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2 Theory

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5 Graph

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Contest (1)

template.cpp

18 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()
#define pb push_back
#define eb emplace_back
typedef long long ll;
typedef pair<int, int> pii;
typedef vector<int> vi;

constexpr int oo = ((unsigned int)-1) >> 1;

int main() {
    cin.tie(0)->sync_with_stdio(0);
    cin.exceptions(cin.failbit);
}
```

.bashrc

3 lines

```
alias c='g++ -Wall -Wconversion -Wfatal-errors -g -std=c++17 \
-fsanitize=undefined,address'
xmodmap -e 'clear lock' -e 'keycode 66=less greater' #caps = <
```

.vimrc

6 lines

```
set cin aw ai is ts=4 sw=4 tm=50 nu noeb bg=dark ru cul
sy on | im jk <esc> | im kj <esc> | no ;
" Select region and then type :Hash to hash your selection.
" Useful for verifying that there aren't mistypes.
ca Hash w !cpp -D D -P -fpreprocessed \| tr -d '['space:]' \
 \| md5sum \| cut -c-6
```

hash.sh

3 lines

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

troubleshoot.txt

52 lines

Pre-submit:
Write a few simple test cases if sample is not enough.

1	Are time limits close? If so, generate max cases. Is the memory usage fine? Could anything overflow?
1	Make sure to submit the right file.
4	Wrong answer: Print your solution! Print debug output, as well. Are you clearing all data structures between test cases?
9	Can your algorithm handle the whole range of input? Read the full problem statement again.
13	Do you handle all corner cases correctly? Have you understood the problem correctly? Any uninitialized variables?
20	Any overflows? Confusing N and M, i and j, etc.? Are you sure your algorithm works?
24	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.
25	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?

Theory (2)

2.1 General Math

2.1.1 Equations

$$ax^2 + bx + c = 0 \Rightarrow x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

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

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

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

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

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

2.1.2 Recurrences

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

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

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

2.1.3 Trigonometry

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

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

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

$$\sin v + \sin w = 2 \sin \frac{v+w}{2} \cos \frac{v-w}{2}$$

$$\cos v + \cos w = 2 \cos \frac{v+w}{2} \cos \frac{v-w}{2}$$

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

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

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

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

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

2.1.4 Derivatives/Integrals

$$\frac{d}{dx} \arcsin x = \frac{1}{\sqrt{1-x^2}} \quad \frac{d}{dx} \arccos x = -\frac{1}{\sqrt{1-x^2}}$$

$$\frac{d}{dx} \tan x = 1 + \tan^2 x \quad \frac{d}{dx} \arctan x = \frac{1}{1+x^2}$$

$$\int \tan ax = -\frac{\ln |\cos ax|}{a} \quad \int x \sin ax = \frac{\sin ax - ax \cos ax}{a^2}$$

$$\int e^{-x^2} = \frac{\sqrt{\pi}}{2} \operatorname{erf}(x) \quad \int x e^{ax} dx = \frac{e^{ax}}{a^2} (ax - 1)$$

Integration by parts:

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

2.1.5 Sums

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

$$1 + 2 + 3 + \dots + n = \frac{n(n+1)}{2}$$

$$1^2 + 2^2 + 3^2 + \dots + n^2 = \frac{n(2n+1)(n+1)}{6}$$

$$1^3 + 2^3 + 3^3 + \dots + n^3 = \frac{n^2(n+1)^2}{4}$$

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

2.1.6 Series

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

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

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

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

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

2.1.7 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.

2.2 Geometry

2.2.1 Triangles

Side lengths: a, b, c

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

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

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

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

Length of median (divides triangle into two equal-area triangles):

$$m_a = \frac{1}{2}\sqrt{2b^2 + 2c^2 - a^2}$$

template .bashrc .vimrc hash troubleshoot

Length of bisector (divides angles in two):

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

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

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

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

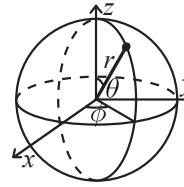
2.2.2 Quadrilaterals

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

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

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

2.2.3 Spherical coordinates



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

2.3 Probability theory

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

Expectation is linear:

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

For independent X and Y ,

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

2.3.1 Discrete distributions

Binomial distribution

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

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

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

$\text{Bin}(n, p)$ 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 $\text{Fs}(p)$, $0 \leq p \leq 1$.

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

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

Poisson distribution

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

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

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

2.3.2 Continuous distributions

Uniform distribution

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

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

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

Exponential distribution

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

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

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

Normal distribution

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

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

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

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

2.3.3 Markov chains

A *Markov chain* is a discrete random process with the property that the next state depends only on the current state. Let X_1, X_2, \dots be a sequence of random variables generated by the Markov process. Then there is a transition matrix $\mathbf{P} = (p_{ij})$, with $p_{ij} = \Pr(X_n = i | X_{n-1} = j)$, and $\mathbf{p}^{(n)} = \mathbf{P}^n \mathbf{p}^{(0)}$ is the probability distribution for X_n (i.e., $p_i^{(n)} = \Pr(X_n = i)$), where $\mathbf{p}^{(0)}$ is the initial distribution.

π is a stationary distribution if $\pi = \pi\mathbf{P}$. If the Markov chain is *irreducible* (it is possible to get to any state from any state), then $\pi_i = \frac{1}{\mathbb{E}(T_i)}$ where $\mathbb{E}(T_i)$ is the expected time between two visits in state i . π_j/π_i is the expected number of visits in state j between two visits in state i .

For a connected, undirected and non-bipartite graph, where the transition probability is uniform among all neighbors, π_i is proportional to node i 's degree.

A Markov chain is *ergodic* if the asymptotic distribution is independent of the initial distribution. A finite Markov chain is ergodic iff it is irreducible and *aperiodic* (i.e., the gcd of cycle lengths is 1). $\lim_{k \rightarrow \infty} \mathbf{P}^k = \mathbf{1}\pi$.

A Markov chain is an A-chain if the states can be partitioned into two sets **A** and **G**, such that all states in **A** are absorbing ($p_{ii} = 1$), and all states in **G** leads to an absorbing state in **A**. The probability for absorption in state $i \in \mathbf{A}$, when the initial state is j , is $a_{ij} = p_{ij} + \sum_{k \in \mathbf{G}} a_{ik}p_{kj}$. The expected time until absorption, when the initial state is i , is $t_i = 1 + \sum_{k \in \mathbf{G}} p_{ki}t_k$.

2.4 Combinatorics

2.4.1 Permutations

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.

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

Burnside's lemma

Given a group G of symmetries and a set X , the number of elements of X up to symmetry equals

$$\frac{1}{|G|} \sum_{g \in G} |X^g|,$$

where X^g are the elements fixed by g ($g \cdot x = x$).

If $f(n)$ counts “configurations” (of some sort) of length n , we can ignore rotational symmetry using $G = \mathbb{Z}_n$ to get

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

2.4.2 Partitions and subsets

Partition function

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

$$\begin{aligned} p(0) &= 1, \quad p(n) = \sum_{k \in \mathbb{Z} \setminus \{0\}} (-1)^{k+1} p(n - k(3k-1)/2) \\ p(n) &\sim 0.145/n \cdot \exp(2.56\sqrt{n}) \\ \begin{array}{c|cccccccccc} n & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 20 & 50 & 100 \\ \hline p(n) & 1 & 1 & 2 & 3 & 5 & 7 & 11 & 15 & 22 & 30 & 627 & \sim 2e5 & \sim 2e8 \end{array} \end{aligned}$$

Lucas' Theorem

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

2.4.3 General purpose numbers

Bernoulli numbers

EGF of Bernoulli numbers is $B(t) = \frac{t}{e^t - 1}$ (FFT-able).

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

Sums of powers:

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

Euler-Maclaurin formula for infinite sums:

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

Stirling numbers of the first kind

Number of permutations on n items with k cycles.

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

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

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

Eulerian numbers

Number of permutations $\pi \in S_n$ in which exactly k elements are greater than the previous element. k :s s.t. $\pi(j) > \pi(j+1)$, $k+1$:s s.t. $\pi(j) \geq j$, k :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. $B(n) = 1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, \dots$. 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 : $n_1 n_2 \dots n_k n^{k-2}$

with degrees d_i : $(n-2)! / ((d_1-1)! \dots (d_n-1)!)$

Catalan numbers

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

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

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

- sub-diagonal monotone paths in an $n \times n$ grid.

- strings with n pairs of parenthesis, correctly nested.
- binary trees with $n+1$ 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.

2.5 Number Theory

2.5.1 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

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

2.5.2 Highly composite numbers

Up to: number of divisors (number itself)

$10^2 : 12(60)$ $10^3 : 32(840)$ $10^4 : 64(7560)$ $10^5 : 128(83160)$
 $10^6 : 240(720720)$ $10^7 : 448(8648640)$ $10^8 : 768(73513440)$
 $10^9 : 1344(735134400)$ $10^{10} : 2304(6983776800)$
 $10^{11} : 4032(97772875200)$ $10^{12} : 6720(963761198400)$
 $10^{13} : 10752(9316358251200)$ $10^{14} : 17280(97821761637600)$
 $10^{15} : 26880(866421317361600)$ $10^{16} : 41472(8086598962041600)$
 $10^{17} : 64512(74801040398884800)$
 $10^{18} : 103680(897612484786617600)$

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

2.5.4 Estimates

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

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

2.5.5 Möbius Function

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

Möbius Inversion:

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

Other useful formulas/forms:

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

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

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

2.6 Graphs

2.6.1 Number of Spanning Trees

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

2.6.2 Erdős–Gallai theorem

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

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

Math (3)

3.1 Misc

3.1.1 Combinatorics

multinomial.h

Description: Computes $\binom{k_1 + \dots + k_n}{k_1, k_2, \dots, k_n} = \frac{(\sum k_i)!}{k_1!k_2!\dots k_n!}$. a0a312, 5 lines

```
11 multinomial(vi& v) {
    11 c = 1, m = v.empty() ? 1 : v[0];
    rep(i, 1, sz(v)) rep(j, 0, v[i]) c = c * ++m / (j+1);
    return c;
} // a0a312
```

Combinatorics.h

Description: combinatorics structure

Memory: $\mathcal{O}(mn)$

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

.../math/ModPow.h

```
int mul(int a, int b) {return (int)((ll)a * b % mod);}
struct Combinatorics{
    vi f, fi;
    Combinatorics(int mxn):f(mxn), fi(mxn){
        f[0] = 1; rep(i, 1, mxn)f[i]=mul(f[i-1], i);
        fi[mxn-1] = modpow(f[mxn-1], mod-2);
        for(int i=mxn-1; i>0; i--) fi[i-1] = mul(fi[i], i);
    } // 5e6a1f
    int choose(int n, int k){return mul(f[n], mul(fi[k], fi[n-k]));
    }
}; // ff0ee09
```

3.1.2 Polynomial Calculus

Polynomial.h

c9b7b0, 17 lines

struct Poly {

```
vector<double> a;
double operator()(double x) const {
    double val = 0;
    for (int i = sz(a); i--;) (val *= x) += a[i];
    return val;
} // ae76f3
void diff() {
    rep(i, 1, sz(a)) a[i-1] = i*a[i];
    a.pop_back();
} // afcae
void divroot(double x0) {
    double b = a.back(), c; a.back() = 0;
    for(int i=sz(a)-1; i--;) c = a[i], a[i] = a[i+1]*x0+b, b=c;
    a.pop_back();
} // 3f874a
}; // c9b7b0
```

PolyRoots.h

Description: Finds the real roots to a polynomial.

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

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

*Polynomial.h" b00bfe, 23 lines

```
vector<double> polyRoots(Poly p, double xmin, double xmax) {
    if (sz(p.a) == 2) { return {-p.a[0]/p.a[1]}; }
    vector<double> ret;
    Poly der = p;
    der.diff();
    auto dr = polyRoots(der, xmin, xmax);
    dr.push_back(xmin-1);
    dr.push_back(xmax+1);
    sort(all(dr));
    rep(i, 0, sz(dr)-1) {
        double l = dr[i], h = dr[i+1];
        bool sign = p(l) > 0;
        if (sign ^ (p(h) > 0)) {
            rep(it, 0, 60) { // while (h - l > 1e-8)
                double m = (l + h) / 2, f = p(m);
                if ((f <= 0) ^ sign) l = m;
                else h = m;
            } // b69f41
            ret.push_back((l + h) / 2);
        } // fc22f0
    } // d15986
    return ret;
} // b00bfe
```

PolyInterpolate.h

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

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

typedef vector<double> vd;
vd interpolate(vd x, vd y, int n) {
 vd res(n), temp(n);
 rep(k, 0, n-1) rep(i, k+1, n)
 y[i] = (y[i] - y[k]) / (x[i] - x[k]);
 double last = 0; temp[0] = 1;
 rep(k, 0, n) rep(i, 0, n) {
 res[i] += y[k] * temp[i];
 swap(last, temp[i]);
 temp[i] -= last * x[k];
 } // 4c74fe
 return res;
} // 285367

3.1.3 Recurrences and Sums

BerlekampMassey.h

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

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

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

./math/ModPow.h" 96548b, 17 lines

```
vector<ll> berlekampMassey(vector<ll> s) {
    int n = sz(s), L = 0, m = 0;
    vector<ll> C(n), B(n), T;
    C[0] = B[0] = 1, ll b = 1;
    rep(i, 0, n) { ++m;
        ll d = s[i] % mod;
        rep(j, 1, L+1) d = (d + C[j] * s[i - j]) % mod;
        if (!d) continue;
        T = C; ll coef = d * modpow(b, mod-2) % mod;
        rep(j, m, n) C[j] = (C[j] - coef * B[j - m]) % mod;
        if (2 * L > i) continue;
        L = i + 1 - L; B = T; b = d; m = 0;
    } // 8c2376
    C.resize(L + 1); C.erase(C.begin());
    for (ll& x : C) x = (mod - x) % mod;
    return C;
} // 96548b
```

LinearRecurrence.h

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

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

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

f4e444, 21 lines

```
typedef vector<ll> Poly;
ll linearRec(Poly S, Poly tr, ll k) {
    int n = sz(tr);
    auto combine = [&](Poly a, Poly b) {
        Poly res(n * 2 + 1);
        rep(i, 0, n+1) rep(j, 0, n+1)
            res[i + j] = (res[i + j] + a[i] * b[j]) % mod;
        for (int i = 2 * n; i > n; --i) rep(j, 0, n)
            res[i - 1 - j] = (res[i - 1 - j] + res[i] * tr[j]) % mod;
        res.resize(n + 1);
        return res;
    }; // 55c8ab
    Poly pol(n + 1), e(pol); pol[0] = e[1] = 1;
    for (++k; k; k /= 2) {
        if (k % 2) pol = combine(pol, e);
        e = combine(e, e);
    } // 8137be
    ll res = 0;
    rep(i, 0, n) res = (res + pol[i + 1] * S[i]) % mod;
    return res;
} // 5948dc
```

FloorModSum.h

Description: Floor sum and Mod sum.

modsum(to, c, k, m) = $\sum_{i=0}^{to-1} (ki + c) \% m$. divsum is similar but for floored division.

Time: $\log(m)$, with a large constant.

5c5bc5, 16 lines

typedef unsigned long long ull;

ull sumsq(ull to) { return to / 2 * ((to-1) + 1); }

```
ull divsum(ull to, ull c, ull k, ull m) {
    ull res = k / m * sumsq(to) + c / m * to;
    k %= m; c %= m;
} // 2fe74a
```

```
if (!k) return res;
ull to2 = (to * k + c) / m;
return res + (to - 1) * to2 - divsum(to2, m-1 - c, m, k);
} // 78bfc8

11 modsum(ull to, 11 c, 11 k, 11 m) {
    c = ((c % m) + m) % m;
    k = ((k % m) + m) % m;
    return to * c + k * sumsq(to) - m * divsum(to, c, k, m);
} // 5daf3e
```

3.2 Optimization

3.2.1 Fractions and Real Numbers

FracBinarySearch.h

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

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

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

27ab3e, 25 lines

```
struct Frac { 11 p, q; };

template<class F>
Frac fracBS(F f, 11 N) {
    bool dir = 1, A = 1, B = 1;
    Frac lo{0, 1}, hi{1, 1}; // Set hi to 1/0 to search (0, N]
    if (f(lo)) return lo;
    assert(f(hi));
    while (A || B) {
        ll adv = 0, step = 1; // move hi if dir, else lo
        for (int si = 0; step; (step *= 2) >>= si) {
            adv += step;
            Frac mid{lo.p * adv + hi.p, lo.q * adv + hi.q};
            if (abs(mid.p) > N || mid.q > N || dir == !f(mid)) {
                adv -= step; si = 2;
            } // cacde6
        } // d6d2f6
        hi.p += lo.p * adv;
        hi.q += lo.q * adv;
        dir = !dir;
        swap(lo, hi);
        A = B; B = !!adv;
    } // 7df851
    return dir ? hi : lo;
} // ef9d52
```

GoldenSectionSearch.h

Description: Finds the argument minimizing the function f in the interval $[a, b]$ assuming f is unimodal on the interval, i.e. has only one local minimum and no local maximum. The maximum error in the result is eps . Works equally well for maximization with a small change in the code. See TernarySearch.h in the Various chapter for a discrete version.

Usage: double func(double x) { return 4*x+.3*x*x; }

double xmin = gss(-1000, 1000, func);

Time: $\mathcal{O}(\log((b - a)/\epsilon))$

31d45b, 14 lines

```
double gss(double a, double b, double (*f)(double)) {
    double r = (sqrt(5)-1)/2, eps = 1e-7;
    double x1 = b - r*(b-a), x2 = a + r*(b-a);
    double f1 = f(x1), f2 = f(x2);
    while (b-a > eps) {
        if (f1 < f2) { //change to > to find maximum
            b = x2; x2 = x1; f2 = f1;
            x1 = b - r*(b-a); f1 = f(x1);
        } else { // 4513d0
            a = x1; x1 = x2; f1 = f2;
            x2 = a + r*(b-a); f2 = f(x2);
        } // 2fe74a
    }
}
```

```
return a;
} // 31d45b
```

ContinuedFractions.h

Description: Given N and a real number $x \geq 0$, finds the closest rational approximation p/q with $p, q \leq N$. It will obey $|p/q - x| \leq 1/qN$.

For consecutive convergents, $p_{k+1}q_k - q_{k+1}p_k = (-1)^k$. (p_k/q_k alternates between $> x$ and $< x$) If x is rational, y eventually becomes ∞ ; if x is the root of a degree 2 polynomial the a 's eventually become cyclic.

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

dd6c5e, 21 lines

```
typedef double d; // for N ~ 1e7; long double for N ~ 1e9
pair<11, 11> approximate(d x, 11 N) {
    11 LP = 0, LQ = 1, P = 1, Q = 0, inf = LLONG_MAX; d y = x;
    for (;;) {
        11 lim = min(P ? (N-LP) / P : inf, Q ? (N-LQ) / Q : inf),
            a = (11)floor(y), b = min(a, lim),
            NP = b*P + LP, NQ = b*Q + LQ;
        if (a > b) {
            // If b > a/2, we have a semi-convergent that gives us a
            // better approximation; if b = a/2, we *may* have one.
            // Return {P, Q} here for a more canonical approximation.
            return (abs(x - (d)NP / (d)NQ) < abs(x - (d)P / (d)Q)) ?
                make_pair(NP, NQ) : make_pair(P, Q);
        } // 3abeb0
    } // 2f
```

3.2.2 Functions and Calculus

Integrate.h/8b

Description: Simple integration of a function over an interval using Simpson's rule. The error should be proportional to h^4 , although in practice you will want to verify that the result is stable to desired precision when epsilon changes. 1f58 4756fc, 7 lines

```
template<class F>
double quad(double a, double b, F f, const int n = 1000) {
    double h = (b - a) / 2 / n, v = f(a) + f(b);
    rep(i, 1, n*2)
        v += f(a + i*h) * (i&1 ? 4 : 2);
    return v * h / 3;
} // ddce2
```

IntegrateAdaptive.h

Description: Fast integration using an adaptive Simpson's rule.

Usage: double sphereVolume = quad(-1, 1, []()double x) {
 return quad(-1, 1, [&]double y) {
 return quad(-1, 1, [&]double z) {
 return x*x + y*y + z*z < 1; });
 };
} // 92dd79, 15 lines

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

template <class F>

```
d rec(F& f, d a, d b, d eps, d S) {
    d c = (a + b) / 2;
    d S1 = S(a, c), S2 = S(c, b), T = S1 + S2;
    if (abs(T - S) <= 15 * eps || b - a < 1e-10)
        return T + (T - S) / 15;
    return rec(f, a, c, eps / 2, S1) + rec(f, c, b, eps / 2, S2);
} // 720738
```

template<class F>

```
d quad(d a, d b, F f, d eps = 1e-8) {
    return rec(f, a, b, eps, S(a, b));
```

```
} // 1e3820
```

Simplex.h

Description: Solves a general linear maximization problem: maximize $c^T x$ subject to $Ax \leq b$, $x \geq 0$. Returns -inf if there is no solution, inf if there are arbitrarily good solutions, or the maximum value of $c^T x$ otherwise. The input vector is set to an optimal x (or in the unbounded case, an arbitrary solution fulfilling the constraints). Numerical stability is not guaranteed. For better performance, define variables such that $x = 0$ is viable.

Usage: vvd A = {{1,-1}, {-1,1}, {-1,-2}};

vd b = {1,1,-4}, c = {-1,-1}, x;

T val = LPSolver(A, b, c).solve(x);

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

aa8530, 68 lines

```
typedef double T; // long double, Rational, double + modP>...
```

```
typedef vector<T> vd;
```

```
typedef vector<vd> vvd;
```

```
const T eps = 1e-8, inf = 1/.0;
```

```
#define MP make_pair
```

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

```
struct LPSolver {
```

```
int m, n;
```

```
vi N, B;
```

```
vvd D;
```

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

// 6ff8e9

```
void pivot(int r, int s) {
```

```
    T *a = D[r].data(), inv = 1 / a[s];
    rep(i,0,m+2) if (i != r && abs(D[i][s]) > eps) {
        T *b = D[i].data(), inv2 = b[s] * inv;
        rep(j,0,n+2) b[j] -= a[j] * inv2;
        b[s] = a[s] * inv2;
    } // ca4460
    rep(j,0,n+2) if (j != s) D[r][j] *= inv;
    rep(i,0,m+2) if (i != r) D[i][s] *= -inv;
    D[r][s] = inv;
    swap(B[r], N[s]);
}
```

// 9cd0a8

