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## Contest (1)

.bashrc

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

3 lines

.vimrc

```
set cin aw ai is ts=4 sw=4 tm=50 nu noeB bg=dark ru cul
sy on | im kj <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 -dD -P -fpreprocessed \| tr -d '[:space:]' \
 \| md5sum \| cut -c-6
```

6 lines

hash.sh

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

3 lines

debug.sh

```
set -e
g++ code.cpp -o code
g++ gen.cpp -o gen
```

17 lines

```
1 g++ brute.cpp -o brute
for((i = 1; ; ++i)); do
    ./gen $i > input_file
    ./code < input_file > myAnswer
    ./brute < input_file > correctAnswer
    diff -Z myAnswer correctAnswer > /dev/null || break
    echo "Passed test: " $i
8 done
echo "WA on the following test:"
cat input_file
echo "Your answer is:"
cat myAnswer
echo "Correct answer is:"
cat correctAnswer
16
```

## Mathematics (2)

### 2.1 Math notes

#### 2.1.1 Derangements

Count the number of permutations of length  $n$  with 0 fixed points (i.e  $p(i) \neq i$  for all  $i \leq n$ )

$$f(n) = \begin{cases} 1, & n = 0, \\ 0, & n = 1, \\ (n-1)(f(n-1) + f(n-2)), & n \geq 2. \end{cases}$$

#### 2.1.2 Catalan Numbers

- Correctly matched parentheses expressions of length  $2n$ ,
- Rooted binary trees with  $n+1$  leaves,
- Dyck paths of length  $2n$ ,
- Ways to triangulate a polygon with  $n+2$  sides,
- Different binary search trees that can be constructed with  $n$  distinct keys.

$$C_n = \frac{1}{n+1} \binom{2n}{n}, \quad n \geq 0.$$

$$C_n = \binom{2n}{n} - \binom{2n}{n+1}, \quad n \geq 0.$$

$$C_0 = 1, \quad C_{n+1} = \sum_{i=0}^n C_i C_{n-i}, \quad n \geq 0.$$

The first few values of the sequence  $(C_n)$  are

$$1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, \dots$$

### 2.1.3 Binet's Formula

$$F_0 = 0, \quad F_1 = 1, \quad F_n = F_{n-1} + F_{n-2} \quad \text{for } n \geq 2.$$

$$F_n = \frac{\phi^n - \psi^n}{\sqrt{5}},$$

where  $\phi = \frac{1+\sqrt{5}}{2}$  is the golden ratio and  $\psi = \frac{1-\sqrt{5}}{2}$  is its conjugate.

### 2.1.4 Sums

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

### 2.1.5 Stirling number of the second kind

The Stirling number of the second kind,  $S(n, k)$ , counts the number of ways to partition a set of  $n$  objects into  $k$  non-empty, unlabeled subsets. The formula is recursive and is given by:

$$S(n, k) = k \cdot S(n-1, k) + S(n-1, k-1), \quad S(0, 0) = 1, \quad S(n, 0) = 0 \quad \text{for } n > 0.$$

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

### 2.1.6 Möbius

$$s_{f*g}(n) = \sum_{i=1}^n \sum_{d|i} g(d) f\left(\frac{i}{d}\right)$$

$$\begin{aligned} s_{f*g}(n) &= \sum_{d=1}^n \sum_{p=1}^{\lfloor \frac{n}{d} \rfloor} g(d) f(p) \\ s_{f*g}(n) &= g(1) \sum_{p=1}^n f(p) + \sum_{d=2}^n \sum_{p=1}^{\lfloor \frac{n}{d} \rfloor} g(d) f(p) = g(1)s_f(n) + \sum_{d=2}^n g(d)s_f\left(\lfloor \frac{n}{d} \rfloor\right) \\ s_f(n) &= \frac{s_{f*g}(n) - \sum_{d=2}^n s_f\left(\lfloor \frac{n}{d} \rfloor\right)g(d)}{g(1)} \end{aligned}$$

### 2.1.7 Combinatorics

$$\sum_{k=0}^x \frac{\binom{x}{k}}{\binom{n}{k}} = \frac{n+1}{n-x+1}.$$

## 2.2 Algorithms

MillerRabin.h

Description: Primality check for numbers up to  $7 \cdot 10^{18}$ , extend bases for larger number

Time:  $\mathcal{O}(7 \log \maxValue)$

Status: Tested on judge.yosupo.jp

c63d96, 35 lines

```
namespace MillerRabin {
    using T = unsigned long long;

    T binpow(T x, T y, T mod) {
        T ans = 1; x %= mod;
        while (y > 0) {
            if (y & 1) ans = (Int)ans * x % mod;
            x = (Int)x * x % mod, y >= 1;
        }
        return ans;
    }

    bool notPrime(T n, T base, T d, int s) {
        if (base % n == 0) return false;
        T x = binpow(base % n, d, n);
        if (x == 1 || x == n - 1) return false;
        for (int r = 1; r < s; ++r) {
            x = (Int)x * x % n;
        }
    }
}
```

```

    if (x == n - 1) return false;
}
return true;
}

bool isPrime(T n) {
    if (n < 2 || n % 6 % 4 != 1) return (n + 1) == 3;
    int s = CTZ(n - 1); T d = n >> s;

    const T bases[] = {2, 325, 9375, 28178, 450775, 9780504,
        1795265022};

    for (T base : bases) {
        if (notPrime(n, base, d, s)) return false;
    }
    return true;
}

