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## 1 Data Structure

## 1.1 Dsu With Rollback [89 lines] bc2588

```
struct dsu_save {
    int v, rnk, u, rnku;
    dsu_save() {}
    dsu_save(int _v, int _rnk, int _u, int _rnku) : v(_v), rnk(_rnk), u(_u), rnku(_rnku) {}
};

struct dsu_with_rollbacks {
    vector<int> p, rnk;
    int comps;
    stack<dsu_save> op;
    dsu_with_rollbacks() {}
    dsu_with_rollbacks(int n) {
        p.resize(n);
        rnk.resize(n);
        for (int i = 0; i < n; i++) {
            p[i] = i;
            rnk[i] = 0;
        }
        comps = n;
    }
    int find_set(int v) { return (v == p[v]) ? v : find_set(p[v]); }
    bool unite(int v, int u) {
        v = find_set(v);
        u = find_set(u);
        if (v == u) return false;
        comps--;
        if (rnk[v] > rnk[u]) swap(v, u);
        op.push(dsu_save(v, rnk[v], u, rnk[u]));
```

```
p[v] = u;
if (rnk[u] == rnk[v]) rnk[u]++;
return true;
}

void rollback() {
    if (op.empty()) return;
    dsu_save x = op.top();
    op.pop();
    comps++;
    p[x.v] = x.v;
    rnk[x.v] = x.rnk;
    p[x.u] = x.u;
    rnk[x.u] = x.rnk;
}

};

struct query {
    int v, u;
    bool united;
    query(int _v, int _u) : v(_v), u(_u) {}
};

struct QueryTree {
    vector<vector<query>> t;
    dsu_with_rollbacks dsu;
    int T;
    QueryTree() {}
    QueryTree(int _T, int n) : T(_T) {
        dsu = dsu_with_rollbacks(n);
        t.resize(4 * T + 4);
    }
    void add_to_tree(int v, int l, int r, int ul, int ur, query& q) {
        if (ul > ur) return;
        if (l == ul && r == ur) {
            t[v].push_back(q);
            return;
        }
        int mid = (l + r) / 2;
        add_to_tree(2 * v, l, mid, ul, min(ur, mid), q);
        add_to_tree(2 * v + 1, mid + 1, r, max(ul, mid + 1), ur, q);
    }
    void add_query(query q, int l, int r) {
        add_to_tree(1, 0, T - 1, l, r, q);
    }
    void dfs(int v, int l, int r, vector<int>& ans) {
        for (query& q : t[v]) {
            q.united = dsu.unite(q.v, q.u);
        }
        if (l == r)
            ans[l] = dsu.comps;
        else {
            int mid = (l + r) / 2;
            dfs(2 * v, l, mid, ans);
            dfs(2 * v + 1, mid + 1, r, ans);
        }
        for (query q : t[v]) {
            if (q.united) dsu.rollback();
        }
    }
    vector<int> solve() {
        vector<int> ans(T);
        dfs(1, 0, T - 1, ans);
        return ans;
    }
};
```

**1.2 MO with Update** [43 lines]

2fbf87

```
//1 indexed
//Complexity:  $O(S \times Q + Q \times \frac{N^2}{S^2})$ 
//S =  $(2*n^2)^{(1/3)}$ 
const int block_size = 2720; // 4310 for 2e5
const int mx = 1e5 + 5;
struct Query {
    int L, R, T, id;
    Query() {}
    Query(int _L, int _R, int _T, int _id) : L(_L),
        R(_R), T(_T), id(_id) {}
    bool operator<(const Query &x) const {
        if (L / block_size == x.L / block_size) {
            if (R / block_size == x.R / block_size) return T <
                x.T;
            return R / block_size < x.R / block_size;
        }
        return L / block_size < x.L / block_size;
    }
} Q[mx];
struct Update {
    int pos;
    int old, cur;
    Update(){};
    Update(int _p, int _o, int _c) : pos(_p), old(_o),
        cur(_c){};
} U[mx];
int ans[mx];
inline void add(int id) {}
inline void remove(int id) {}
inline void update(int id, int L, int R) {}
inline void undo(int id, int L, int R) {}
inline int get() {}
void MO(int nq, int nu) {
    sort(Q + 1, Q + nq + 1);
    int L = 1, R = 0, T = nu;
    for (int i = 1; i <= nq; i++) {
        Query q = Q[i];
        while (T < q.T) update(++T, L, R);
        while (T > q.T) undo(T--, L, R);
        while (L > q.L) add(--L);
        while (R < q.R) add(++R);
        while (L < q.L) remove(L++);
        while (R > q.R) remove(R--);
        ans[q.id] = get();
    }
}
```

**1.3 MO** [28 lines]

bed3e5

```
const int N = 2e5 + 5;
const int Q = 2e5 + 5;
const int SZ = sqrt(N) + 1;
struct qry {
    int l, r, id, blk;
    bool operator<(const qry& p) const {
        return blk == p.blk ? r < p.r : blk < p.blk;
    }
};
qry query[Q];
ll ans[Q];
void add(int id) {}
void remove(int id) {}
ll get() {}
int n, q;
```

```
void MO() {
    sort(query, query + q);
    int cur_l = 0, cur_r = -1;
    for (int i = 0; i < q; i++) {
        qry q = query[i];
        while (cur_l > q.l) add(--cur_l);
        while (cur_r < q.r) add(++cur_r);
        while (cur_l < q.l) remove(cur_l++);
        while (cur_r > q.r) remove(cur_r--);
        ans[q.id] = get();
    }
}
/* 0 indexed. */
```

**1.4 Persistent Segment Tree** [53 lines]

359d65

```
const int mxn = 1e5+5; //CHECK here for problem
int root[mxn], leftchild[25*mxn], rightchild[25*mxn],
    value[25*mxn], a[mxn];
int now = 0, n;
int build(int L, int R){
    int node = ++now;
    if(L == R) return node;
    int mid = (L+R)>>1;
    leftchild[node] = build(L, mid);
    rightchild[node] = build(mid+1, R);
    //initialize value[node]
    return node;
}

int update(int nownode, int L, int R, int val){
    int node = ++now;
    if(L == R){
        //value[node] = value[nownode]+1;
        //update value[node]
        return node;
    }
    int mid = (L+R)>>1;
    leftchild[node] = leftchild[nownode];
    rightchild[node] = rightchild[nownode];
    if(mid <= val){ //change condition as required
        leftchild[node] = update(leftchild[nownode], L,
            mid, val);
    }
    else{
        rightchild[node] = update(rightchild[nownode],
            mid+1, R, val);
    }
    //value[node] = value[nownode]+1;
    //update value[node]
    return node;
}

int query(int leftnode, int rightnode, int L, int R, int
    k){
    if(L==R) return L;
    //int leftcnt = value[leftchild[rightnode]]-
        value[leftchild[leftnode]];a
    //change as required
    int mid = (L+R)>>1;
    if(leftcnt >= k){ //change condition as required
        return query(leftchild[leftnode],
            leftchild[rightnode], L, mid, k);
    }
    else{
```

```
        return query(rightchild[leftnode],
            rightchild[rightnode], mid+1, R, k-leftcnt);
    }
}

void persistentsegtree(){
    root[0] = build(0, mxn);
    for(int i=1; i<=n; i++){
        root[i] = update(root[i-1], 0, mxn, a[i]);
    }
}
```

**1.5 SQRT Decomposition** [96 lines]

a772d3

```
struct sqrtDecomposition {
    static const int sz = 320; //sz = sqrt(N);
    int numberofblocks;

    struct node {
        int L, R;
        bool lazy = false;
        ll lazyval=0;
        //extra data needed for different problems
        void ini(int l, int r) {
            for(int i=l; i<=r; i++) {
                //...initialize as need
            }
            L=l, R=r;
        }
        void semiupdate(int l, int r, ll val) {
            if(l>r) return;
            if(lazy){
                for(int i=L; i<=R; i++){
                    //...distribute lazy to everyone
                }
                lazy = 0;
                lazyval = 0;
            }
            for(int i=l; i<=r; i++){
                //...do it manually
            }
        }
        void fullupdate(ll val){
            if(lazy){
                //...only update lazyval
            }
            else{
                for(int i=L; i<=R; i++){
                    //...everyone are not equal, make them equal
                }
                lazy = 1;
                //update lazyval
            }
        }
        void update(int l, int r, ll val){
            if(l<=L && r>=R) fullupdate(val);
            else semiupdate(max(l, L), min(r, R), val);
        }
        ll semiquery(int l, int r){
            if(l>r) return 0;
            if(lazy){
                for(int i=L; i<=R; i++){
                    //...distribute lazy to everyone
                }
                lazy = 0;
```

```

        lazyval = 0;
    }
    ll ret = 0;
    for(int i=l; i<=r; i++){
        //...take one by one
    }
    return ret;
}
ll fullquery(){
    //return stored value;
}
ll query(int l, int r){
    if(l<=L && r>=R) return fullquery();
    else return semiquery(max(l, L), min(r, R));
}
};
vector<node> blocks;
void init(int n){
    numberofblocks = (n+sz-1)/sz;
    int curL = 1, curR = sz;
    blocks.resize(numberofblocks+5);
    for(int i=1; i<=numberofblocks; i++){
        curR = min(n, curR);
        blocks[i].ini(curL, curR);
        curL += sz;
        curR += sz;
    }
}
void update(int l, int r, ll val){
    int left = (l-1)/sz+1;
    int right = (r-1)/sz+1;
    for(int i=left; i<=right; i++){
        blocks[i].update(l, r, val);
    }
}
ll query(int l, int r){
    int left = (l-1)/sz+1;
    int right = (r-1)/sz+1;
    ll ret = 0;
    for(int i=left; i<=right; i++){
        ret += blocks[i].query(l, r);
    }
    return ret;
}
};

```

## 1.6 Segment Tree [73 lines]

c1fe4f

```

/*edit: data, combine, build check datatype*/
template<typename T>
struct SegmentTree {
#define lc (C << 1)
#define rc (C << 1 | 1)
#define M ((L+R)>>1)
    struct data {
        T sum;
        data() : sum(0) {};
    };
    vector<data> st;
    vector<bool> isLazy;
    vector<T> lazy;
    int N;
    SegmentTree(int _N) : N(_N) {
        st.resize(4 * N);
        isLazy.resize(4 * N);
        lazy.resize(4 * N);
    }
};

```

```

}
void combine(data& cur, data& l, data& r) {
    cur.sum = l.sum + r.sum;
}
void push(int C, int L, int R) {
    if (!isLazy[C]) return;
    if (L != R) {
        isLazy[lc] = 1;
        isLazy[rc] = 1;
        lazy[lc] += lazy[C];
        lazy[rc] += lazy[C];
    }
    st[C].sum = (R - L + 1) * lazy[C];
    lazy[C] = 0;
    isLazy[C] = false;
}
void build(int C, int L, int R) {
    if (L == R) {
        st[C].sum = 0;
        return;
    }
    build(lc, L, M);
    build(rc, M + 1, R);
    combine(st[C], st[lc], st[rc]);
}
data Query(int i, int j, int C, int L, int R) {
    push(C, L, R);
    if (j < L || i > R || L > R) return data(); //
    default val 0/INF
    if (i <= L && R <= j) return st[C];
    data ret;
    data d1 = Query(i, j, lc, L, M);
    data d2 = Query(i, j, rc, M + 1, R);
    combine(ret, d1, d2);
    return ret;
}
void Update(int i, int j, T val, int C, int L, int R)
{
    push(C, L, R);
    if (j < L || i > R || L > R) return;
    if (i <= L && R <= j) {
        isLazy[C] = 1;
        lazy[C] = val;
        push(C, L, R);
        return;
    }
    Update(i, j, val, lc, L, M);
    Update(i, j, val, rc, M + 1, R);
    combine(st[C], st[lc], st[rc]);
}
void Update(int i, int j, T val) {
    Update(i, j, val, 1, 1, N);
}
T Query(int i, int j) {
    return Query(i, j, 1, 1, N).sum;
}
};

```

## 1.7 Sqrt Tricks [8 lines]

addf19

1. Size of the block is not always Sqrt, adjust it as necessary. if  $O(n/b+b)$  then take  $n/b = b$  and calculate  $b$ .
2. MO's Algorithm

\*it is possible to solve a Mo problem without any remove operation. For L in one block R only increases, for every range we can start L from the last of that block

3. Sqrt Decomposition by time of queries.
  - \*keep overall solution and  $\sqrt{n}$  updates in a vector and for a query iterate over all of them, when the vector size exceeds  $\sqrt{n}$  you can add these updates with overall solution using  $O(n)$
4. If sum of N positive numbers are S, there are at most  $\sqrt{S}$  distinct values.
5. Randomization
6. Baby step, giant step

## 1.8 Treap [166 lines]

8eef59

```

struct Treap {
    struct Node {
        int val, priority, cnt; // value, priority, subtree
        size
        Node* l, * r; // left child, right child
        pointer
        Node() {} //rng from template
        Node(int key) : val(key), priority(rng()),
        l(nullptr), r(nullptr) {}
    };
    typedef Node* node;
    node root;
    Treap() : root(0) {}
    int cnt(node t) { return t ? t->cnt : 0; } // return
    subtree size
    void updateCnt(node t) {
        if (t) t->cnt = 1 + cnt(t->l) + cnt(t->r); //
        update subtree size
    }
    void push(node cur) {
        ; // Lazy Propagation
    }

    void combine(node& cur, node l, node r) {
        if (!l) {
            cur = r;
            return;
        }
        if (!r) {
            cur = l;
            return;
        }
        // Merge Operations like in segment tree
    }

    void reset(node& cur) {
        if (!cur) return; // To reset other fields of cur
        except value and cnt
    }

    void operation(node& cur) {
        if (!cur) return;
        reset(cur);
        combine(cur, cur->l, cur);
        combine(cur, cur, cur->r);
    }

    // Split(T, key): split the tree in two tree. Left
    pointer contains all value
    // less than or equal to key. Right pointer contains
    the rest.
}

