffixArray {
716  vector<int> sa, lcp;
d91  SuffixArray(string s, int lim=256) {
59b    s.push_back('$');
323    int n = sz(s), k = 0, a, b;
9f1    vector<int> x(all(s)), y(n), ws(max(n, lim));
af4    sa = lcp = y, iota(all(sa), 0);
25d    for(int j = 0, p = 0; p < n; j= max(1, j*2), lim = p) {
3cd      p = j, iota(all(y), n - j);
603      for(int i=0; i<n; i++){
071        if (sa[i] >= j) y[p++] = sa[i] - j;
cb4      }
911      fill(all(ws), 0);
483      for(int i=0; i<n; i++) ws[x[i]]++;
5d9      for(int i=1; i<lim; i++) ws[i] += ws[i - 1];
a9e      for (int i = n; i--;) sa[--ws[x[y[i]]]] = y[i];
c7d      swap(x, y), p = 1, x[sa[0]] = 0;
6f5      for(int i=1; i<n; i++){
93f        a = sa[i - 1], b = sa[i];
ddb        x[b] = p-1;
a32        if(y[a] != y[b] || y[a+j] != y[b+j]) x[b] = p++;
1ba      }
c36    }
65b    for (int i = 0, j; i < n - 1; lcp[x[i++]] = k)
904      for (k && k--, j = sa[x[i] - 1];
262          s[i + k] == s[j + k]; k++);
68a    sa = vector<int>(sa.begin() + 1, sa.end());
5d4    lcp = vector<int>(lcp.begin() + 1, lcp.end());
4db  }
048 };
```

Zfunc.h

Description: z[i] computes the length of the longest common prefix of s[i:] and s, except z[0] = 0. (abacaba -> 0010301) 495392, 13 lines

```
572 vector<int> ZFunc(const string& s) {
d6b     int n = sz(s), a = 0, b = 0;
2b1     vector<int> z(n, 0);
29a     if (!z.empty()) z[0] = 0;
6f5     for (int i = 1; i < n; i++) {
fe0         int end = i;
98f         if (i < b) end = min(i + z[i - a], b);
65f         while (end < n && s[end] == s[end - i]) ++end;
816         z[i] = end - i; if (end > b) a = i, b = end;
253     }
070     return z;
495 }
```

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 688e56, 23 lines

```
37c string day[] = { "Mon", "Tue", "Wed", "Thu", "Fri", "Sat",
        "Sun" };
fb9 int dateToInt(int m, int d, int y) {
e70     return
773         1461 * (y + 4800 + (m - 14) / 12) / 4 +
649         367 * (m - 2 - (m - 14) / 12 * 12) / 12 -
fa0         3 * ((y + 4900 + (m - 14) / 12) / 100) / 4 +
3aa         d - 32075;
a73 }
3fe void intToDate(int jd, int& m, int& d, int& y) {
ee1     int x, n, i, j;
33a     x = jd + 68569;
403     n = 4 * x / 146097;
33e     x -= (146097 * n + 3) / 4;
6fc     i = (4000 * (x + 1)) / 1461001;
b1d     x -= 1461 * i / 4 - 31;
fc9     j = 80 * x / 2447;
c8d     d = x - 2447 * j / 80;
179     x = j / 11;
```

```
335      m = j + 2 - 12 * x;
23d      y = 100 * (n - 49) + i + x;
cbb  }
04e  string intToDay(int jd) { return day[jd % 7]; }
```

MultisetHash.h

5648da, 8 lines

```
cdc  ull hashify(ull sum) {
7b8      sum += FIXED_RANDOM;
6ec      sum += 0x9e3779b97f4a7c15;
dc6      sum = (sum ^ (sum >> 30)) * 0xbf58476d1ce4e5b9;
005      sum = (sum ^ (sum >> 27)) * 0x94d049bb133111eb;
358      return sum ^ (sum >> 31);
564  }
```

Rand.h

2de3f8, 8 lines

```
c8a  mt19937 rng(chrono::steady_clock::now().time_since_epoch()
     .count());
     // _64

463  int uniform(int l, int r) { // [l, r]
a7f      uniform_int_distribution<int> uid(l, r);
f54      return uid(rng);
d9e  }
```

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 $f(b,c) \le f(a,d)$ and $f(a,c) + f(b,d) \le f(a,d) + f(b,c)$ for all $a \le b \le c \le d$. Another sufficient criteria is: $opt[i][j-1] \le opt[i][j] \le opt[i+1][j]$
Time: $\mathcal{O}\left(N^2\right)$

fea016, 22 lines

```
7cc  ll knuth(){
6a7      memset(opt, -1, sizeof opt);
45b      for(int i=n-1; i>=0; i--){
8e7          dp[i][i] = 0; // base case
b28          opt[i][i] = i;
94f          for(int j=i+1; j<n; j++){
2e2              int optL = (!j ? 0 : opt[i][j-1]);
dc4              int optR = (~opt[i+1][j] ? opt[i+1][j] : n-1);
554              ll cst = cost(i, j);
f12              dp[i][j] = INF;
3bb              optL = max(i, optL), optR = min(j-1, optR);
349              for(int k=optL; k<=optR; k++){
f8b                  ll now = dp[i][k] + dp[k+1][j] + cst;
e83                  if(now <= dp[i][j]){
960                      dp[i][j] = now;
14d                      opt[i][j] = k;
5fc                  }
114              }
4ce          }
96c      }
fea  }
```

DivideAndConquerDP.h

Description: Divide and Conquer DP maintaining cost, can be used when $opt[i][j] \le opt[i][j+1]$. In this code everything is 1-based. Memory can be optmized by keeping only the last row
Time: $\mathcal{O}\left(MN\log N\right)$

c7cb38, 42 lines

```
129  void add(int idx) {}
404  void rem(int idx) {}

749  void deC(int i, int l, int r, int optL, int optR) {
de6      if (l > r) return;
995      int j = (l + r) / 2;
d9a      for (int k = r; k > j; k--) rem(k);
c45      int opt = optL;
364      for (int k = optL; k <= min(optR, j); k++) {
             // cost = cost[k, j]
597          int val = dp[i - 1][k - 1] + cost;
532          if (val < dp[i][j]) {
482              dp[i][j] = val;
613              opt = k;
178          }
183          rem(k);
93f      }
5d9      for (int k = min(optR, j); k >= optL; k--) add(k);
446      rem(j);
ace      deC(i, l, j - 1, optL, opt);

ebd      for (int k = j; k <= r; k++) add(k);
648      for (int k = optL; k < opt; k++) rem(k);
0b6      deC(i, j + 1, r, opt, optR);

9bb      for (int k = optL; k < opt; k++) add(k);
460  }

d57  int solve(int N, int M) { // 1-based
d9f      for (int i = 0; i <= M; i++) {
138          for (int j = 0; j <= N; j++){
3db              dp[i][j] = inf; // base case
a26          }
e0f      }
c21      cost = 0; // neutral value
c62      for (int i = 1; i <= N; i++) add(i);
143      for (int i = 1; i <= M; i++) {
156          deC(i, 1, N, 1, N);
c97      }
01a      return dp[M][N];
3ab  }
```