```

## FastFourierTransform.h

**Description:** FFT to multiply two polynomials.**Usage:** Get the real answer then convert to integer and modulo.**Time:**  $\mathcal{O}(N \log N)$  where N is the total sizes of two polynomials**Status:** Well-tested

## FastFourierTransform

```

inline cmplx sub(cmplx& c1, cmplx& c2) {
    return {c1.a - c2.a, c1.b - c2.b};
}

inline cmplx mult(cmplx& c1, cmplx& c2) {
    return {c1.a * c2.a - c1.b * c2.b, c1.a * c2.b + c1.b * c2.a};
}

void fft(vector<cmplx> &a, int n) {
    for (int i = 1, j = 0; i < n; ++i) {
        int bit = n >> 1;
        for (; j >= bit; bit >>= 1) j -= bit;
        j += bit;
        if (i < j) swap(a[i], a[j]);
    }
    for (int k = 1; k < n; k *= 2) {
        ld phi = pi / k;
        cmplx wt(cos(phi), sin(phi));
        for (int i = 0; i < n; i += 2 * k) {
            cmplx w(1, 0);
            for (int j = 0; j < k; ++j) {
                cmplx u = a[i + j], v = mult(a[i + j + k], w);
                a[i + j] = sum(u, v);
                a[i + j + k] = sub(u, v);
                w = mult(w, wt);
            }
        }
    }
}

vector<int> multiply(vector<int> &s, vector<int> &t) {
    int need = (int) s.size() + t.size() - 1, sz = 1;
    while (sz < need) sz <<= 1;
    vector<cmplx> a(sz), b(sz);
    for (int i = 0; i < sz; ++i) {
        if(i < (int)s.size()) a[i] = cmplx(s[i], 0);
        else a[i] = cmplx(0, 0);
        if(i < (int)t.size()) b[i] = cmplx(t[i], 0);
        else b[i] = cmplx(0, 0);
    }
    fft(a, sz);
    fft(b, sz);
    for (int i = 0; i < sz; ++i) {

```

---

```

namespace FFT {
    const ld pi = atan2(1, 1) * 4;

    struct cmplx {
        ld a, b;

        cmplx() {
            a = 0, b = 0;
        }

        cmplx(ld a1, ld b1) {
            a = a1, b = b1;
        }
    };

    inline cmplx sum(cmplx& c1, cmplx& c2) {
        return {c1.a + c2.a, c1.b + c2.b};
    }
}
```

28f50c, 76 lines

```

        a[i] = mult(a[i], b[i]);
    }

fft(a, sz);
reverse(a.begin() + 1, a.end());

vector<int> ans(need);
for (int i = 0; i < need; ++i) ans[i] = (Int)(round(a[i].a / sz))
    % MOD;
return ans;
}

vector<int> operator * (vector<int> &s, vector<int> &t) {
    return FFT::multiply(s, t);
}

```

## GaussElimination.h

**Description:** Gauss elimination to solve system of linear equations**Usage:** variables are numbered 0 -> m-1, the m-th column is the right hand side**Time:**  $\mathcal{O}(min(N, M) \cdot N \cdot M)$  where N = equations, M = variables**Status:** Tested on VNOI

9990b6, 38 lines

```

int gauss(vector<vector<double>> &a, vector<double> &ans) {
    const double EPS = 1e-9;
    int n = a.size(), m = a[0].size() - 1;

    vector<int> where(m, -1);
    for (int col = 0, row = 0; col < m && row < n; ++col) {
        int p = row;
        for (int i = row; i < n; ++i)
            if (abs(a[i][col]) > abs(a[p][col])) p = i;

        if (abs(a[p][col]) < EPS) continue;

        swap(a[row], a[p]);
        where[col] = row;

        for (int i = 0; i < n; ++i) if (i != row) {
            double c = a[i][col] / a[row][col];
            for (int j = col; j <= m; ++j)
                a[i][j] -= a[row][j] * c;
        }
        ++row;
    }
}
```

## GaussElimination GaussElimination2

```

    }

    ans.assign(m, 0);
    for (int i = 0; i < m; ++i) if (where[i] != -1) {
        ans[i] = a[where[i]][m] / a[where[i]][i];
    }

    for (int i = 0; i < n; ++i) {
        double sum = 0;
        for (int j = 0; j < m; ++j) sum += ans[j] * a[i][j];
        if (abs(sum - a[i][m]) > EPS) return 0;
    }

    for (int i = 0; i < m; ++i)
        if (where[i] == -1) return 2;
    return 1;
}
```

## GaussElimination2.h

**Description:** Gauss elimination to solve system of linear equations (mod 2)**Usage:** all roots of the system have the form: ans + sum(c(i) \* basis(i))**Time:**  $\mathcal{O}\left(\frac{\min(N, M) \cdot N \cdot M}{64}\right)$  where N = equations, M = variables**Status:** Tested on judge.yosupo.jp

e796d6, 54 lines

```

namespace Gauss {
    // n: num equations, m: num variables
    // left hand side: 0 -> m-1, right hand side: column m
    const int M = 4096 + 5;
    using T = bitset<M>;

    int n, m;
    int where[M];
    vector<T> a;
    T ans;

    void init(int _n, int _m, const vector<T> &_a) {
        n = _n, m = _m, a = _a;
    }

    int gauss() {
        for (int i = 0; i < m; ++i) where[i] = -1;
        int row = 0;
        for (int col = 0; col < m && row < n; ++col) {