```

```

void split(node t, node& l, node& r, int key) {
    if (!t)
        return void(l = r = nullptr);
    push(t);
    if (t->val <= key) {
        split(t->r, t->r, r, key), l = t;
    }
    else {
        split(t->l, l, t->l, key), r = t;
    }
    updateCnt(t);
    operation(t);
}

void splitPos(node t, node& l, node& r, int k, int add
= 0) {
    if (!t) return void(l = r = 0);
    push(t);
    int idx = add + cnt(t->l);
    if (idx <= k)
        splitPos(t->r, t->r, r, k, idx + 1), l = t;
    else
        splitPos(t->l, l, t->l, k, add), r = t;
    updateCnt(t);
    operation(t);
}

// Merge(T1,T2): merges 2 tree into one.The tree with
// root of higher
// priority becomes the new root.
void merge(node& t, node l, node r) {
    push(l);
    push(r);
    if (!l || !r)
        t = l ? l : r;
    else if (l->priority > r->priority)
        merge(l->r, l->r, r), t = l;
    else
        merge(r->l, l, r->l), t = r;
    updateCnt(t);
    operation(t);
}

node merge_treap(node l, node r) {
    if (!l) return r;
    if (!r) return l;
    if (l->priority < r->priority) swap(l, r);
    node L, R;
    split(r, L, R, l->val);
    l->r = merge_treap(l->r, R);
    l->l = merge_treap(L, l->l);
    updateCnt(l);
    operation(l);
    return l;
}

// insert creates a set.all unique value.
void insert(int val) {
    if (!root) {
        root = new Node(val);
        return;
    }
    node l, r, mid, mid2, rr;
    mid = new Node(val);
    split(root, l, r, val);

```

```

merge(l, l, mid); // these 3 lines will create
multiset.
merge(root, l, r);
/*split(root, l, r, val - 1); // l contains all
small values.
merge(l, l, mid); // l contains new val
too.
split(r, mid2, rr, val); // rr contains all
greater values.
merge(root, l, rr);*/
}
// removes all similar values.
void erase(int val) {
    node l, r, mid;
    /* Removes all similar element*/
    split(root, l, r, val - 1);
    split(r, mid, r, val);
    merge(root, l, r);
    /*Removes single instance*/
    /*split(root, l, r, val - 1);
    split(r, mid, r, val);
    merge(mid, mid->l, mid->r);
    merge(l, l, mid);
    merge(root, l, r);*/
}

void clear(node cur) {
    if (!cur) return;
    clear(cur->l), clear(cur->r);
    delete cur;
}

void clear() { clear(root); }
void inorder(node t) {
    if (!t) return;
    inorder(t->l);
    cout << t->val << ' ';
    inorder(t->r);
}

void inorder() {
    inorder(root);
    puts("");
}

//1 indexed - with element after sorting.
int find_by_order(int x) {
    if (!x) return -1;
    x--;
    node l, r, mid;
    splitPos(root, l, r, x - 1);
    splitPos(r, mid, r, 0);
    int ans = -1;
    if (cnt(mid) == 1) ans = mid->val;
    merge(r, mid, r);
    merge(root, l, r);
}

// 1 indexed. index of val in sorted array. -1 if not
found.
int order_of_key(int val) {
    node l, r, mid;
    split(root, l, r, val - 1);
    split(r, mid, r, val);
    int ans = -1;
    if (cnt(mid) == 1) ans = 1 + cnt(l);
    merge(r, mid, r);
    merge(root, l, r);
}

```

```

        return ans;
    }
};

1.9 Trie Bit [61 lines] 390174
struct Trie {
    struct node {
        int next[2];
        int cnt, fin;
        node() : cnt(0), fin(0) {
            for (int i = 0; i < 2; i++) next[i] = -1;
        }
    };
    vector<node> data;
    Trie() {
        data.push_back(node());
    }
    void key_add(int val) {
        int cur = 0;
        for (int i = 30; i >= 0; i--) {
            int id = (val >> i) & 1;
            if (data[cur].next[id] == -1) {
                data[cur].next[id] = data.size();
                data.push_back(node());
            }
            cur = data[cur].next[id];
            data[cur].cnt++;
        }
        data[cur].fin++;
    }
    int key_search(int val) {
        int cur = 0;
        for (int i = 30; ~i; i--) {
            int id = (val >> i) & 1;
            if (data[cur].next[id] == -1) return 0;
            cur = data[cur].next[id];
        }
        return data[cur].fin;
    }
    void key_delete(int val) {
        int cur = 0;
        for (int i = 30; ~i; i--) {
            int id = (val >> i) & 1;
            cur = data[cur].next[id];
            data[cur].cnt--;
        }
        data[cur].fin--;
    }
    bool key_remove(int val) {
        if (key_search(val)) return key_delete(val), 1;
        return 0;
    }
    int maxXor(int x) {
        int cur = 0;
        int ans = 0;
        for (int i = 30; ~i; i--) {
            int b = (x >> i) & 1;
            if (data[cur].next[!b] + 1 &&
                data[data[cur].next[!b]].cnt > 0) {
                ans += (1LL << i);
                cur = data[cur].next[!b];
            }
            else cur = data[cur].next[b];
        }
    }
};

```



```

    return ans;
}
};

```

## 2 Dynamic Programming

### 2.1 Convex Hull Trick [91 lines]

62db2e

```

struct Hull_Static{
    /*all m need to be decreasing order
    if m is in increasing order then negate the
        m(like, add_line(-m, c)),
    remember in query you have to negate the x also*/
    const ll inf=1000000000000000000;
    int min_or_max; //if min then 0 otherwise 1
    int pointer; /*keep track for the best line for
        previous query, requires all insert first*/
    vector<ll> M, C; //y=m*x+c;
    inline void clear(){
        min_or_max=0; //initially with minimum trick
        pointer=0;
        M.clear();
        C.clear();
    }
    Hull_Static(){clear();}
    Hull_Static(int _min_or_max){
        clear();
        this->min_or_max=_min_or_max;
    }
    bool bad_min(int idx1, int idx2, int idx3){
        return (C[idx3]-C[idx1])*(M[idx1]-M[idx2]) <
            (C[idx2]-C[idx1])*(M[idx1]-M[idx3]);
        return 1.0*(C[idx3]-C[idx1])*(M[idx1]-M[idx2]) <
            1.0*(C[idx2]-C[idx1])*(M[idx1]-M[idx3]); //for
            overflow
    }
    bool bad_max(int idx1, int idx2, int idx3){
        return (C[idx3]-C[idx1])*(M[idx1]-M[idx2]) >
            (C[idx2]-C[idx1])*(M[idx1]-M[idx3]);
        return 1.0*(C[idx3]-C[idx1])*(M[idx1]-M[idx2]) >
            1.0*(C[idx2]-C[idx1])*(M[idx1]-M[idx3]); //for
            overflow
    }
    bool bad(int idx1, int idx2, int idx3){
        if(!min_or_max) return bad_min(idx1, idx2, idx3);
        else return bad_max(idx1, idx2, idx3);
    }
    void add_line(ll m, ll c){/*add line where m is given
        in decreasing order
    //if(M.size()>0 and M.back()==m) return; //same
        gradient, no need to add
    above line added from tarango khan, this line cost me
        several wa, but some code got ac with this*/
        M.push_back(m);
        C.push_back(c);
        while(M.size()>=3 and bad((int)M.size()-3,
            (int)M.size()-2, (int)M.size()-1)){
            M.erase(M.end()-2);
            C.erase(C.end()-2);
        }
    }
    ll getval(ll idx, ll x){
        return M[idx]*x+C[idx];
    }
    ll getminval(ll x){/*if queries are non-decreasing
        order*/

```

```

        while(pointer<(int)M.size()-1 and getval(pointer+
            1, x)<getval(pointer, x)) pointer++;
        return M[pointer]*x+C[pointer];
    }
    ll getmaxval(ll x){
        while(pointer<(int)M.size()-1 and getval(pointer+
            1, x)>getval(pointer, x)) pointer++;
        return M[pointer]*x+C[pointer];
    }
    ll getminvalternary(ll x){
        ll lo=0, hi=(ll)M.size()-1;
        ll ans=inf; /*change with problem*/
        while(lo<=hi){
            ll mid1=lo+(hi-lo)/3;
            ll mid2=hi-(hi-lo)/3;
            ll val1=getval(mid1, x);
            ll val2=getval(mid2, x);
            if(val1<val2){
                ans=min(ans, val2);
                hi=mid2-1;
            }
            else{
                ans=min(ans, val1);
                lo=mid1+1;
            }
        }
        return ans;
    }
    ll getmaxvalternary(ll x){
        ll lo=0, hi=(ll)M.size()-1;
        ll ans=-inf; /*change with problem*/
        while(lo<=hi){
            ll mid1=lo+(hi-lo)/3;
            ll mid2=hi-(hi-lo)/3;
            ll val1=getval(mid1, x);
            ll val2=getval(mid2, x);
            if(val1<val2){
                ans=max(ans, val2);
                lo=mid1+1;
            }
            else{
                ans=max(ans, val1);
                hi=mid2-1;
            }
        }
        return ans;
    }
};

```

### 2.2 Divide and Conquer DP [26 lines]

6d8559

```

ll G, L; //total group, cell size
ll dp[8001][801], cum[8001];
ll C[8001]; //value of each cell
inline ll cost(ll l, ll r){
    return (cum[r]-cum[l-1])*(r-l+1);
}
void fn(ll g, ll st, ll ed, ll r1, ll r2){
    if(st>ed) return;
    ll mid=(st+ed)/2, pos=-1;
    dp[mid][g]=inf;
    for(int i=r1; i<=r2; i++){
        ll tcost=cost(i, mid)+dp[i-1][g-1];
        if(tcost<dp[mid][g]){
            dp[mid][g]=tcost, pos=i;
        }
    }
}

```

```

    }
    fn(g, st, mid-1, r1, pos);
    fn(g, mid+1, ed, pos, r2);
}
int main(){
    for(int i=1; i<=L; i++){
        cum[i]=cum[i-1]+C[i];
    }
    for(int i=1; i<=L; i++){
        dp[i][1]=cost(1, i);
    }
    for(int i=2; i<=G; i++){
        fn(i, 1, L, 1, L);
    }
}

```

### 2.3 Knuth Optimization [32 lines]

911417

/\*It is applicable where recurrence is in the form :  
 $dp[i][j] = \min_{k < j} \{ dp[i][k] + dp[k][j] + C[i][j] \}$   
 condition for applicability is:  
 $A[i, j-1] \leq A[i, j] \leq A[i+1, j]$   
 Where,  
 $A[i][j]$  - the smallest  $k$  that gives optimal answer, like-  
 $dp[i][j] = dp[i-1][k] + C[k][j]$   
 $C[i][j]$  - given cost function  
 also applicable if:  $C[i][j]$  satisfies the following 2  
 conditions:  
 $C[a][c] + C[b][d] \leq C[a][d] + C[b][c], a \leq b \leq c \leq d$   
 $C[b][c] \leq C[a][d], a < b < c \leq d$   
 reduces time complexity from  $O(n^3)$  to  $O(n^2)$ \*/  
 for(int s=0; s<=k; s++){ //s-length(size) of substring  
 for(int l=0; l+s<=k; l++){ //l-left point  
 int r=l+s; //r-right point  
 if(s<2){  
 res[l][r]=0; //DP base-nothing to break  
 mid[l][r]=1; /\*mid is equal to left border\*/  
 continue;  
 }  
 int mleft=mid[l][r-1]; /\*Knuth's trick: getting  
 bounds on m\*/  
 int mright=mid[l+1][r];  
 res[l][r]=inf;  
 for(int m=mleft; m<=mright; m++){ /\*iterating for m in  
 the bounds only\*/  
 int64 tres=res[l][m]+res[m][r]+(x[r]-x[l]);  
 if(res[l][r]>tres){ //relax current solution  
 res[l][r]=tres;  
 mid[l][r]=m;  
 }  
 }  
 }  
 }  
 int64 answer=res[0][k];

### 2.4 LIS O(nlogn) with full path [17 lines]

e7e81f

```

int num[MX], mem[MX], prev[MX], array[MX], res[MX], maxlen;
void LIS(int SZ, int num[]){
    CLR(mem), CLR(prev), CLR(array), CLR(res);
    int i, k;
    maxlen=1;
    array[0]=-inf;
    RFOR(i, 1, SZ+1) array[i]=inf;
    prev[0]=-1, mem[0]=num[0];
    FOR(i, SZ){
        k=lower_bound(array, array+maxlen+1, num[i])-array;
        if(k==1) array[k]=num[i], mem[k]=i, prev[i]=-1;
        else array[k]=num[i], mem[k]=i, prev[i]=mem[k-1];
        if(k>maxlen) maxlen=k;
    }
}

```

```

}
k=0;
for(i=mem[maxlen];i!=-1;i=prev[i])res[k++]=num[i];
}
2.5 SOS DP [18 lines] 5063f0
//iterative version
for(int mask = 0; mask < (1<<N); ++mask){
    dp[mask][0] = A[mask]; //handle base case separately
    (leaf states)
    for(int i = 0; i < N; ++i){
        if(mask & (1<<i))
            dp[mask][i] = dp[mask][i-1] +
            dp[mask^(1<<i)][i-1];
        else
            dp[mask][i] = dp[mask][i-1];
    }
    F[mask] = dp[mask][N-1];
}
//memory optimized, super easy to code.
for(int i = 0; i < (1<<N); ++i)
    F[i] = A[i];
for(int i = 0; i < N; ++i) for(int mask = 0; mask <
    (1<<N); ++mask){
    if(mask & (1<<i))
        F[mask] += F[mask^(1<<i)];
}
}

```

```

2.6 Sibling DP [26 lines] cfc5ff
/*dividing tree into min group such that each group
cost not exceed k*/
ll n,k,dp[mx][mx];
vector<pair<ll,ll>>adj[mx];///must be rooted tree
ll sibling_dp(ll par,ll idx,ll remk){
    if(remk<0)return inf;
    if(adj[par].size()<idx+1)return 0;
    ll u=adj[par][idx].first;
    if(dp[u][remk]!=-1)
        return dp[u][remk];
    ll ret=inf,under=0,sibling=0;
    if(par!=0){//creating new group
        under=1+dfs(u,0,k);
        sibling=dfs(par,idx+1,remk);
        ret=min(ret,under+sibling);
    }
    //divide the current group
    ll temp=remk-adj[par][idx].second;
    for(ll chk=temp;chk>=0;chk--){
        ll siblingk=temp-chk;
        under=0,sibling=0;
        under=dfs(u,0,chk);
        sibling=dfs(par,idx+1,siblingk);
        ret=min(ret,under+sibling);
    }
    return dp[u][remk]=ret;
}
}