```
bool simplex(int phase) {
    int x = m + phase - 1;
    for (;;) {

```

```
        int s = -1;

```

```
        rep(j,0,n+1) if (N[j] != -phase) ltj(D[x]);

```

```
        if (D[x][s] >= -eps) return true;

```

```
        int r = -1;

```

```
        rep(i,0,m) {

```

```
            if (D[i][s] <= eps) continue;

```

```
            if (r == -1 || MP(D[i][n+1] / D[i][s], B[i])
                < MP(D[r][n+1] / D[r][s], B[r])) r = i;

```

} // 46853f

```
        if (r == -1) return false;

```

```
        pivot(r, s);

```

} // 7d839b

} // f15644

```
T solve(vd &x) {
    int r = 0;

```

```
    rep(i,1,m) if (D[i][n+1] < D[r][n+1]) r = i;

```

```
if (D[r][n+1] < -eps) {
    pivot(r, n);
    if (!simplex(2) || D[m+1][n+1] < -eps) return -inf;
    rep(i,0,m) if (B[i] == -1) {
        int s = 0;
        rep(j,1,n+1) ltj(D[i]);
        pivot(i, s);
    } // 683310
} // b6559f
bool ok = simplex(1); x = vd(n);
rep(i,0,m) if (B[i] < n) x[B[i]] = D[i][n+1];
return ok ? D[m][n+1] : inf;
} // 396a95
}; // c57b35
```

HillClimbing.h

Description: Poor man's optimization for unimodal functions.

Seeefaf, 14 lines

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

```
template<class F> pair<double, P> hillClimb(P start, F f) {
    pair<double, P> cur(f(start), start);
    for (double jmp = 1e9; jmp > 1e-20; jmp /= 2) {
        rep(j,0,100) rep(dx,-1,2) rep(dy,-1,2) {
            P p = cur.second;
            p[0] += dx*jmp;
            p[1] += dy*jmp;
            cur = min(cur, make_pair(f(p), p));
        } // cc6436
    } // 8d9318
    return cur;
} // 75cdd9
```

3.3 Matrices

3.3.1 General

Determinant.h

Description: Calculates determinant of a matrix. Destroys the matrix.

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

bd5cec, 15 lines

```
double det(vector<vector<double>>& a) {
    int n = sz(a); double res = 1;
    rep(i,0,n) {
        int b = i;
        rep(j,i+1,n) if (fabs(a[j][i]) > fabs(a[b][i])) b = j;
        if (i != b) swap(a[i], a[b]), res *= -1;
        res *= a[i][i];
        if (res == 0) return 0;
        rep(j,i+1,n) {
            double v = a[j][i] / a[i][i];
            if (v != 0) rep(k,i+1,n) a[j][k] -= v * a[i][k];
        } // 4ec6a2
    } // ee1466
    return res;
} // bd5cec
```

IntDeterminant.h

Description: Calculates determinant using modular arithmetics. Modulos can also be removed to get a pure-integer version.

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

3313dc, 18 lines

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

```

```
                    a[i][k] = (a[i][k] - a[j][k] * t) % mod;
                    swap(a[i], a[j]);
                    ans *= -1;
            } // e81b29
        } // 30d1b2
        ans = ans * a[i][i] % mod;
        if (!ans) return 0;
    } // f39a45
    return (ans + mod) % mod;
} // 5e85f0
```

MatrixInverse.h

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

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

ebfff6, 35 lines

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

    rep(i,0,n) {
        int r = i, c = i;
        rep(j,i,n) rep(k,i,n)
            if (fabs(A[j][k]) > fabs(A[r][c]))
                r = j, c = k;
        if (fabs(A[r][c]) < 1e-12) return i;
        A[i].swap(A[r]); tmp[i].swap(tmp[r]);
        rep(j,0,n)
            swap(A[j][i], A[j][c]), swap(tmp[j][i], tmp[j][c]);
        swap(col[i], col[c]);
        double v = A[i][i];
        rep(j,i+1,n) {
            double f = A[j][i] / v;
            A[j][i] = 0;
            rep(k,i+1,n) A[j][k] -= f*A[i][k];
            rep(k,0,n) tmp[j][k] -= f*tmp[i][k];
        } // ebeea3
        rep(j,i+1,n) A[i][j] /= v;
        rep(j,0,n) tmp[i][j] /= v;
        A[i][i] = 1;
    } // 26d90b

    for (int i = n-1; i > 0; --i) rep(j,0,i) {
        double v = A[j][i];
        rep(k,0,n) tmp[j][k] -= v*tmp[i][k];
    } // 03ae0c

    rep(i,0,n) rep(j,0,n) A[col[i]][col[j]] = tmp[i][j];
    return n;
} // ebfff6
```

3.3.2 Linear Systems

SolveLinear.h

Description: Solves $A * x = b$. If there are multiple solutions, an arbitrary one is returned. Returns rank, or -1 if no solutions. Data in A and b is lost.

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

44c9ab, 38 lines

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

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

    rep(i,0,n) {
```

```

double v, bv = 0;
rep(r,i,n) rep(c,i,m)
    if ((v = fabs(A[r][c])) > bv)
        br = r, bc = c, bv = v;
if (bv <= eps) {
    rep(j,i,n) if (fabs(b[j]) > eps) return -1;
    break;
} // c92205
swap(A[i], A[br]);
swap(b[i], b[br]);
swap(col[i], col[bc]);
rep(j,0,n) swap(A[j][i], A[j][bc]);
bv = 1/A[i][i];
rep(j,i+1,n) {
    double fac = A[j][i] * bv;
    b[j] -= fac * b[i];
    rep(k,i+1,m) A[j][k] -= fac*A[i][k];
} // 881860
rank++;
} // 0f0f0f

x.assign(m, 0);
for (int i = rank; i--;) {
    b[i] /= A[i][i];
    x[col[i]] = b[i];
    rep(j,0,i) b[j] -= A[j][i] * b[i];
} // ed1d08
return rank; // (multiple solutions if rank < m)
} // ade67b

```

SolveLinear2.h

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

"SolveLinear.h" 08e495, 7 lines

```

rep(j,0,n) if (j != i) // instead of rep(j, i+1,n)
// ... then at the end:
x.assign(m, undefined);
rep(i,0,rank) {
    rep(j,rank,m) if (fabs(A[i][j]) > eps) goto fail;
    x[col[i]] = b[i] / A[i][i];
fail; } // 87878c

```

SolveLinearBinary.h

Description: Solves $Ax = b$ over \mathbb{F}_2 . If there are multiple solutions, one is returned arbitrarily. Returns rank, or -1 if no solutions. Destroys A and b .

Time: $\mathcal{O}(n^2m)$ fa2d7a, 34 lines

typedef bitset<1000> bs;

```

int solveLinear(vector<bs>& A, vi& b, bs& x, int m) {
    int n = sz(A), rank = 0, br;
    assert(m <= sz(x));
    vi col(m); iota(all(col), 0);
    rep(i,0,n) {
        for (br=i; br<n; ++br) if (A[br].any()) break;
        if (br == n) {
            rep(j,i,n) if(b[j]) return -1;
            break;
        } // 80687c
        int bc = (int)A[br]._Find_next(i-1);
        swap(A[i], A[br]);
        swap(b[i], b[br]);
        swap(col[i], col[bc]);
        rep(j,0,n) if (A[j][i] != A[j][bc]) {
            A[j].flip(i); A[j].flip(bc);
        } // b44a9b
        rep(j,i+1,n) if (A[j][i]) {
            b[j] ^= b[i];
            A[j] ^= A[i];
        }
    }
}

```

```

} // 87192e
rank++;
} // fe9281

x = bs();
for (int i = rank; i--;) {
    if (!b[i]) continue;
    x[col[i]] = 1;
    rep(j,0,i) b[j] ^= A[j][i];
} // 8fdab1
return rank; // (multiple solutions if rank < m)
} // 26d73e

```

Tridiagonal.h

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

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

This is useful for solving problems on the type

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

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

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

Fails if the solution is not unique.

If $|d_i| > |p_i| + |q_{i-1}|$ for all i , or $|d_i| > |p_{i-1}| + |q_i|$, or the matrix is positive definite, the algorithm is numerically stable and neither tr nor the check for $\text{diag}[i] == 0$ is needed.

Time: $\mathcal{O}(N)$ 8f9fa8, 26 lines

```

typedef double T;
vector<T> tridiagonal(vector<T> diag, const vector<T>& super,
const vector<T>& sub, vector<T> b) {
    int n = sz(b); vi tr(n);
    rep(i,0,n-1) {
        if (abs(diag[i]) < 1e-9 * abs(super[i])) { // diag[i] == 0
            b[i+1] -= b[i] * diag[i+1] / super[i];
            if (i+2 < n) b[i+2] -= b[i] * sub[i+1] / super[i];
            diag[i+1] = sub[i]; tr[++i] = 1;
        } else { // 464c09
            diag[i+1] -= super[i]*sub[i]/diag[i];
            b[i+1] -= b[i]*sub[i]/diag[i];
        } // 62de5a
    } // ed9cce
    for (int i = n; i--;) {
        if (tr[i]) {
            swap(b[i], b[i-1]);
            diag[i-1] = diag[i];
            b[i] /= super[i-1];
        } else { // 0543e4
            b[i] /= diag[i];
            if (i) b[i-1] -= b[i]*super[i-1];
        } // aa91c6
    } // 28af28
    return b;
} // 06d549

```

3.4 Convolutions

FastFourierTransform.h

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

Time: $\mathcal{O}(N \log N)$ with $N = |A| + |B|$ ($\sim 1s$ for $N = 2^{22}$) 00ced6, 35 lines

```

typedef complex<double> C;
typedef vector<double> vd;
void fft(vector<C>& a) {
    int n = sz(a), L = 31 - __builtin_clz(n);
    static vector<complex<long double>> R(2, 1);
    static vector<C> rt(2, 1); // (^ 10% faster if double)
    for (static int k = 2; k < n; k *= 2) {
        R.resize(n); R.resize(n);
        auto x = polar(1.0L, acos(-1.0L) / k);
        rep(i,k,2*k) rt[i] = R[i] = i&1 ? R[i/2] * x : R[i/2];
    } // a8a74e
    vi rev(n);
    rep(i,0,n) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
    rep(i,0,n) if (i < rev[i]) swap(a[i], a[rev[i]]);
    for (int k = 1; k < n; k *= 2)
        for (int i = 0; i < n; i += 2 * k) rep(j,0,k) {
            C z = rt[j+k] * a[i+j+k]; // (25% faster if hand-rolled)
            a[i + j + k] = a[i + j] - z;
            a[i + j] += z;
        } // 577e9c
    } // 01fd0d
    vd conv(const vd& a, const vd& b) {
        if (a.empty() || b.empty()) return {};
        vd res(sz(a) + sz(b) - 1);
        int L = 32 - __builtin_clz(sz(res)), n = 1 << L;
        vector<C> in(n), out(n);
        copy(all(a), begin(in));
        rep(i,0,sz(b)) in[i].imag(b[i]);
        fft(in);
        for (C& x : in) x *= x;
        rep(i,0,n) out[i] = in[-i & (n - 1)] - conj(in[i]);
        fft(out);
        rep(i,0,sz(res)) res[i] = imag(out[i]) / (4 * n);
        return res;
    } // 873509

```

FastFourierTransformMod.h

Description: Higher precision FFT, can be used for convolutions modulo arbitrary integers as long as $N \log_2 N \cdot \text{mod} < 8.6 \cdot 10^{14}$ (in practice 10^{16} or higher). Inputs must be in $[0, \text{mod}]$.

Time: $\mathcal{O}(N \log N)$, where $N = |A| + |B|$ (twice as slow as NTT or FFT)

"FastFourierTransform.h" b82773, 22 lines

```

typedef vector<ll> vl;
template<int M> vl convMod(const vl &a, const vl &b) {
    if (a.empty() || b.empty()) return {};
    vl res(sz(a) + sz(b) - 1);
    int B=32-__builtin_clz(sz(res)), n=1<<B, cut=__sqrt(M);
    vector<C> L(n), R(n), outs(n), outl(n);
    rep(i,0,sz(a)) L[i] = C((int)a[i] / cut, (int)a[i] % cut);
    rep(i,0,sz(b)) R[i] = C((int)b[i] / cut, (int)b[i] % cut);
    fft(L), fft(R);
    rep(i,0,n) {
        int j = -i & (n - 1);
        outl[j] = (L[i] + conj(L[j])) * R[i] / (2.0 * n);
        outs[j] = (L[i] - conj(L[j])) * R[i] / (2.0 * n) / li;
    } // cb3017
    fft(outl), fft(outs);
    rep(i,0,sz(res)) {
        ll av = ll(real(outl[i])+.5), cv = ll(imag(outs[i])+.5);
        ll bv = ll(imag(outl[i])+.5) + ll(real(outs[i])+.5);
        res[i] = ((av % M * cut + bv) % M * cut + cv) % M;
    }
}

```

```
} // 58fa4f
return res;
} // c1f2f1
```

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

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

`.../math/ModPow.h` ced03d, 35 lines

```
const ll mod = (119 << 23) + 1, root = 62; // = 998244353
// For p < 2^30 there is also e.g. 5 << 25, 7 << 26, 479 << 21
// and 483 << 21 (same root). The last two are > 10^9.
typedef vector<ll> vl;
void ntt(vl &a) {
    int n = sz(a), L = 31 - __builtin_clz(n);
    static vl rt(2, 1);
    for (static int k = 2, s = 2; k < n; k *= 2, s++) {
        rt.resize(n);
        ll z[] = {1, modpow(root, mod >> s)};
        rep(i, k, 2*k) rt[i] = rt[i / 2] * z[i & 1] % mod;
    } // f39127
    vi rev(n);
    rep(i, 0, n) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
    rep(i, 0, n) if (i < rev[i]) swap(a[i], a[rev[i]]);
    for (int k = 1; k < n; k *= 2)
        for (int i = 0; i < n; i += 2 * k) rep(j, 0, k) {
            ll z = rt[j + k] * a[i + j + k] % mod, &ai = a[i + j];
            a[i + j + k] = ai - z + (z > ai ? mod : 0);
            ai += (ai + z >= mod ? z - mod : z);
        } // 9a8565
    } // 3b763b
vl conv(const vl &a, const vl &b) {
    if (a.empty() || b.empty()) return {};
    int s = sz(a) + sz(b) - 1, B = 32 - __builtin_clz(s),
        n = 1 << B;
    int inv = modpow(n, mod - 2);
    vl L(a), R(b), out(n);
    L.resize(n), R.resize(n);
    ntt(L, ntt(R));
    rep(i, 0, n)
        out[-i & (n - 1)] = (ll)L[i] * R[i] % mod * inv % mod;
    ntt(out);
    return {out.begin(), out.begin() + s};
} // 3876bf
```

FastSubsetTransform.h

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

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

464cf3, 16 lines

```
void FST(vi &a, bool inv) {
    for (int n = sz(a), step = 1; step < n; step *= 2) {
        for (int i = 0; i < n; i += 2 * step) rep(j, i + step) {
            int &u = a[j], &v = a[j + step]; tie(u, v) =
                inv ? pii(v - u, u) : pii(v, u + v); // AND
                inv ? pii(v, u - v) : pii(u + v, u); // OR
                pii(u + v, u - v); // XOR
        } // 7b7e71
    } // faec61
    if (inv) for (int &x : a) x /= sz(a); // XOR only
} // 57eeaf
vi conv(vi a, vi b) {
```

```
FST(a, 0); FST(b, 0);
rep(i, 0, sz(a)) a[i] *= b[i];
FST(a, 1); return a;
} // 3cbd18
```

3.5 Number Theory

3.5.1 Modular Arithmetic

CRT.h

Description: Chinese Remainder Theorem.

`crt(a, m, b, n)` computes x such that $x \equiv a \pmod{m}$, $x \equiv b \pmod{n}$. If $|a| < m$ and $|b| < n$, x will obey $0 \leq x < \text{lcm}(m, n)$. Assumes $mn < 2^{62}$.

Time: $\log(n)$

`.../math/ModPow.h` 04d93a, 7 lines

```
ll crt(ll a, ll m, ll b, ll n) {
    if (n > m) swap(a, b), swap(m, n);
    ll x, y, g = euclid(m, n, x, y);
    assert((a - b) % g == 0); // else no solution
    x = (b - a) % n * x % n / g * m + a;
    return x < 0 ? x + m*n/g : x;
} // 04d93a
```

ModPow.h

b83e45, 7 lines

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

```
11 modpow(ll b, ll e) {
    ll ans = 1;
    for (; e; b = b * b % mod, e /= 2)
        if (e & 1) ans = ans * b % mod;
    return ans;
} // d1ec54
```

ModMuLL.h

Description: Calculate $a \cdot b \pmod{c}$ (or $a^b \pmod{c}$) 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, 11 lines

```
typedef unsigned long long ull;
ull modmul(ull a, ull b, ull M) {
    ll ret = a * b - M * ull(1.L / M * a * b);
    return ret + M * (ret < 0) - M * (ret >= (ll)M);
} // e9309c
ull modpow(ull b, ull e, ull mod) {
    ull ans = 1;
    for (; e; b = modmul(b, b, mod), e /= 2)
        if (e & 1) ans = modmul(ans, b, mod);
    return ans;
} // 100b91
```

ModLog.h

Description: Returns the smallest $x > 0$ s.t. $a^x \equiv b \pmod{m}$, or -1 if no such x exists. `modLog(a, 1, m)` can be used to calculate the order of a .

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

c040b8, 11 lines

```
11 modLog(ll a, ll b, ll m) {
    11 n = (11) sqrt(m) + 1, e = 1, f = 1, j = 1;
    unordered_map<ll, 11> A;
    while (j <= n && (e = f = e * a % m) != b % m)
        A[e * b % m] = j++;
    if (e == b % m) return j;
    if (__gcd(m, e) == __gcd(m, b))
        rep(i, 2, n+2) if (A.count(e = e * f % m))
            return n * i - A[e];
    return -1;
} // c040b8
```

ModSqrt.h

Description: Tonelli-Shanks algorithm for modular square roots. Finds x s.t. $x^2 \equiv a \pmod{p}$ ($-x$ gives the other solution).

Time: $\mathcal{O}(\log^2 p)$ worst case, $\mathcal{O}(\log p)$ for most p

`"ModPow.h"`

19a793, 20 lines

```
11 sqrt(ll a, 11 p) {
    a %= p; if (a < 0) a += p;
    if (a == 0) return 0;
    assert(modpow(a, (p-1)/2, p) == 1); // else no solution
    if (p % 4 == 3) return modpow(a, (p+1)/4, p);
    //  $a^{(n+3)/8}$  or  $2^{(n+3)/8} \cdot 2^{(n-1)/4}$  works if  $p \% 8 == 5$ 
    11 s = p - 1, n = 2;
    int r = 0, m;
    while (s % 2 == 0) ++r, s /= 2;
    while (modpow(n, (p - 1) / 2, p) != p - 1) ++n;
    11 x = modpow(a, (s + 1) / 2, p);
    11 b = modpow(a, s, p), g = modpow(n, s, p);
    for (; r = m) {
        11 t = b;
        for (m = 0; m < r && t != 1; ++m) t = t * t % p;
        if (m == 0) return x;
        11 gs = modpow(g, 1LL << (r - m - 1), p);
        g = gs * gs % p; x = x * gs % p; b = b * g % p;
    } // e3aa6f
} // 19a793
```

3.5.2 Primality and Divisibility

FastEratosthenes.h

Description: Prime sieve for generating all primes smaller than `LIM`.

Time: $\text{LIM} = 10^9 \approx 1.5s$

6b2912, 20 lines

```
const int LIM = 1e6;
bitset<LIM> isPrime;
vi eratosthenes() {
    const int S = (int)round(sqrt(LIM)), R = LIM / 2;
    vi pr = {2}, sieve(S+1); pr.reserve(int(LIM/log(LIM)*1.1));
    vector<pii> cp;
    for (int i = 3; i <= S; i += 2) if (!sieve[i]) {
        cp.push_back({i, i * i / 2});
        for (int j = i * i; j <= S; j += 2 * i) sieve[j] = 1;
    } // d22e52
    for (int L = 1; L <= R; L += S) {
        array<bool, S> block{};
        for (auto &p, idx : cp)
            for (int i=idx; i < S+L; idx = (i+=p)) block[i-L] = 1;
        rep(i, 0, min(S, R - L))
            if (!block[i]) pr.push_back((L + i) * 2 + 1);
    } // 5b6623
    for (int i : pr) isPrime[i] = 1;
    return pr;
} // 8ee6d2
```

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 $a^b \pmod{c}$.

`"ModMuLL.h"`

60dc1, 12 lines

```
bool isPrime(ull n) {
    if (n < 2 || n % 6 % 4 != 1) return (n | 1) == 3;
    ull A[] = {2, 325, 9375, 28178, 450775, 9780504, 1795265022},
        s = __builtin_ctzll(n-1), d = n >> s;
    for (ull a : A) { // count trailing zeroes
        ull p = modpow(a, n, d, n), i = s;
        while (p != 1 && p != n - 1 && a % n && i--)
            p = modmul(p, p, n);
        if (p != n-1 && i != s) return 0;
    } // edfaf1
    return 1;
} // 60dc1
```

PollardRho.h

Description: Pollard-rho randomized factorization algorithm. Returns prime factors of a number, in arbitrary order (e.g. 2299 -> {11, 19, 11}).

Time: $\mathcal{O}(n^{1/4})$, less for numbers with small factors.