```

```

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

for (int i = 0; i < m; ++i) if (where[i] != -1) {
    ans[i] = a[where[i]][m];
}

for (int i = 0; i < n; ++i) {
    bool sum = 0;
    for (int j = 0; j < m; ++j) sum ^= ans[j] & a[i][j];
    if (sum != a[i][m]) return -1;
}
return row;
}

vector<T> get_basis() { // assume gauss() has been called
    vector<T> basis;
    for (int i = 0; i < m; ++i) if (where[i] == -1) {
        T x; x[i] = 1;
        // x(j) + a[where[j]][i] * x[i] = 0
        for (int j = 0; j < m; ++j)
            if (where[j] != -1) x[j] = a[where[j]][i];
        basis.emplace_back(x);
    }
    return basis;
}

```

## Data structures (3)

LichaoTree.h

**Description:** LichaoTree -> use for DP convex hull trick

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

**Status:** Tested by KickingKun

### LichaoTree

```

struct LiChaoTree {
    static const ll lim = 1e9;
    struct Line {
        ll a, b;
        ll operator()(ll x) {
            return a * x + b;
        }
    };
    struct node {
        Line line;
        node *l, *r;
        node() {
            line = {0, INF};
            l = r = NULL;
        }
    };
    node *root = new node();

    ll query(node *i, ll l, ll r, ll x) {
        if (i == NULL || x < l || x > r) return INF;
        ll m = (l + r) >> 1;
        ll ans = i->line(x);
        minimize(ans, query(i->l, l, m, x));
        minimize(ans, query(i->r, m + 1, r, x));
        return ans;
    }

    ll query(ll x) {
        return query(root, -lim, lim, x);
    }

    void add(Line li, node *&cur, ll l, ll r) {
        if (cur == nullptr){
            cur = new node(); cur->line = li;
            return;
        }
        ll mid = (l + r) >> 1;
        if (li(mid) < cur->line(mid)) swap(li, cur->line);
        if (li(l) < cur->line(l)) add(li, cur->l, l, mid);
        if (li(r) < cur->line(r)) add(li, cur->r, mid + 1, r);
    }
}

```

4a9142, 48 lines

```

void add(ll m, ll b) {
    add({m, b}, root, -lim, lim);
}
} cht;

```

## FastSegmentTree.h

**Description:** Non-recursion segment tree with point updates and range sum queries.**Usage:** Call mytree.resize(n) before any operations.**Time:**  $\mathcal{O}(\log N)$  for each operation**Status:** Well-tested

ad3579, 31 lines

```

struct SegmentTree {
    vector<ll> nodes;
    int n;

    SegmentTree() {}

    void resize(int _n) {
        n = _n; nodes.assign(2 * n + 5, 0);
        build();
    }

    void build() { // 1-index
        for (int i = 1; i <= n; ++i) nodes[i + n] = a[i];
        for (int i = n; i > 0; --i)
            nodes[i] = nodes[i << 1] + nodes[i << 1 | 1];
    }

    void update(int p, int val) {
        for (nodes[p += n] += val; p >>= 1;)
            nodes[p] = nodes[p << 1] + nodes[p << 1 | 1];
    }

    ll get(int l, int r) {
        ll ansL = 0, ansR = 0;
        for (l += n, r += n + 1; l < r; l >>= 1, r >>= 1) {
            if (l & 1) ansL = ansL + nodes[l++];
            if (r & 1) ansR = nodes[--r] + ansR;
        }
        return ansL + ansR;
    }
} mytree;

```

## PersistentIT.h

**Description:** Persistent segment tree with point updates and range sum queries.**Usage:** Remember to call mytree.resize(n) before any operations.

Make sure to check for integer overflows in update values.

**Memory:**  $\mathcal{O}(\log N \cdot \text{numUpdates})$ **Time:**  $\mathcal{O}(\log N)$  for each operation**Status:** Tested on CSES

7b58c2, 55 lines

```

struct Node {
    int le, ri;
    ll sum;

    Node(int _le = 0, int _ri = 0, ll _sum = 0) {
        le = _le, ri = _ri, sum = _sum;
    }
} nodes[N * LG];
int numNode = 0;
vector<int> version;

struct PersistentIT { // 1-indexed
    int n;

    PersistentIT(int _n = 0) {
        resize(_n);
    }

    void resize(int _n) {
        n = _n;
    }

    int update(int oldId, int l, int r, int p, int val) {
        if (l > p || r < p) return oldId;

        int id = ++numNode;
        if (l == r) {
            nodes[id] = nodes[oldId];
            nodes[id].sum += val;
            return id;
        }

        int mid = (l + r) >> 1;
        nodes[id].le = update(nodes[oldId].le, l, mid, p, val);
        nodes[id].ri = update(nodes[oldId].ri, mid + 1, r, p, val);
    }
}