```

### 3 Flow

```

3.1 Blossom [58 lines] 1b2a6f
// Finds Maximum matching in General Graph
// Complexity O(NM)
// mate[i] = j means i is paired with j
// source: https://codeforces.com/blog/entry/
// 92339?#comment=810242
vector<int> Blossom(vector<vector<int>>& graph) {

```

```

//mate contains matched edge.
int n = graph.size(), timer = -1;
vector<int> mate(n, -1), label(n), parent(n),
orig(n), aux(n, -1), q;
auto lca = [&](int x, int y) {
    for (timer++; ; swap(x, y)) {
        if (x == -1) continue;
        if (aux[x] == timer) return x;
        aux[x] = timer;
        x = (mate[x] == -1 ? -1 : orig[parent[mate[x]]]);
    }
};
auto blossom = [&](int v, int w, int a) {
    while (orig[v] != a) {
        parent[v] = w; w = mate[v];
        if (label[w] == 1) label[w] = 0, q.push_back(w);
        orig[v] = orig[w] = a; v = parent[w];
    }
};
auto augment = [&](int v) {
    while (v != -1) {
        int pv = parent[v], nv = mate[pv];
        mate[v] = pv; mate[pv] = v; v = nv;
    }
};
auto bfs = [&](int root) {
    fill(label.begin(), label.end(), -1);
    iota(orig.begin(), orig.end(), 0);
    q.clear();
    label[root] = 0; q.push_back(root);
    for (int i = 0; i < (int)q.size(); ++i) {
        int v = q[i];
        for (auto x : graph[v]) {
            if (label[x] == -1) {
                label[x] = 1; parent[x] = v;
                if (mate[x] == -1)
                    return augment(x), 1;
                label[mate[x]] = 0; q.push_back(mate[x]);
            }
            else if (label[x] == 0 && orig[v] != orig[x]) {
                int a = lca(orig[v], orig[x]);
                blossom(x, v, a); blossom(v, x, a);
            }
        }
    }
    return 0;
};
// Time halves if you start with (any) maximal
// matching.
for (int i = 0; i < n; i++)
    if (mate[i] == -1)
        bfs(i);
return mate;
}

```

### 3.2 Dinic [72 lines] a786f1

```

/*Complexity: O(V^2 E)
.Call Dinic with total number of nodes.
.Nodes start from 0.
.Capacity is long long data.
.make graph with create edge(u,v,capacity).
.Get max flow with maxFlow(src,des).*/
#define eb emplace_back
struct Dinic {
    struct Edge {

```

```

        int u, v;
        ll cap, flow = 0;
        Edge() {}
        Edge(int u, int v, ll cap) :u(u), v(v), cap(cap) {}
    };
    int N;
    vector<Edge>edge;
    vector<vector<int>>adj;
    vector<int>d, pt;
    Dinic(int N) :N(N), edge(0), adj(N), d(N), pt(N) {}
    void addEdge(int u, int v, ll cap) {
        if (u == v) return;
        edge.eb(u, v, cap);
        adj[u].eb(edge.size() - 1);
        edge.eb(v, u, 0);
        adj[v].eb(edge.size() - 1);
    }
    bool bfs(int s, int t) {
        queue<int>q({s});
        fill(d.begin(), d.end(), N + 1);
        d[s] = 0;
        while (!q.empty()) {
            int u = q.front();q.pop();
            if (u == t) break;
            for (int k : adj[u]) {
                Edge& e = edge[k];
                if (e.flow<e.cap && d[e.v]>d[e.u] + 1) {
                    d[e.v] = d[e.u] + 1;
                    q.emplace(e.v);
                }
            }
        }
        return d[t] != N + 1;
    }
    ll dfs(int u, int T, ll flow = -1) {
        if (u == T || flow == 0) return flow;
        for (int& i = pt[u]; i < adj[u].size();i++) {
            Edge& e = edge[adj[u][i]];
            Edge& oe = edge[adj[u][i] ^ 1];
            if (d[e.v] == d[e.u] + 1) {
                ll amt = e.cap - e.flow;
                if (flow != -1 && amt > flow) amt = flow;
                if (ll pushed = dfs(e.v, T, amt)) {
                    e.flow += pushed;
                    oe.flow -= pushed;
                    return pushed;
                }
            }
        }
        return 0;
    }
    ll maxFlow(int s, int t) {
        ll total = 0;
        while (bfs(s, t)) {
            fill(pt.begin(), pt.end(), 0);
            while (ll flow = dfs(s, t)) {
                total += flow;
            }
        }
        return total;
    }
};

```

### 3.3 Flow [6 lines] 6ebca7

Covering Problems:

- > Maximum Independent Set(Bipartite): Largest set of nodes which do not have any edge between them. sol: V-(MaxMatching)
- > Minimum Vertex Cover(Bipartite): -Smallest set of nodes to cover all the edges -sol: MaxMatching
- > Minimum Edge Cover(General graph): -Smallest set of edges to cover all the nodes -sol: V-(MaxMatching) (if edge cover exists, does not exit for isolated nodes)
- > Minimum Path Cover(Vertex disjoint) DAG: -Minimum number of vertex disjoint paths that visit all the nodes -sol: make a bipartite graph using same nodes in two sides, one side is "from" other is "to", add edges from "from" to "to", then ans is V-(MaxMatching)
- > Minimum Path Cover(Vertex Not Disjoint) General graph: -Minimum number of paths that visit all the nodes -sol: consider cycles as nodes then it will become a path cover problem with vertex disjoint on DAG

### 3.4 HopcroftKarp [67 lines] fac9fc

*/\* Finds Maximum Matching In a bipartite graph*

*.Complexity  $O(E\sqrt{V})$   
 .1-indexed  
 .No default constructor  
 .add single edge for (u, v)\*/*

```
struct HK {
    static const int inf = 1e9;
    int n;
    vector<int> matchL, matchR, dist;
    //matchL contains value of matched node for L part.
    vector<vector<int>> adj;
    HK(int n) : n(n), matchL(n + 1),
    matchR(n + 1), dist(n + 1), adj(n + 1) {}

    void addEdge(int u, int v) {
        adj[u].push_back(v);
    }
    bool bfs() {
        queue<int> q;
        for (int u = 1; u <= n; u++) {
            if (!matchL[u]) {
                dist[u] = 0;
                q.push(u);
            }
            else dist[u] = inf;
        }
        dist[0] = inf; //unmatched node matches with 0.
        while (!q.empty()) {
            int u = q.front();
            q.pop();
            for (auto v : adj[u]) {
                if (dist[matchR[v]] == inf) {
                    dist[matchR[v]] = dist[u] + 1;
                    q.push(matchR[v]);
                }
            }
        }
        return dist[0] != inf;
    }
};
```

```
bool dfs(int u) {
    if (!u) return true;
    for (auto v : adj[u]) {
        if (dist[matchR[v]] == dist[u] + 1
            && dfs(matchR[v])) {
            matchL[u] = v;
            matchR[v] = u;
            return true;
        }
    }
    dist[u] = inf;
    return false;
}

int max_match() {
    int matching = 0;
    while (bfs()) {
        for (int u = 1; u <= n; u++) {
            if (!matchL[u])
                if (dfs(u))
                    matching++;
        }
    }
    return matching;
}
};
```

### 3.5 Hungarian [116 lines] 64902f

*/\* Complexity:  $O(n^3)$  but optimized*

*It finds minimum cost maximum matching.  
 For finding maximum cost maximum matching  
 add -cost and return -matching()  
 1-indexed \*/*

```
struct Hungarian {
    long long c[N][N], fx[N], fy[N], d[N];
    int l[N], r[N], arg[N], trace[N];
    queue<int> q;
    int start, finish, n;
    const long long inf = 1e18;
    Hungarian() {}
    Hungarian(int n1, int n2) : n(max(n1, n2)) {
        for (int i = 1; i <= n; ++i) {
            fy[i] = l[i] = r[i] = 0;
            for (int j = 1; j <= n; ++j) c[i][j] = inf;
        }
    }
    void add_edge(int u, int v, long long cost) {
        c[u][v] = min(c[u][v], cost);
    }
    inline long long getC(int u, int v) {
        return c[u][v] - fx[u] - fy[v];
    }
    void initBFS() {
        while (!q.empty()) q.pop();
        q.push(start);
        for (int i = 0; i <= n; ++i) trace[i] = 0;
        for (int v = 1; v <= n; ++v) {
            d[v] = getC(start, v);
            arg[v] = start;
        }
        finish = 0;
    }
    void findAugPath() {
        while (!q.empty()) {
            int u = q.front();
```

```
q.pop();
        for (int v = 1; v <= n; ++v) if (!trace[v]) {
            long long w = getC(u, v);
            if (!w) {
                trace[v] = u;
                if (!r[v]) {
                    finish = v;
                    return;
                }
                q.push(r[v]);
            }
            if (d[v] > w) {
                d[v] = w;
                arg[v] = u;
            }
        }
    }
}

void subX_addY() {
    long long delta = inf;
    for (int v = 1; v <= n; ++v) if (trace[v] == 0 &&
    d[v] < delta) {
        delta = d[v];
    }
    // Rotate
    fx[start] += delta;
    for (int v = 1; v <= n; ++v) if (trace[v]) {
        int u = r[v];
        fy[v] -= delta;
        fx[u] += delta;
    }
    else d[v] -= delta;
    for (int v = 1; v <= n; ++v) if (!trace[v] && !d[v]) {
        trace[v] = arg[v];
        if (!r[v]) {
            finish = v;
            return;
        }
        q.push(r[v]);
    }
}

void Enlarge() {
    do {
        int u = trace[finish];
        int nxt = l[u];
        l[u] = finish;
        r[finish] = u;
        finish = nxt;
    } while (finish);
}

long long maximum_matching() {
    for (int u = 1; u <= n; ++u) {
        fx[u] = c[u][1];
        for (int v = 1; v <= n; ++v) {
            fx[u] = min(fx[u], c[u][v]);
        }
    }
    for (int v = 1; v <= n; ++v) {
        fy[v] = c[1][v] - fx[1];
        for (int u = 1; u <= n; ++u) {
            fy[v] = min(fy[v], c[u][v] - fx[u]);
        }
    }
}
```





```

pt(T _x,T _y):x(_x),y(_y){}
pt operator+(pt p){
    return{x+p.x,y+p.y};
}
pt operator-(pt p){
    return{x-p.x,y-p.y};
}
pt operator*(T d){
    return{x*d,y*d};
}
pt operator*(pt d){/*I added for General linear
transformation,not sure about that function*/
    return{x*d.x,y*d.y};
}
pt operator/(T d){
    return{x/d,y/d};/*only for floating point*/
}
pt operator/(pt d){/*I added for General linear
transformation,not sure about that function*/
    return{x/d.x,y/d.y};
}
bool operator<(const pt& p)const {
    if(x!=p.x)
        return x<p.x;
    return y<p.y;
}
bool operator==(pt b){
    return x==b.x && y==b.y;
}
bool operator!=(pt b){
    return !(*this)==b;
}
friend ostream& operator<<(ostream& os,const pt p){
    return os<<"("<p.x<<","<p.y<<")";
}
friend istream& operator>>(istream& is,pt &p){
    is>>p.x>>p.y;
    return is;
}
};
T sq(pt p){
    return p.x*p.x+p.y*p.y;
}
double Abs(pt p){
    return sqrtl(sq(p));
}
pt translate(pt v,pt p){ /*To translate an object by a
vector v*/
    return p+v;
}
pt scale(pt c,double factor,pt p){/*To scale an object
by a certain ratio factor around a center*/
    return c+(p-c)*factor;
}
pt rot(pt p,double a){/*To rotate a point by angle
a*/
    return{p.x*cos(a)-p.y*sin(a),p.x*sin(a)+p.y*
cos(a)};
}
pt perp(pt p){/*To rotate a point 90 degree*/
    return{-p.y,p.x};
}
pt linearTransfo(pt p,pt q,pt r,pt fp,pt fq){/*so far
don't know about that function*/

```

```

    return fp+(r-p)*(fq-fp)/(q-p);
}
T dot(pt v,pt w){
    return v.x*w.x+v.y*w.y;
}
bool isPerp(pt v,pt w){
    return dot(v,w)==0;
}
double angle(pt v,pt w){/*Find the smallest angle of
two vector*/
    double cosTheta=dot(v,w)/Abs(v)/Abs(w);
    return acos(max(-1.0,min(1.0,cosTheta)));
}
T cross(pt v,pt w){
    return v.x*w.y-v.y*w.x;
}
T orient(pt a,pt b,pt c){
    return cross(b-a,c-a); /*if c is left side+ve,c is
right side-ve,on line 0*/
}
bool inAngle(pt a,pt b,pt c,pt p){/*if p is in the
angle*/
    assert(orient(a,b,c)!=0);
    if(orient(a,b,c)<0)
        swap(b,c);
    return orient(a,b,p)>=0 && orient(a,c,p)<=0;
}
double orientedAngle(pt a,pt b,pt c){/*the actual
angle from ab to ac*/
    if(orient(a,b,c)>=0)
        return angle(b-a,c-a);
    else
        return 2*M_PI-angle(b-a,c-a);
}
///line
struct line{
    pt v;
    T c;
    line(){}
    line(pt p,pt q){/*From points P and Q*/
        v=(q-p),this->c=cross(v,p);
    }
    line(T a,T b,T c){/*From equation ax+by=c*/
        v=pt(b,-a),this->c=c;
    }
    line(pt v,T c){/*From direction vector v and offset
c*/
        this->v=v,this->c=c;
    }
    double getY(double x){/*self made,not sure if it is
okay*/
        assert(v.x!=0);
        double ret=(double)(c+v.y*x)/v.x;
        return ret;
    }
    double getX(double y){/*self made,not sure if it is
okay*/
        assert(v.y!=0);
        double ret=(double)(c-v.x*y)/-v.y;
        return ret;
    }
    T side(pt p){/*which side a point is*/
        return cross(v,p)-c;
    }
}