"ModMull.h", "MillerRabin.h" d8d98d, 18 lines

```
ull pollard(ull n) {
    ull x = 0, y = 0, t = 30, prd = 2, i = 1, q;
    auto f = [&](ull x) { return modmul(x, x, n) + i; };
    while (t++ % 40 || __gcd(prd, n) == 1) {
        if (x == y) x = ++i, y = f(x);
        if ((q = modmul(prd, max(x,y) - min(x,y), n))) prd = q;
        x = f(x), y = f(f(y));
    } // 989d40
    return __gcd(prd, n);
} // cd2ac3
vector<ull> factor(ull n) {
    if (n == 1) return {};
    if (isPrime(n)) return {n};
    ull x = pollard(n);
    auto l = factor(x), r = factor(n / x);
    l.insert(l.end(), all(r));
    return l;
} // d54ba8
```

euclid.h

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

33ba8f, 5 lines

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

phiFunction.h

Description: Euler's ϕ function up to LIM. Note that $\sum_{d|n} \phi(d) = n$, $\sum_{1 \leq k \leq n, \gcd(k,n)=1} k = n\phi(n)/2$, $n > 1$

Time: $\mathcal{O}(n \log \log n)$ cf7d6d, 7 lines

```
const int LIM = 5000000;
int phi[LIM];
void calculatePhi() {
    rep(i, 0, LIM) phi[i] = i&1 ? i : i/2;
    for (int i = 3; i < LIM; i += 2) if(phi[i] == i)
        for (int j = i; j < LIM; j += i) phi[j] -= phi[j] / i;
} // 04349b
```

Geometry (4)

4.1 Geometric primitives

Point.h

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

47ec0a, 28 lines

```
template <class T> int sgn(T x) { return (x > 0) - (x < 0); }
template <class T>
struct Point {
    typedef Point P;
    T x, y;
    explicit Point(T x=0, T y=0) : x(x), y(y) {}
    bool operator<(P p) const { return tie(x,y) < tie(p.x,p.y); }
    bool operator==(P p) const { return tie(x,y)==tie(p.x,p.y); }
    P operator+(P p) const { return P(x+p.x, y+p.y); }
    P operator-(P p) const { return P(x-p.x, y-p.y); }
    P operator*(T d) const { return P(x*d, y*d); }
```

```
P operator/(T d) const { return P(x/d, y/d); }
T dot(P p) const { return x*p.x + y*p.y; }
T cross(P p) const { return x*p.y - y*p.x; }
T cross(P a, P b) const { return (a-*this).cross(b-*this); }
T dist2() const { return x*x + y*y; }
double dist() const { return sqrt((double)dist2()); }
// angle to x-axis in interval [-pi, pi]
double angle() const { return atan2(y, x); }
P unit() const { return *this/dist(); } // makes dist()==1
P perp() const { return P(-y, x); } // rotates +90 degrees
P normal() const { return perp().unit(); }
// returns point rotated 'a' radians ccw around the origin
P rotate(double a) const {
    return P(x*cos(a)-y*sin(a), x*sin(a)+y*cos(a)); } // 4822a3
friend ostream& operator<<(ostream& os, P p) {
    return os << "(" << p.x << "," << p.y << ")"; } // 9a9c95
}; // d2d691
```

lineDistance.h

Description:

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

"point.h" f6bf6b, 4 lines

```
template<class P>
double lineDist(const P& a, const P& b, const P& p) {
    return (double)(b-a).cross(p-a)/(b-a).dist();
} // 00891c
```

SegmentDistance.h

Description:

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

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

"point.h" 5c88f4, 6 lines

```
typedef Point<double> P;
double segDist(P& s, P& e, P& p) {
    if (s==e) return (p-s).dist();
    auto d = (e-s).dist2(), t = min(d, max(.0, (p-s).dot(e-s)));
    return ((p-s)*d-(e-s)*t).dist()/d;
} // ac751a
```

SegmentIntersection.h

Description:

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

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

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

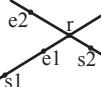
```
template<class P> vector<P> segInter(P a, P b, P c, P d) {
    auto oa = c.cross(d, a), ob = c.cross(d, b),
          oc = a.cross(b, c), od = a.cross(b, d);
    // Checks if intersection is single non-endpoint point.
    if (sgn(oa) * sgn(ob) < 0 && sgn(oc) * sgn(od) < 0)
```

```
return {(a * ob - b * oa) / (ob - oa)};
set<P> s;
if (onSegment(c, d, a)) s.insert(a);
if (onSegment(c, d, b)) s.insert(b);
if (onSegment(a, b, c)) s.insert(c);
if (onSegment(a, b, d)) s.insert(d);
return {all(s)};
} // 9d57f2
```

lineIntersection.h

Description:

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



Usage: `auto res = lineInter(s1,e1,s2,e2);`

```
if (res.first == 1)
    cout << "intersection point at " << res.second << endl;
"Point.h" a01f81, 8 lines
```

template<class P>

```
pair<int, P> lineInter(P s1, P e1, P s2, P e2) {
    auto d = (e1 - s1).cross(e2 - s2);
    if (d == 0) // if parallel
        return {-1, (s1.cross(e1, s2) == 0, P(0, 0))};
    auto p = s2.cross(e1, e2), q = s2.cross(e2, s1);
    return {1, (s1 * p + e1 * q) / d};
} // 47279a
```

sideOf.h

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

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

"Point.h" 3af81c, 9 lines

template<class P>

int sideOf(P s, P e, P p) { return sgn(s.cross(e, p)); }

template<class P>

```
int sideOf(const P& s, const P& e, const P& p, double eps) {
    auto a = (e-s).cross(p-s);
    double l = (e-s).dist()*eps;
    return (a > l) - (a < -l);
} // 33fa03
```

OnSegment.h

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

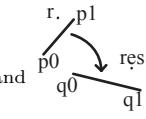
"Point.h" c597e8, 3 lines

```
template<class P> bool onSegment(P s, P e, P p) {
    return p.cross(s, e) == 0 && (s - p).dot(e - p) <= 0;
} // c597e8
```

linearTransformation.h

Description:

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



"Point.h" 03a306, 6 lines

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

```
return q0 + P((r-p0).cross(num), (r-p0).dot(num))/dp.dist2();
} // 45ea01
```

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`

of0602, 35 lines

```
struct Angle {
    int x, y;
    int t;
    Angle(int x, int y, int t=0) : x(x), y(y), t(t) {}
    Angle operator-(Angle b) const { return {x-b.x, y-b.y, t}; }
    int half() const {
        assert(x || y);
        return y < 0 || (y == 0 && x < 0);
    } // c935fb
    Angle t90() const { return {-y, x, t + (half() && x >= 0)}; }
    Angle t180() const { return {-x, -y, t + half()}; }
    Angle t360() const { return {x, y, t + 1}; }
}; // e258c0
bool operator<(Angle a, Angle b) {
    // add a.dist2() and b.dist2() to also compare distances
    return make_tuple(a.t, a.half(), a.y * (ll)b.x) <
           make_tuple(b.t, b.half(), a.x * (ll)b.y);
} // ce5ed3
```

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

```
pair<Angle, Angle> segmentAngles(Angle a, Angle b) {
    if (b < a) swap(a, b);
    return (b < a.t180() ?
            make_pair(a, b) : make_pair(b, a.t360()));
} // 5eac29
Angle operator+(Angle a, Angle b) { // point a + vector b
    Angle r(a.x + b.x, a.y + b.y, a.t);
    if (a.t180() < r.r.t--) r.r.t--;
    return r.t180() < a ? r.t360() : r;
} // 3d8073
Angle angleDiff(Angle a, Angle b) { // angle b - angle a
    int tu = b.t - a.t; a.t = b.t;
    return (a.x*b.x + a.y*b.y, a.x*b.y - a.y*b.x, tu - (b < a));
} // ba3082
```

4.2 Circles

CircleIntersection.h

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

```
"Point.h" 84d6d3, 11 lines
```

```
typedef Point<double> P;
bool circleInter(P a,P b,double r1,double r2,pair<P, P*>* out) {
    if (a == b) { assert(r1 != r2); return false; }
    P vec = b - a;
    double d2 = vec.dist2(), sum = r1+r2, dif = r1-r2,
           p = (d2 + r1*r1 - r2*r2)/(d2*2), h2 = r1*r1 - p*p*d2;
    if (sum*sum < d2 || dif*dif > d2) return false;
    P mid = a + vec*p, per = vec.perp() * sqrt(fmax(0, h2) / d2);
    *out = {mid + per, mid - per};
    return true;
} // c64785
```

CircleTangents.h

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

```
"Point.h" b0153d, 13 lines
template<class P>
vector<pair<P, P>> tangents(P c1, double r1, P c2, double r2) {
    P d = c2 - c1;
    double dr = r1 - r2, d2 = d.dist2(), h2 = d2 - dr * dr;
    if (dr == 0 || h2 < 0) return {};
    vector<pair<P, P>> out;
    for (double sign : {-1, 1}) {
        P v = (d * dr + d.perp() * sqrt(h2) * sign) / d2;
        out.push_back({c1 + v * r1, c2 + v * r2});
    } // e25263
    if (h2 == 0) out.pop_back();
    return out;
} // 4835b9
```

CirclePolygonIntersection.h

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

```
".../content/geometry/Point.h" 19add1, 19 lines
typedef Point<double> P;
#define arg(p, q) atan2(p.cross(q), p.dot(q))
double circlePoly(P c, double r, vector<P> ps) {
    auto tri = [&](P p, P q) {
        auto r2 = r * r / 2;
        P d = q - p;
        auto a = d.dot(p)/d.dist2(), b = (p.dist2()-r*r)/d.dist2();
        auto det = a * a - b;
        if (det <= 0) return arg(p, q) * r2;
        auto s = max(0., -a-sqrt(det)), t = min(1., -a+sqrt(det));
        if (t < 0 || 1 <= s) return arg(p, q) * r2;
        P u = p + d * s, v = q + d * (t-1);
        return arg(p,u) * r2 + u.cross(v)/2 + arg(v,q) * r2;
    }; // a526f
    auto sum = 0.0;
    rep(i,0,sz(ps))
        sum += tri(ps[i] - c, ps[(i + 1) % sz(ps)] - c);
    return sum;
} // f082e0
```

circumcircle.h

Description:

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

```
"Point.h" 1caa3a, 9 lines
```

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

```
"circumcircle.h" 09dd0a, 17 lines
pair<P, double> mec(vector<P> ps) {
    shuffle(all(ps), mt19937(time(0)));
    P o = ps[0];
    double r = 0, EPS = 1 + 1e-8;
    rep(i,0,sz(ps)) if ((o - ps[i]).dist() > r * EPS) {
        o = ps[i], r = 0;
    } if ((o - ps[j]).dist() > r * EPS) {
        o = (ps[i] + ps[j]) / 2;
        r = (o - ps[i]).dist();
    } if ((o - ps[k]).dist() > r * EPS) {
        o = ccCenter(ps[i], ps[j], ps[k]);
        r = (o - ps[i]).dist();
    } // 64802f
} // 7b0ecf
} // dcf0de
return {o, r};
} // 09dd0a
```

4.3 Polygons

InsidePolygon.h

Description: Returns true if p lies within the polygon. If strict is true, it returns false for points on the boundary. The algorithm uses products in intermediate steps so watch out for overflow.

Usage: `vector<P> v = {P{4,4}, P{1,2}, P{2,1}};`
`bool in = inPolygon(v, P{3, 3}, false);`

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

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

```
template<class P>
bool inPolygon(vector<P> &p, P a, bool strict = true) {
    int cnt = 0, n = sz(p);
    rep(i,0,n) {
        P q = p[(i + 1) % n];
        if (onSegment(p[i], q, a)) return !strict;
        //or: if (segDist(p[i], q, a) <= eps) return !strict;
        cnt ^= ((a.y<p[i].y) - (a.y<q.y)) * a.cross(p[i], q) > 0;
    } // 1b9961
    return cnt;
} // c7225e
```

PolygonArea.h

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

```
"Point.h" f12300, 6 lines
```

template<class T>

```
T polygonArea2(vector<Point<T>>& v) {
    T a = v.back().cross(v[0]);
    rep(i,0,sz(v)-1) a += v[i].cross(v[i+1]);
    return a;
} // 6939b3
```

PolygonCenter.h

Description: Returns the center of mass for a polygon.

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

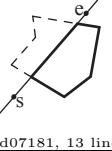
```
"Point.h" 9706dc, 9 lines
typedef Point<double> P;
P polygonCenter(const vector<P>& v) {
    P res(0, 0); double A = 0;
    for (int i = 0, j = sz(v) - 1; i < sz(v); j = i++) {
        res = res + (v[i] + v[j]) * v[j].cross(v[i]);
        A += v[j].cross(v[i]);
    } // 307102
    return res / A / 3;
} // 0d0d84
```

MinimumEnclosingCircle.h

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

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"`

```
typedef Point<double> P;
vector<P> polygonCut(const vector<P>& poly, P s, P e) {
    vector<P> res;
    rep(i, 0, sz(poly)) {
        P cur = poly[i], prev = i ? poly[i-1] : poly.back();
        auto a = s.cross(e, cur), b = s.cross(e, prev);
        if ((a < 0) != (b < 0))
            res.push_back(cur + (prev - cur) * (a / (a - b)));
        if (a < 0)
            res.push_back(cur);
    } // 757c0d
    return res;
} // 42c993
```

ConvexHull.h**Description:**

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



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

```
"Point.h"
typedef Point<ll> P;
vector<P> convexHull(vector<P> pts) {
    if (sz(pts) <= 1) return pts;
    sort(all(pts));
    vector<P> h(sz(pts)+1);
    int s = 0, t = 0;
    for (int it = 2; it-->0; s = --t, reverse(all(pts)))
        for (P p : pts) {
            while (t >= s + 2 && h[t-2].cross(h[t-1], p) <= 0) t--;
            h[t++] = p;
        } // bf0344
    return {h.begin(), h.begin() + t - (t == 2 && h[0] == h[1])};
} // ec85f8
```

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"
typedef Point<ll> P;
array<P, 2> hullDiameter(vector<P> S) {
    int n = sz(S), j = n < 2 ? 0 : 1;
    pair<ll, array<P, 2>> res({0, {S[0], S[0]}});
    rep(i, 0, j)
        for (; j = (j + 1) % n; {
            res = max(res, {(S[i] - S[j]).dist2(), {S[i], S[j]}});
            if ((S[(j + 1) % n] - S[j]).cross(S[i + 1] - S[i]) >= 0)
                break;
        } // 56cc40
    return res.second;
} // 5f726b
```

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"`

`typedef Point<ll> P;`

```
bool inHull(const vector<P>& l, P p, bool strict = true) {
    int a = 1, b = sz(l) - 1, r = !strict;
    if (sz(l) < 3) return r && onSegment(l[0], l.back(), p);
    if (sideOf(l[0], l[a], l[b]) > 0) swap(a, b);
    if (sideOf(l[0], l[a], p) >= r || sideOf(l[0], l[b], p) <= -r)
        return false;
    while (abs(a - b) > 1) {
        int c = (a + b) / 2;
        (sideOf(l[0], l[c], p) > 0 ? b : a) = c;
    } // b265ab
    return sgn(l[a].cross(l[b], p)) < r;
} // c74639
```

LineHullIntersection.h

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

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

```
"Point.h"
#define cmp(i, j) sgn(dir.perp().cross(poly[(i)%n]-poly[(j)%n]))
#define extr(i) cmp(i + 1, i) >= 0 && cmp(i, i - 1 + n) < 0
template <class P> int extrVertex(vector<P>& poly, P dir) {
    int n = sz(poly), lo = 0, hi = n;
    if (extr(0)) return 0;
    while (lo + 1 < hi) {
        int m = (lo + hi) / 2;
        if (extr(m)) return m;
        int ls = cmp(lo + 1, lo), ms = cmp(m + 1, m);
        (ls < ms || (ls == ms && ls == cmp(lo, m)) ? hi : lo) = m;
    } // 68a24c
    return lo;
} // 7f0477

#define cmpL(i) sgn(a.cross(poly[i], b))
template <class P>
array<int, 2> lineHull(P a, P b, vector<P>& poly) {
    int endA = extrVertex(poly, (a - b).perp());
    int endB = extrVertex(poly, (b - a).perp());
    if (cmpL(endA) < 0 || cmpL(endB) > 0)
        return {-1, -1};
    array<int, 2> res;
    rep(i, 0, 2) {
        int lo = endB, hi = endA, n = sz(poly);
        while ((lo + 1) % n != hi) {
            int m = ((lo + hi + (lo < hi ? 0 : n)) / 2) % n;
            (cmpL(m) == cmpL(endB) ? lo : hi) = m;
        } // 52528c
        res[i] = (lo + !cmpL(hi)) % n;
        swap(endA, endB);
    } // c05c70
    if (res[0] == res[1]) return {res[0], -1};
    if (!cmpL(res[0]) && !cmpL(res[1]))
        switch ((res[0] - res[1] + sz(poly) + 1) % sz(poly)) {
            case 0: return {res[0], res[0]};
            case 2: return {res[1], res[1]};
        } // 8fa383
    return res;
} // 36fc8e
```

PolygonContainmentTree.h

Description: building tree of polygon containment

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

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

```
struct P { ll x, y; };
int current_x;
struct Segment {
    int idx; P p1, p2; bool is_upper;
    Segment(P p, P q, int i): idx(i), p1(p), p2(q), is_upper(p2.x < p1.x) { if (is_upper) swap(p1, p2); }
    ld get_y(ll x) const { return (ld)(p2.y - p1.y) / (p2.x - p1.x) * (x - p1.x) + p1.y; }
    tuple<id, bool, int> get_comp() const { return {get_y(current_x), is_upper, p2.x}; }
    bool operator<(const Segment & o) const { return get_comp() < o.get_comp(); }
}; // fc8b4f

vector<int> build(vector<vector<P>>& polygons) {
    int n = sz(polygons);
    vector<tuple<int, int, int>, Segment> edges; // polygon edges
    rep(idx, 0, n) {
        const auto & v = polygons[idx];
        rep(i, 0, sz(v)) {
            int j = (i + 1) % sz(v);
            if (v[i].x == v[j].x) continue; // ignores vertical edges
            Segment seg = Segment(v[i], v[j], idx);
            edges.eb(seg.p1.x, 0, -seg.p1.y, seg);
            edges.eb(seg.p2.x, 1, -seg.p2.y, seg);
        } // b2876
    } // 2603da
    sort(edges.begin(), edges.end());
    set<Segment> s;
    vector pai(n+1, n), vis(n, 0);
    for (auto [l, t, y, seg]: edges) {
        current_x = l;
        int i = seg.idx;
        if (t == 0) {
            if (not vis[i]) {
                vis[i] = true;
                auto it = s.upper_bound(seg);
                if (it == s.end()) pai[i] = ntq;
                else if (it->is_upper) pai[i] = it->idx;
                else pai[i] = pai[it->idx];
            } // a8607f
            s.insert(seg);
        } // 3aed6
        else s.erase(seg);
    } // f96148
    return pai;
} // e3cb8b
```

4.4 Misc. Point Set Problems**ClosestPair.h**

Description: Finds the closest pair of points.

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

```
"Point.h"
typedef Point<ll> P;
pair<P, P> closest(vector<P> v) {
    assert(sz(v) > 1);
    set<P> S;
    sort(all(v), [] (P a, P b) { return a.y < b.y; });
    pair<ll, pair<P, P>> ret(LLONG_MAX, {P(), P()});
    int j = 0;
    for (P p : v) {
        P d[1 + (ll)sqrt(ret.first), 0];
        while (v[j].y <= p.y - d.x) S.erase(v[j++]);
        auto lo = S.lower_bound(p - d), hi = S.upper_bound(p + d);
        ret = min(ret, {(*lo - p).dist2(), {*lo, p}});
    }
}
```

```

S.insert(p);
} // 5b096c
return ret.second;
} // bf22c6

kdTree.h
Description: KD-tree (2d, can be extended to 3d)
"Point.h"                                bac5b0, 63 lines
typedef long long T;
typedef Point<T> P;
const T INF = numeric_limits<T>::max();

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

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

    T distance(const P& p) { // min squared distance to a point
        T x = (p.x < x0 ? x0 : p.x) > x1 ? x1 : p.x;
        T y = (p.y < y0 ? y0 : p.y) > y1 ? y1 : p.y;
        return (P(x,y) - p).dist2();
    } // ca4da5

    Node(vector<P>&& vp) : pt(vp[0]) {
        for (P p : vp) {
            x0 = min(x0, p.x); x1 = max(x1, p.x);
            y0 = min(y0, p.y); y1 = max(y1, p.y);
        } // 31010d
        if (vp.size() > 1) {
            // split on x if width >= height (not ideal...)
            sort(all(vp), x1 - x0 >= y1 - y0 ? on_x : on_y);
            // divide by taking half the array for each child (not
            // best performance with many duplicates in the middle)
            int half = sz(vp)/2;
            first = new Node({vp.begin(), vp.begin() + half});
            second = new Node({vp.begin() + half, vp.end()});
        } // 66e741
    } // 2044ae
}; // a77e97

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

    pair<T, P> search(Node *node, const P& p) {
        if (!node->first) {
            // uncomment if we should not find the point itself:
            // if (p == node->pt) return {INF, P()};
            return make_pair((p - node->pt).dist2(), node->pt);
        } // 1199af

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

        // search closest side first, other side if needed
        auto best = search(f, p);
        if (bsec < best.first)
            best = min(best, search(s, p));
        return best;
    } // 74c273

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

```

kdTree FastDelaunay PolyhedronVolume Point3D

```

} // 94cda0
}; // 6f5c51

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:  $\mathcal{O}(n \log n)$                                               eefdf5, 88 lines
"Point.h"                                eefdf5, 88 lines
typedef Point<ll> P;
typedef struct Quad* Q;
typedef __int128_t lli; // (can be ll if coords are < 2e4)
P arb(LLONG_MAX,LLONG_MAX); // not equal to any other point

struct Quad {
    Q rot, o; P p = arb; bool mark;
    P& F() { return r()>p; }
    Q& r() { return rot->rot; }
    Q prev() { return rot->o->rot; }
    Q next() { return r()>prev(); }
} *H; // 18059e

bool circ(P p, P a, P b, P c) { // is p in the circumcircle?
    lli p2 = p.dist2(), A = a.dist2()-p2,
        B = b.dist2()-p2, C = c.dist2()-p2;
    return p.cross(a,b)*C + p.cross(b,c)*A + p.cross(c,a)*B > 0;
} // 6aff7b

Q makeEdge(P orig, P dest) {
    Q r = H ? H : new Quad{new Quad{new Quad{new Quad{0}}}};
    H = r->o; r->r()>r() = r;
    rep(i,0,4) r = r->rot, r->p = arb, r->o = i & 1 ? r : r->r();
    r->p = orig; r->F() = dest;
    return r;
} // b3b5b1

void splice(Q a, Q b) {
    swap(a->o->rot->o, b->o->rot->o); swap(a->o, b->o);
} // 86ce01