```

```

    nodes[id].sum = nodes[nodes[id].le].sum + nodes[nodes[id].ri].sum;
    return id;
}

int update(int root, int p, int val) {
    return update(root, 1, n, p, val);
}

ll get(int id, int l, int r, int u, int v) {
    if (l > v || r < u) return 0;
    if (u <= l && r <= v) return nodes[id].sum;
    int mid = (l + r) >> 1;
    return get(nodes[id].le, l, mid, u, v) + get(nodes[id].ri, mid +
        1, r, u, v);
}

ll get(int root, int u, int v) {
    return get(root, 1, n, u, v);
}
} mytree;

```

## PersistentLazyIT.h

**Description:** Persistent segment tree with range updates and range sum queries.

**Usage:** Remember to call mytree.resize(n) before any operations.

**Memory:**  $\mathcal{O}(4 \cdot \log N \cdot \text{numUpdates})$

**Time:**  $\mathcal{O}(\log N)$  for each operation

**Status:** Not tested

## PersistentLazyIT

```

    }

void resize(int _n) {
    n = _n;
}

int newlazykid(int oldId, int l, int r, ll val) {
    int id = ++numNode;
    nodes[id] = nodes[oldId];

    nodes[id].sum += ll * val * (r - l + 1);
    nodes[id].lazy += val;

    return id;
}

int newparent(int le, int ri) {
    int id = ++numNode;
    nodes[id].le = le, nodes[id].ri = ri;
    nodes[id].sum = nodes[le].sum + nodes[ri].sum;
    return id;
}

void push(int id, int l, int r) {
    if (nodes[id].lazy == 0) return;
    if (l != r) {
        int mid = (l + r) >> 1;
        nodes[id].le = newlazykid(nodes[id].le, l, mid, nodes[id].lazy
            );
        nodes[id].ri = newlazykid(nodes[id].ri, mid + 1, r, nodes[id].lazy);
    }
    nodes[id].lazy = 0;
}

int update(int oldId, int l, int r, int u, int v, ll val) {
    if (l > v || r < u) return oldId;
    if (u <= l && r <= v) return newlazykid(oldId, l, r, val);
    push(oldId, l, r); int mid = (l + r) >> 1;
    int le = update(nodes[oldId].le, l, mid, u, v, val),
        ri = update(nodes[oldId].ri, mid + 1, r, u, v, val);
    return newparent(le, ri);
}

```

---

a6f504, 73 lines

```

struct Node {
    int le, ri;
    ll lazy, sum;

    Node(int _le = 0, int _ri = 0, ll _lazy = 0, ll _sum = 0) {
        le = _le, ri = _ri, lazy = _lazy, sum = _sum;
    }
} nodes[4 * N * LG];
int numNode = 0;
vector<int> version;

struct PersistentLazyIT {
    int n;

    PersistentLazyIT(int _n = 0) {
        resize(_n);
    }
}

```

```

int update(int root, int u, int v, int val) {
    return update(root, 1, n, u, v, val);
}

ll get(int id, int l, int r, int u, int v) {
    if (l > v || r < u) return 0;
    if (u <= l && r <= v) return nodes[id].sum;
    push(id, l, r); int mid = (l + r) >> 1;
    return get(nodes[id].le, l, mid, u, v) + get(nodes[id].ri, mid +
        1, r, u, v);
}

ll get(int root, int u, int v) {
    return get(root, 1, n, u, v);
}
} mytree;

```

## Graph (4)

### 4.1 Graph theory

#### 4.1.1 Number of Spanning Trees

Create an  $N \times N$  matrix  $\text{mat}$ , 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).

#### 4.1.2 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  $k = 1 \dots n$ ,

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

### TwoSat

## 4.2 Algorithms

### TwoSat.h

**Description:** 2sat -> finding an arbitrary equation

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

**Status:** Tested by KickingKun

28a9c5, 66 lines

```

struct TwoSat { // convert vector -> array to get higher speed ....
    int n; vector<int> lab, num, low; vector<vector<int>> adj;
    int timeDfs, scc; stack<int> st;

    TwoSat (int _n) {
        this->n = _n; lab.assign(n * 2 + 1, 0); low.assign(n * 2 + 1, 0);
        num.assign(n * 2 + 1, 0); adj.assign(n * 2 + 1, vector<int>());
        timeDfs = scc = 0; while (!st.empty()) st.pop();
    }

    int NON(int u) {
        return u <= n ? u + n : u - n;
    }

    void add(int u, int v) {
        adj[u].emplace_back(v);
    }

    void add_u_or_v(int u, int v) { // u or v = 1
        adj[NON(u)].emplace_back(v); adj[NON(v)].emplace_back(u);
    }

    void assign(int u, bool val) { // u = val
        if (val == 1) add_u_or_v(u, u);
        else add_u_or_v(NON(u), NON(u));
    }

    void add_equal(int u, int v) { // u = v
        add_u_or_v(u, NON(v)); add_u_or_v(NON(u), v);
    }

    void add_non_equal(int u, int v) { // u != v
        add_u_or_v(u, v); add_u_or_v(NON(u), NON(v));
    }

    void dfs(int u) {
        low[u] = num[u] = ++timeDfs; st.emplace(u);
        for (int v: adj[u]) {
            if (lab[v]) continue;
            if (!num[v]) dfs(v), minimize(low[u], low[v]);
        }
    }
}