```

```

double dist(pt p){/*point to line dist*/
    return abs(side(p))/Abs(v);
}
double sqDist(pt p){/*square dist*/
    return side(p)*side(p)/(double)sq(v);
}
line perpThrough(pt p){/*perpendicular line with
point p*/
    return line(p,p+perp(v));
}
bool cmpProj(pt p,pt q){/*compare function to sort
points on a line*/
    return dot(v,p)<dot(v,q);
}
line translate(pt t){/*translate with vector t*/
    return line(v,c+cross(v,t));
}
line shiftLeft(double dist){/*translate with
distance dist*/
    return line(v,c+dist*Abs(v));
}
pt proj(pt p){
    return p-perp(v)*side(p)/sq(v);
}
pt refl(pt p){
    return p-perp(v)*2*side(p)/sq(v);
}
};
bool areParallel(line l1,line l2){
    return(l1.v.x*l2.v.y==l1.v.y*l2.v.x);
}
bool areSame(line l1,line l2){
    return areParallel(l1,l2)and(l1.v.x*l2.c==l2.v.x*
l1.c)and(l1.v.y*l2.c==l2.v.y*l1.c);
}
bool inter(line l1,line l2,pt& out){
    T d=cross(l1.v,l2.v);
    if(d==0)return false;
    out=(l2.v*l1.c-l1.v*l2.c)/d;
    return true;
}
line intBisector(line l1,line l2,bool interior){/*if
change sign then returns the other one*/
    assert(cross(l1.v,l2.v)!=0);
    double sign=interior?-1;
    return line(l2.v/Abs(l2.v)+l1.v*sign/Abs(l1.v),
l2.c/Abs(l2.v)+l1.c*sign/Abs(l1.v));
}
//segment
bool inDisk(pt a,pt b,pt p){/*check weather point p is
in diameter AB*/
    return dot(a-p,b-p)<=0;
}
bool onSegment(pt a,pt b,pt p){/*check weather point p
is in segment AB*/
    return orient(a,b,p)==0 and inDisk(a,b,p);
}
bool properInter(pt a,pt b,pt c,pt d,pt& i){
    double oa=orient(c,d,a),
ob=orient(c,d,b),
oc=orient(a,b,c),
od=orient(a,b,d);
//Proper intersection exists iff opposite signs
if(oa*ob<0 and oc*od<0){

```

```

    i=(a*ob-b*oa)/(ob-oa);
    return 1;
}
return 0;
}
/*To create sets of points we need a comparison
function*/
struct cmpX{
    bool operator()(pt a,pt b){
        return make_pair(a.x,a.y)<make_pair(b.x,b.y);
    }
};
set<pt,cmpX>inters(pt a,pt b,pt c,pt d){
    pt out;
    if(properInter(a,b,c,d,out))
        return{out};
    set<pt,cmpX>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 s;
}
bool LineSegInter(line l,pt a,pt b,pt& out){
    if(l.side(a)*l.side(b)>eps)return 0;
    return inter(l,line(a,b),out);
}
double segPoint(pt a,pt b,pt p){/*returns distance
from a point p to segment AB*/
    if(a!=b){
        line l(a,b);
        if(l.cmpProj(a,p)and l.cmpProj(p,b))
            return l.dist(p);
    }
    return min(Abs(p-a),Abs(p-b));
}
double segSeg(pt a,pt b,pt c,pt d){/*returns distance
from a segment AB to segment CD*/
    pt dummy;
    if(properInter(a,b,c,d,dummy))return 0;
    return min(min(min(segPoint(a,b,c),segPoint(a,b,
d)),segPoint(c,d,a)),segPoint(c,d,b));
}
/*int latticePoints(pt a,pt b){
// requires int representation
return __gcd(abs(a.x-b.x),abs(a.y-b.y))+1;
} // A = i+(b/2)-1; here
A=area,i=pointsinside,b=pointsonline
Polygon*/
bool isConvex(vector<pt>&p){
    bool hasPos=0,hasNeg=0;
    for(int i=0,n=p.size();i<n;i++){
        int o=orient(p[i],p[(i+1)%n],p[(i+2)%n]);
        if(o>0)hasPos=1;
        if(o<0)hasNeg=true;
    }
    return!(hasPos and hasNeg);
}
double areaTriangle(pt a,pt b,pt c){
    return abs(cross(b-a,c-a))/2.0;
}
double areaPolygon(const vector<pt>&p){
    double area=0.0;
    for(int i=0,n=p.size();i<n;i++){

```

```

        area+=cross(p[i],p[(i+1)%n]);
    }
    return fabs(area)/2.0;
}
bool pointInPolygon(const vector<pt>&p,pt q){/*returns
true if pt q is in polygon p*/
    bool c=false;
    for(int i=0,n=p.size();i<n;i++){
        int j=(i+1)%p.size();
        if((p[i].y<=q.y and q.y<p[j].y or p[j].y<=q.y and
q.y<p[i].y)and
q.x<p[i].x+(p[j].x-p[i].x)*(q.y-p[i].y)/
(p[j].y-p[i].y))
            c=!c;
    }
    return c;
}
ll is_point_in_convex(vector<pt>&p, pt &x) { // O(log
n)
    ll n = p.size(); /*this function from
YouKnowWho*/
    if (n < 3) return 1;
    ll a =orient(p[0], p[1], x), b = orient(p[0], p[n
- 1], x);
    if (a < 0 || b > 0) return 1;
    ll l = 1, r = n - 1;
    while (l + 1 < r) {
        int mid = l + r >> 1;
        if (orient(p[0], p[mid], x) >= 0) l = mid;
        else r = mid;
    }
    ll k = orient(p[l], p[r], x);
    if (k <= 0) return -k;
    if (l == 1 && a == 0) return 0;
    if (r == n - 1 && b == 0) return 0;
    return -1;
}
pt centroidPolygon(vector<pt>&p){/*from rezaul,i don't
know about that*/
    pt c(0,0);
    double scale=6.0*areaPolygon(p);
    // if(scale<eps)return c;
    for(int i=0,n=p.size();i<n;i++){
        int j=(i+1)%n;
        c=c+(p[i]+p[j])*cross(p[i],p[j]);
    }
    return c/scale;
}
///Circle
pt circumCenter(pt a,pt b,pt c){/*return the center of
the circle go through point a,b,c*/
    b=b-a,c=c-a;
    assert(cross(b,c)!=0);
    return a+perp(b*sq(c)-c*sq(b))/cross(b,c)/2;
}
bool circle2PtsRad(pt p1,pt p2,double r,pt& c){
    double d2=sq(p1-p2);
    double det=r*r/d2-0.25;
    if(det<0.0)return false;
    double h=sqrt(det);
    c.x=(p1.x+p2.x)*0.5+(p1.y-p2.y)*h;
    c.y=(p1.y+p2.y)*0.5+(p2.x-p1.x)*h;
    return true;
}

```

```

int circleLine(pt c,double r,line l,pt&pt,pt&
out){/*circle line intersection*/
    double h2=r*r-l.sqDist(c);
    if(h2<0)return 0;/*the line doesn't touch the
circle;*/
    pt p=l.proj(c);
    pt h=l.v*sqrt(h2)/Abs(l.v);
    out=make_pair(p-h,p+h);
    return 1+(h2>0);
}
int circleCircle(pt c1,double r1,pt c2,double
r2,pt&pt,pt& out){/*circle circle intersection*/
    pt d=c2-c1;
    double d2=sq(d);
    if(d2==0){/*concentric circles
        assert(r1!=r2);
        return 0;
    }
    double pd=(d2+r1*r1-r2*r2)/2;
    double h2=r1*r1-pd*pd/d2;//h ^ 2
    if(h2<0)return 0;
    pt p=c1+d*pd/d2,h=perp(d)*sqrt(h2/d2);
    out=make_pair(p-h,p+h);
    return 1+h2>0;
}
int tangents(pt c1,double r1,pt c2,double r2,bool
inner,vector<pair<pt,pt>>&out){
    if(inner)r2=-r2;/*returns tangent(the line which
touch a circle in one point)of two circle*/
    pt d=c2-c1;/*the same code can be used to find the
tangent to a circle passing through a point by
setting r2 to 0*/
    double dr=r1-r2,d2=sq(d),h2=d2-dr*dr;
    if(d2==0 or h2<0){
        assert(h2!=0);
        return 0;
    }
    for(int sign :{-1,1}){
        pt v=pt(d*dr+perp(d)*sqrt(h2)*sign)/d2;
        out.push_back(make_pair(c1+v*r1,c2+v*r2));
    }
    return 1+(h2>0);
}
//Convex Hull-Monotone Chain
pt H[100000+5];
vector<pt>monotoneChain(vector<pt>&points){
    sort(points.begin(),points.end());
    vector<pt>ret;
    ret.clear();
    int st=0;
    for(int i=0,sz=points.size();i<sz;i++){
        while(st>=2 and
orient(H[st-2],H[st-1],points[i])<0)st--;
        H[st++]=points[i];
    }
    int taken=st-1;
    for(int i=points.size()-2;i>=0;i--){
        while(st>=taken+2 and
orient(H[st-2],H[st-1],points[i])<0)st--;
        H[st++]=points[i];
    }
    for(int i=0;i<st;i++)ret.push_back(H[i]);
    return ret;
}

```

```
//Convex Hull-Monotone Chain from you_know_who
int sz;
vector<pt> monotoneChain(vector<pt> &v) {
    if(v.size()==1) return v;
    sort(v.begin(), v.end());
    vector<pt> up(2*v.size()+2), down(2*v.size()+2);
    int szup=0, szdw=0;
    for(int i=0;i<v.size();i++) {
        while(szup>1 && orient(up[szup-2],
            up[szup-1], v[i])>=0)
            szup--;
        while(szdw>1 && orient(down[szdw-2],
            down[szdw-1], v[i])<=0)
            szdw--;
        up[szup++]=v[i];
        down[szdw++]=v[i];
    }
    if(szdw>1) szdw--;
    reverse(up.begin(), up.end()+szup);
    for(int i=0;i<szup-1;i++) down[szdw++]= up[i];
    if(szdw==2 && down[0].x==down[1].x &&
        down[0].y==down[1].y)
        szdw--;
    sz = szdw;
    return down;
}
double cosA(double a,double b,double c){
    double val=b*b+c*c-a*a;
    val/=(2*b*c);
    return acos(val);
}
double triangle(double a,double b,double c){
    double s=(a+b+c)/2;
    return sqrt(1*s*(s-a)*(s-b)*(s-c));
}
}
using namespace Geometry;
```

## 5.2 Rotation Matrix [39 lines]

f97f03

```
struct { double x; double y; double z; } Point;
double rMat[4][4];
double inMat[4][1] = {0.0, 0.0, 0.0, 0.0};
double outMat[4][1] = {0.0, 0.0, 0.0, 0.0};
void mulMat() {
    for(int i = 0; i < 4; i++) {
        for(int j = 0; j < 1; j++) {
            outMat[i][j] = 0;
            for(int k = 0; k < 4; k++)
                outMat[i][j] += rMat[i][k] * inMat[k][j];
        }
    }
}
void setMat(double ang, double u, double v, double w){
    double L = (u * u + v * v + w * w);
    ang = ang * PI / 180.0; /*converting to radian
    value*/
    double u2 = u*u; double v2 = v*v; double w2 = w*w;
    rMat[0][0]=(u2+(v2+w2)*cos(ang))/L;
    rMat[0][1]=(u*v*(1-cos(ang))-w*sqrt(L)*sin(ang))/L;
    rMat[0][2]=(u*w*(1-cos(ang))+v*sqrt(L)*sin(ang))/L;
    rMat[0][3]=0.0;
    rMat[1][0]=(u*v*(1-cos(ang))+w*sqrt(L)*sin(ang))/L;
    rMat[1][1]=(v2+(u2+w2)*cos(ang))/L;
    rMat[1][2]=(v*w*(1-cos(ang))-u*sqrt(L)*sin(ang))/L;
    rMat[1][3]=0.0;
```

```
rMat[2][0]=(u*w*(1-cos(ang))-v*sqrt(L)*sin(ang))/L;
rMat[2][1]=(v*w*(1-cos(ang))+u*sqrt(L)*sin(ang))/L;
rMat[2][2]=(w2 + (u2 + v2) * cos(ang)) / L;
rMat[2][3]=0.0; rMat[3][0]=0.0; rMat[3][1]=0.0;
rMat[3][2]=0.0; rMat[3][3]=1.0;
}
/*double ang;
double u, v, w; //points = the point to be rotated
Point point, rotated; //u,v,w=unit vector of line
inMat[0][0] = points.x; inMat[1][0] = points.y;
inMat[2][0] = points.z; inMat[3][0] = 1.0;
setMat(ang, u, v, w); mulMat();
rotated.x = outMat[0][0]; rotated.y = outMat[1][0];
rotated.z = outMat[2][0];*/
```