Q connect(Q a, Q b) {
    Q q = makeEdge(a->F(), b->p);
    splice(q, a->next());
    splice(q->r(), b);
    return q;
} // 4a4fc2

pair<Q,Q> rec(const vector<P>& s) {
    if (sz(s) <= 3) {
        Q a = makeEdge(s[0], s[1]), b = makeEdge(s[1], s.back());
        if (sz(s) == 2) return {a, a->r()};
        splice(a->r(), b);
        auto side = s[0].cross(s[1], s[2]);
        Q c = side ? connect(b, a) : 0;
        return {side < 0 ? c->r() : a, side < 0 ? c : b->r()};
    } // c9e598

#define H(e) e->F(), e->p
#define valid(e) (e->F().cross(H(base)) > 0)

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

#define DEL(e, init, dir) Q e = init->dir; if (valid(e)) \

```

```

while (circ(e->dir->F(), H(base), e->F())) { \
    Q t = e->dir; \
    splice(e, e->prev()); \
    splice(e->r(), e->r()->prev()); \
    e->o = H; H = e; e = t; \
} // a2e9b5

for (;;) {
    DEL(LC, base->r(), o); DEL(RC, base, prev());
    if (!valid(LC) && !valid(RC)) break;
    if (!valid(LC) || (valid(RC) & circ(H(RC), H(LC)))) {
        base = connect(RC, base->r());
    } else {
        base = connect(base->r(), LC->r());
    } // fc7ef
    return {ra, rb};
} // 7cf639

vector<P> triangulate(vector<P> pts) {
    sort(all(pts)); assert(unique(all(pts)) == pts.end());
    if (sz(pts) < 2) return {};
    Q e = rec(pts).first;
    vector<Q> q = {e};
    int qi = 0;
    while (e->F().cross(e->p) < 0) e = e->o;
    #define ADD { Q c = e; do { c->mark = 1; pts.push_back(c->p); \
        q.push_back(c->r()); c = c->next(); } while (c != e); } // 43e195
    ADD; pts.clear();
    while (qi < sz(q)) if (!(e = q[qi++])->mark) ADD;
    return pts;
} // a02307

4.5 3D
PolyhedronVolume.h
Description: Magic formula for the volume of a polyhedron. Faces should
point outwards.                                              3058c3, 6 lines
template<class V, class L>
double signedPolyVolume(const V& p, const L& trilist) {
    double v = 0;
    for (auto i : trilist) v += p[i.a].cross(p[i.b]).dot(p[i.c]);
    return v / 6;
} // fca9df

Point3D.h
Description: Class to handle points in 3D space. T can be e.g. double or
long long.                                              8058ae, 32 lines
template<class T> struct Point3D {
    typedef Point3D P;
    typedef const P & R;
    T x, y, z;
    explicit Point3D(T x=0, T y=0, T z=0) : x(x), y(y), z(z) {}
    bool operator<(R p) const {
        return tie(x, y, z) < tie(p.x, p.y, p.z); } // 8eeef6b
    bool operator==(R p) const {
        return tie(x, y, z) == tie(p.x, p.y, p.z); } // bd6a08
    P operator+(R p) const { return P(x+p.x, y+p.y, z+p.z); }
    P operator-(R p) const { return P(x-p.x, y-p.y, z-p.z); }
    P operator*(T d) const { return P(x*d, y*d, z*d); }
    P operator/(T d) const { return P(x/d, y/d, z/d); }
    T dot(R p) const { return x*p.x + y*p.y + z*p.z; }
    P cross(R p) const {
        return P(y*p.z - z*p.y, z*p.x - x*p.z, x*p.y - y*p.x); }
    } // a77b7e
    T dist2() const { return x*x + y*y + z*z; }
    double dist() const { return sqrt(double)dist2(); }
    //Azimuthal angle (longitude) to x-axis in interval [-pi, pi]
    double phi() const { return atan2(y, x); }
}

```

```
//Zenith angle (latitude) to the z-axis in interval [0, pi]
double theta() const { return atan2(sqrt(x*x+y*y),z); }
P unit() const { return *this/(T)dist(); } //makes dist()=1
//returns unit vector normal to *this and p
P normal(P p) const { return cross(p).unit(); }
//returns point rotated 'angle' radians ccw around axis
P rotate(double angle, P axis) const {
    double s = sin(angle), c = cos(angle); P u = axis.unit();
    return u*dot(u)*(1-c) + (*this)*c - cross(u)*s;
} // 73af70
}; // 8058ae
```

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, 49 lines

typedef Point3D<double> P3;

```
struct PR {
    void ins(int x) { (a == -1 ? a : b) = x; }
    void rem(int x) { (a == x ? a : b) = -1; }
    int cnt() { return (a != -1) + (b != -1); }
    int a, b;
}; // cf7c9e
```

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

```
vector<F> hull3d(const vector<P3>& A) {
    assert(sz(A) >= 4);
    vector<vector<PR>> E(sz(A), vector<PR>(sz(A), {-1, -1}));
#define E(x,y) E[f.x][f.y]
    vector<F> FS;
    auto mf = [&](int i, int j, int k, int l) {
        P3 q = (A[j] - A[i]).cross((A[k] - A[i]));
        if (q.dot(A[l]) > q.dot(A[i]))
            q = q * -1;
        F f{q, i, j, k};
        E(a,b).ins(k); E(a,c).ins(j); E(b,c).ins(i);
        FS.push_back(f);
    }; // d73a06
    rep(i,0,4) rep(j,i+1,4) rep(k,j+1,4)
        mf(i, j, k, 6 - i - j - k);
}; // 220067
```

```
rep(i,4,sz(A)) {
    rep(j,0,sz(FS)) {
        F f = FS[j];
        if(f.q.dot(A[i]) > f.q.dot(A[f.a])) {
            E(a,b).rem(f.c);
            E(a,c).rem(f.b);
            E(b,c).rem(f.a);
            swap(FS[j-], FS.back());
            FS.pop_back();
        } // 5cd5dc
    } // 220067
    int nw = sz(FS);
    rep(j,0,nw) {
        F f = FS[j];
    } // 220067
```

```
#define C(a, b, c) if (E(a,b).cnt() != 2) mf(f.a, f.b, i, f.c);
    C(a, b, c); C(a, c, b); C(b, c, a);
} // 248ed4
}; // 47289c
for (F& it : FS) if ((A[it.b] - A[it.a]).cross(
    A[it.c] - A[it.a]).dot(it.q) <= 0) swap(it.c, it.b);
return FS;
}; // be2ca2
```

sphericalDistance.h

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

611f07, 8 lines

```
double sphericalDistance(double f1, double t1,
                        double f2, double t2, double radius) {
    double dx = sin(t2)*cos(f2) - sin(t1)*cos(f1);
    double dy = sin(t2)*sin(f2) - sin(t1)*sin(f1);
    double dz = cos(t2) - cos(t1);
    double d = sqrt(dx*dx + dy*dy + dz*dz);
    return radius*2*asin(d/2);
} // 4fa19e
```

Graph (5)

5.1 Fundamentals

BellmanFord.h

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

830a8f, 23 lines

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

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

    int lim = sz(nodes) / 2 + 2; // /3+100 with shuffled vertices
    rep(i,0,lim) for (Ed ed : eds) {
        Node cur = nodes[ed.a], &dest = nodes[ed.b];
        if (abs(cur.dist) == inf) continue;
        ll d = cur.dist + ed.w;
        if (d < dest.dist) {
            dest.prev = ed.a;
            dest.dist = (i < lim-1 ? d : -inf);
        } // 452019
    } // 75a370
    rep(i,0,lim) for (Ed e : eds) {
        if (nodes[e.a].dist == -inf)
            nodes[e.b].dist = -inf;
    } // 1d7315
} // fa39de
```

FloydWarshall.h

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

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

531245, 12 lines

```
const ll inf = 1LL << 62;
void floydWarshall(vector<vector<ll>>& m) {
    int n = sz(m);
    rep(i,0,n) m[i][i] = min(m[i][i], OLL);
    rep(k,0,n) rep(i,0,n) rep(j,0,n)
        if (m[i][k] != inf && m[k][j] != inf) {
            auto newDist = max(m[i][k] + m[k][j], -inf);
            m[i][j] = min(m[i][j], newDist);
        }
} // 571434
```

```
} // f12f13
if (m[k][k] < 0) rep(i,0,n) rep(j,0,n)
    if (m[i][k] != inf && m[k][j] != inf) m[i][j] = -inf;
} // f12f13
```

TopoSort.h

Description: Topological sorting. Given is an oriented graph. Output is an ordering of vertices, such that there are edges only from left to right. If there are cycles, the returned list will have size smaller than $n - \text{nodes reachable from cycles}$.

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

d678d8, 8 lines

vi topoSort(**const** vector<vi>& gr) {

```
    vi indeg(sz(gr)), q;
    for (auto& li : gr) for (int x : li) indeg[x]++;
    rep(i,0,sz(gr)) if (indeg[i] == 0) q.push_back(i);
    rep(j,0,sz(q)) for (int x : gr[q[j]]) {
        if (--indeg[x] == 0) q.push_back(x);
    }
} // d678d8
```

FunctGraph.h

Description: Functional Graph

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

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

152fc5, 25 lines

```
struct FunctGraph{
    int n;
    vi head, comp;
    vector<vi> gr, cycles;
```

FunctGraph(vi& fn):

```
    n(sz(fn)), head(n, -1), comp(n), gr(n) {
        rep(i, 0, n) gr[fn[i]].pb(i);
        vi visited(n, 0);
        auto dfs = [&] (auto rec, int v, int c) -> void{
            head[v] = c; visited[v] = 1;
            for (int f : gr[v]) if (head[f] != f) rec(rec, f, c);
        }; // e1fa06
        rep(i, 0, n) {
            if (visited[i]) continue;
            int l=fn[i], r=fn[fn[i]];
            while(l!=r) l=fn[l], r=fn[fn[r]];
            vi cur = {r};
            for(l=fn[l]; l!=r; l=fn[l]) cur.pb(l);
            for (int x : cur) head[x] = c, comp[x] = sz(cycles);
            cycles.pb(cur);
            for (int x : cur) dfs(dfs, x, x);
        } // 01a153
    } // 0a2937
}; // 152fc5
```

5.2 Network flow

PushRelabel.h

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

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

0ae1d4, 48 lines

```
struct PushRelabel {
    struct Edge {
        int dest, back;
        ll f, c;
    }; // 571434
    vector<vector<Edge>> g;
    vector<ll> ec;
    vector<Edge*> cur;
    vector<vi> hs; vi H;
```

```

PushRelabel(int n) : g(n), ec(n), cur(n), hs(2*n), H(n) {}

void addEdge(int s, int t, ll cap, ll rcap=0) {
    if (s == t) return;
    g[s].push_back({t, sz(g[t]), 0, cap});
    g[t].push_back({s, sz(g[s])-1, 0, rcap});
} // 817b95

void addFlow(Edge& e, ll f) {
    Edge &back = g[e.dest][e.back];
    if (!ec[e.dest] && f) hs[H[e.dest]].push_back(e.dest);
    e.f += f; e.c -= f; ec[e.dest] += f;
    back.f -= f; back.c += f; ec[back.dest] -= f;
} // 340b4e

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

    for (int hi = 0;;) {
        while (hs[hi].empty()) if (!hi--) return -ec[s];
        int u = hs[hi].back(); hs[hi].pop_back();
        while (ec[u] > 0) // discharge u
            if (cur[u] == g[u].data() + sz(g[u])) {
                H[u] = 1e9;
                for (Edge& e : g[u]) if (e.c && H[u] > H[e.dest]+1)
                    H[u] = H[e.dest]+1, cur[u] = &e;
                if (++co[H[u]], !--co[hi] && hi < v)
                    rep(i, 0, v) if (hi < H[i] && H[i] < v)
                        --co[H[i]], H[i] = v+1;
                hi = H[u];
            } else if (cur[u]->c && H[u] == H[cur[u]->dest]+1) // aafe8e
                addFlow(*cur[u], min(ec[u], cur[u]->c));
            else ++cur[u];
        } // 1206ba
    } // 291fbf
    bool leftOfMinCut(int a) { return H[a] >= sz(g); }
}; // 0ae1d4

```

MinCostMaxFlow.h

Description: Min-cost max-flow. If costs can be negative, call setpi before maxflow, but note that negative cost cycles are not supported. To obtain the actual flow, look at positive values only.

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

58385b, 79 lines

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

```

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

struct MCMF {
    struct edge {
        int from, to, rev;
        ll cap, cost, flow;
    }; // 092ff8
    int N;
    vector<vector<edge>> ed;
    vi seen;
    vector<ll> dist, pi;
    vector<edge*> par;

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

    void addEdge(int from, int to, ll cap, ll cost) {
        if (from == to) return;
        ed[from].push_back(edge{from, to, sz(ed[to]), cap, cost, 0});
        ed[to].push_back(edge{to, from, sz(ed[from])-1, 0, -cost, 0});
    } // c71528
};
```

```

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

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

    while (!q.empty()) {
        s = q.top().second; q.pop();
        seen[s] = 1; di = dist[s] + pi[s];
        for (edge& e : ed[s]) if (!seen[e.to]) {
            ll val = di - pi[e.to] + e.cost;
            if (e.cap - e.flow > 0 && val < dist[e.to]) {
                dist[e.to] = val;
                par[e.to] = &e;
                if (its[e.to] == q.end())
                    its[e.to] = q.push({-dist[e.to], e.to});
                else
                    q.modify(its[e.to], {-dist[e.to], e.to});
            } // ca07f4
        } // 4cd18f
    } // 062b8f
    rep(i, 0, N) pi[i] = min(pi[i] + dist[i], INF);
} // 7e4cbe

pair<ll, ll> maxflow(int s, int t) {
    ll totflow = 0, totcost = 0;
    while (path(s), seen[t]) {
        ll fl = INF;
        for (edge* x = par[t]; x; x = par[x->from])
            fl = min(fl, x->cap - x->flow);

        totflow += fl;
        for (edge* x = par[t]; x; x = par[x->from]) {
            x->flow += fl;
            ed[x->to][x->rev].flow -= fl;
        } // 3bfaf3
    } // 8d9a6a
    rep(i, 0, N) for (edge& e : ed[i]) totcost += e.cost * e.flow;
    return {totflow, totcost/2};
} // 24f5a0

// If some costs can be negative, call this before maxflow:
void setpi(int s) { // (otherwise, leave this out)
    fill(all(pi), INF); pi[s] = 0;
    int it = N, ch = 1; ll v;
    while (ch-- && it--)
        rep(i, 0, N) if (pi[i] != INF)
            for (edge& e : ed[i]) if (e.cap)
                if ((v = pi[i] + e.cost) < pi[e.to])
                    pi[e.to] = v, ch = 1;
            assert(it >= 0); // negative cost cycle
    } // 6847d8
}; // b3692f

```

EdmondsKarp.h

Description: Flow algorithm with guaranteed complexity $O(VE^2)$. To get edge flow values, compare capacities before and after, and take the positive values only.

```
482fe0, 36 lines

template<class T> T edmondsKarp(vector<unordered_map<int, T>>&
    graph, int source, int sink) {
    assert(source != sink);
    T flow = 0;
    vi par(sz(graph)), q = par;
```

```

for (;;) {
    fill(all(par), -1);
    par[source] = 0;
    int ptr = 1;
    q[0] = source;

    rep(i, 0, ptr) {
        int x = q[i];
        for (auto e : graph[x]) {
            if (par[e.first] == -1 && e.second > 0) {
                par[e.first] = x;
                q[ptr++] = e.first;
                if (e.first == sink) goto out;
            } // 3a4373
        } // 6e8ea0
    } // 56e958
    return flow;
out:
    T inc = numeric_limits<T>::max();
    for (int y = sink; y != source; y = par[y])
        inc = min(inc, graph[par[y]][y]);

    flow += inc;
    for (int y = sink; y != source; y = par[y]) {
        int p = par[y];
        if ((graph[p][y] -= inc) <= 0) graph[p].erase(y);
        graph[y][p] += inc;
    } // 548c55
} // ff82bd
} // 261f29

```

MinCut.h

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

GlobalMinCut.h

Description: Find a global minimum cut in an undirected graph, as represented by an adjacency matrix.

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

```
8b0e19, 21 lines

pair<int, vi> globalMinCut(vector<vi> mat) {
    pair<int, vi> best = {INT_MAX, {}};
    int n = sz(mat);
    vector<vi> co(n);
    rep(i, 0, n) co[i] = {i};
    rep(ph, 1, n) {
        vi w = mat[0];
        size_t s = 0, t = 0;
        rep(it, 0, n-ph) { // O(E log V) with prio. queue
            w[t] = INT_MIN;
            s = t, t = max_element(all(w)) - w.begin();
            rep(i, 0, n) w[i] += mat[t][i];
        } // ec93df
        best = min(best, {w[t] - mat[t][t], co[t]});
        co[s].insert(co[s].end(), all(co[t]));
        rep(i, 0, n) mat[s][i] += mat[t][i];
        rep(i, 0, n) mat[i][s] = mat[s][i];
        mat[0][t] = INT_MIN;
    } // ca0062
    return best;
} // 8b0e19
```

GomoryHu.h

Description: Given a list of edges representing an undirected flow graph, returns edges of the Gomory-Hu tree. The max flow between any pair of vertices is given by minimum edge weight along the Gomory-Hu tree path.

Time: $\mathcal{O}(V)$ Flow Computations

```
"PushRelabel.h"
typedef array<ll, 3> Edge;
vector<Edge> gomoryHu(int N, vector<Edge> ed) {
    vector<Edge> tree;
    vi par(N);
    rep(i, 1, N) {
        PushRelabel D(N); // Dinic also works
        for (Edge t : ed) D.addEdge(t[0], t[1], t[2], t[2]);
        tree.push_back({i, par[i], D.calc(i, par[i])});
        rep(j, i+1, N)
            if (par[j] == par[i] && D.leftOfMinCut(j)) par[j] = i;
    } // 93c5ff
    return tree;
} // 65c0c2
```

5.3 Matching

HopcroftKarp.h

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

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

```
731cfb, 20 lines
int hopcroftKarp(vector<vi>& g, vi& r) {
    int n = sz(g), res = 0;
    vi l(n, -1), q(n), d(n);
    auto dfs = [&](auto f, int u) -> bool {
        int t = exchange(d[u], 0) + 1;
        for (int v : g[q[u]]) {
            if (r[v] == -1 || (d[r[v]] == t && f(f, r[v])))
                return 1[u] = v, r[v] = u, 1;
        }
        return 0;
    }; // a95e38
    for (int t = 0, f = 0;; t = f = 0, d.assign(n, 0)) {
        rep(i, 0, n) if (l[i] == -1) q[t++] = i, d[i] = 1;
        rep(i, 0, t) for (int v : g[q[i]]) {
            if (r[v] == -1) f = 1;
            else if (!d[r[v]]) d[r[v]] = d[q[i]] + 1, q[t++] = r[v];
        } // 64af74
        if (!f) return res;
        rep(i, 0, n) if (l[i] == -1) res += dfs(dfs, i);
    } // cdf3b2
} // 731cfb
```

DFSMatching.h

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

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

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

```
522b98, 22 lines
bool find(int j, vector<vi>& g, vi& btoa, vi& vis) {
    if (btoa[j] == -1) return 1;
    vis[j] = 1; int di = btoa[j];
    for (int e : g[di])
        if (!vis[e] && find(e, g, btoa, vis)) {
            btoa[e] = di;
            return 1;
        } // 6ba49a
    return 0;
} // d13a81
int dfsMatching(vector<vi>& g, vi& btoa) {
    vi vis;
    rep(i, 0, sz(g))
        vis.assign(sz(btoa), 0);
    for (int j : g[i])
```

```
        if (find(j, g, btoa, vis)) {
            btoa[j] = i;
            break;
        } // 829ce5
    } // df282b
    return sz(btoa) - (int)count(all(btoa), -1);
} // f24825
```

MinimumVertexCover.h

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

```
"DFSMatching.h"
da4196, 20 lines
vi cover(vector<vi>& g, int n, int m) {
    vi match(m, -1);
    int res = dfsMatching(g, match);
    vector<bool> lfound(n, true), seen(m);
    for (int it : match) if (it != -1) lfound[it] = false;
    vi q, cover;
    rep(i, 0, n) if (lfound[i]) q.push_back(i);
    while (!q.empty()) {
        int i = q.back(); q.pop_back();
        lfound[i] = 1;
        for (int e : g[i]) if (!seen[e] && match[e] != -1) {
            seen[e] = true;
            q.push_back(match[e]);
        } // 46e035
    } // 069994
    rep(i, 0, n) if (!lfound[i]) cover.push_back(i);
    rep(i, 0, m) if (seen[i]) cover.push_back(n+i);
    assert(sz(cover) == res);
    return cover;
} // da4196
```

WeightedMatching.h

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

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

```
1e0fe9, 31 lines
pair<int, vi> hungarian(const vector<vi> &a) {
    if (a.empty()) return {0, {}};
    int n = sz(a) + 1, m = sz(a[0]) + 1;
    vi u(n), v(m), p(m), ans(n - 1);
    rep(i, 1, n) {
        p[0] = i;
        int j0 = 0; // add "dummy" worker 0
        vi dist(m, INT_MAX), pre(m, -1);
        vector<bool> done(m + 1);
        do { // dijkstra
            done[j0] = true;
            int i0 = p[j0], jl, delta = INT_MAX;
            rep(j, 1, m) if (!done[j]) {
                auto cur = a[i0 - 1][j - 1] - u[i0] - v[j];
                if (cur < dist[j]) dist[j] = cur, pre[j] = jl;
                if (dist[j] < delta) delta = dist[j], jl = j;
            } // b7c105
            rep(j, 0, m) {
                if (done[j]) u[p[j]] += delta, v[j] -= delta;
                else dist[j] -= delta;
            } // 8c9ba2
            j0 = jl;
        } while (p[j0]); // 546805
        while (j0) { // update alternating path
            int jl = pre[j0];
            p[j0] = p[jl], j0 = jl;
        } // f55064
    } // 36bba8
    for (int i = N + 1; i > 0; --i) ofs[i] = ofs[i - 1];
    ofs[0] = 0;
} // a78156
int maximum_matching() {
    initialize(); int match = 0;
```

```
} // 1f3f03
rep(j, 1, m) if (p[j]) ans[p[j] - 1] = j - 1;
return {-v[0], ans}; // min cost
} // 1e0fe9
```

GeneralMatching.h

Description: Matching for general graphs. 1-indexed vertices.