```

```

    else minimize(low[u], num[v]);
}

if (low[u] == num[u]) {
    ++scc;
    while (true) {
        int v = st.top(); st.pop();
        lab[v] = scc; if (v == u) break;
    }
}

bool check_exist() {
    for (int i = 1; i <= n; i++) {
        if (!lab[NON(i)]) dfs(NON(i));
        if (!lab[i]) dfs(i);
    }
    for (int i = 1; i <= n; i++)
        if (lab[i] == lab[NON(i)]) return false;
    return true;
}

vector<int> get_equation() {
    if (!check_exist()) return {-1};
    vector<int> ans = {0};
    for (int i = 1; i <= n; i++) ans.emplace_back(lab[i] < lab[NON(i)]);
    return ans;
}

```

## BipartieMatching.h

**Description:** use for max matching**Time:**  $\mathcal{O}(E * \sqrt{V})$ **Status:** approved by KickingKun

## BipartieMatching

```

}

void add(int u, int v) {
    adj[u].emb(v);
}

bool bfs() {
    fill(dist.begin(), dist.end(), -1);
    int queBegin = 1, queEnd = 1;
    for (int u = 1; u <= n; ++u) {
        if (match1[u] == -1) dist[u] = 0, que[queEnd++] = u;
    }
    bool success = false;
    while (queBegin < queEnd) {
        int u = que[queBegin++];
        for (int v : adj[u]) {
            if (match2[v] == -1) {
                success = true;
            } else if (dist[match2[v]] == -1) {
                dist[match2[v]] = dist[u] + 1;
                que[queEnd++] = match2[v];
            }
        }
    }
    return success;
}

bool dfs(int u) {
    for (int v : adj[u]) {
        if (match2[v] == -1 || (dist[match2[v]] == dist[u] + 1 && dfs(match2[v]))) {
            match1[u] = v; match2[v] = u; dist[u] = n + m;
            return true;
        }
    }
    dist[u] = n + m;
    return false;
}

int max_matching() {
    while (bfs()) {
        for (int u = 1; u <= n; ++u) {

```

---

```

struct bipartite_matching {
    const int n, m;
    vector<int> match1, match2, que, dist;
    vector<vector<int>> adj;

    bipartite_matching(int _n, int _m) : n(_n), m(_m) {
        match1.assign(n + 1, -1); match2.assign(m + 1, -1);
        que.assign(n + 1, 0); dist.assign(n + 1, 0); adj.assign(n + 1, vector<int>());
    }
}
```

213423, 82 lines

```

    if (match1[u] == -1) dfs(u);
}
}

return n - count(match1.begin() + 1, match1.end(), -1);
}

pair <vector <int>, vector <int>> minimum_vertex_cover() {
    vector <int> L, R;
    for (int u = 1; u <= n; ++u) {
        if (dist[u] == -1) L.emb(u);
        else if (match1[u] != -1) R.emb(match1[u]);
    }
    return {L, R};
}

pair <vector <int>, vector <int>> maximum_independent_set() {
    auto [_L, _R] = minimum_vertex_cover();
    vector <int> L, R;
    vector <bool> mark1(n + 2), mark2(m + 2);
    for (int x: _L) mark1[x] = true; for (int x: _R) mark2[x] = true;
    for (int u = 1; u <= n; u++) if (!mark1[u]) L.emb(u);
    for (int u = 1; u <= m; u++) if (!mark2[u]) R.emb(u);
    return {_L, _R};
}

vector <pii> get_edges() { // get from max matching
    vector <pii> ans;
    for (int u = 1; u <= n; ++u)
        if (match1[u] != -1) ans.emplace_back(u, match1[u]);
    return ans;
}
};

MaxFlow.h

```

**Description:** Dinitz's algorithm to find max-flow.

**Usage:** Call myflow.resize(num\_vertices, source, sink) to initialize the network.

**Time:**  $\mathcal{O}(V^2 \cdot E)$  in worst cases

**Status:** Well-tested

## MaxFlow

```

struct MaxFlow {
    struct FlowEdge {
        int u, v;
        ll capacity, flow = 0;
        FlowEdge(int _u = 0, int _v = 0, ll _capacity = 0) {
            u = _u, v = _v, capacity = _capacity, flow = 0;
        }
    };
};

const ll FLOW_INF = (ll)2e18;
vector<FlowEdge> edges;
vector<vector<int>> adj;
vector<int> level, ptr;
int n, m;
int source, sink;

MaxFlow(int _n = 0, int _s = 0, int _t = 0) {
    resize(_n, _s, _t);
}

void resize(int _n, int _s, int _t) {
    n = _n, m = 0, source = _s, sink = _t;
    adj.assign(n + 1, vector<int>()), level.assign(n + 1, -1);
    ptr.assign(n + 1, 0); edges.clear();
}

void reset_flow() {
    for (auto &edge : edges) edge.flow = 0;
}

void add(int u, int v, ll capacity) {
    edges.emplace_back(u, v, capacity);
    edges.emplace_back(v, u, 0);
    adj[u].emplace_back(m++), adj[v].emplace_back(m++);
}

bool bfs() {
    fill(level.begin(), level.end(), -1); level[source] = 0;
    queue<int> q; q.emplace(source);
    while (!q.empty()) {
        int u = q.front(); q.pop();
        for (auto id : adj[u]) {
            if (edges[id].capacity - edges[id].flow <= 0) continue;
            if (level[edges[id].v] != -1) continue;
            level[edges[id].v] = level[u] + 1;
            q.emplace(edges[id].v);
        }
    }
}