## 6 Graph

### 6.1 2SAT [92 lines]

5289ec

```
struct TwoSat {
    vector<bool>vis;
    vector<vector<int>>adj, radj;
    vector<int>dfs_t, ord, par;
    int n, intime; //For n node there will be 2*n node in
    SAT.
    void init(int N) {
        n = N;
        intime = 0;
        vis.assign(N * 2 + 1, false);
        adj.assign(N * 2 + 1, vector<int>());
        radj.assign(N * 2 + 1, vector<int>());
        dfs_t.resize(N * 2 + 1);
        ord.resize(N * 2 + 1);
        par.resize(N * 2 + 1);
    }
    inline int neg(int x) {
        return x <= n ? x + n : x - n;
    }
    inline void add_implication(int a, int b) {
        if (a < 0) a = n - a;
        if (b < 0) b = n - b;
        adj[a].push_back(b);
        radj[b].push_back(a);
    }
    inline void add_or(int a, int b) {
        add_implication(-a, b);
        add_implication(-b, a);
    }
    inline void add_xor(int a, int b) {
        add_or(a, b);
        add_or(-a, -b);
    }
    inline void add_and(int a, int b) {
        add_or(a, b);
        add_or(a, -b);
        add_or(-a, b);
    }
    inline void force_true(int x) {
        if (x < 0) x = n - x;
        add_implication(neg(x), x);
    }
    inline void add_xnor(int a, int b) {
        add_or(a, -b);
        add_or(-a, b);
    }
    inline void add_nand(int a, int b) {
```

```
        add_or(-a, -b);
    }
    inline void add_nor(int a, int b) {
        add_and(-a, -b);
    }
    inline void force_false(int x) {
        if (x < 0) x = n - x;
        add_implication(x, neg(x));
    }
    inline void topsort(int u) {
        vis[u] = 1;
        for (int v : radj[u]) if (!vis[v]) topsort(v);
        dfs_t[u] = ++intime;
    }
    inline void dfs(int u, int p) {
        par[u] = p, vis[u] = 1;
        for (int v : adj[u]) if (!vis[v]) dfs(v, p);
    }
    void build() {
        int i, x;
        for (i = n * 2, intime = 0; i >= 1; i--) {
            if (!vis[i]) topsort(i);
            ord[dfs_t[i]] = i;
        }
        vis.assign(n * 2 + 1, 0);
        for (i = n * 2; i > 0; i--) {
            x = ord[i];
            if (!vis[x]) dfs(x, x);
        }
    }
    bool satisfy(vector<int>& ret) //ret contains the value
    that are true if the graph is satisfiable.
    {
        build();
        vis.assign(n * 2 + 1, 0);
        for (int i = 1; i <= n * 2; i++) {
            int x = ord[i];
            if (par[x] == par[neg(x)]) return 0;
            if (!vis[par[x]]) {
                vis[par[x]] = 1;
                vis[par[neg(x)]] = 0;
            }
        }
        for (int i = 1; i <= n; i++) if (vis[par[i]])
            ret.push_back(i);
        return 1;
    }
};
```

### 6.2 BridgeTree [66 lines]

f8e197

```
int N, M, timer, compid;
vector<pair<int, int>> g[mx];
bool used[mx], isBridge[mx];
int comp[mx], tin[mx], minAncestor[mx];
vector<int> Tree[mx]; // Store 2-edge-connected
component tree.(Bridge tree).
void markBridge(int v, int p) {
    tin[v] = minAncestor[v] = ++timer;
    used[v] = 1;
    for (auto& e : g[v]) {
        int to, id;
        tie(to, id) = e;
        if (to == p) continue;
```

```

if (used[to]) minAncestor[v] = min(minAncestor[v],
tin[to]);
else {
    markBridge(to, v);
    minAncestor[v] = min(minAncestor[v],
minAncestor[to]);
    if (minAncestor[to] > tin[v]) isBridge[id] = true;
    // if (tin[u] <= minAncestor[v]) ap[u] = 1;
}
}
}

void markComp(int v, int p) {
    used[v] = 1;
    comp[v] = compid;
    for (auto& e : g[v]) {
        int to, id;
        tie(to, id) = e;
        if (isBridge[id]) continue;
        if (used[to]) continue;
        markComp(to, v);
    }
}

vector<pair<int, int>> edges;
void addEdge(int from, int to, int id) {
    g[from].push_back({ to, id });
    g[to].push_back({ from, id });
    edges[id] = { from, to };
}

void initB() {
    for (int i = 0; i <= compid; ++i) Tree[i].clear();
    for (int i = 1; i <= N; ++i) used[i] = false;
    for (int i = 1; i <= M; ++i) isBridge[i] = false;
    timer = compid = 0;
}

void bridge_tree() {
    initB();
    markBridge(1, -1); //Assuming graph is connected.
    for (int i = 1; i <= N; ++i) used[i] = 0;
    for (int i = 1; i <= N; ++i) {
        if (!used[i]) {
            markComp(i, -1);
            ++compid;
        }
    }
    for (int i = 1; i <= M; ++i) {
        if (isBridge[i]) {
            int u, v;
            tie(u, v) = edges[i];
            // connect two componets using edge.
            Tree[comp[u]].push_back(comp[v]);
            Tree[comp[v]].push_back(comp[u]);
            int x = comp[u];
            int y = comp[v];
        }
    }
}
}

```

### 6.3 Centroid Decomposition [49 lines] 3fb5b1

```

ll n,subsize[mx];
vector<ll>adj[mx];
char ans[mx];
bool brk[mx];
void calculatesize(ll u,ll par){
    subsize[u]=1;
    for(ll i=0;i<(ll)adj[u].size();i++){

```

```

        ll v=adj[u][i];
        if(v==par or brk[v]==true)continue;
        calculatesize(v,u);
        subsize[u]+=subsize[v];
    }
}

ll getcentroid(ll u,ll par,ll n){
    ll ret=u;
    for(ll i=0;i<(ll)adj[u].size();i++){
        ll v=adj[u][i];
        if(v==par or brk[v]==true)continue;
        if(subsize[v]>(n/2)){
            ret=getcentroid(v,u,n);
            break;
        }
    }
    return ret;
}

void decompose(ll u,char rank){
    calculatesize(u,-1);
    ll c=getcentroid(u,-1,subsize[u]);
    brk[c]=true;
    ans[c]=rank;
    for(ll i=0;i<(ll)adj[c].size();i++){
        ll v=adj[c][i];
        if(brk[v]==true)continue;
        decompose(v,rank+1);
    }
}

int main(){
    scanf("%lld",&n);
    for(ll i=0;i<n-1;i++){
        ll a,b;
        scanf("%lld %lld",&a,&b);
        adj[a].push_back(b);
        adj[b].push_back(a);
    }
    decompose(1,'A');
    for(ll i=1;i<=n;i++){
        printf("%c",ans[i]);
    }
}

```

### 6.4 DSU on Tree [56 lines] 391fb6

```

int n;
//extra data you need
vector<int> adj[mxn];
vector<int> *dsu[mxn];
void call(int u, int p=-1){
    sz[u] = 1;
    for(auto v: adj[u]){
        if(v != p){
            dep[v] = dep[u]+1;
            call(v, u);
            sz[u] += sz[v];
        }
    }
}

void dfs(int u, int p = -1, int isb = 1){
    int mx=-1, big=-1;
    for(auto v: adj[u]){
        if(v != p && sz[v]>mx){
            mx = sz[v];
            big = v;
        }
    }
}

```

```

}
for(auto v: adj[u]){
    if(v != p && v != big){
        dfs(v, u, 0);
    }
}
if(big != -1){
    dfs(big, u, 1);
    dsu[u] = dsu[big];
}
else{
    dsu[u] = new vector<int>();
}
dsu[u]->push_back(u);
//calculation
for(auto v: adj[u]){
    if(v == p || v == big) continue;
    for(auto x: *dsu[v]){
        dsu[u]->push_back(x);
        //calculation
    }
}
//calculate ans for node u
if(isb == 0){
    for(auto x: *dsu[u]){
        //reverse calculation
    }
}
}

int main() {
    //input graph
    dep[1] = 1;
    call(1);
    dfs(1);
}

```

### 6.5 Heavy Light Decomposition [73 lines]

d0e24f

```

/*Heavy Light Decomposition
Build Complexity O(n)
Query Complexity O(lg^2 n)
Call init()with number of nodes
It's probably for the best to not do"using namespace
hld"*/
namespace hld {
    //N is the maximum number of nodes
    /*par,lev,size corresponds to
    parent,depth,subtree-size*/
    //head[u]is the starting node of the chain u is in
    //in[u]to out[u]keeps the subtree indices
    const int N=100000+7;
    vector<int>g[N];
    int par[N],lev[N],head[N],size[N],in[N],out[N];
    int cur_pos,n;
    //returns the size of subtree rooted at u
    /*maintains the child with the largest subtree at the
    front of g[u]*/
    //WARNING: Don't change anything here specially with
    size[]if Jon Snow
    int dfs(int u,int p){
        size[u]=1,par[u]=p;
        lev[u]=lev[p]+1;
        for(auto &v : g[u]){
            if(v==p)continue;

```



```

    size[u] += dfs(v, u);
    if (size[v] > size[g[u].front()]) {
        swap(v, g[u].front());
    }
}
return size[u];
}
//decomposed the tree in an array
//note that there is no physical array here
void decompose(int u, int p) {
    in[u] = ++cur_pos;
    for (auto &v : g[u]) {
        if (v == p) continue;
        head[v] = (v == g[u].front() ? head[u] : v);
        decompose(v, u);
    }
    out[u] = cur_pos;
}
//initializes the structure with _n nodes
void init(int _n, int root = 1) {
    n = _n;
    cur_pos = 0;
    dfs(root, 0);
    head[root] = root;
    decompose(root, 0);
}
//checks whether p is an ancestor of u
bool isances(int p, int u) {
    return in[p] <= in[u] and out[u] <= out[p];
}
//Returns the maximum node value in the path u-v
ll query(int u, int v) {
    ll ret = -INF;
    while (!isances(head[u], v)) {
        ret = max(ret, seg.query(1, 1, n, in[head[u]], in[u]));
        u = par[head[u]];
    }
    swap(u, v);
    while (!isances(head[u], v)) {
        ret = max(ret, seg.query(1, 1, n, in[head[u]], in[u]));
        u = par[head[u]];
    }
    if (in[v] < in[u]) swap(u, v);
    ret = max(ret, seg.query(1, 1, n, in[u], in[v]));
    return ret;
}
//Adds val to subtree of u
void update(int u, ll val) {
    seg.update(1, 1, n, in[u], out[u], val);
}
};

6.6 K'th Shortest path [40 lines] 9f3788
int m, n, deg[MM], source, sink, K, val[MM][12];
struct edge {
    int v, w;
} adj[MM][500];
struct info {
    int v, w, k;
    bool operator<(const info &b) const {
        return w > b.w;
    }
};
priority_queue<info, vector<info>>, Q;
void kthBestShortestPath() {

```

```

    int i, j;
    info u, v;
    for (i = 0; i < n; i++)
        for (j = 0; j < K; j++) val[i][j] = inf;
    u.v = source, u.k = 0, u.w = 0;
    Q.push(u);
    while (!Q.empty()) {
        u = Q.top();
        Q.pop();
        for (i = 0; i < deg[u.v]; i++) {
            v.v = adj[u.v][i].v;
            int cost = adj[u.v][i].w + u.w;
            for (v.k = u.k; v.k < K; v.k++) {
                if (cost == inf) break;
                if (val[v.v][v.k] > cost) {
                    swap(cost, val[v.v][v.k]);
                    v.w = val[v.v][v.k];
                    Q.push(v);
                    break;
                }
            }
            for (v.k++; v.k < K; v.k++) {
                if (cost == inf) break;
                if (val[v.v][v.k] > cost) swap(cost, val[v.v][v.k]);
            }
        }
    }
}

6.7 LCA [46 lines] 9de12b
const int Lg = 22;
vector<int> adj[mx];
int level[mx];
int dp[Lg][mx];
void dfs(int u) {
    for (int i = 1; i < Lg; i++)
        dp[i][u] = dp[i - 1][dp[i - 1][u]];
    for (int v : adj[u]) {
        if (dp[0][u] == v) continue;
        level[v] = level[u] + 1;
        dp[0][v] = u;
        dfs(v);
    }
}
int lca(int u, int v) {
    if (level[v] < level[u]) swap(u, v);
    int diff = level[v] - level[u];
    for (int i = 0; i < Lg; i++)
        if (diff & (1 << i))
            v = dp[i][v];
    for (int i = Lg - 1; i >= 0; i--)
        if (dp[i][u] != dp[i][v])
            u = dp[i][u], v = dp[i][v];
    return u == v ? u : dp[0][u];
}
int kth(int u, int k) {
    for (int i = Lg - 1; i >= 0; i--)
        if (k & (1 << i))
            u = dp[i][u];
    return u;
}
//kth node from u to v. 0th is u.
int go(int u, int v, int k) {
    int l = lca(u, v);
    int d = level[u] + level[v] - (level[l] << 1);

```

```

    assert(k <= d);
    if (level[l] + k <= level[u]) return kth(u, k);
    k -= level[u] - level[l];
    return kth(v, level[v] - level[l] - k);
}
/*
    LCA(u,v) with root r:
    lca(u,v) ^ lca(u,r) ^ lca(v,r)
    Distance between u,v:
    level(u) + level(v) - 2*level(lca(u,v))
    */

6.8 SCC [43 lines] 4da431
/*components: number of SCC.
sz: size of each SCC.
comp: component number of each node.
Create reverse graph.
Run find_scc() to find SCC.
Might need to create condensation graph by
    create_condensed().
Think about indeg/outdeg
for multiple test cases- clear
    adj/radj/comp/vis/sz/topo/condensed.*/
vector<int> adj[mx], radj[mx];

int comp[mx], vis[mx], sz[mx], components;
vector<int> topo;
void dfs(int u) {
    vis[u] = 1;
    for (int v : adj[u])
        if (!vis[v]) dfs(v);
    topo.push_back(u);
}
void dfs2(int u, int val) {
    comp[u] = val;
    sz[val]++;
    for (int v : radj[u])
        if (comp[v] == -1)
            dfs2(v, val);
}
void find_scc(int n) {
    memset(vis, 0, sizeof vis);
    memset(comp, -1, sizeof comp);
    for (int i = 1; i <= n; i++)
        if (!vis[i])
            dfs(i);
    reverse(topo.begin(), topo.end());
    for (int u : topo)
        if (comp[u] == -1)
            dfs2(u, ++components);
}
vector<int> condensed[mx];
void create_condensed(int n) {
    for (int i = 1; i <= n; i++)
        for (int v : adj[i])
            if (comp[i] != comp[v])
                condensed[comp[i]].push_back(comp[v]);
}

7 Math

7.1 Big Sum [13 lines] 8d9520
ll bigsum(ll a, ll b, ll m) {
    if (b == 0) return 0;