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

Time: $\mathcal{O}(\sqrt{nm} \log_{\max\{2, 1+m/n\}} n)$

```
9437b5, 314 lines
class MaximumMatching {
public:
    struct Edge { int from, to;};
    static constexpr int Inf = 1 << 30;

private:
    enum Label {
        kInner = -1, // should be < 0
        kFree = 0 // should be 0
    }; // c09e7e
    struct Link { int from, to;};
    struct Log { int v, par;};
    struct LinkedList {
        LinkedList() {}
        LinkedList(int N, int M) : N(N), next(M) { clear(); }
        void clear() { head.assign(N, -1); }
        void push(int h, int u) { next[u] = head[h], head[h] = u; }
        int N; vector<int> head, next;
    }; // 1a51c7
    template <typename T> struct Queue {
        Queue() {}
        Queue(int N) : qh(0), qt(0), data(N) {}
        T operator[](int i) const { return data[i]; }
        void enqueue(int u) { data[qt++] = u; }
        int dequeue() { return data[qh++]; }
        bool empty() const { return qh == qt; }
        void clear() { qh = qt = 0; }
        int size() const { return qt; }
        int qh, qt; vector<T> data;
    }; // 4bfceb
    struct DisjointSetUnion {
        DisjointSetUnion() {}
        DisjointSetUnion(int N) : par(N) { for (int i = 0; i < N; ++i) par[i] = i; }
        int find(int u) { return par[u] == u ? u : (par[u] = find(par[u])); }
        void unite(int u, int v) {
            u = find(u), v = find(v);
            if (u != v) par[v] = u;
        } // 461e55
        vector<int> par;
    }; // a21f68
public:
    MaximumMatching(int N, const vector<Edge> &in) {
        : N(N), NH(N >> 1), ofs(N + 2, 0), edges(in.size() * 2) {
            for (auto &e : in) ofs[e.from + 1] += 1, ofs[e.to + 1] += 1;
            for (int i = 1; i <= N + 1; ++i) ofs[i] += ofs[i - 1];
            for (auto &e : in) {
                edges[ofs[e.from]++] = e;
                edges[ofs[e.to]++] = {e.to, e.from};
            } // 36bba8
            for (int i = N + 1; i > 0; --i) ofs[i] = ofs[i - 1];
            ofs[0] = 0;
        } // a78156
        int maximum_matching() {
            initialize(); int match = 0;
```

```

while (match * 2 + 1 < N) {
    reset_count();
    bool has_augmenting_path = do_edmonds_search();
    if (!has_augmenting_path) break;
    match += find_maximal();
    clear();
} // 8c0a2c
return match;
} // da7b99
vector<Edge> get_edges() {
    vector<Edge> ans;
    for (int i = 1, j = i; i <= N; ++i) if (mate[i] > i) ans.push_back(Edge{i, mate[i]});
    return ans;
} // f8586b
private:
void reset_count() {
    time_current_ = 0;
    time_augment_ = Inf;
    contract_count_ = 0;
    outer_id_ = 1;
    dsu_changelog_size_ = dsu_changelog_last_ = 0;
} // 6c73d5
void clear() {
    que.clear();
    for (int u = 1; u <= N; ++u) potential[u] = 1;
    for (int u = 1; u <= N; ++u) dsu.par[u] = u;
    for (int t = time_current_; t <= N / 2; ++t) list.head[t] = -1;
    for (int u = 1; u <= N; ++u) blossom.head[u] = -1;
} // 6e020f
inline void grow(int x, int y, int z) {
    label[y] = kInner;
    potential[y] = time_current_; // visited time
    link[z] = {x, y};
    label[z] = label[x];
    potential[z] = time_current_ + 1;
    que.enqueue(z);
} // 5a596b
void contract(int x, int y) {
    int bx = dsu.find(x), by = dsu.find(y);
    const int h = -(++contract_count_) + kInner;
    label[mate[bx]] = label[mate[by]] = h;
    int lca = -1;
    while (1) {
        if (mate[by] != 0) swap(bx, by);
        bx = lca = dsu.find(link[bx].from);
        if (label[mate[bx]] == h) break;
        label[mate[bx]] = h;
    } // d03cb2
    for (auto bv : {dsu.par[x], dsu.par[y]}) {
        for (; bv != lca; bv = dsu.par[link[bv].from]) {
            int mv = mate[bv];
            link[mv] = {x, y};
            label[mv] = label[x];
            potential[mv] =
                1 + (time_current_ - potential[mv]) +
                time_current_;
            que.enqueue(mv);
            dsu.par[bv] = dsu.par[mv] = lca;
            dsu_changelog[dsu_changelog_last_++] = {bv, lca};
        };
        dsu_changelog[dsu_changelog_last_++] = {mv, lca};
    } // 8fef02
} // 2b0c42
// a9547e
bool find_augmenting_path() {
    while (!que.empty()) {

```

```

        int x = que.dequeue(), lx = label[x], px =
            potential[x],
            bx = dsu.find(x);
        for (int eid = ofs[x]; eid < ofs[x + 1]; ++eid) {
            int y = edges[eid].to;
            if (label[y] > 0) { // outer blossom/vertex
                int time_next = (px + potential[y]) >> 1;
                if (lx != label[y]) {
                    if (time_next == time_current_) return true;
                    time_augment_ = min(time_next, time_augment_);
                } else { // a6d4c5
                    if (bx == dsu.find(y)) continue;
                    if (time_next == time_current_) {
                        contract(x, y);
                        bx = dsu.find(x);
                    } else if (time_next <= NH) // 1efde3
                        list.push(time_next, eid);
                } // 1666ad
            } else if (label[y] == kFree) { // free vertex
                // c17e44
                int time_next = px + 1;
                if (time_next == time_current_) grow(x, y, mate[y]);
                else if (time_next <= NH)
                    list.push(time_next, eid);
            } // 48780d
        } // 30c821
    } // 1f7dd0
    return false;
} // 5f1707
bool adjust_dual_variables() {
    const int time_lim = min(NH + 1, time_augment_);
    for (++time_current_; time_current_ <= time_lim; ++time_current_) {
        dsu_changelog_size_ = dsu_changelog_last_;
        if (time_current_ == time_lim) break;
        bool updated = false;
        for (int h = list.head[time_current_]; h >= 0; h =
            list.next[h]) {
            auto &e = edges[h];
            int x = e.from, y = e.to;
            if (label[y] > 0) {
                if (potential[x] + potential[y] != (
                    time_current_ << 1))
                    continue;
                if (dsu.find(x) == dsu.find(y)) continue;
                if (label[x] != label[y]) {
                    time_augment_ = time_current_;
                    return false;
                } // e7c864
                contract(x, y);
                updated = true;
            } else if (label[y] == kFree) { // 1a7dca
                grow(x, y, mate[y]);
                updated = true;
            } // ebac0d
        } // 7bf910
        list.head[time_current_] = -1;
        if (updated) return false;
    } // a2963f
    return time_current_ > NH;
} // 361891
bool do_edmonds_search() {
    label[0] = kFree;
    for (int u = 1; u <= N; ++u) {
        if (mate[u] == 0) {
            que.enqueue(u);

```

```

        label[u] = u; // component id
    } else // 52e61c
        label[u] = kFree;
} // 585bc4
while (1) {
    if (find_augmenting_path()) break;
    bool maximum = adjust_dual_variables();
    if (maximum) return false;
    if (time_current_ == time_augment_) break;
} // 3b82c1
for (int u = 1; u <= N; ++u) {
    if (label[u] > 0)
        potential[u] -= time_current_;
    else if (label[u] < 0)
        potential[u] = 1 + (time_current_ - potential[u]);
} // c77cf7
return true;
} // e1fc96
void rematch(int v, int w) {
    int t = mate[v];
    mate[v] = w;
    if (mate[t] != v) return;
    if (link[v].to == dsu.find(link[v].to)) {
        mate[t] = link[v].from;
        rematch(mate[t], t);
    } else { // 45eff2
        int x = link[v].from, y = link[v].to;
        rematch(x, y);
        rematch(y, x);
    } // 4a404f
} // c4e2e9
bool dfs_augment(int x, int bx) {
    int px = potential[x], lx = label[bx];
    for (int eid = ofs[x]; eid < ofs[x + 1]; ++eid) {
        int y = edges[eid].to;
        if (px + potential[y] != 0) continue;
        int by = dsu.find(y), ly = label[by];
        if (ly > 0) { // outer
            if (lx >= ly) continue;
            int stack_beg = stack_last_;
            for (int bv = by; bv != bx; bv = dsu.find(link[bv].from)) {
                int bw = dsu.find(mate[bv]);
                stack[stack_last_++] = bw;
                link[bw] = {x, y};
                dsu.par[bw] = dsu.par[bw] = bx;
            } // 211d3e
            while (stack_last_ > stack_beg) {
                int bv = stack[--stack_last_];
                for (int v = blossom.head[bv]; v >= 0;
                    v = blossom.next[v]) {
                    if (!dfs_augment(v, bx)) continue;
                    stack_last_ = stack_beg;
                } // 9ded5e
            } // 476c04
        } else if (ly == kFree) { // e5357f
            label[by] = kInner;
            int z = mate[by];
            if (z == 0) {
                rematch(x, y);
                rematch(y, x);
            } // 781371
            int bz = dsu.find(z);
            link[bz] = {x, y};
            label[bz] = outer_id_++;
        } // a9547e
    } // 2b0c42
}
```

```

        for (int v = blossom.head[bz]; v >= 0; v =
            blossom.next[v]) {
                if (dfs_augment(v, bz)) return true;
            } // 5ea9e4
        } // 1c508f
    } // 7f2ab3
    return false;
} // 44c41a
int find_maximal() {
    for (int u = 1; u <= N; ++u) dsu.par[u] = u;
    for (int i = 0; i < dsu_changelog_size_; ++i) {
        dsu.par[dsu_changelog[i].v] = dsu_changelog[i].par;
    } // 384510
    for (int u = 1; u <= N; ++u) {
        label[u] = kFree;
        blossom.push(dsu.find(u), u);
    } // 2a02fd
    int ret = 0;
    for (int u = 1; u <= N; ++u)
        if (!mate[u]) {
            int bu = dsu.par[u];
            if (label[bu] != kFree) continue;
            label[bu] = outer_id_++;
            for (int v = blossom.head[bu]; v >= 0; v =
                blossom.next[v])
                if (!dfs_augment(v, bu)) continue;
            ret += 1;
            break;
        } // e4fb6a
    } // 4db9e3
    assert(ret >= 1); return ret;
} // 500171
void initialize() {
    que = Queue<int>(N);
    mate.assign(N + 1, 0);
    potential.assign(N + 1, 1);
    label.assign(N + 1, kFree);
    link.assign(N + 1, {0, 0});
    dsu_changelog.resize(N);
    dsu = DisjointSetUnion(N + 1);
    list = LinkedList(NH + 1, edges.size());
    blossom = LinkedList(N + 1, N + 1);
    stack.resize(N);
    stack_last_ = 0;
} // be011c
private:
    const int N, NH;
    vector<int> ofs;
    vector<Edge> edges;
    Queue<int> que;
    vector<int> mate, potential;
    vector<int> label;
    vector<Link> link;
    vector<Log> dsu_changelog;
    int dsu_changelog_last_, dsu_changelog_size_;
    DisjointSetUnion dsu;
    LinkedList list, blossom;
    vector<int> stack;
    int stack_last_;
    int time_current_, time_augment_;
    int contract_count_, outer_id_;
}; // b7724d
using Edge = MaximumMatching::Edge;
void example() { // Graph of Love problem
    int n; cin >> n;
    vector<Edge> edges(n, {0, 0});
    for (int i = 1, j; i <= n; i++) cin >> j, edges[i-1] = {i, j};
    auto M = MaximumMatching(n, edges);
}

```

OnlineMatching SCC BiconnectedComponents

```

        cout << M.maximum_matching() << '\n';
} // 0523ec

OnlineMatching.h
Description: Modified khun developed for specific question able to run  $2 * 10^6$  queries, in  $2 * 10^6 \times 10^6$  graph in 3 seconds codeforces
Time:  $\mathcal{O}(confia)$  6ac539, 42 lines
struct OnlineMatching {
    int n, m = 0;
    vector<int> vis, match, dist;
    vector<vector<int>> g;
    vector<int> last;
    int t = 0;

    OnlineMatching(int n_, int m_) : n(n_), m(m_),
        vis(n, 0), match(m, -1), dist(n, n+1), g(n), last(n, -1) {}

    void add(int a, int b) {
        g[a].pb(b);
    } // 746097

    bool kuhn(int a) {
        vis[a] = t;
        for(int b: g[a]) {
            int c = match[b];
            if (c == -1) {
                match[b] = a;
                return true;
            } // 38b210
            if (last[c] != t || (dist[a] + 1 < dist[c]))
                dist[c] = dist[a] + 1, last[c] = t;
        } // d30675
        for (int b: g[a]) {
            int c = match[b];
            if (dist[a] + 1 == dist[c] && vis[c] != t && kuhn(c)) {
                match[b] = a;
                return true;
            } // 2dac75
        } // e58bd5
        return false;
    } // b533ee
    bool can_match(int a) {
        t++;
        last[a] = t;
        dist[a] = 0;
        return kuhn(a);
    } // 32302b
}; // 6ac539

```

5.4 DFS algorithms

SCC.h

Description: Finds strongly connected components in a directed graph. If vertices u, v belong to the same component, we can reach u from v and vice versa.

Usage: `scc(graph, [&](vi& v) { ... })` visits all components in reverse topological order. `comp[i]` holds the component index of a node (a component only has edges to components with lower index). `ncomps` will contain the number of components.

Time: $\mathcal{O}(E + V)$ 76b5c9, 24 lines

```

vi val, comp, z, cont;
int Time, ncomps;
template<class G, class F> int dfs(int j, G& g, F& f) {
    int low = val[j] = ++Time, x; z.push_back(j);
    for (auto e : g[j]) if (comp[e] < 0)
        low = min(low, val[e] ?: dfs(e, g, f));
}

```

```

if (low == val[j]) {
    do {
        x = z.back(); z.pop_back();
        comp[x] = ncomps;
        cont.push_back(x);
    } while (x != j); // ae85bd
    f(cont); cont.clear();
    ncomps++;
} // 64c1b9
return val[j] = low;
} // 3513bd
template<class G, class F> void scc(G& g, F f) {
    int n = sz(g);
    val.assign(n, 0); comp.assign(n, -1);
    Time = ncomps = 0;
    rep(i, 0, n) if (comp[i] < 0) dfs(i, g, f);
} // 56b050

```

BiconnectedComponents.h

Description: Finds all biconnected components in an undirected graph. In a biconnected component there are at least two internally disjoint paths between any two nodes a cycle exists through them. Note that a node can be in several components. Every edge is in a single component. Nodes without edges will not be in any components

Time: $\mathcal{O}(E + V)$ 61b438, 53 lines

```

vector<pair<int, int>> edges; // edges
vector<vector<pair<int, int>>> g; // [b, edge idx]
vi tin, st, art;
int dfstime = 0;
vector<vi> bcc;

int dfs(int a, int p) {
    int top = tin[a] = ++dfstime;
    bool child = (p != -1);
    for (auto [b, e]: g[a]) {
        if (tin[b]) {
            top = min(top, tin[b]);
            if (tin[b] < tin[a]) st.pb(e);
        } // 0df373
        else {
            int si = sz(st);
            int up = dfs(b, e);
            top = min(top, up);
            if (up > tin[a]) { /*e is a bridge */
                if (up >= tin[a]) {
                    st.pb(e);
                    bcc.eb(st.begin() + si, st.end());
                    st.resize(si);
                    art[a] += child;
                    child = true;
                } // 46103a
            else if (up < tin[a]) st.pb(e);
        } // 38ea8a
    } // 59a60e
    return top;
} // 17df2f

```

```

void bicomps() {
    int n = sz(g);
    tin.assign(n, 0), art.assign(n, 0);
    rep(i, 0, n) if (!tin[i]) dfs(i, -1);
} // 600614

```

```

vi comp;
vector<vi> tree;
void build_tree() { // Optional
    int n = sz(g);
    comp.resize(n), tree.resize(n + sz(bcc));
}

```

```

rep(i, 0, sz(bcc)) {
    for (int eid: bcc[i]) {
        auto [a, b] = edges[eid];
        if (art[a] && (empty(tree[a]) || tree[a].back() != n+i))
            tree[a].pb(n+i), tree[n+i].pb(a);
        if (art[b] && (empty(tree[b]) || tree[b].back() != n+i))
            tree[b].pb(n+i), tree[n+i].pb(b);
        comp[a] = comp[b] = n + i;
    } // 2e7ad5
} // 8e4c66
rep(i, 0, n) if (art[i]) comp[i] = i;
} // b645e9

```

TwoCC.h

Description: Finds all two edge connected components in an undirected graph.

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

af5478. 44 lines

```

vector<vector<pair<int, int>>> g;
vector<pair<int, int>> edges;
vi tin, st, bridges;
int dfstime = 0;
vector<vi> twocc;

int dfs(int a, int p) {
    int top = tin[a] = ++dfstime;
    int si = st.size();
    st.pb(a);
    for (auto [b, e]: g[a]) if (e != p) {
        if (tin[b]) top = min(top, tin[b]);
        else {
            int up = dfs(b, e);
            top = min(top, up);
            if (up > tin[a]) bridges.pb(e);
        } // 1dd281
    } // ada038
    if (top == tin[a]) {
        twocc.eb(st.begin() + si, st.end());
        st.resize(si);
    } // 0f03f3
    return top;
} // 55bb17

void twocomps() {
    int n = sz(g);
    tin.assign(n, 0);
    rep(i, 0, n) if (!tin[i]) dfs(i, -1);
} // 9a2d22

vi comp;
vector<vi> tree;
void build_tree() { // Optional
    int n = sz(g);
    tree.resize(sz(twocc)); comp.resize(n);
    rep(i, 0, sz(twocc))
        for (int a: twocc[i]) comp[a] = i;

    for (int eid: bridges) {
        auto [a, b] = edges[eid];
        tree[comp[a]].pb(comp[b]), tree[comp[b]].pb(comp[a]);
    } // 1a7e1f
} // c306f0

```

2sat.h

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

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

5f9706, 56 lines

```

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

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

    int addVar() { // (optional)
        gr.emplace_back();
        gr.emplace_back();
        return N++;
    } // 7b5f84

    void either(int f, int j) {
        f = max(2*f, -1-2*f);
        j = max(2*j, -1-2*j);
        gr[f].push_back(j^1);
        gr[j].push_back(f^1);
    } // 516db0
    void setValue(int x) { either(x, x); }

    void atMostOne(const vi& li) { // (optional)
        if (sz(li) <= 1) return;
        int cur = ~li[0];
        rep(i, 2, sz(li)) {
            int next = addVar();
            either(cur, ~li[i]);
            either(cur, next);
            either(~li[i], next);
            cur = ~next;
        } // 8d3782
        either(cur, ~li[1]);
    } // 10f2ea

    vi val, comp, z; int time = 0;
    int dfs(int i) {
        int low = val[i] = ++time, x; z.push_back(i);
        for (int e: gr[i]) if (!comp[e])
            low = min(low, val[e] ?: dfs(e));
        if (low == val[i]) do {
            x = z.back(); z.pop_back();
            comp[x] = low;
            if (values[x>>1] == -1)
                values[x>>1] = x&1;
        } while (x != i); // b15351
        return val[i] = low;
    } // ef583a

    bool solve() {
        values.assign(N, -1);
        val.assign(2*N, 0); comp = val;
        rep(i, 0, 2*N) if (!comp[i]) dfs(i);
        rep(i, 0, N) if (comp[2*i] == comp[2*i+1]) return 0;
        return 1;
    } // 2bb76d
} // 5f9706

```

EulerWalk.h

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

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

780b64, 15 lines

```

vi eulerWalk(vector<vector<pii>> & gr, int nedges, int src=0) {
    int n = sz(gr);
    vi D(n), its(n), eu(nedges), ret, s = {src};
    D[src]++;
    while (!s.empty()) {
        int x = s.back(), y, e, &it = its[x], end = sz(gr[x]);
        if (it == end) { ret.push_back(x); s.pop_back(); continue; }
        tie(y, e) = gr[x][it++];
        if (!eu[e]) {
            D[x]--;
            D[y]++;
            eu[e] = 1; s.push_back(y);
        } // 22a87a // 94de26
        for (int x : D) if (x < 0 || sz(ret) != nedges+1) return {};
        ret.rbegin(), ret.rend();
    } // 780b64

```

DominatorTree.h

Description: Dominator Tree, creates the graph tree, where all ancestors of a in the tree are necessary in the path from the root to u

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

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

69af96, 57 lines

```

struct DominatorTree {
    int n;
    vector<vector<int>> g, gt, tree, bucket, down;
    vector<int> S;
    vector<int> dsu, label, sdom, idom, id;
    int dfstime = 0;

    DominatorTree(vector<vector<int>> & _g, int root)
        : n(sz(_g)), g(_g), gt(n), tree(n), bucket(n), down(n),
        S(n), dsu(n), label(n), sdom(n), idom(n), id(n) {
        prep(root); reverse(S.begin(), S.begin() + dfstime);
        for (int u : S) {
            for (int v : gt[u]) {
                int w = fnd(v);
                if (id[sdom[w]] < id[sdom[u]]) sdom[u] = sdom[w];
            } // e059b2
            gt[u].clear();
            if (u != root) bucket[sdom[u]].push_back(u);
            for (int v : bucket[u]) {
                int w = fnd(v);
                if (sdom[w] == sdom[v]) idom[v] = sdom[v];
                else idom[v] = w;
            } // 72077b
            bucket[u].clear();
            for (int v : down[u]) dsu[v] = u;
            down[u].clear();
        } // 3197c4
        reverse(S.begin(), S.begin() + dfstime);
        for (int u : S) if (u != root) {
            if (idom[u] != sdom[u]) idom[u] = idom[idom[u]];
            tree[idom[u]].push_back(u);
        } // 96e582
        idom[root] = root;
    } // b239ba
    void prep(int u) {
        S[dfstime] = u;
        id[u] = ++dfstime;
        label[u] = sdom[u] = dsu[u] = u;

        for (int v : g[u]) {

```

```
if(!id[v])
    prep(v), down[u].push_back(v);
    gt[v].push_back(u);
} // 4d7944
} // 4351b9
```

```
int fnd(int u, int flag = 0){
    if(u == dsu[u]) return u;
    int v = fnd(dsu[u], 1), b = label[dsu[u]];
    if(id[sdom[b]] < id[sdom[label[u]]])
        label[u] = b;
    dsu[u] = v;
    return flag ? v : label[u];
} // d64927

}; // 69af96
```

5.5 Coloring

EdgeColoring.h

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

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

e210e2, 31 lines

```
vi edgeColoring(int N, vector<pii> eds) {
    vi cc(N + 1), ret(sz(eds)), fan(N), free(N), loc;
    for (pii e : eds) ++cc[e.first], ++cc[e.second];
    int u, v, ncols = *max_element(all(cc)) + 1;
    vector<vi> adj(N, vi(ncols, -1));
    for (pii e : eds) {
        tie(u, v) = e;
        fan[0] = v;
        loc.assign(ncols, 0);
        int at = u, end = u, d, c = free[u], ind = 0, i = 0;
        while (d = free[v], !loc[d] && (v = adj[u][d]) != -1)
            loc[d] = ++ind, cc[ind] = d, fan[ind] = v;
        cc[loc[d]] = c;
        for (int cd = d; at != -1; cd ^= c ^ d, at = adj[at][cd])
            swap(adj[at][cd], adj[end] = at)[cd ^= c ^ d]);
        while (adj[fan[i]][d] != -1) {
            int left = fan[i], right = fan[++i], e = cc[i];
            adj[u][e] = left;
            adj[left][e] = u;
            adj[right][e] = -1;
            free[right] = e;
        } // 316eb7
        adj[u][d] = fan[i];
        adj[fan[i]][d] = u;
        for (int y : {fan[0], u, end})
            for (int& z = free[y] = 0; adj[y][z] != -1; z++);
    } // fdc6d3
    rep(i, 0, sz(eds))
        for (tie(u, v) = eds[i]; adj[u][ret[i]] != v;) ++ret[i];
    return ret;
} // e210e2
```

5.6 Heuristics

MaximalCliques.h

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

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

b0d5b1, 12 lines

```
typedef bitset<128> B;
template<class F>
void cliques(vector<B>& eds, F f, B P = ~B(), B X = {}, B R = {}) {
    if (!P.any()) { if (!X.any()) f(R); return; }
```

```
auto q = (P | X).find_first();
auto cands = P & ~eds[q];
rep(i, 0, sz(eds)) if (cands[i]) {
    R[i] = 1;
    cliques(eds, f, P & eds[i], X & eds[i], R);
    R[i] = P[i] = 0; X[i] = 1;
} // 181f8f
} // c9dc5f
```

MaximumClique.h

Description: Quickly finds a maximum clique of a graph (given as symmetric bitset matrix; self-edges not allowed). Can be used to find a maximum independent set by finding a clique of the complement graph.