```

455f5c, 95 lines

```

    }
}

return level[sink] != -1;
}

ll dfs(int u, ll pushed) {
    if (pushed == 0) return 0;
    if (u == sink) return pushed;
    for (int &cid = ptr[u]; cid < (int)adj[u].size(); ++cid) {
        int id = adj[u][cid], v = edges[id].v;
        if (level[u] + 1 != level[v] || edges[id].capacity - edges[id].
            flow <= 0) continue;
        ll amount = dfs(v, min(pushed, edges[id].capacity - edges[id].
            flow));
        if (amount == 0) continue;
        edges[id].flow += amount, edges[id ^ 1].flow -= amount;
        return amount;
    }
    return 0;
}

ll maxFlow() {
    ll flow = 0;
    while (bfs()) {
        fill(ptr.begin(), ptr.end(), 0);
        while (ll pushed = dfs(source, FLOW_INF)) flow += pushed;
    }
    return flow;
}

vii minCut() {
    queue<int> q; q.emplace(source);
    fill(ptr.begin(), ptr.end(), 0); vector<bool> vis(n + 1, false);
    while (!q.empty()) {
        int u = q.front(); q.pop();
        if (vis[u]) continue;
        vis[u] = true;
        for (int &cid = ptr[u]; cid < (int)adj[u].size(); ++cid) {
            int id = adj[u][cid], v = edges[id].v;
            if (level[u] + 1 != level[v] || edges[id].capacity - edges[id].
                flow <= 0) continue;
            q.emplace(v);
        }
    }
}

```

**MinCostMaxFlow**

```

    }
    vii cut;
    for (auto it : edges) {
        if (vis[it.u] && !vis[it.v]) cut.emplace_back(it.u, it.v);
    }
    return cut;
}
} myflow;

```

**MinCostMaxFlow.h**

**Description:** Edmond-Karp algorithm with SPFA to find the shortest path.

**Usage:** Call `myflow.resize(num_vertices, source, sink)` to initialize the network.

**Time:**  $\mathcal{O}(F \cdot V \cdot E)$  in worst cases

**Status:** Well-tested

Occe52, 117 lines

---

```

struct MCMF {
    struct FlowEdge {
        int u, v;
        ll capacity, cost, flow = 0;

        FlowEdge(int _u = 0, int _v = 0, ll _capacity = 0, ll _cost = 0) {
            u = _u, v = _v, capacity = _capacity, cost = _cost, flow = 0;
        }
    };

    const ll FLOW_INF = (ll)2e18;
    vector<FlowEdge> edges;
    vector<vector<int>> adj;
    vector<int> level, ptr;
    int n, m;
    int source, sink;

    MCMF(int _n = 0, int _s = 0, int _t = 0) {
        resize(_n, _s, _t);
    }

    void resize(int _n, int _s, int _t) {
        n = _n, m = 0, source = _s, sink = _t;
        adj.assign(n + 1, vector<int>()), level.assign(n + 1, -1);
        ptr.assign(n + 1, 0); edges.clear();
    }

    void reset_flow() {

```

```

        for (auto &edge : edges) edge.flow = 0;
    }

void add(int u, int v, ll capacity, ll cost) {
    edges.emplace_back(u, v, capacity, cost);
    edges.emplace_back(v, u, 0, -cost);
    adj[u].emplace_back(m++), adj[v].emplace_back(m++);
}

bool bfs() {
    fill(level.begin(), level.end(), -1); level[source] = 0;
    queue<int> q; q.emplace(source);
    while (!q.empty()) {
        int u = q.front(); q.pop();
        for (auto id : adj[u]) {
            if (edges[id].capacity - edges[id].flow <= 0) continue;
            if (level[edges[id].v] != -1) continue;
            level[edges[id].v] = level[u] + 1;
            q.emplace(edges[id].v);
        }
    }
    return level[sink] != -1;
}

ll dfs(int u, ll pushed) {
    if (pushed == 0) return 0;
    if (u == sink) return pushed;
    for (int &cid = ptr[u]; cid < (int)adj[u].size(); ++cid) {
        int id = adj[u][cid], v = edges[id].v;
        if (level[u] + 1 != level[v] || edges[id].capacity - edges[id].flow <= 0) continue;
        ll amount = dfs(v, min(pushed, edges[id].capacity - edges[id].flow));
        if (amount == 0) continue;
        edges[id].flow += amount, edges[id ^ 1].flow -= amount;
        return amount;
    }
    return 0;
}

ll maxFlow() {
    ll flow = 0;
    while (bfs()) {