```

```

11 sum; a %= m;
if (b & 1) {
    sum = bigsum((a * a) % m, (b - 1) / 2, m);
    sum = (sum + (a * sum) % m) % m;
    sum = (1 + (a * sum) % m) % m;
} else {
    sum = bigsum((a * a) % m, b / 2, m);
    sum = (sum + (a * sum) % m) % m;
}
return sum;
}
}

7.2 CRT [52 lines] 59a568
11 ext_gcd(11 A, 11 B, 11* X, 11* Y) {
11 x2, y2, x1, y1, x, y, r2, r1, q, r;
x2 = 1; y2 = 0;
x1 = 0; y1 = 1;
for (r2 = A, r1 = B; r1 != 0; r2 = r1, r1 = r, x2 =
    x1, y2 = y1, x1 = x, y1 = y) {
    q = r2 / r1;
    r = r2 % r1;
    x = x2 - (q * x1);
    y = y2 - (q * y1);
}
*X = x2; *Y = y2;
return r2;
}
/*-----BlackBox-----*/
class ChineseRemainderTheorem {
    typedef long long vlong;
    typedef pair<vlong, vlong> pll;
    /** CRT Equations stored as pairs of vector. See
        addEquation()*/
    vector<pll> equations;
public:
    void clear() {
        equations.clear();
    }
    /** Add equation of the form  $x = r \pmod m$ */
    void addEquation(vlong r, vlong m) {
        equations.push_back({ r, m });
    }
    pll solve() {
        if (equations.size() == 0) return { -1, -1 }; /// No
        equations to solve
        vlong a1 = equations[0].first;
        vlong m1 = equations[0].second;
        a1 %= m1;
        /** Initially  $x = a_0 \pmod{m_0}$ */
        /** Merge the solution with remaining equations */
        for (int i = 1; i < equations.size(); i++) {
            vlong a2 = equations[i].first;
            vlong m2 = equations[i].second;
            vlong g = __gcd(m1, m2);
            if (a1 % g != a2 % g) return { -1, -1 }; ///
            Conflict in equations
            /** Merge the two equations*/
            vlong p, q;
            ext_gcd(m1 / g, m2 / g, &p, &q);
            vlong mod = m1 / g * m2;
            vlong x = ((__int128)a1 * (m2 / g) % mod * q % mod
                + (__int128)a2 * (m1 / g) % mod * p % mod) % mod;
            /** Merged equation*/
            a1 = x;
            if (a1 < 0) a1 += mod;

```

```

        m1 = mod;
    }
    return { a1, m1 };
}
};

7.3 FFT [85 lines] 4ca8f0
template<typename float_t>
struct mycomplex {
    float_t x, y;
    mycomplex<float_t>(float_t _x = 0, float_t _y = 0) :
        x(_x), y(_y) {}
    float_t real() const { return x; }
    float_t imag() const { return y; }
    void real(float_t _x) { x = _x; }
    void imag(float_t _y) { y = _y; }
    mycomplex<float_t>& operator+=(const
        mycomplex<float_t> &other) { x += other.x; y +=
        other.y; return *this; }
    mycomplex<float_t>& operator-=(const
        mycomplex<float_t> &other) { x -= other.x; y -=
        other.y; return *this; }
    mycomplex<float_t> operator+(const mycomplex<float_t>
        &other) const { return mycomplex<float_t>(*this) +=
        other; }
    mycomplex<float_t> operator-(const mycomplex<float_t>
        &other) const { return mycomplex<float_t>(*this) -=
        other; }
    mycomplex<float_t> operator*(const mycomplex<float_t>
        &other) const {
        return {x * other.x - y * other.y, x * other.y +
        other.x * y};
    }
    mycomplex<float_t> operator*(float_t mult) const {
        return {x * mult, y * mult};
    }
    friend mycomplex<float_t> conj(const
        mycomplex<float_t> &c) {
        return {c.x, -c.y};
    }
    friend ostream& operator<<(ostream &stream, const
        mycomplex<float_t> &c) {
        return stream << '(' << c.x << ", " << c.y << ')';
    }
};
using cd = mycomplex<double>;
void fft(vector<cd> &a, bool invert) {
    int n = a.size();
    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 len = 2; len <= n; len <<= 1) {
        double ang = 2 * PI / len * (invert ? -1 : 1);
        cd wlen(cos(ang), sin(ang));
        for (int i = 0; i < n; i += len) {
            cd w(1);
            for (int j = 0; j < len / 2; j++) {
                cd u = a[i+j], v = a[i+j+len/2] * w;
                a[i+j] = u + v;
                a[i+j+len/2] = u - v;

```

```

                w = w*wlen;
            }
        }
    }
    if (invert) {
        for (cd &x : a){
            double z = n;
            z=1/z;
            x = x*z;
        }
        // x /= n;
    }
}

void multiply (const vector<bool> &a, const
    vector<bool> &b, vector<bool> &res) {///change all
    the bool to your type needed
    vector<cd> fa (a.begin(), a.end()), fb (b.begin(),
        b.end());
    size_t n = 1;
    while (n < max (a.size(), b.size())) n <<= 1;
    n <<= 1;
    fa.resize (n), fb.resize (n);
    fft (fa, false), fft (fb, false);
    for (size_t i=0; i<n; ++i)
        fa[i] =fa[i] * fb[i];
    fft (fa, true);
    res.resize (n);
    for (size_t i=0; i<n; ++i)
        res[i] = round(fa[i].real());
    while(res.back()==0) res.pop_back();
}

void pow(const vector<bool> &a, vector<bool> &res, long
    long int k){
    vector<bool> po=a;
    res.resize(1);
    res[0] = 1;
    while(k){
        if(k&1){
            multiply(po, res, res);
        }
        multiply(po, po, po);
        k/=2;
    }
}
}

```

```

7.4 GaussElimination [39 lines] aa53e0

template<typename ld>
int gauss(vector<vector<ld>>& a, vector<ld>& ans) {
    const ld EPS = 1e-9;
    int n = a.size();///number of equations
    int m = a[0].size() - 1;///number of variables
    vector<int>where(m, -1);///indicates which row
    contains the solution
    int row, col;
    for (col = 0, row = 0; col < m && row < n; ++col) {
        int sel = row;///which row contains the maximum
        value/
        for (int i = row + 1; i < n; i++)
            if (abs(a[i][col]) > abs(a[sel][col]))
                sel = i;
        if (abs(a[sel][col]) < EPS) continue;///it's
        basically 0.
        a[sel].swap(a[row]);///taking the max row up

```

```

where[col] = row;
ld t = a[row][col];
for (int i = col; i <= m; i++) a[row][i] /= t;
for (int i = 0; i < n; i++) {
    if (i != row) {
        ld c = a[i][col];
        for (int j = col; j <= m; j++)
            a[i][j] -= a[row][j] * c;
    }
}
row++;
}
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++) {
    ld sum = 0;
    for (int j = 0; j < m; j++)
        sum += ans[j] * a[i][j];
    if (abs(sum - a[i][m]) > EPS) ///L.H.S!=R.H.S
        ans.clear(); ///No solution
}
return row;
}

```

#### 7.5 GaussMod2 [44 lines]

e8fae4

```

template<typename T>
struct Gauss {
    int bits = 60;
    vector<T>table;
    Gauss() {
        table = vector<T>(bits, 0);
    }
    ///call with constructor to define bit size.
    Gauss(int _bits) {
        bits = _bits;
        table = vector<T>(bits, 0);
    }
    int basis() ///return rank/size of basis
    {
        int ans = 0;
        for (int i = 0; i < bits; i++)
            if (table[i])
                ans++;
        return ans;
    }
    bool can(T x) ///can x be obtained from the basis
    {
        for (int i = bits - 1; i >= 0; i--) x = min(x, x ^
            table[i]);
        return x == 0;
    }
    void add(T x) {
        for (int i = bits - 1; i >= 0 && x; i--) {
            if (table[i] == 0) {
                table[i] = x;
                x = 0;
            }
            else x = min(x, x ^ table[i]);
        }
    }
    T getBest() {
        T x = 0;
        for (int i = bits - 1; i >= 0; i--)

```

```

        x = max(x, x ^ table[i]);
        return x;
    }
    void Merge(Gauss& other) {
        for (int i = bits - 1; i >= 0; i--)
            add(other.table[i]);
    }
};

```

#### 7.6 Karatsuba Idea [5 lines]

6944e1

Three subproblems:

```

a = xH yH
d = xL yL
e = (xH + xL)(yH + yL) - a - d
Then xy = a rn + e rn/2 + d

```

#### 7.7 Linear Diophantine [12 lines]

86858c

```

/*x'=x+(k*B/g),y'=y-(k*A/g);infinite soln
if A=B=0,C must equal 0 and any x,y is solution;
if A/B=0,(x,y)=(C/A,k)|(k,C/B)*/
bool LDE(int A,int B,int C,int*x,int*y){
    int g=gcd(A,B);
    if(C%g!=0)return false;
    int a=A/g,b=B/g,c=C/g;
    extended_gcd(a,b,x,y); ///ax+by=1
    if(g<0)a*=-1;b*=-1;c*=-1; ///Ensure gcd(a,b)=1
    *x*=c;*y*=c; ///ax+by=c
    return true; ///Solution Exists
}

```

#### 7.8 Matrix [100 lines]

a33f18

```

template<typename T>
struct Matrix {
    T MOD = 1e9 + 7; ///change if necessary
    T add(T a, T b) const {
        T res = a + b;
        if (res >= MOD) return res - MOD;
        return res;
    }
    T sub(T a, T b) const {
        T res = a - b;
        if (res < 0) return res + MOD;
        return res;
    }
    T mul(T a, T b) const {
        T res = a * b;
        if (res >= MOD) return res % MOD;
        return res;
    }
    int R, C;
    vector<vector<T>>mat;
    Matrix(int _R = 0, int _C = 0) {
        R = _R, C = _C;
        mat.resize(R);
        for (auto& v : mat) v.assign(C, 0);
    }
    void print() {
        for (int i = 0; i < R; i++)
            for (int j = 0; j < C; j++)
                cout << mat[i][j] << " \n"[j == C - 1];
    }
    void createIdentity() {
        for (int i = 0; i < R; i++)
            for (int j = 0; j < C; j++)
                mat[i][j] = (i == j);
    }
}

```

```

}
Matrix operator+(const Matrix& o) const {
    Matrix res(R, C);
    for (int i = 0; i < R; i++)
        for (int j = 0; j < C; j++)
            res[i][j] = add(mat[i][j] + o.mat[i][j]);
}
Matrix operator-(const Matrix& o) const {
    Matrix res(R, C);
    for (int i = 0; i < R; i++)
        for (int j = 0; j < C; j++)
            res[i][j] = sub(mat[i][j] + o.mat[i][j]);
}
Matrix operator*(const Matrix& o) const {
    Matrix res(R, o.C);
    for (int i = 0; i < R; i++)
        for (int j = 0; j < o.C; j++)
            for (int k = 0; k < C; k++)
                res.mat[i][j] = add(res.mat[i][j],
                    mul(mat[i][k], o.mat[k][j]));
    return res;
}
Matrix pow(long long x) {
    Matrix res(R, C);
    res.createIdentity();
    Matrix<T> o = *this;
    while (x) {
        if (x & 1) res = res * o;
        o = o * o;
        x >>= 1;
    }
    return res;
}
Matrix inverse() ///Only square matrix && non-zero determinant
{
    Matrix res(R, R + R);
    for (int i = 0; i < R; i++) {
        for (int j = 0; j < R; j++)
            res.mat[i][j] = mat[i][j];
        res.mat[i][R + i] = 1;
    }
    for (int i = 0; i < R; i++) {
        ///find row 'r' with highest value at [r][i]
        int tr = i;
        for (int j = i + 1; j < R; j++)
            if (abs(res.mat[j][i]) > abs(res.mat[tr][i]))
                tr = j;
        ///swap the row
        res.mat[tr].swap(res.mat[i]);
        ///make 1 at [i][i]
        T val = res.mat[i][i];
        for (int j = 0; j < R + R; j++) res.mat[i][j] /= val;
        ///eliminate [r][i] from every row except i.
        for (int j = 0; j < R; j++) {
            if (j == i) continue;
            for (int k = R + R - 1; k >= i; k--) {
                res.mat[j][k] -= res.mat[i][k] * res.mat[j][i]
            }
        }
    }
}

```

```
Matrix ans(R, R);
for (int i = 0; i < R; i++)
    for (int j = 0; j < R; j++)
        ans.mat[i][j] = res.mat[i][R + j];
return ans;
}
```

### 7.9 Miller-Rabin-Pollard-Rho [68 lines] 3e3e5f

```
ll powmod(ll a, ll p, ll m) {/// $(a^p \% m)$ 
    ll result = 1;
    a %= m;
    while (p) {
        if (p & 1)
            result = (vll)result * a % m;
        a = (vll)a * a % m;
        p >>= 1;
    }
    return result;
}

bool check_composite(ll n, ll a, ll d, int s) {
    ll x = powmod(a, d, n);
    if (x == 1 || x == n - 1)
        return false;
    for (int r = 1; r < s; r++) {
        x = (vll)x * x % n;
        if (x == n - 1)
            return false;
    }
    return true;
}

bool MillerRabin(ll n) {
    if (n < 2) return false;
    int r = 0;
    ll d = n - 1;
    while ((d & 1) == 0) {
        d >>= 1;
        r++;
    }
    for (int a : {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37}) {
        if (n == a) return true;
        if (check_composite(n, a, d, r))
            return false;
    }
    return true;
}

ll mult(ll a, ll b, ll mod) {
    return (vll)a * b % mod;
}

ll f(ll x, ll c, ll mod) {
    return (mult(x, x, mod) + c) % mod;
}

ll rho(ll n) {
    if (n % 2 == 0) return 2;
    ll x = myrand() % n + 1, y = x, c = myrand() % n + 1,
    g = 1;
    while (g == 1) {
        x = f(x, c, n);
        y = f(y, c, n);
        y = f(y, c, n);
        g = __gcd(abs(x - y), n);
    }
    return g;
}
```

```
set<ll> prime;
void prime_factorization(ll n) {
    if (n == 1) return;
    if (MillerRabin(n)) {
        prime.insert(n);
        return;
    }
    ll x = n;
    while (x == n) x = rho(n);
    prime_factorization(x);
    prime_factorization(n / x);
}

//call prime_factorization(n) for prime factors.
//call MillerRabin(n) to check if prime.
```

### 7.10 Mod Inverse [5 lines] 772679

```
int modInv(int a, int m) {
    int x, y; //if g==1 Inverse doesn't exist
    int g = gcdExt(a, m, x, y);
    return (x % m + m) % m;
}
```