Time: Runs in about 1s for n=155 and worst case random graphs (p=.90). Runs faster for sparse graphs.

f7c0bc, 49 lines

```
typedef vector<bitset<200>> vb;
struct Maxclique {
    double limit=0.025, pk=0;
    struct Vertex { int i, d=0; };
    typedef vector<Vertex> vv;
    vb e;
    vv V;
    vector<vi> C;
    vi qmax, q, S, old;
    void init(vv& r) {
        for (auto& v : r) v.d = 0;
        for (auto& v : r) for (auto j : r) v.d += e[v.i][j.i];
        sort(all(r), [](auto a, auto b) { return a.d > b.d; });
        int mxD = r[0].d;
        rep(i, 0, sz(r)) r[i].d = min(i, mxD) + 1;
    } // 7c428e
    void expand(vv& R, int lev = 1) {
        S[lev] += S[lev - 1] - old[lev];
        old[lev] = S[lev - 1];
        while (sz(R)) {
            if (sz(q) + R.back().d <= sz(qmax)) return;
            q.push_back(R.back().i);
        }
        vv T;
        for (auto v:R) if (e[R.back().i][v.i]) T.push_back({v.i});
        if (sz(T)) {
            if (S[lev]++ / ++pk < limit) init(T);
            int j = 0, mxk = 1, mnk = max(sz(qmax) - sz(q) + 1, 1);
            C[1].clear(), C[2].clear();
            for (auto v : T) {
                int k = 1;
                auto f = [&](int i) { return e[v.i][i]; };
                while (any_of(all(C[k]), f)) k++;
                if (k > mxk) mxk = k, C[mxk + 1].clear();
                if (k < mnk) T[j++].i = v.i;
                C[k].push_back(v.i);
            } // 3221ac
            if (j > 0) T[j - 1].d = 0;
            rep(k, mnk, mxk + 1) for (int i : C[k])
                T[j].i = i, T[j++].d = k;
            expand(T, lev + 1);
        } else if (sz(q) > sz(qmax)) qmax = q; // 2a0537
        q.pop_back(), R.pop_back();
    } // 87639b
} // f0a49d
vi maxClique() { init(V), expand(V); return qmax; }
Maxclique(vb conn) : e(conn), C(sz(e)+1), S(sz(C)), old(S) {
    rep(i, 0, sz(e)) V.push_back({i});
} // 36acab
}; // b63641
```

MaximumIndependentSet.h

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

5.7 Trees

CompressTree.h

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

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

LCA.h

```
struct LCA {
    vi time;
    int lca(int a, int b) { return -1; }
}; // 32d408
```

```
typedef vector<pair<int, int>> vpi;
vpi compressTree(LCA& lca, const vi& subset) {
    static vi rev; rev.resize(sz(lca.time));
    vi li = subset, &T = lca.time;
    auto cmp = [&](int a, int b) { return T[a] < T[b]; };
    sort(all(li), cmp);
    int m = sz(li)-1;
    rep(i, 0, m) {
        int a = li[i], b = li[i+1];
        li.push_back(lca.lca(a, b));
    } // 677c62
    sort(all(li), cmp);
    li.erase(unique(all(li)), li.end());
    rep(i, 0, sz(li)) rev[li[i]] = i;
    vpi ret = {pii(0, li[0])};
    rep(i, 0, sz(li)-1) {
        int a = li[i], b = li[i+1];
        ret.emplace_back(rev[lca.lca(a, b)], b);
    } // 5fe90
    return ret;
} // 83c9a2
```

HLD.h

Description: Decomposes a tree into vertex disjoint heavy paths and light edges such that the path from any leaf to the root contains at most $\log(n)$ light edges. Code does additive modifications and max queries, but can support commutative segtree modifications/queries on paths and subtrees. Takes as input the full adjacency list. VALS_EDGES being true means that values are stored in the edges, as opposed to the nodes. All values initialized to the segtree default. Root must be 0.

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

../data_structures/LazySegmentTree.h

```
template <bool VALS_EDGES> struct HLD {
    int N, tim = 0;
    vector<vi> adj;
    vi par, siz, rt, pos;
    Node *tree;
    HLD(vector<vi> adj_) {
        : N(sz(adj_)), adj(adj_), par(N, -1), siz(N, 1),
          rt(N), pos(N), tree(new Node(0, N)){dfsSz(0); dfsHld(0); }
    void dfsSz(int v) {
        for (int u : adj[v]) {
            adj[u].erase(find(all(adj[u]), v));
            par[u] = v;
            dfsSz(u);
            siz[v] += siz[u];
            if (siz[u] > siz[adj[v][0]]) swap(u, adj[v][0]);
        } // 9f610f
    } // db817b
```

```

void dfsHld(int v) {
    pos[v] = tim++;
    for (int u : adj[v]) {
        rt[u] = (u == adj[v][0] ? rt[v] : u);
        dfsHld(u);
    } // ee65b7
} // 044fde
template <class B> void process(int u, int v, B op) {
    for (; v = par[rt[v]] {
        if (pos[u] > pos[v]) swap(u, v);
        if (rt[u] == rt[v]) break;
        op(pos[rt[v]], pos[v] + 1);
    } // 00190c
    op(pos[u] + VALS_EDGES, pos[v] + 1);
} // 431b66
void modifyPath(int u, int v, int val) {
    process(u, v, [&](int l, int r) { tree->add(l, r, val); });
} // a181b8
int queryPath(int u, int v) { // Modify depending on problem
    int res = -le9;
    process(u, v, [&](int l, int r) {
        res = max(res, tree->query(l, r));
    }); // b1dde7
    return res;
} // 1a6944
int querySubtree(int v) { // modifySubtree is similar
    return tree->query(pos[v] + VALS_EDGES, pos[v] + siz[v]);
} // e86b89
}; // 9547af

```

LinkCutTree.h

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

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

0fb462, 90 lines

```

struct Node { // Splay tree. Root's pp contains tree's parent.
    Node *p = 0, *pp = 0, *c[2];
    bool flip = 0;
    Node() { c[0] = c[1] = 0; fix(); }
    void fix() {
        if (c[0]) c[0]->p = this;
        if (c[1]) c[1]->p = this;
        // (+ update sum of subtree elements etc. if wanted)
    } // 454758
    void pushFlip() {
        if (!flip) return;
        flip = 0; swap(c[0], c[1]);
        if (c[0]) c[0]->flip ^= 1;
        if (c[1]) c[1]->flip ^= 1;
    } // 0cc949
    int up() { return p ? p->c[1] == this : -1; }
    void rot(int i, int b) {
        int h = i ^ b;
        Node *x = c[i], *y = b == 2 ? x : x->c[h], *z = b ? y : x;
        if ((y->p = p)) p->c[up()] = y;
        c[i] = z->c[i ^ 1];
        if (b < 2) {
            x->c[h] = y->c[h ^ 1];
            y->c[h ^ 1] = x;
        } // 1a82cf
        z->c[i ^ 1] = this;
        fix(); x->fix(); y->fix();
        if (p) p->fix();
        swap(pp, y->pp);
    } // 1cf643
    void splay() {
        for (pushFlip(); p; ) {
            if (p->p) p->p->pushFlip();

```

```

            p->pushFlip(); pushFlip();
            int c1 = up(), c2 = p->up();
            if (c2 == -1) p->rot(c1, 2);
            else p->p->rot(c2, c1 != c2);
        } // e639f4
    } // bf1f7
    Node* first() {
        pushFlip();
        return c[0] ? c[0]->first() : (splay(), this);
    } // 67f9a1
}; // 225109

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

    void link(int u, int v) { // add an edge (u, v)
        assert(!connected(u, v));
        makeRoot(&node[u]);
        node[u].pp = &node[v];
    } // 60799e
    void cut(int u, int v) { // remove an edge (u, v)
        Node *x = &node[u], *top = &node[v];
        makeRoot(top); x->splay();
        assert(top == (x->pp ?: x->c[0]));
        if (x->pp) x->pp = 0;
        else {
            x->c[0] = top->p = 0;
            x->fix();
        } // 8acbe8
    } // a58ec7
    bool connected(int u, int v) { // are u, v in the same tree?
        Node* nu = access(&node[u])->first();
        return nu == access(&node[v])->first();
    } // b80a22
    void makeRoot(Node* u) {
        access(u);
        u->splay();
        if (u->c[0]) {
            u->c[0]->p = 0;
            u->c[0]->flip ^= 1;
            u->c[0]->pp = u;
            u->c[0] = 0;
            u->fix();
        } // 586a65
    } // 74c908
    Node* access(Node* u) {
        u->splay();
        while (Node* pp = u->pp) {
            pp->splay(); u->pp = 0;
            if (pp->c[1]) {
                pp->c[1]->p = 0; pp->c[1]->pp = pp; } // 1ccdfc
                pp->c[1] = u; pp->fix(); u = pp;
        } // b10f33
        return u;
    } // 4ac291
}; // ceab83

```

DirectedMST.h

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

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

..../data-structures/UnionFindRollback.h

39e620, 60 lines

```

struct Edge { int a, b, ll w; };
struct Node {
    Edge key;
    Node *l, *r;
    ll delta;
    void prop() {

```

```

        key.w += delta;
        if (l) l->delta += delta;
        if (r) r->delta += delta;
        delta = 0;
    } // 0d348f
    Edge top() { prop(); return key; }
}; // ab4902
Node* merge(Node *a, Node *b) {
    if (!a || !b) return a ?: b;
    a->prop(), b->prop();
    if (a->key.w > b->key.w) swap(a, b);
    swap(a->l, (a->r = merge(b, a->r)));
    return a;
} // c5109e
void pop(Node*& a) { a->prop(); a = merge(a->l, a->r); }

pair<ll, vi> dmst(int n, int r, vector<Edge>& g) {
    RollbackUF uf(n);
    vector<Node*> heap(n);
    for (Edge e : g) heap[e.b] = merge(heap[e.b], new Node(e));
    ll res = 0;
    vi seen(n, -1), path(n), par(n);
    seen[r] = r;
    vector<Edge> Q(n), in(n, {-1, -1}), comp;
    deque<tuple<int, int, vector<Edge>>> cycs;
    rep(s, 0, n) {
        int u = s, qi = 0, w;
        while (seen[u] < 0) {
            if (!heap[u]) return {-1, {}};
            Edge e = heap[u]->top();
            heap[u]->delta -= e.w, pop(heap[u]);
            Q[qi] = e, path[qi++] = u, seen[u] = s;
            res += e.w, u = uf.find(e.a);
            if (seen[u] == s) {
                Node* cyc = 0;
                int end = qi, time = uf.time();
                do cyc = merge(cyc, heap[w = path[--qi]]);
                while (uf.join(u, w));
                u = uf.find(u), heap[u] = cyc, seen[u] = -1;
                cycs.push_front({u, time, {&Q[qi], &Q[end]}});
            } // 00a339
        } // c8f0da
        rep(i, 0, qi) in[uf.find(Q[i].b)] = Q[i];
    } // fa3c2c

    for (auto& [u, t, comp] : cycs) { // restore sol (optional)
        uf.rollback(t);
        Edge inEdge = in[u];
        for (auto& e : comp) in[uf.find(e.b)] = e;
        in[uf.find(inEdge.b)] = inEdge;
    } // 4f9b56
    rep(i, 0, n) par[i] = in[i].a;
    return {res, par};
} // efa3a4

```

Data structures (6)

6.1 General

HashMap.h

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

d77092, 7 lines

```

#include <bits/extc++.h>
// To use most bits rather than just the lowest ones:
struct hash { // large odd number for C
    const uint64_t C = 11(4e18 * acos(0)) | 71;

```

```
11 operator()(ll x) const { return __builtin_bswap64(x*C); }
}; // cdd37e
__gnu_pbds::gp_hash_table<ll,int,hash> h({},{},{}),{},{{1<<16}};
```

OrderedSet.h

Description: ordered/indexed set and multiset Bad constant factor, works only in Linux

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

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

<bits/extc++.h> //include it before any defines

b8c30a, 15 lines

```
using namespace __gnu_pbds;
template<class T, class B = null_type> using ordered_set = tree
<T, B, less<T>, rb_tree_tag,
tree_order_statistics_node_update>;
```

```
template<class T>
struct ordered_multiset{
    ordered_set<pair<T, int>> o; int c;
    ordered_multiset():c(0){}
    unsigned order_of_key(T x){return o.order_of_key({x, -1});}
    const T* find_by_order(int p){return &(*o.find_by_order(p)).first;}
    void insert(T x){o.insert({x, c++});}
    void erase(T x){o.erase(o.lower_bound({x, 0}));}
    unsigned size(){return o.size();}
    const T* lower_bound(T x){return &(*o.lower_bound({x, 0})).first;}
    const T* upper_bound(T x){return &(*o.upper_bound({x, c})).first;}
}; // d4e54f
```

UnionFindRollback.h

Description: Disjoint-set data structure with undo. If undo is not needed, skip st, time() and rollback().

Usage: int t = uf.time(); ...; uf.rollback(t);

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

de4ad0, 21 lines

```
struct RollbackUF {
    vi e; vector<pi> st;
    RollbackUF(int n) : e(n, -1) {}
    int size(int x) { return -e[find(x)]; }
    int find(int x) { return e[x] < 0 ? x : find(e[x]); }
    int time() { return sz(st); }
    void rollback(int t) {
        for (int i = time(); i --> t)
            e[st[i].first] = st[i].second;
        st.resize(t);
    } // 30bb61
    bool join(int a, int b) {
        a = find(a), b = find(b);
        if (a == b) return false;
        if (e[a] > e[b]) swap(a, b);
        st.push_back({a, e[a]});
        st.push_back({b, e[b]});
        e[a] += e[b]; e[b] = a;
        return true;
    } // 6c709f
}; // de4ad0
```

StaticCHT.h

Description: static CHT - add must be ordered by slope (a), queries by x. Time: amortized $\mathcal{O}(1)$.

da7e40, 28 lines

```
struct CHT {
    int it; vector<ll> a, b;
    CHT():it(0){}
    ll eval(int i, ll x){return a[i]*x + b[i];}
    bool useless(){
        int sz = a.size();
    }
```

```
int r = sz-1, m = sz-2, l = sz-3;
#warning careful with overflow!
return (b[l] - b[r])*(a[m] - a[1]) <
(b[1] - b[m])*(a[r] - a[1]);
} // c37135
void add(ll A, ll B){
    a.push_back(A); b.push_back(B);
    while (!a.empty()){
        if ((a.size() < 3) || !useless()) break;
        a.erase(a.end() - 2);
        b.erase(b.end() - 2);
    } // b21fc8
    it = min(it, int(a.size()) - 1);
} // 6df532
ll get(ll x){
    while (it+1 < a.size()){
        if (eval(it+1, x) > eval(it, x)) it++;
        else break;
    } // fe9dba
    return eval(it, x);
} // b44949
}; // da7e40
```

LineContainer.h

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

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

8ec1c7, 30 lines

```
struct Line {
    mutable ll k, m, p;
    bool operator<(const Line& o) const { return k < o.k; }
    bool operator<(ll x) const { return p < x; }
}; // 7e3ecf

struct LineContainer : multiset<Line, less<>> {
    // (for doubles, use inf = 1./0, div(a,b) = a/b)
    static const ll inf = LLONG_MAX;
    ll div(ll a, ll b) { // floored division
        return a / b - ((a ^ b) < 0 && a % b); } // 10f081
    bool isect(iterator x, iterator y) {
        if (y == end()) return x->p = inf, 0;
        if (x->k == y->k) x->p = x->m > y->m ? inf : -inf;
        else x->p = div(y->m - x->m, x->k - y->k);
        return x->p >= y->p;
    } // 2fac86
    void add(ll k, ll m) {
        auto z = insert({k, m, 0}), y = z++, x = y;
        while (isect(y, z)) z = erase(z);
        if (x != begin() && isect(--x, y)) isect(x, y = erase(y));
        while ((y = x) != begin() && (--x)->p >= y->p)
            isect(x, erase(y));
    } // 08625f
    ll query(ll x) {
        assert(!empty());
        auto l = *lower_bound(x);
        return l.k * x + l.m;
    } // d21e2f
}; // 5771f0
```

6.2 Range Queries

Spec.h

Description: Algebraic structures for RQDS. Includes Ruan's version.

Time: varies

6260e7, 67 lines

```
struct Group { //sum
    using T = int;
    static constexpr T id = 0;
    static T op(T a, T b){return a+b;}
```

```
static T inv(T a){return -a;}
}; // 3e6767

struct LazySpecRuan { //sum
    using S = int;
    using K = int;
    static S op(S a, S b) { return max(a, b); }
    static S update(K f, S a) { return f + a; }
    static K compose(const K f, const K g) { return f + g; }
    static S id() { return 0; }
}; // 69c889
```

```
struct LazySpecArthur { //set add sum
    using T = ll;
    using L = pair<int, ll>;
    static constexpr T id = 0;
    static T op(T a, T b){return a + b; }
    static T ch(T past, L upd, int lx, int rx){
        ll s = rx-lx;
        auto [t, x] = upd;
        if (t) return s*x;
        else return past+s*x;
    } // 442906
    static L cmp(L cur, L upd){
        auto [t1, x1] = cur;
        auto [t2, x2] = upd;
        if (t2) return upd;
        else return {t1, x1+x2};
    } // e78ccc
}; // c4da38
```

```
struct node{int max1,max2,maxc; ll sum;};
struct BeatsSpec{ //chmin sum
    using T = node; using L = int;
    static constexpr T id = node{-oo,-oo,0,0};
    static T op(T a, T b){
        node n;
        if (a.max1 > b.max1){
            n.max1 = a.max1;
            n.max2 = max(a.max2, b.max1);
            n.maxc = a.maxc;
        } // 60044a
        else if (a.max1 == b.max1){
            n.max1 = a.max1;
            n.max2 = max(a.max2, b.max2);
            n.maxc = a.maxc+b.maxc;
        } // 89a062
        else{
            n.max1 = b.max1;
            n.max2 = max(b.max2, a.max1);
            n.maxc = b.maxc;
        } // dbf86a
        n.sum=a.sum+b.sum;
        return n;
    } // 7311b8
    static T ch(T a, L b, int l, int r){
        if (a.max2 <= b.a.sum -= (ll)(a.max1-b)*a.maxc, a.max1 = b.a.sum)
            return a;
    } // 6f5ec4
    static L cmp(L a, L b){return min(a,b);}
    static bool brk(L a, T b){return b.max1 <= a;}
    static bool tag(L a, T b){return b.max2 < a;}
}; // 0a5678
```

Treap.h

Description: A short self-balancing tree. It acts as a sequential container with log-time splits/joins, and is easy to augment with additional data.

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

1754b4, 53 lines

```

struct Node {
    Node *l = 0, *r = 0;
    int val, y, c = 1;
    Node(int val) : val(val), y(rand()) {}
    void recalc();
}; // daabb7

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

template<class F> void each(Node* n, F f) {
    if (n) { each(n->l, f); f(n->val); each(n->r, f); }
} // 75295c

pair<Node*, Node*> split(Node* n, int k) {
    if (!n) return {};
    if (cnt(n->l) >= k) { // "n->val >= k" for lower_bound(k)
        auto [L,R] = split(n->l, k);
        n->l = R;
        n->recalc();
        return {L, n};
    } else { // f7155f
        auto [L,R] = split(n->r, k - cnt(n->l) - 1); // and just "k"
        n->r = L;
        n->recalc();
        return {n, R};
    } // 63911a
} // e8be20

```

```

Node* merge(Node* l, Node* r) {
    if (!l) return r;
    if (!r) return l;
    if (l->y > r->y) {
        l->r = merge(l->r, r);
        return l->recalc(), l;
    } else { // f7c66a
        r->l = merge(l, r->l);
        return r->recalc(), r;
    } // 520567
} // 1594e3

```

```

Node* ins(Node* t, Node* n, int pos) {
    auto [l,r] = split(t, pos);
    return merge(merge(l, n), r);
} // 32c794

```

```

// Example application: move the range [l, r) to index k
void move(Node*& t, int l, int r, int k) {
    Node *a, *b, *c;
    tie(a,b) = split(t, l); tie(b,c) = split(b, r - 1);
    if (k <= l) t = merge(ins(a, b, k), c);
    else t = merge(a, ins(c, b, k - r));
} // 9c4818

```

FenwickTree.h

Description: Computes partial sums $a[0] + a[1] + \dots + a[pos - 1]$, and updates single elements $a[i]$, taking the difference between the old and new value.