```

```

        fill(ptr.begin(), ptr.end(), 0);
        while (ll pushed = dfs(source, FLOW_INF)) flow += pushed;
    }
    return flow;
}

bool spfa(vector<ll> &dist, vector<int> &par) {
    dist.assign(n + 1, INF), par.assign(n + 1, -1);
    vector<bool> inQueue(n + 1, false); queue<int> q;
    dist[source] = 0; inQueue[source] = true; q.emplace(source);
    while (!q.empty()) {
        int u = q.front(); q.pop();
        inQueue[u] = false;
        for (auto id : adj[u]) {
            int v = edges[id].v;
            if (edges[id].capacity - edges[id].flow <= 0) continue;
            if (minimize(dist[v], dist[u] + edges[id].cost)) {
                par[v] = id;
                if (!inQueue[v]) {
                    inQueue[v] = true;
                    q.emplace(v);
                }
            }
        }
    }
    return dist[sink] != INF;
}

ll minCost() {
    ll flow = 0, cost = 0; vector<ll> dist; vector<int> par;
    while (spfa(dist, par)) {
        ll amount = FLOW_INF - flow; int cur = sink;
        while (cur != source) {
            minimize(amount, edges[par[cur]].capacity - edges[par[cur]].flow);
            cur = edges[par[cur]].u;
        }

        flow += amount, cost += amount * dist[sink], cur = sink;
        while (cur != source) {
            edges[par[cur]].flow += amount;
            edges[par[cur] ^ 1].flow -= amount;
            cur = edges[par[cur]].u;
        }
    }
}
```

```

    }
}

    return cost;
}
} myflow;

```

## Geometry (5)

Geometry.h

Description: Geometric Template

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

Status: Seems OK

```

struct Point {
    double x, y;
    Point() {}
    Point (double _x, double _y) {
        this->x = _x; this->y = _y;
    }

    double len() {
        return x * x + y * y;
    }

    Point operator - (Point other) {
        return {x - other.x, y - other.y};
    }

    Point operator - () {
        return Point(-x, -y);
    }

    bool operator == (Point other) {
        return x == other.x && y == other.y;
    }

    bool operator != (Point other) {
        return x != other.x || y != other.y;
    }

    void show() {
        cout << x << ' ' << y << '\n';
    }
}

```

## Geometry

c47ef0, 134 lines

```

    }

};

struct Line {
    double a, b, c;
    Line() {}
    Line (double _a, double _b, double _c) {
        this->a = _a; this->b = _b; this->c = _c;
    }

    void simplify() { // if double = ll
        double d = __gcd(__gcd((ll)a, (ll)b), (ll)c);
        a /= d, b /= d, c /= d;
        // else do nothing
    }

    void show() {
        cout << a << ' ' << b << ' ' << c << '\n';
    }

    double dot(Point A, Point B) { // dot product
        return A.x * B.x + A.y * B.y;
    }

    double cross(Point A, Point B) { // cross product
        return A.x * B.y - A.y * B.x;
    }

    int sign(double x) {
        if (x < 0) return -1;
        if (x == 0) return 0;
        return 1;
    }

    double dis(Point A, Point B) {
        return sqrt((B.x - A.x) * (B.x - A.x) + (B.y - A.y) * (B.y - A.y));
    }

    double dis(Point m, Line d) { // d(M, delta)
        return abs(d.a * m.x + d.b * m.y + d.c) / sqrt(d.a * d.a + d.b * d.b);
    }

    double polygon_area(vector <Point> p) {

```

```

double res = 0;
for (int i = 1; i < p.size() - 1; i++)
    res += cross(p[i] - p[0], p[i + 1] - p[0]);
return abs(res) / 2.0;
} // tested

bool same_side(Point A, Point B, Line d) { // out of line
    double y1 = d.a * A.x + d.b * A.y + d.c;
    double y2 = d.a * B.x + d.b * B.y + d.c;
    return (y1 > 0 && y2 > 0) || (y1 < 0 && y2 < 0);
} // tested by eyes

Line lineVector(Point A, Point n) { // Point + vector n
    return Line(n.x, n.y, -n.x * A.x - n.y * A.y);
}

Line line(Point A, Point B) { // Point A, B
    Point n(A.y - B.y, B.x - A.x);
    return Line(n.x, n.y, -n.x * A.x - n.y * A.y);
}

bool inside_line(Point A, Line d) { // inside of line
    return d.a * A.x + d.b * A.y + d.c == 0;
}

bool inside_segment(Point M, Point A, Point B) { // inside of segment AB
    if (M.x > max(A.x, B.x) || M.x < min(A.x, B.x)) return false;
    if (M.y > max(A.y, B.y) || M.y < min(A.y, B.y)) return false;
    return inside_line(M, line(A, B));
} // tested CSES / VNOI

Point intersect(Line A, Line B) { // find p(x, y)
    Point res; if (A.b == 0) swap(A, B);
    res.x = (B.c * A.b - A.c * B.b) / (A.a * B.b - B.a * A.b);
    res.y = (-A.c - A.a * res.x) / A.b;
    return res;
} // seem OK

Line perpendicular(Point A, Line d) {
    Point n(-d.b, d.a);
    return Line(n.x, n.y, -n.x * A.x - n.y * A.y);
} // tested

```

## AhoCorasick

```

bool obtuse(Point M, Point A, Point B) { // MAB > 90
    return (M - A).len() + (B - A).len() < (M - B).len();
} // tested

double dist(Point M, Point A, Point B) { // dis(M, segment AB)
// check MBA <= 90 && MAB <= 90
    if (obtuse(M, A, B) || obtuse(M, B, A)) return min(dis(M, A), dis(M, B));
    ;
    return dis(M, line(A, B));
} // tested at VNOI

bool intersect(Point A, Point B, Point C, Point D) { // segment AB and CD
    int x = sign(cross(C - A, B - A)), y = sign(cross(D - A, B - A));
    int u = sign(cross(A - C, D - C)), v = sign(cross(B - C, D - C));
    if (x == 0 && inside_segment(C, A, B)) return true;
    if (y == 0 && inside_segment(D, A, B)) return true;
    if (u == 0 && inside_segment(A, C, D)) return true;
    if (v == 0 && inside_segment(B, C, D)) return true;
    return (x != y && u != v);
} // tested at CSES