### 7.11 NTT [96 lines] 6faca3

```
ll power(ll a, ll p, ll mod) {
    if (p == 0) return 1;
    ll ans = power(a, p/2, mod);
    ans = (ans * ans) % mod;
    if (p % 2) ans = (ans * a) % mod;
    return ans;
}

int primitive_root(int p) {
    vector<int> factor;
    int phi = p - 1, n = phi;
    for (int i = 2; i * i <= n; i++) {
        if (n % i) continue;
        factor.push_back(i);
        while (n % i == 0) n /= i;
    }
    if (n > 1) factor.push_back(n);
    for (int res = 2; res <= p; res++) {
        bool ok = true;
        for (int i = 0; i < factor.size() && ok; i++)
            ok &= power(res, phi / factor[i], p) != 1;
        if (ok) return res;
    }
    return -1;
}

int nttdata(int mod, int &root, int &inv, int &pw) {
    int c = 0, n = mod - 1;
    while (n % 2 == 0) c++, n /= 2;
    pw = (mod - 1) / n;
    int g = primitive_root(mod);
    root = power(g, n, mod);
    inv = power(root, mod - 2, mod);
    return c;
}

const int M = 786433;
struct NTT {
    int N;
    vector<int> perm;
    int mod, root, inv, pw;
    NTT() {}
    NTT(int mod, int root, int inv, int pw) : mod(mod),
        root(root), inv(inv), pw(pw) {}
    void precalculate() {
```

```
perm.resize(N);
perm[0] = 0;
for (int k = 1; k < N; k <= 1) {
    for (int i = 0; i < k; i++) {
        perm[i] <= 1;
        perm[i + k] = 1 + perm[i];
    }
}

void fft(vector<ll> &v, bool invert = false) {
    if (v.size() != perm.size()) {
        N = v.size();
        assert(N && (N & (N - 1)) == 0);
        precalculate();
    }
    for (int i = 0; i < N; i++)
        if (i < perm[i])
            swap(v[i], v[perm[i]]);
    for (int len = 2; len <= N; len <= 1) {
        ll factor = invert ? inv : root;
        for (int i = len; i < pw; i <= 1)
            factor = (factor * factor) % mod;
        for (int i = 0; i < N; i += len) {
            ll w = 1;
            for (int j = 0; j < len / 2; j++) {
                ll x = v[i + j], y = (w * v[i + j + len / 2]) % mod;
                v[i + j] = (x + y) % mod;
                v[i + j + len / 2] = (x - y + mod) % mod;
                w = (w * factor) % mod;
            }
        }
    }
    if (invert) {
        ll n1 = power(N, mod - 2, mod);
        for (ll &x: v) x = (x * n1) % mod;
    }
}

vector<ll> multiply(vector<ll> a, vector<ll> &b) {
    while (a.size() && a.back() == 0) a.pop_back();
    while (b.size() && b.back() == 0) b.pop_back();
    int n = 1;
    while (n < a.size() + b.size()) n <= 1;
    a.resize(n);
    b.resize(n);
    fft(a);
    fft(b);
    for (int i = 0; i < n; i++) a[i] = (a[i] * b[i]) % M;
    fft(a, true);
    while (a.size() && a.back() == 0) a.pop_back();
    return a;
}

// int mod=786433, root, inv, pw;
// nttdata(mod, root, inv, pw);
// NTT nn = NTT(mod, root, inv, pw);
};
```

### 7.12 No of Digits in n! in base B [7 lines] 86bfaf

```
ll NoOfDigitInNFactInBaseB(ll N, ll B) {
    ll i;
    double ans = 0;
    for (i = 1; i <= N; i++) ans += log(i);
    ans = ans / log(B), ans = ans + 1;
    return (ll)ans;
}
```



**7.13 SOD Upto N** [16 lines] d8aa2c

```

11 SOD_UpTo_N(11 N){
    11 i,j,ans=0;///upto N in Sqrt(N)
    for(i=1;i*i<=N;i++){
        j=N/i;
        ans+=((j*(j+1))/2)-(((i-1)*i)/2);
        ans+=((j-i)*i);
    }
    return ans;
}
11 SODUptoN(11 N){
    11 res=0,u=sqrt(N);
    for(11 i=1;i<=u;i++){
        res+=(N/i)-i;
        res*=2,res+=u;
        return res;
    }
}

```

**7.14 Sieve Phi Mobius** [26 lines] 353c39

```

const int N = 1e7;
vector<int>pr;
int mu[N + 1], phi[N + 1], lp[N + 1];
void sieve() {
    phi[1] = 1, mu[1] = 1;
    for (int i = 2; i <= N; i++) {
        if (lp[i] == 0) {
            lp[i] = i;
            phi[i] = i - 1;
            pr.push_back(i);
        }
        for (int j = 0; j < pr.size() && i * pr[j] <= N; j++) {
            lp[i * pr[j]] = pr[j];
            if (i % pr[j] == 0) {
                phi[i * pr[j]] = phi[i] * pr[j];
                break;
            }
            else
                phi[i * pr[j]] = phi[i] * phi[pr[j]];
        }
        for (int i = 2; i <= N; i++) {
            if (lp[i / lp[i]] == lp[i]) mu[i] = 0;
            else mu[i] = -1 * mu[i / lp[i]];
        }
    }
}

```

**8 Misc****8.1 Bit hacks** [12 lines] dd22ef

# x & -x is the least bit in x.  
 # iterate over all the subsets of the mask  
 for (int s=m; ; s=(s-1)&m) {  
 ... you can use s ...  
 if (s==0) break;  
 }  
 # c = x&-x, r = x+c; (((r^x) >> 2)/c) | r is the  
 next number after x with the same number of bits set.  
 # \_\_builtin\_popcount(x) //number of ones in binary  
 \_\_builtin\_popcountll(x) // for long long  
 # \_\_builtin\_clz(x) // number of leading zeros  
 \_\_builtin\_ctz(x) // number of trailing zeros, they  
 also have long long version

**8.2 Bitset C++** [13 lines] a6a7a4

```

bitset<17>BS;
BS[1] = BS[7] = 1;
cout<<BS._Find_first()<<endl; // prints 1
bs._Find_next(idx). This function returns first set bit
after index idx.for example:

bitset<17>BS;
BS[1] = BS[7] = 1;
cout<<BS._Find_next(1)<<','<<BS._Find_next(3)<<endl; //
prints 7,7
So this code will print all of the set bits of BS:

for(int i=BS._Find_first();i< BS.size();i =
BS._Find_next(i))
    cout<<i<<endl;
//Note that there isn't any set bit after idx,
BS._Find_next(idx) will return BS.size(); same as
calling BS._Find_first() when bitset is clear;

```

**8.3 Template** [33 lines] 7aea62

```

// #pragma GCC optimize("O3,unroll-loops")
// #pragma GCC target("avx2,bmi,bmi2,lzcnt,popcnt")
#include <bits/stdc++.h>
#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace std;
using namespace __gnu_pbds;

template <typename A, typename B> ostream&
operator<<(ostream& os, const pair<A, B>& p) {
    return os << '(' << p.first << ", " << p.second <<
    ')'; }

template <typename T_container, typename T = typename
enable_if<!is_same<T_container, string>::value,
typename T_container::value_type>::type> ostream&
operator<<(ostream& os, const T_container& v) { os
<< '{'; string sep; for (const T& x : v) os << sep
<< x, sep = ", "; return os << '}'; }

void dbg_out() { cerr << endl; }
template <typename Head, typename... Tail> void
dbg_out(Head H, Tail... T) { cerr << " " << H;
    dbg_out(T...); }

#ifdef SMIE
#define debug(args...) cerr << "(" << #args << "):",
    dbg_out(args)
#else
#define debug(args...)
#endif

```

```

template <typename T> inline T gcd(T a, T b) { T c;while
(b) { c = b;b = a % b;a = c; }return a; } // better
than __gcd
11 powmod(11 a, 11 b, 11 MOD) { 11 res = 1;a %=
MOD;assert(b >= 0);for (; b; b >>= 1) { if (b &
1)res = res * a % MOD;a = a * a % MOD; }return res;
}

template <typename T>using orderedSet = tree<T,
null_type, less_equal<T>, rb_tree_tag,
tree_order_statistics_node_update>;
//order_of_key(k) - number of element strictly less than
k
//find_by_order(k) - k'th element in set.(0
indexed)(iterator)

```

```

mt19937
rng(chrono::steady_clock::now().time_since_epoch()
.count());
//uniform_int_distribution<int>(0, i)(rng)
int main(int argc, char* argv[]) {
    ios_base::sync_with_stdio(false);//DON'T CC++
    cin.tie(NULL);//DON'T use for interactive
    int seed = atoi(argv[1]);
}

```

**8.4 build** [2 lines] 801989

```

#!/bin/bash
>&2 echo -e "Making [$2]\t: $1.cpp" && g++ -std=gnu++17
-Wshadow -Wall -Wextra -Wno-unused-result -O2 -g
-fsanitize=undefined -fsanitize=address $2 "$1.cpp"
-o "$1"

```

**8.5 check** [15 lines] 478053

```

#!/bin/bash
build $1
TESTNO=0
for INP in $1.in*; do
    printf "\n=====\\n"
    printf "INPUT %d" $TESTNO
    printf "\n=====\\n"
    cat $INP
    printf "\n=====\\n"
    printf "OUTPUT %d" $TESTNO
    printf "\n=====\\n"
    ./$1 < $INP
    mv $INP $1.in$TESTNO 2>/dev/null
    TESTNO=$((TESTNO+1))
done

```

**8.6 debug** [3 lines] 859f78

```

#!/bin/bash
build "$1" -DSMIE && >&2 echo -e "Running\t\t:
$1\n-----" && "./$1"

```

**8.7 stress** [15 lines] 62e61a

```

#!/bin/bash
build $1 $2 && build $1_gen $2 && build $1_brute $2 &&
for((i = 1; ; ++i)); do
    echo -e "\nTest Case \"$i
./$1_gen $i > inp
./$1 < inp > out1
./$1_brute < inp > out2
diff -w out1 out2 || break
done
echo -e "=====\\nINPUT\\n-----"
cat inp
echo -e "\\nOUTPUT\\n-----"
cat out1
echo -e "\\nEXPECTED\\n-----"
cat out2

```

**8.8 vimrc** [14 lines] fdf4e

```
filetype plugin indent on
set rnu wfw hls is ar aw wrap mouse=a
```

```
let mapleader=' '
im jk <esc>
tno jk <c-w>N
no <leader>d "_d
im {<cr> {<cr>}<esc>0
nn ff :let @+ = expand("%:~")<cr>
nn cd :cd %:~<cr>
```

```
au BufNewFile *.cpp -r ./template.cpp | 14
```

```
ca hash w !cpp -dD -P -fpreprocessed \\\ tr -d
'[:space:]' \\\ md5sum \\\ cut -c-6
```

**9 String****9.1 Aho-Corasick** [124 lines] 2d8d6c

```
const int NODE=3000500; //Maximum Nodes
const int LGN=30; //Maximum Number of Tries
const int MXCHR=53; //Maximum Characters
const int MXP=5005; //
struct node {
    int val;
    int child[MXCHR];
    vector<int>graph;
    void clear(){
        CLR(child,0);
        val=0;
        graph.clear();
    }
}Trie[NODE+10];
int maxNodeId,fail[NODE+10],par[NODE+10];
int nodeSt[NODE+10],nodeEd[NODE+10];
vlong csum[NODE+10],pLoc[MXP];
void resetTrie(){
    maxNodeId=0;
}
int getNode(){
    int curNodeId=++maxNodeId;
    Trie[curNodeId].clear();
    return curNodeId;
}
inline void upd(vlong pos){
    csum[pos]++;
}
inline vlong qry(vlong pos){
    vlong res=csum[pos];
    return res;
}
struct AhoCorasick {
    int root,size,euler;
    void clear(){
        root=getNode();
        size=euler=0;
    }
    inline int getName(char ch){
        if(ch=='-')return 52;
        else if(ch>='A' && ch<='Z')return 26+(ch-'A');
        else return (ch-'a');
    }
    void addToTrie(string &s,int id){
        //Add string s to the Trie in general way
```

```
int len=SZ(s),cur=root;
FOR(i,0,len-1){
    int c=getname(s[i]);
    if(Trie[cur].child[c]==0){
        int curNodeId=getNode();
        Trie[curNodeId].val=c;
        Trie[cur].child[c]=curNodeId;
    }
    cur=Trie[cur].child[c];
}
pLoc[id]=cur;
size++;
}
void calcFailFunction(){
    queue<int>Q;
    Q.push(root);
    while(!Q.empty()){
        int s=Q.front();
        Q.pop();
        //Add all the children to the queue:
        FOR(i,0,MXCHR-1){
            int t=Trie[s].child[i];
            if(t!=0){
                Q.push(t);
                par[t]=s;
            }
        }
        if(s==root){/*Handle special case when s is root*/
            fail[s]=par[s]=root;
            continue;
        }
        //Find fall back of s:
        int p=par[s],f=fail[p];
        int val=Trie[s].val;
        /*Fall back till you found a node who has got val as a child*/
        while(f!=root && Trie[f].child[val]==0){
            f=fail[f];
        }
        fail[s]=(Trie[f].child[val]==0)? root :
        Trie[f].child[val];
        //Self fall back not allowed
        if(s==fail[s]){
            fail[s]=root;
        }
        Trie[fail[s]].graph.push_back(s);
    }
}
void dfs(int pos){
    ++euler;
    nodeSt[pos]=euler;
    for(auto x: Trie[pos].graph){
        dfs(x);
    }
    nodeEd[pos]=euler;
}
//Returns the next state
int goTo(int state,int c){
    if(Trie[state].child[c]!=0){/*No need to fall back*/
        return Trie[state].child[c];
    }
    //Fall back now:
```

```
int f=fail[state];
while(f!=root && Trie[f].child[c]==0){
    f=fail[f];
}
int res=(Trie[f].child[c]==0)?
root:Trie[f].child[c];
return res;
}
/*Iterate through the whole text and find all the matchings*/
void findmatching(string &s){
    int cur=root,idx=0;
    int len=SZ(s);
    while(idx<len){
        int c=getname(s[idx]);
        cur=goTo(cur,c);
        upd(nodeSt[cur]);
        idx++;
    }
}
}acorasick;
```