Time: Both operations are $\mathcal{O}(\log N)$.

e62fac, 22 lines

```

struct FT {
    vector<ll> s;
    FT(int n) : s(n) {}
    void update(int pos, ll dif) { // a[pos] += dif
        for (; pos < sz(s); pos |= pos + 1) s[pos] += dif;
    } // a388f1
    ll query(int pos) { // sum of values in [0, pos)
        ll res = 0;
        for (; pos > 0; pos &= pos - 1) res += s[pos-1];
    } // 0f7fae
}; // e62fac

```

```

    return res;
} // 6defa0
int lower_bound(ll sum) { // min pos st sum of [0, pos] >= sum
    // Returns n if no sum is >= sum, or -1 if empty sum is.
    if (sum <= 0) return -1;
    int pos = 0;
    for (int pw = 1 << 25; pw; pw >>= 1) {
        if (pos + pw <= sz(s) && s[pos + pw-1] < sum)
            pos += pw, sum -= s[pos-1];
    } // 63f005
    return pos;
} // ea70d8
} // e62fac

```

FenwickTree2d.h

Description: Computes sums $a[i,j]$ for all $i < I, j < J$, and increases single elements $a[i,j]$. Requires that the elements to be updated are known in advance (call fakeUpdate() before init()).

Time: $\mathcal{O}(\log^2 N)$. (Use persistent segment trees for $\mathcal{O}(\log N)$.)

"FenwickTree.h" 157f07, 22 lines

```

struct FT2 {
    vector<vi> ys; vector<FT> ft;
    FT2(int limx) : ys(limx) {}
    void fakeUpdate(int x, int y) {
        for (; x < sz(ys); x |= x + 1) ys[x].push_back(y);
    } // 01fc7b
    void init() {
        for (vi& v : ys) sort(all(v)), ft.emplace_back(sz(v));
    } // d5ca1f
    int ind(int x, int y) {
        return (int)(lower_bound(all(ys[x]), y) - ys[x].begin());
    } // aee02d
    void update(int x, int y, ll dif) {
        for (; x < sz(ys); x |= x + 1)
            ft[x].update(ind(x, y), dif);
    } // bb1454
    ll query(int x, int y) {
        ll sum = 0;
        for (; x; x &= x - 1)
            sum += ft[x-1].query(ind(x-1, y));
        return sum;
    } // 8334c3
}; // 157f07

```

MoQueries.h

Description: Answer interval or tree path queries. Includes interval version without deletion. If values are on tree edges, change step to add/remove the edge (a, c) and remove the initial add call (but keep in).

Time: $\mathcal{O}(N\sqrt{Q})$ 5377e, 76 lines

```

void add(int ind, int end) { ... } // add a[ind] (end = 0 or 1)
void del(int ind, int end) { ... } // remove a[ind]
int calc() { ... } // compute current answer

```

```

vi mo(vector<pii> Q) {
    int L = 0, R = 0, blk = 350; // ~N/sqrt(Q)
    vi s(sz(Q)), res = s;
    define K(x) pii(x.first/bk, x.second ^ -(x.first/bk & 1))
    iota(all(s), 0);
    sort(all(s), [&](int s, int t){ return K(Q[s]) < K(Q[t]); });
    for (int qi : s) {
        pii q = Q[qi];
        while (L > q.first) add(--L, 0);
        while (R < q.second) add(R++, 1);
        while (L < q.first) del(L++, 0);
        while (R > q.second) del(--R, 1);
        res[qi] = calc();
    } // 0f7fae
    return res;
} // fe1e74

```

} // e3731f

```

vi moTree(vector<array<int, 2>> Q, vector<vi> ed, int root=0) {
    int N = sz(ed), pos[2] = {}, blk = 350; // ~N/sqrt(Q)
    vi s(sz(Q)), res = s, I(N), L(N), R(N), in(N), par(N);
    add(0, 0), in[0] = 1;
    auto dfs = [&](int x, int p, int dep, auto& f) -> void {
        par[x] = p;
        L[x] = N;
        if (dep) I[x] = N++;
        for (int y : ed[x]) if (y != p) f(y, x, !dep, f);
        if (!dep) I[x] = N++;
        R[x] = N;
    }; // 329c88
    dfs(root, -1, 0, dfs);
#define K(x) pii(I[x[0]] / blk, I[x[1]] ^ -(I[x[0]] / blk & 1))
    iota(all(s), 0);
    sort(all(s), [&](int s, int t){ return K(Q[s]) < K(Q[t]); });
    for (int qi : s) rep(end, 0, 2) {
        int &a = pos[qi], b = Q[qi][end], i = 0;
#define step(c) { if (in[c]) { del(a, end); in[a] = 0; } \
            else { add(c, end); in[c] = 1; } a = c; } //
    } // 3839ba
    while (! (L[b] <= I[a] && R[a] <= R[b])) {
        I[i++], b, b = par[b];
        while (a != b) step(par[a]);
        while (i--) step(I[i]);
        if (end) res[qi] = calc();
    } // c880be
    return res;
} // ce9c1e

```

```

vector<int> mo_no_deletion(vector<pii> qs, int n) {
    int q = sz(qs), sq = (int)sqrt(q)+1, blk = (n+sq+1)/sq;
    vector<vi> o((n+blk-1)/blk);
    rep(i, 0, q)o[qs[i].first/bk].pb(i);
    for(auto& vq : o)sort(all(vq), [&](int i, int j){return qs[i].second < qs[j].second});
    vector<int> ans(q);
    rep(i, 0, sz(o)) {
        auto& vq = o[i];
        int l = blk*i + blk, r = l-1;
        // prepare to answer queries
        for(int qi : vq) {
            auto [ql, qr] = qs[qi];
            if (qr <= l) { //if it does not extrapolate
                rep(j, ql, qr+1)add(j, 1); //solving manually
                continue;
            } // b94913
            while(r < qr)add(++r, 1);
            int ml = 1; //we will move l manually
            // prepare checkpoint
            while(ml > ql)add(--ml, 0);
            ans[qi] = calc();
            // revert checkpoint: discard changes made by moving l
        } // 6569ca
    } // 09ff2d
    return ans;
} // fe1e74

```

ColorUpdate.h

Description: Adds intervals and keep information about them

Memory: $\mathcal{O}(Q)$

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

afa378, 34 lines

```

struct ColorUpdate {
    using IT = pair<pair<int, int>, int>;
    map<int, ll> freq; set<IT> rgs;
    vector<set<IT>::iterator> intersect(int l, int r) {

```

```
// Return all ranges that intersects with [l, r]
vector<set<IT>>::iterator> ans;
auto it = rgs.lower_bound(pair(pair(r+1, -1), -1));
while(it != rgs.begin()) {
    it = prev(it);
    auto [lx, rx] = it->first;
    if (rx < l) break;
    ans.pb(it);
} // dda9d0
return ans;
} // 9480c5
void add(int l, int r, int c) {
    // Adds a range [l, r] with color c
    auto v = intersect(l, r);
    vector<IT> to_add = {{l, r}, c};
    for (auto it: intersect(l, r)) {
        // Remove it information
        freq[it->second] -= it->first.second - it->first.first + 1;
        to_add.pb({{it->first.first, l-1}, it->second});
        to_add.pb({{r+1, it->first.second}, it->second});
        rgs.erase(it);
    } // 00093e
    for (auto [x, c]: to_add) {
        if (x.first > x.second) continue;
        rgs.insert({x, c});
        // Add x c information
        freq[c] += x.second - x.first + 1;
    } // 56edf2
} // 6fd6a1
}; // afa378
```

MergeSortTree.h

Description: Merge Sort Tree
Memory: $\mathcal{O}(N \log N)$
Time: $\mathcal{O}(\log^2 N)$

7c1cf9, 38 lines

```
template<class T> struct MGST{
    int h; vector<vector<T>> t;
    int lg(int x){return __builtin_clz(1)-__builtin_clz(x);}
    MGST(vector<T> v): n(sz(v)), h(lg(n)){
        if (n != (1<<h)) n = 1<<(++h);
        t.assign(h, vector<T>(n));
        rep(i, 0, sz(v)) t[0][i] = v[i];
        rep(i, sz(v), n) t[0][i] = oo; //non-existent
        rep(k, 0, h) for(int i = 0, s = 1<<k; i < n; i += 2*s){
            int p1=0, p2=0;
            rep(p, i, i+2*s){
                if (p1==s)t[k+1][p] = t[k][i+s+p2], p2++;
                else if (p2==s)t[k+1][p] = t[k][i+p1], p1++;
                else if (t[k][i+p1] < t[k][i+s+p2])t[k+1][p] = t[k][i+p1], p1++;
                else t[k+1][p] = t[k][i+s+p2], p2++;
            } // 690730
        } // b7e287
        T query_helper(T x, int k, int l){
            auto it = upper_bound(t[k]+l, t[k]+l+(1<<k), x);
            if (it == t[k]+l) return 0;
            else return *prev(it);
        } // ef2397
        T lb(T x, int l, int r){ //biggest <= x in [l, r]
            T ans = 0; r++;
            for(int k = 0; l < r; k++){
                if ((1>k)&1){
                    ans = max(ans, query_helper(x, k, l));
                    l += 1<<k;
                } // 1bf09f
                if ((r>k)&1){
```

```
r -= 1<<k;
ans = max(ans, query_helper(x, k, r));
} // aa3bad
} // b63c49
return ans;
} // 8e4027
}; // 7c1cf9
```

MPsum.h

Description: Multidimensional Psum Requires Abelian Group (op, inv, id)
Memory: $\mathcal{O}(N^D)$
Time: $\mathcal{O}(2^D)$

3c2845, 20 lines

```
#define MAs template<class... As> //multiple arguments
template<int D, class S> struct Psum{
    using T = typename S::T;
    int n; vector<Psum<D-1, S>> v;
    MAs Psum(int s, As... ds):n(s+1),v(n,Psum<D-1, S>(ds...)){}
    MAs void set(T x, int p, As... ps){v[p+1].set(x, ps...);}
    void push(Psum& p)(rep(i, 1, n)v[i].push(p.v[i]);}
    void init(){rep(i, 1, n)v[i].init(),v[i].push(v[i-1]);}
    MAs T query(int l, int r, As... ps){
        return S::op(v[r+1].query(ps...),S::inv(v[l].query(ps...)));
    }
}; // eac6a8
}; // 4f6c04
template<class S> struct Psum<0, S>{
    using T = typename S::T;
    T val=S::id;
    void set(T x){val=x;}
    void push(Psum& a){val=S::op(a.val,val);}
    void init(){}
    T query(){return val;}
}; // 713694
```

Dist.h

Description: Disjoint Sparse Table Requires Monoid (op, id)
Memory: $\mathcal{O}(N \log N)$
Time: $\mathcal{O}(\log N)$

2f4715, 21 lines

```
#define repinv(i, a, b) for(int i = (a); i >= (b); i--)
template<class S> struct DiST{
    using T = typename S::T;
    int n, h; vector<vector<T>> t;
    int lg(signed x){return __builtin_clz(1)-__builtin_clz(x);}
    DiST(vector<T> v): n(sz(v)), h(lg(n)){
        if (n != (1<<h)) n = 1<<(++h);
        t.assign(h, vector<T>(n));
        for(int d = 0, s = 1; d < h; d++, s *= 2)
            for(int m = s; m < n; m += 2*s){
                t[d][m] = v[m]; t[d][m-1] = v[m-1];
                rep(i, m+1, m+s)t[d][i] = S::op(t[d][i-1], v[i]);
                repinv(i, m-2, m-s)t[d][i] = S::op(v[i], t[d][i+1]);
            }
        } // 3b44fe
    } // 1c2aa0
    T query(int l, int r){
        if (l==r) return t[0][l];
        int k = lg(l^r);
        return S::op(t[k][l], t[k][r]);
    }
}; // 612c6a
```

SparseTable.h

Description: Sparse Table Requires Idempotent Monoid S (op, inv, id)
Memory: $\mathcal{O}(n \log n)$
Time: $\mathcal{O}(1)$ query, $\mathcal{O}(n \log n)$ build

276609, 14 lines

```
template<class S> struct SpTable{
```

```
using T = typename S::T;
int n; vector<vector<T>> tab;
int lg(signed x){return __builtin_clz(1)-__builtin_clz(x);}
SpTable(vector<T> v):n(sz(v)),tab(1+lg(n),vector<T>(n,S::id)){
    rep(i, 0, n)tab[0][i] = v[i];
    rep(i, 0, lg(n))rep(j, 0, n-(1<<i))
        tab[i+1][j] = S::op(tab[i][j], tab[i][j+(1<<i)]);
}
}; // c105d7
T query(int l, int r){
    int k = lg(++r-l);
    return S::op(tab[k][l], tab[k][r-(1<<k)]);
}
}; // e06689
}; // 276609
```

SqrtDecomp.h

Description: Sqrt Decomposition
Memory: $\mathcal{O}(n)$

Time: $\mathcal{O}(n)$ build, $\mathcal{O}(\sqrt{n})$ queries

f45235, 41 lines

```
struct SqrtDecomp {
    using K = ll; // single element information
    using T = ll; // block information
    int n, bsz, n_block;
    vector<T> v;
    vector<int> id;
    vector<K> block;
    SqrtDecomp(const vector<T> & x): n(sz(x)), v(x), id(n) {
        bsz = sqrt(n) + 1;
        n_block = (n + bsz - 1) / bsz; // ceil(n, bsz)
        rep(i, 0, n) id[i] = i / bsz;
        // Add information to block
        block = vector<K>(n_block, oo);
        rep(i, 0, n) block[id[i]] = min(block[id[i]], v[i]);
    }
}; // 3bc167
void update(int idx, ll x) { // Update set idx to x
    int bid = id[idx];
    block[bid] = oo;
    v[idx] = x;
    rep(i, bid * bsz, min((bid+1)*bsz, n)) block[bid] = min(
        block[bid], v[i]);
} // 7aff89
ll query(int l, int r) { // Query of min in interval [l, r]
    assert(l <= r); // Or return id;
    ll ans = oo;
    auto sblk = [&](int bid, int flag) { // flag [left, right, both]
        rep(i, max(l, bid*bsz), min((bid+1)*bsz, r+1)) ans = min(
            ans, v[i]);
    };
}; // f49504
auto allblk = [&](int bid) { // Solve entire block
    ans = min(ans, block[bid]);
}; // 3566fc
if (id[l] == id[r]) {
    sblk(id[l], 2);
} // 340382
else {
    sblk(id[l], 0);
    rep(i, id[l]+1, id[r]) allblk(i);
    sblk(id[r], 1);
} // e1769a
return ans;
}; // 7a0d23
}; // f45235
```

6.2.1 Segment Tree

SegmentTree.h

Description: Iterative SegTree Can be changed by modifying Spec

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

607842, 18 lines

```
template<typename LS> struct SegTree {
    using S = typename LS::S;
    using K = typename LS::K;
    int n; vector<S> seg;
    SegTree(int _n) : n(_n), seg(2*n, LS::id()) {}
    void update(int no, K val) {
        no += n; seg[no] = LS::update(val, seg[no]);
        while (no > 1) no /= 2, seg[no] = LS::op(seg[no*2], seg[no*2+1]);
    } // adca9b
    S query(int l, int r) { // [l, r)
        S vl = LS::id(), vr = LS::id();
        for (l += n, r += n; l < r; l /= 2, r /= 2) {
            if (l & 1) vl = LS::op(vl, seg[l++]);
            if (r & 1) vr = LS::op(seg[--r], vr);
        } // 77c5ac
        return LS::op(vl, vr);
    } // edc68a
}; // 607842
```

LazySegmentTree.h

Description: Lazy Seg (half-open). Can be transformed into Seg Beats by uncommenting conditions.

Time: $\mathcal{O}(\log N * (ch + cmp))$.

fa8696, 30 lines

```
template<class S> struct SegBeats{ // n MUST be a power of 2
    using T = typename S::T; using L = typename S::L;
    int n; vector<T> seg; vector<L> lz; vector<bool> ig;
    SegBeats(int s):n(s),seg(2*n,S::id()),lz(2*n),ig(2*n,1){}
    void apply(int p, L v, int l, int r){
        seg[p] = S::ch(seg[p],v,l,r);
        if (r-l>1)lz[p] = ig[p] ? v : S::cmp(lz[p], v), ig[p] = 0;
    } // f453ff
    void prop(int p, int l, int r){
        if (ig[p])return;
        int m = (l+r)/2; ig[p] = 1;
        apply(2*p, lz[p], l, m);
        apply(2*p+1, lz[p], m, r);
    } // f09d8e
    void update(L v, int l, int r){return update(v,l,r,1,0,n);}
    void update(L v, int lq, int rq, int no, int lx, int rx){
        if (rq <= lx or rx <= lq /*or S::brk(v,seg[no])*/*)return;
        if (lq <= lx and rx <= rq /*and S::tag(v,seg[no])*/*)return
            apply(no, v, lx, rx);
        int mid = (lx+rx)/2; prop(no, lx, rx);
        update(v,lq,rq,2*no,1x,mid); update(v,lq,rq,2*no+1,mid,rx);
        seg[no] = S::op(seg[2*no],seg[2*no+1]);
    } // 04eed2
    T query(int l, int r){return query(l,r,1,0,n);}
    T query(int lq, int rq, int no, int lx, int rx){
        if (rq <= lx or rx <= lq)return S::id();
        if (lq <= lx and rx <= rq)return seg[no];
        int mid = (lx+rx)/2; prop(no, lx, rx);
        return S::op(query(lq,rq,2*no,1x,mid),query(lq,rq,2*no+1,
            mid,rx));
    } // fb0086
}; // fa8696
```

MSegTree.h

Description: Multidimensional SegTree Requires Monoid (op, id)

Memory: $\mathcal{O}(N^D)$

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

e335e5, 26 lines

```
#define MAs template<class... As> //multiple arguments
template<int D, class S> struct MSegTree{
    using T = typename S::T;
    int n; vector<MSegTree<D-1, S>> seg;
    MAs MSegTree(int s, As... ds):n(s),seg(2*n, MSegTree<D-1, S>(
        ds...)){}
    MAs T get(int p, As... ps){return seg[p+n].get(ps...);}
    MAs void update(T x, int p, As... ps){
        seg[p+n].update(x, ps...);
        while(p!=2)seg[p].update(S::op(seg[2*p].get(ps...),seg[2*p
            +1].get(ps...)), ps...));
    } // 2c8b52
    MAs T query(int l, int r, As... ps){
        T lv=S::id,rv=S::id;
        for(l+=n,r+=n;l<r;l/=2,r/=2){
            if (l&1)lv = S::op(lv,seg[l++].query(ps...));
            if (r&1)rv = S::op(seg[--r].query(ps...),rv);
        } // 1569b6
        return S::op(lv,rv);
    } // bc7474
}; // da06ff
template<class S> struct MSegTree<0, S>{
    using T = typename S::T;
    T val=S::id;
    T get(){return val;}
    void update(T x){val=x;} //set update!
    T query(){return val;}
}; // 50402e
```

LazySparseSeg.h

Description: Lazy Sparse Seg (half-open). Lazy can be removed (prop, lz, ig, ch/cmp)

Time: $\mathcal{O}(\log N * (ch + cmp))$.

d8f4f1, 37 lines

```
template<class I, class S> struct LazySparseSeg{ //I is index
    type
    using T = typename S::T; //value type
    using L = typename S::L; //update type
    struct Node{int lc, rc; T val; L lz; bool ig;};
    I n; vector<Node> v;
    int new_node(){return v.eb(0,0,S::id,L(),1), sz(v)-1;}
    LazySparseSeg(I s):n(s){
        //v.reserve(MXN); //faster node creation
        new_node(); new_node(); //blank and root node
    } // c4ba1b
    void apply(int i, L x, I lx, I rx){
        v[i].val = S::ch(v[i].val, x, lx, rx);
        if ((rx-lx)>1)v[i].lz = v[i].ig ? x : S::cmp(v[i].lz, x), v[i
            ].ig = 0;
    } // 9ccb90
    void prop(int i, I lx, I rx){
        if (!v[i].lc)v[i].lc = new_node(), v[i].rc = new_node();
        if (v[i].ig)return;
        I mx = (lx+(rx-lx)/2); v[i].ig = 1;
        apply(v[i].lc, v[i].lz, lx, mx); apply(v[i].rc, v[i].lz, mx
            , rx);
    } // a00350
    void update(L x, I l, I r){return update(x, l, r, 1, 0, n-1);}
    void update(L x, I l, I r, int i, I lx, I rx){
        if (r <= lx or rx <= l)return;
        if (l <= lx and rx <= r)apply(i, x, lx, rx);
        I mx = (lx+(rx-lx)/2); prop(i, lx, rx);
        int lc = v[i].lc, rc = v[i].rc;
        update(x, l, r, lc, lx, mx); update(x, l, r, rc, mx, rx);
        v[i].val = S::op(v[lc].val, v[rc].val);
    } // f721de
    T query(I l, I r){return query(l, r, 1, 0, n-1);}
    T query(I l, I r, int i, I lx, I rx){

```

```
        if (r <= lx or rx <= l)return S::id;
        if (l <= lx and rx <= r)return v[i].val;
        I mx = (lx+(rx-lx)/2); prop(i, lx, rx);
        return S::op(query(l, r, v[i].lc, lx, mx), query(l, r, v[i
            ].rc, mx, rx));
    } // 52a49e
}; // d8f4f1
```

LazyPersistentSeg.h

Description: Persistent Lazy Sparse Segment Tree Can be changed by modifying Spec