```

## Strings (6)

### AhoCorasick.h

**Description:** Aho-corasick.

**Usage:** Call init() before any operations.

**Time:**  $\mathcal{O}(\text{len}(s))$  for addition,  $\mathcal{O}(\text{total}\text{len})$  for build(),  $\mathcal{O}(\text{len}(x))$  or  $\mathcal{O}(\text{numofoccurrences})$  for query()

**Status:** Tested on some problems

0cf417, 68 lines

```

struct AhoCorasick {
    static const int SIZE = 26;
    static const char START_CHAR = 'a';

    struct Node {
        int fail, link;
        int child[SIZE], nxt[SIZE];
        int output;

        Node() {
            fail = 0, link = -1, output = 0;
            memset(child, -1, sizeof child);
            memset(nxt, -1, sizeof nxt);
        }
    };
}
```

```

    }
};

vector<Node> nodes;

void init() {
    nodes.clear(), nodes.emplace_back(Node());
}

void add(string &s, int id) {
    int v = 0;
    for (char ch : s) {
        int c = ch - START_CHAR;
        if (nodes[v].child[c] == -1) {
            nodes[v].child[c] = nodes.size();
            nodes.emplace_back(Node());
        }
        v = nodes[v].child[c];
    }
    ++nodes[v].output;
}

void build() {
    nodes[0].fail = nodes[0].link = 0;
    for (int i = 0; i < SIZE; ++i)
        nodes[0].nxt[i] = (nodes[0].child[i] == -1 ? 0 : nodes[0].
            child[i]);

    queue<int> q; q.emplace(0);
    while (!q.empty()) {
        int u = q.front(); q.pop();

        for (int c = 0; c < SIZE; ++c) if (nodes[u].child[c] != -1) {
            int v = nodes[u].child[c];
            nodes[v].fail = (u == 0 ? 0 : nodes[nodes[u].fail].nxt[c])
                ;
            for (int d = 0; d < SIZE; ++d)
                nodes[v].nxt[d] = (nodes[v].child[d] == -1 ? nodes[
                    nodes[v].fail].nxt[d] : nodes[v].child[d]);
            if (nodes[nodes[v].fail].output != 0) nodes[v].link =
                nodes[v].fail;
            else nodes[v].link = nodes[nodes[v].fail].link;
            q.emplace(v);
        }
    }
}

```

**SuffixArray**

```

    }
}

int query(string &x) {
    int ans = 0, p = 0;
    for (auto ch : x) {
        int c = ch - 'a', nxt = nodes[p].nxt[c];
        for (int u = nxt; u != 0; u = nodes[u].link) {
            ans += nodes[u].output;
        }
        p = nxt;
    }
    return ans;
} aho;

```

**SuffixArray.h**

**Description:** Suffix array using prefix doubling to sort with Kasai's algorithm for LCP

**Time:**  $\mathcal{O}(N \log^2 N)$  for construcing suffix array and  $\mathcal{O}(n)$  for construcing LCP array

**Status:** Tested on judge.yosupo.jp

2dcf7a, 54 lines

```

struct SuffixArray {
    string str;
    vector<int> sa, lcp, order, rank;
    vector<ll> weight;
    int n;

    SuffixArray(string _str = "") {
        str = _str, n = str.size();
        sa.assign(n, 0), lcp.assign(n, 0), order.assign(n, 0);
        rank.assign(n, 0), weight.assign(n, 0);
        get(), getLCP();
    }

    void getSA() {
        for (int i = 0; i < n; ++i)
            sa[i] = i;
        weight[i] = int(str[i]);
    }

    auto cmp = [&] (int x, int y) {
        return weight[x] < weight[y];
    };
}

```

```

sort (sa.begin(), sa.end(), cmp);

for (int len = 1; len <= n; len <<= 1) {
    int cnt = 0;
    for (int i = 0; i < n; ++i) {
        if (i > 0 && weight[sa[i]] == weight[sa[i - 1]]) order[sa[i]] = order[sa[i - 1]];
        else order[sa[i]] = ++cnt;
    }
    if (cnt == n) break;
    for (int i = 0; i < n; ++i) {
        weight[i] = 111 * order[i] * (n + 1) + (i + len < n ? order[i + len] : 0);
    }
    for (int i = 0, j = 0; i < n; i = j) {
        while (j < n && order[sa[j]] == order[sa[i]]) ++j;
        sort (sa.begin() + i, sa.begin() + j, cmp);
    }
}

void getLCP() {
    for (int i = 0; i < n; ++i) rank[sa[i]] = i;
    for (int i = 0, k = 0; i < n; lcp[rank[i++]] = k) {
        if (rank[i] > 0) {
            int j = sa[rank[i] - 1];
            if (k > 0) --k;
            while (str[i + k] == str[j + k]) ++k;
        }
        else k = 0;
    }
}
} T;

```

## Various (7)

### 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  $[0, 2b)$ .

**Status:** proven correct, stress-tested

### 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;
}

```

38ea39, 7 lines

```
struct FastMod {
```