Time: $\mathcal{O}(\log N * (ch + cmp))$

b43ed0, 39 lines

```
template<class I, class S> struct LazyPersistentSeg{ //I is
    index type
    using T = typename S::T; //value type
    using L = typename S::L; //lazy type
    struct Node{int lc, rc; T val; L lz; bool ig;};
    I n; vector<Node> v;
    int new_node(int l=0, int r=0){return v.eb(l,r,S::op(v[l].val
        ,v[r].val),L(),1), sz(v)-1;}
    LazyPersistentSeg(){ //only creates object, should be "init"
        ed to get root
        //v.reserve(MXN); //faster node creation
        v.eb(0,0,S::id,L(),1); //blank node
    } // 00247f
    int init(I s){return n = s, new_node();}
    int lazy_clone(int i, L lz, I lx, I rx){
        int ni = new_node(v[i].lc, v[i].rc);
        v[ni].lz = v[i].ig ? lz : S::cmp(v[i].lz, lz);
        v[ni].ig = 0; v[ni].val = S::ch(v[i].val, lz, lx, rx);
        return ni;
    } // 4c0efb
    void prop(int i, I lx, I rx){
        if (v[i].ig)return;
        int mx = lx + (rx - lx) / 2; v[i].ig = 1;
        if (lx < rx)
            v[i].lc = lazy_clone(v[i].lc, v[i].lz, lx, mx),
            v[i].rc = lazy_clone(v[i].rc, v[i].lz, mx, rx);
    } // 551bde
    int update(L lz, I l, I r, int root){return update(lz, l, r,
        root, 0, n);}
    int update(L lz, I l, I r, int i, I lx, I rx){
        if (r <= lx or rx <= l)return i;
        if (l <= lx and rx <= r) return lazy_clone(i, lz, lx, rx);
        I mx = lx + (rx - lx) / 2; prop(i, lx, rx);
        return new_node(update(lz, l, r, v[i].lc, lx, mx), update(
            lz, l, r, v[i].rc, mx, rx));
    } // ca252e
    T query(I l, I r, int root){return query(l, r, root, 0, n);}
    T query(I l, I r, int i, I lx, I rx){
        if (r <= lx or rx <= l)return S::id;
        if (l <= lx and rx <= r) return v[i].val;
        I mx = lx + (rx - lx) / 2; prop(i, lx, rx);
        return S::op(query(l, r, v[i].lc, lx, mx), query(l, r, v[i
            ].rc, mx, rx));
    } // 893689
}; // b43ed0
```

Strings (7)

Hashing.h

Description: String hashing (multiple mods and 2^{32})

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

Time: $\mathcal{O}(1)$ query, $\mathcal{O}(n)$ build

c40ee3, 23 lines

```
typedef uint64_t ull;
template<int M, class B> struct A {
```

```

int x; B b; A(int x=0) : x(x), b(x) {}
A(int x, B b) : x(x), b(b) {}
A operator+(A o) const {int y = x+o.x; return{y - (y>=M)*M, b + o.b};}
A operator-(A o) const {int y = x-o.x; return{y + (y< 0)*M, b - o.b};}
A operator*(A o) const { return {(int)((ll)x*o.x % M), b*o.b};}
explicit operator ull() const { return x ^ (ull) b << 21; }
}; // e03276
typedef A<1000000007, A<1000000009, unsigned> H;
static int C; // initialize to a number less than MOD or random
struct HashInterval {
    int n; vector<H> ha, pw;
    template<typename S>
    HashInterval(const S & str) : n(sz(str)), ha(n+1), pw(n+1) {
        pw[0] = 1;
        rep(i,0,n)
            ha[i+1] = ha[i] * C + str[i],
            pw[i+1] = pw[i] * C;
    } // 185a86
    H query(int a, int b) { return ha[b] - ha[a] * pw[b-a]; }
    H queryI(int a, int b) { return query(n-b, n-a); }
}; // 434a8c

```

KMP.h**Description:** KMP automaton**Memory:** $\mathcal{O}(N)$ **Time:** $\mathcal{O}(N)$ build, $\mathcal{O}(1)$ query (amortized)

8f8450, 19 lines

```

struct KMP {
    string P; int n; vector<int> nb;
    KMP(string& p) : P(p), n((int)P.size()), nb(n+1) {
        for(int k = 1; k < n; k++) nb[k+1] = nxt(nb[k], P[k]);
    } // ca6dc8
    int nxt(int i, char c){
        for(; i; i = nb[i]) if (i < n and P[i]==c) return i+1;
        return P[0]==c;
    } // 2b99e2
    vector<vector<int>> dfa;
    void build_dfa(){
        dfa.assign(n+1, vector<int>(26));
        dfa[0][P[0]-'a'] = 1; //only way to advance at 0
        for(int k = 1; k <= n; k++)
            for(int c = 0; c < 26; c++)
                if (k < n and P[k] == 'a'+c) dfa[k][c] = k+1;
                else dfa[k][c] = dfa[nb[k]][c];
    } // f47d83
}; // 8f8450

```

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

ee09e2, 9 lines

```

vi Z(const string& S) {
    vi z(sz(S)); int l = -1, r = -1;
    rep(i,1,sz(S)) {
        z[i] = i >= r ? 0 : min(r - i, z[i - 1]);
        while (i + z[i] < sz(S) && S[i + z[i]] == S[z[i]]) z[i]++;
        if (i + z[i] > r) l = i, r = i + z[i];
    } // 44be47
    return z;
} // ee09e2

```

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

```

array<vi, 2> manacher(const string& s) {
    int n = sz(s); array<vi,2> p = {vi(n+1), vi(n)};
    rep(z,0,2) for (int i=0,l=0,r=0; i < n; i++) {
        int t = r-i+1;
        if (i < r) p[z][i] = min(t, p[z][l+t]);
        int L = i-p[z][i], R = i+p[z][i]-!z;
        while (L>=1 && R+1<n && s[L-1] == s[R+1]) p[z][i]++, L--, R++;
        if (R>r) l=L, r=R;
    } // a843d3
    return p;
} // e7ad79

```

e7ad79, 11 lines

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

d07a42, 8 lines

```

int minRotation(string s) {
    int a=0, N=sz(s); s += s;
    rep(b,0,N) rep(k,0,N) {
        if (a+k == b || s[a+k] < s[b+k]) {b += max(0, k-1); break;}
        if (s[a+k] > s[b+k]) {a = b; break;}
    } // 9374b1
    return a;
} // d07a42

```

Aho.h**Description:** Aho automaton**Memory:** $\mathcal{O}(\text{alphabetsize} * n)$ **Time:** $\mathcal{O}(\text{alphabetsize} * n)$ build, $\mathcal{O}(1)$ query

7fe61a, 35 lines

```

#define vvi vector<vi>
struct Aho {
    int n=1, si; char in;
    vvi tran, nxt;
    vi lnk, term, h;
    Aho(char ain='a', int asi=26) : in(ain), si(asi) { tran.eb(si,-1); term.pb(0); }
    void add(string& s) {
        int cur=0;
        rep(i,0,s.size()) {
            int& nxt=tran[cur][s[i]-in];
            if (nxt != -1) cur=nxt;
            else nxt=cur=n++, term.pb(0), tran.eb(si,-1);
        } // 8426b9
        term[cur]+=1;
    } // f31f2a
    void init() {
        lnk.assign(n,0);
        nxt.assign(n, vi(si));
        h.assign(n,0);
        queue<int> q; q.push(0);
        while (!q.empty()) {
            int a=q.front(); q.pop();
            rep(c,0,si) {
                int b=nxt[a][c];
                int fail=nxt[lnk[a]][c];
                if (tran[a][c] != -1) {
                    b = tran[a][c];
                    lnk[b] = a ? fail : 0;
                    q.push(b);
                    h[b]=h[a]+1;
                } else b=fail; // a1bc18
            } // 83b11a
        } // 494c02
    } // 7f7bf2
} // 483f6b

```

Automaton.h**Description:** Suffix automaton**Memory:** $\mathcal{O}(n * 26)$ **Time:** $\mathcal{O}(n)$ build

7479ba, 35 lines

```

struct Automata {
    int saID = 1, last = 1, n;
    vector<int> len, lnk;
    vector<array<int,27>> to;
    vector<int> occ, fpos;
    vector<int> states;
    Automata(const string &s, const char a = 'a') : n(s.size()), len(2*n+2), lnk(2*n+2), to(2*n+2, {0}), occ(2*n+2), fpos(2*n+2) {
        for (const auto &c: s) push(c-a);
        states.assign(saID, 0);
        iota(all(states), 1);
        sort(all(states), [&](const auto &u, const auto &v) { return len[u] > len[v]; });
        for (auto st: states) occ[lnk[st]] += occ[st];
    } // a267f8
    void push(int c) {
        int a = ++saID, p = last;
        last = a;
        len[a] = len[p] + 1;
        occ[a] = 1;
        fpos[a] = len[a] - 1;
        for (; p > 0 && !to[p][c]; p = lnk[p]) to[p][c] = a;
        int q = to[p][c];
        if (p == 0) lnk[a] = 1;
        else if (len[p] + 1 == len[q]) lnk[a] = q;
        else {
            int clone = ++saID;
            lnk[clone] = lnk[q];
            to[clone] = to[q];
            fpos[clone] = fpos[q];
            len[clone] = len[p] + 1;
            lnk[a] = lnk[q] = clone;
            for (; to[p][c] == q; p = lnk[p]) to[p][c] = clone;
        } // d4d0c5
    } // 070b4e
}; // 7479ba

```

Various (8)**8.1 Intervals****IntervalContainer.h****Description:** Add and remove intervals from a set of disjoint intervals. Will merge the added interval with any overlapping intervals in the set when adding. Intervals are [inclusive, exclusive).**Time:** $\mathcal{O}(\log N)$

edce47, 23 lines

```

set<pii>::iterator addInterval(set<pii>& is, int L, int R) {
    if (L == R) return is.end();
    auto it = is.lower_bound({L, R}), before = it;
    while (it != is.end() && it->first <= R) {
        R = max(R, it->second);
        before = it = is.erase(it);
    } // fe9c77
    if (it != is.begin() && (--it)->second >= L) {
        L = min(L, it->first);
        R = max(R, it->second);
        is.erase(it);
    } // 0dea63
    return is.insert(before, {L,R});
} // d57d47

void removeInterval(set<pii>& is, int L, int R) {

```

```
if (L == R) return;
auto it = addInterval(is, L, R);
auto r2 = it->second;
if (it->first == L) is.erase(it);
else (int&)it->second = L;
if (R != r2) is.emplace(R, r2);
} // 0594c1
```

IntervalCover.h

Description: Compute indices of smallest set of intervals covering another interval. Intervals should be [inclusive, exclusive). To support [inclusive, inclusive], change (A) to add || R.empty(). Returns empty set on failure (or if G is empty).

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

9e9d8d, 19 lines

```
template<class T>
vi cover(pair<T, T> G, vector<pair<T, T>> I) {
    vi S(sz(I)), R;
    iota(all(S), 0);
    sort(all(S), [&](int a, int b) { return I[a] < I[b]; });
    T cur = G.first;
    int at = 0;
    while (cur < G.second) { // (A)
        pair<T, int> mx = make_pair(cur, -1);
        while (at < sz(I) && I[S[at]].first <= cur) {
            mx = max(mx, make_pair(I[S[at]].second, S[at]));
            at++;
        } // c42b58
        if (mx.second == -1) return {};
        cur = mx.first;
        R.push_back(mx.second);
    } // dd14a7
    return R;
} // b8d6e9
```

ConstantIntervals.h

Description: Split a monotone function on [from, to) into a minimal set of half-open intervals on which it has the same value. Runs a callback g for each such interval.

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

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

753a4c, 19 lines

```
template<class F, class G, class T>
void rec(int from, int to, F& f, G& g, int& i, T& p, T q) {
    if (p == q) return;
    if (from == to) {
        g(i, to, p);
        i = to; p = q;
    } else { // 956f3f
        int mid = (from + to) >> 1;
        rec(from, mid, f, g, i, p, f(mid));
        rec(mid+1, to, f, g, i, p, q);
    } // effcac
} // fb5eee
template<class F, class G>
void constantIntervals(int from, int to, F f, G g) {
    if (to <= from) return;
    int i = from; auto p = f(i), q = f(to-1);
    rec(from, to-1, f, g, i, p, q);
    g(i, to, q);
} // 8bf818
```

8.2 Misc. algorithms

TernarySearch.h

Description: Find the smallest i in $[a, b]$ that maximizes $f(i)$, assuming that $f(a) < \dots < f(i) \geq \dots \geq f(b)$. To reverse which of the sides allows non-strict inequalities, change the $<$ marked with (A) to \leq , and reverse the loop at (B). To minimize f , change it to $>$, also at (B).

Usage: int ind = ternSearch(0, n-1, [&](int i){return a[i];});
Time: $\mathcal{O}(\log(b-a))$

```
9155b4, 11 lines
template<class F>
int ternSearch(int a, int b, F f) {
    assert(a <= b);
    while (b - a >= 5) {
        int mid = (a + b) / 2;
        if (f(mid) < f(mid+1)) a = mid; // (A)
        else b = mid+1;
    } // ce7859
    rep(i, a+1, b+1) if (f(a) < f(i)) a = i; // (B)
    return a;
} // 5d6373
```

LIS.h

Description: Compute indices for the longest increasing subsequence.

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

```
2932a0, 17 lines
template<class I> vi lis(const vector<I>& S) {
    if (S.empty()) return {};
    vi prev(sz(S));
    typedef pair<I, int> p;
    vector<p> res;
    rep(i, 0, sz(S)) {
        // change 0 -> i for longest non-decreasing subsequence
        auto it = lower_bound(all(res), p{S[i], 0});
        if (it == res.end()) res.emplace_back(), it = res.end()-1;
        *it = {S[i], i};
        prev[i] = it == res.begin() ? 0 : (it-1)->second;
    } // 14749f
    int L = sz(res), cur = res.back().second;
    vi ans(L);
    while (L--) ans[L] = cur, cur = prev[cur];
    return ans;
} // 2932a0
```

FastKnapsack.h

Description: Given N non-negative integer weights w and a non-negative target t, computes the maximum $S \leq t$ such that S is the sum of some subset of the weights.

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

```
b20ccc, 16 lines
int knapsack(vi w, int t) {
    int a = 0, b = 0, x;
    while (b < sz(w) && a + w[b] <= t) a += w[b++];
    if (b == sz(w)) return a;
    int m = *max_element(all(w));
    vi u, v(2*m, -1);
    v[a+m-t] = b;
    rep(i, b, sz(w)) {
        u = v;
        rep(x, 0, m) v[x+w[i]] = max(v[x+w[i]], u[x]);
        for (x = 2*m; -x > m; ) rep(j, max(0, u[x]), v[x])
            v[x-w[j]] = max(v[x-w[j]], j);
    } // ac5d5a
    for (a = t; v[a+m-t] < 0; a--) ;
    return a;
} // b20ccc
```

Submasks.h

Description: iterating over all submasks of all masks in descending order

Memory: $\mathcal{O}(1)$

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

```
1fe48a, 10 lines
void submaskiteration(){
    int mx = 4;
    for(int mask = 0; mask < (1<<mx); mask++) {
        for(int s = mask; s; s=(s-1)&mask) {
            // s is a non zero submask of mask
    }
```

```
;
} // fc9392
// now process zero submask
} // 98b5a8
} // 1fe48a
```

8.3 Dynamic programming

KnuthDP.h

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

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

DivideAndConquerDP.h

Description: Given $a[i] = \min_{lo(i) \leq k < hi(i)} (f(i, k))$ where the (minimal) optimal k increases with i , computes $a[i]$ for $i = L..R-1$.

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

d38d2b, 18 lines

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

    void rec(int L, int R, int LO, int HI) {
        if (L >= R) return;
        int mid = (L + R) >> 1;
        pair<ll, int> best(LLONG_MAX, LO);
        rep(k, max(LO, lo(mid)), min(HI, hi(mid)))
            best = min(best, make_pair(f(mid, k), k));
        store(mid, best.second, best.first);
        rec(L, mid, LO, best.second, HI);
        rec(mid+1, R, best.second, HI);
    } // 541151
    void solve(int L, int R) { rec(L, R, INT_MIN, INT_MAX); }
}; // d38d2b
```

8.4 Debugging tricks

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

8.5 Optimization tricks

`_builtin_ia32_ldmxcsr(40896);` disables denormals (which make floats 20x slower near their minimum value).

8.5.1 Bit hacks

- $x \& -x$ is the least bit in x .
- for (int x = m; x;) { --x &= m; ... } loops over all subset masks of m (except m itself).

- `c = x&-x, r = x+c; (((r^x) >> 2)/c) | r` is the next number after `x` with the same number of bits set.
- `rep(b,0,K) rep(i,0,(1 << K)) if (i & 1 << b) D[i] += D[i^(1 << b)];` computes all sums of subsets.

8.5.2 Pragmas

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

FastMod.h

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

751a02, 8 lines

```
typedef unsigned long long ull;
struct FastMod {
    ull b, m;
    FastMod(ull b) : b(b), m(-1ULL / b) {}
    ull reduce(ull a) { // a % b + (0 or b)
        return a - (ull)((__uint128_t(m) * a) >> 64) * b;
    } // f67e7e
}; // 38ea39
```

FastInput.h

Description: Read an integer from stdin. Usage requires your program to pipe in input from file.

Usage: `./a.out < input.txt`

Time: About 5x as fast as `cin/scanf`.

7b3c70, 17 lines

```
inline char gc() { // like getchar()
    static char buf[1 << 16];
    static size_t bc, be;
    if (bc >= be) {
        buf[0] = 0, bc = 0;
        be = fread(buf, 1, sizeof(buf), stdin);
    } // d32dbc
    return buf[bc++]; // returns 0 on EOF
} // 0261eb
```

.readInt()

```
int readInt() {
    int a, c;
    while ((a = gc()) < 40);
    if (a == '-') return -readInt();
    while ((c = gc()) >= 48) a = a * 10 + c - 480;
    return a - 48;
} // e0474e
```

BumpAllocator.h

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

745db2, 8 lines

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

```
} // 306d90
void operator delete(void*) {}
```

SmallPtr.h

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

`"BumpAllocator.h"` 2dd6c9, 10 lines

```
template<class T> struct ptr {
    unsigned ind;
    ptr(T* p = 0) : ind(p ? unsigned((char*)p - buf) : 0) {
        assert(ind < sizeof buf);
    } // 77e020
    T& operator*() const { return *(T*)(buf + ind); }
    T* operator->() const { return &*this; }
    T& operator[](int a) const { return (*this)[a]; }
    explicit operator bool() const { return ind; }
}; // 2dd6c9
```

BumpAllocatorSTL.h

Description: BumpAllocator for STL containers.

Usage: `vector<vector<int, small<int>> ed(N);` bb66d4, 14 lines

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

```
template<class T> struct small {
    typedef T value_type;
    small() {}
    template<class U> small(const U&) {}
    T* allocate(size_t n) {
        buf_ind -= n * sizeof(T);
        buf_ind &= 0 - alignof(T);
        return (T*)(buf + buf_ind);
    } // e76df3
    void deallocate(T*, size_t) {}
}; // 1640d4
```

SIMD.h

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

c9ac08, 43 lines

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

```
typedef __m256i mi;
#define L(x) _mm256_loadu_si256((mi*)&(x))
```

// High-level/specific methods:

```
// load(u)?_si256, store(u)?_si256, setzero_si256, _mm_malloc
// blendv_(epi8|ps|pd) (z?y:x), movemask_ep8 (hibits of bytes)
// i32gather-epi32(addr, x, 4): map addr[] over 32-b parts of x
// sad.epu8: sum of absolute differences of u8, outputs 4xi64
// maddubs-epi16: dot product of unsigned i7's, outputs 16xi15
// madd.epi16: dot product of signed i16's, outputs 8xi32
// extractf128_si256_(i, i) (256->128), cvtsi128_si32 (128->lo32)
// permute2f128_si256(x,x,1) swaps 128-bit lanes
// shuffle-epi32(x, 3*64+2*16+1*4+0) == x for each lane
// shuffle-epi8(x, y) takes a vector instead of an imm
```

// Methods that work with most data types (append e.g. _epi32):

```
// set1, blend (i8?x:y), add, adds (sat.), mullo, sub, and/or,
// andnot, abs, min, max, sign(1,x), cmp(gt|eq), unpack(lo|hi)
```

```
int sumi32(mi m) { union { int v[8]; mi m; } u; u.m = m;
    int ret = 0; rep(i,0,8) ret += u.v[i]; return ret; } // 6
    d0af8
mi zero() { return _mm256_setzero_si256(); }
mi one() { return _mm256_set1_epi32(-1); }
bool all_zero(mi m) { return _mm256_testz_si256(m, m); }
bool all_one(mi m) { return _mm256_testc_si256(m, one()); }

ll example_filteredDotProduct(int n, short* a, short* b) {
    int i = 0, ll r = 0;
    mi zero = _mm256_setzero_si256(), acc = zero;
    while (i + 16 <= n) {
        mi va = L(a[i]), vb = L(b[i]); i += 16;
        va = _mm256_and_si256(_mm256_cmplt_ep16(vb, va), va);
        mi vp = _mm256_madd_ep16(va, vb);
        acc = _mm256_add_ep164(_mm256_unpacklo_epi32(vp, zero),
            _mm256_add_ep164(acc, _mm256_unpackhi_epi32(vp, zero)));
    } // b3ac72
    union { ll v[4]; mi m; } u; u.m = acc; rep(i,0,4) r += u.v[i];
    for (i;<n;+i) if (a[i] < b[i]) r += a[i]*b[i]; // <- equiv
    return r;
} // 288660
```

Techniques (A)

techniques.txt

159 lines

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

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

Knuth-Morris-Pratt
 Tries
 Rolling polynomial hashes
 Suffix array
 Suffix tree
 Aho-Corasick
 Manacher's algorithm
 Letter position lists
 Combinatorial search
 Meet in the middle
 Brute-force with pruning
 Best-first (A*)
 Bidirectional search
 Iterative deepening DFS / A*

Data structures
 LCA (2^k -jumps in trees in general)
 Pull/push-technique on trees
 Heavy-light decomposition
 Centroid decomposition
 Lazy propagation
 Self-balancing trees
 Convex hull trick (wcipeg.com/wiki/Convex_hull_trick)
 Monotone queues / monotone stacks / sliding queues
 Sliding queue using 2 stacks
 Persistent segment tree