**9.2 Double Hashing** [50 lines]

1a70c1

```
struct SimpleHash {
    int len;
    long long base, mod;
    vector<int> P, H, R;
    SimpleHash() {}
    SimpleHash(string str, long long b, long long m) {
        base = b, mod = m, len = str.size();
        P.resize(len + 4, 1), H.resize(len + 3, 0),
        R.resize(len + 3, 0);
        for (int i = 1; i <= len + 3; i++)
            P[i] = (P[i - 1] * base) % mod;
        for (int i = 1; i <= len; i++)
            H[i] = (H[i - 1] * base + str[i - 1] + 1007)
        % mod;
        for (int i = len; i >= 1; i--)
            R[i] = (R[i + 1] * base + str[i - 1] + 1007)
        % mod;
    }
    inline int range_hash(int l, int r) {
        int hashval = H[r + 1] - ((long long)P[r - 1 +
        1] * H[1] % mod);
        return (hashval < 0 ? hashval + mod : hashval);
    }
    inline int reverse_hash(int l, int r) {
        int hashval = R[l + 1] - ((long long)P[r - 1 +
        1] * R[r + 2] % mod);
        return (hashval < 0 ? hashval + mod : hashval);
    }
};
struct DoubleHash {
    SimpleHash sh1, sh2;
    DoubleHash() {}
    DoubleHash(string str) {
        sh1 = SimpleHash(str, 1949313259, 2091573227);
        sh2 = SimpleHash(str, 1997293877, 2117566807);
    }
    long long concat(DoubleHash& B, int l1, int r1,
    int l2, int r2) {
        int len1 = r1 - l1 + 1, len2 = r2 - l2 + 1;
        long long x1 = sh1.range_hash(l1, r1),
        x2 = B.sh1.range_hash(l2, r2);
```

```

x1 = (x1 * B.sh1.P[len2]) % 2091573227;
long long newx1 = (x1 + x2) % 2091573227;
x1 = sh2.range_hash(l1, r1);
x2 = B.sh2.range_hash(l2, r2);
x1 = (x1 * B.sh2.P[len2]) % 2117566807;
long long newx2 = (x1 + x2) % 2117566807;
return (newx1 << 32) ^ newx2;
}
inline long long range_hash(int l, int r) {
    return ((long long)sh1.range_hash(l, r) << 32) ^
    sh2.range_hash(l, r);
}
inline long long reverse_hash(int l, int r) {
    return ((long long)sh1.reverse_hash(l, r) << 32)
    ^ sh2.reverse_hash(l, r);
}
};

```

### 9.3 KMP [23 lines] 99c570

```

char P[maxn], T[maxn];
int b[maxn], n, m;
void kmpPreprocess(){
    int i=0, j=-1;
    b[0]=-1;
    while(i<m){
        while(j>=0 and P[i]!=P[j])
            j=b[j];
        j=b[j];
        i++;j++;
        b[i]=j;
    }
}
void kmpSearch(){
    int i=0, j=0;
    while(i<n){
        while(j>=0 and T[i]!=P[j])
            j=b[j];
        j=b[j];
        i++;j++;
        if(j==m){
            //pattern found at index i-j
        }
    }
}

```

### 9.4 Manacher [16 lines] 2b3cab

```

vector<int> manacher_odd(string s) {
    int n = s.size();
    s = "$" + s + "~";
    vector<int> p(n + 2);
    int l = 1, r = 1;
    for(int i = 1; i <= n; i++) {
        p[i] = max(0, min(r - i, p[l + (r - i)]));
        while(s[i - p[i]] == s[i + p[i]]) {
            p[i]++;
        }
        if(i + p[i] > r) {
            l = i - p[i], r = i + p[i];
        }
    }
    return vector<int>(begin(p) + 1, end(p) - 1);
}

```

### 9.5 Palindromic Tree [30 lines] 9ebc05

```

struct PalindromicTree{
    int n,idx,t;
    vector<vector<int>> tree;

```

```

vector<int> len,link;
string s; // 1-indexed
PalindromicTree(string str){
    s="$"+str;
    n=s.size();
    len.assign(n+5,0);
    link.assign(n+5,0);
    tree.assign(n+5,vector<int>(26,0));
}
void extend(int p){
    while(s[p-len[t]-1]!=s[p]) t=link[t];
    int x=link[t],c=s[p]-'a';
    while(s[p-len[x]-1]!=s[p]) x=link[x];
    if(!tree[t][c]){
        tree[t][c]=++idx;
        len[idx]=len[t]+2;
        link[idx]=len[idx]==1?2:tree[x][c];
    }
    t=tree[t][c];
}
void build(){
    len[1]=-1,link[1]=1;
    len[2]=0,link[2]=1;
    idx=t=2;
    for(int i=1;i<n;i++) extend(i);
}
};

```

### 9.6 Suffix Array [78 lines] f2f7a0

```

struct SuffixArray {
    vector<int> p, c, rank, lcp;
    vector<vector<int>> st;
    SuffixArray(string const& s) {
        build_suffix(s + char(1));
        build_rank(p.size());
        build_lcp(s + char(1));
        build_sparse_table(lcp.size());
    }
    void build_suffix(string const& s) {
        int n = s.size();
        const int MX_ASCII = 256;
        vector<int> cnt(max(MX_ASCII, n), 0);
        p.resize(n); c.resize(n);
        for (int i = 0; i < n; i++) cnt[s[i]]++;
        for (int i=1; i<MX_ASCII; i++) cnt[i]+=cnt[i-1];
        for (int i = 0; i < n; i++) p[--cnt[s[i]]] = i;
        c[p[0]] = 0;
        int classes = 1;
        for (int i = 1; i < n; i++) {
            if (s[p[i]] != s[p[i-1]]) classes++;
            c[p[i]] = classes - 1;
        }
        vector<int> pn(n), cn(n);
        for (int h = 0; (1 << h) < n; ++h) {
            for (int i = 0; i < n; i++) {
                pn[i] = p[i] - (1 << h);
                if (pn[i] < 0) pn[i] += n;
            }
            fill(cnt.begin(), cnt.begin() + classes, 0);
            for (int i = 0; i < n; i++) cnt[c[pn[i]]]++;
            for (int i=1; i<classes; i++) cnt[i]+=cnt[i-1];
            for (int i=n-1;i>=0;i--) p[--cnt[c[pn[i]]]]=pn[i];
            cn[p[0]] = 0; classes = 1;
            for (int i = 1; i < n; i++) {

```

```

                pair<int, int> cur = {c[p[i]], c[(p[i] + (1 <<
h)) % n]};
                pair<int, int> prev = {c[p[i-1]], c[(p[i-1] + (1
<< h)) % n]};
                if (cur != prev) ++classes;
                cn[p[i]] = classes - 1;
            }
            c.swap(cn);
        }
    }
    void build_rank(int n) {
        rank.resize(n, 0);
        for (int i = 0; i < n; i++) rank[p[i]] = i;
    }
    void build_lcp(string const& s) {
        int n = s.size(), k = 0;
        lcp.resize(n - 1, 0);
        for (int i = 0; i < n; i++) {
            if (rank[i] == n - 1) {
                k = 0;
                continue;
            }
            int j = p[rank[i] + 1];
            while (i + k < n && j + k < n && s[i+k] == s[j+k])
                k++;
            lcp[rank[i]] = k;
            if (k) k--;
        }
    }
    void build_sparse_table(int n) {
        int lim = __lg(n);
        st.resize(lim + 1, vector<int>(n)); st[0] = lcp;
        for (int k = 1; k <= lim; k++)
            for (int i = 0; i + (1 << k) <= n; i++)
                st[k][i] = min(st[k - 1][i], st[k - 1][i + (1 <<
(k - 1))]);
    }
    int get_lcp(int i) { return lcp[i]; }
    int get_lcp(int i, int j) {
        if (j < i) swap(i, j);
        j--; /*for lcp from i to j we don't need last lcp*/
        int K = __lg(j - i + 1);
        return min(st[K][i], st[K][j - (1 << K) + 1]);
    }
};

```

### 9.7 Suffix Automata [118 lines] 179441

```

const int MXCHR = 26;
/*
take an object of suffixAutomata
call extend(c) for each character c in string
call Process() to initiate the important values
*/
struct suffixAutomata {
    /*
len -> largest string length of the corresponding
endpos-equivalent class
link -> longest suffix that is another endpos-equivalent
class
firstpos -> end position of the first occurrence of the
largest string of that node
*/
    struct state {

```

```

int link, len;
int next[MXCHR];
state() {}
state(int l) {
    len = l;
    link = -1;
    for (int i = 0; i < MXCHR; i++) next[i] = -1;
};
vector<state> node;
int sz, last;
vector<int> cnt, distinct, firstPos, occur, SA;
vector<vector<int>> adj; // suffix links tree
                        // cnt and SA for counting
    sort the nodes.
int L;

suffixAutomata() {
    node.push_back(state(0));
    firstPos.push_back(-1);
    occur.push_back(0);
    last = 0;
    sz = 0;
    L = 0;
}
int getID(char c) {
    return c - 'a'; // change according to problem
}
void extend(char c) {
    int idx = ++sz, p = last, id = getID(c);
    L++;
    node.push_back(state(node[last].len + 1));
    firstPos.push_back(node[idx].len - 1);
    occur.push_back(1);

    while (p != -1 && node[p].next[id] == -1) {
        node[p].next[id] = idx;
        p = node[p].link;
    }
    if (p == -1)
        node[idx].link = 0;
    else {
        int q = node[p].next[id];
        if (node[p].len + 1 == node[q].len)
            node[idx].link = q;
        else {
            int clone = ++sz;
            state x = node[q];
            x.len = node[p].len + 1;
            node.push_back(x);
            firstPos.push_back(firstPos[q]);
            occur.push_back(0);
            while (p != -1 && node[p].next[id] == q) {
                node[p].next[id] = clone;
                p = node[p].link;
            }
            node[idx].link = node[q].link = clone;
        }
    }
    last = idx;
}
void Process() {
    cnt.resize(sz + 1);
    distinct.resize(sz + 1);

```

```

SA.resize(sz + 1);
adj.resize(sz + 1);
for (int i = 0; i <= sz; i++) cnt[node[i].len]++;
for (int i = 1; i <= L; i++) cnt[i] += cnt[i - 1];
for (int i = 0; i <= sz; i++) SA[--cnt[node[i].len]]
= i;
for (int i = sz; i > 0; i--) {
    int idx = SA[i];
    occur[node[idx].link] += occur[idx];
    adj[node[idx].link].push_back(idx);
    distinct[idx] = 1;
    for (int j = 0; j < MXCHR; j++) {
        if (node[idx].next[j] != -1)
            distinct[idx] += distinct[node[idx].next[j]];
    }
} // counts distinct substrings and occurrence of
each state
for (int i = 0; i < MXCHR; i++)
    if (node[0].next[i] != -1) distinct[0] +=
distinct[node[0].next[i]];
}
pair<int, int> lcs(string &str) {
    int mxlen = 0, bestpos = -1, pos = 0, len = 0;
    int u = 0; // LCS of two string. returns start
position and length
    for (char c : str) {
        int v = getID(c);
        while (u && node[u].next[v] == -1) {
            u = node[u].link;
            len = node[u].len;
        }
        if (node[u].next[v] != -1) {
            len++;
            u = node[u].next[v];
        }
        if (len > mxlen) {
            mxlen = len;
            bestpos = pos;
        }
        pos++;
    }
    return {bestpos - mxlen + 1, mxlen};
}
state &operator[](int index) { return node[index]; }
};

```

### 9.8 Trie [28 lines]

408ef5

```

const int maxn=100005;
struct Trie{
    int next[27][maxn];
    int endmark[maxn],sz;
    bool created[maxn];
    void insertTrie(string& s){
        int v=0;
        for(int i=0;i<(int)s.size();i++){
            int c=s[i]-'a';
            if(!created[next[c][v]]){
                next[c][v]=++sz;
                created[sz]=true;
            }
            v=next[c][v];
        }
        endmark[v]++;
    }
};

```

```

bool searchTrie(string& s){
    int v=0;
    for(int i=0;i<(int)s.size();i++){
        int c=s[i]-'a';
        if(!created[next[c][v]])
            return false;
        v=next[c][v];
    }
    return(endmark[v]>0);
}
};

```

### 9.9 Z-Algorithm [19 lines]

e04285

```

void compute_z_function(const char*S,int N){
    int L=0,R=0;
    for(int i=1;i<N;++i){
        if(i>R){
            L=R=i;
            while(R<N && S[R-L]==S[R])++R;
            Z[i]=R-L,--R;
        }
        else{
            int k=i-L;
            if(Z[k]<R-i+1)Z[i]=Z[k];
            else{
                L=i;
                while(R<N && S[R-k]==S[R])++R;
                Z[i]=R-L,--R;
            }
        }
    }
}
}

```



Theoretical Computer Science Cheat Sheet	
Definitions	Series
$f(n) = O(g(n))$	iff $\exists$ positive $c, n_0$ such that $0 \leq f(n) \leq cg(n) \forall n \geq n_0$ .
$f(n) = \Omega(g(n))$	iff $\exists$ positive $c, n_0$ such that $f(n) \geq cg(n) \geq 0 \forall n \geq n_0$ .
$f(n) = \Theta(g(n))$	iff $f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$ .
$f(n) = o(g(n))$	iff $\lim_{n \rightarrow \infty} f(n)/g(n) = 0$ .
$\lim_{n \rightarrow \infty} a_n = a$	iff $\forall \epsilon > 0, \exists n_0$ such that $ a_n - a  < \epsilon, \forall n \geq n_0$ .
$\sup S$	least $b \in \mathbb{R}$ such that $b \geq s, \forall s \in S$ .
$\inf S$	greatest $b \in \mathbb{R}$ such that $b \leq s, \forall s \in S$ .
$\liminf_{n \rightarrow \infty} a_n$	$\lim_{n \rightarrow \infty} \inf \{a_i \mid i \geq n, i \in \mathbb{N}\}$ .
$\limsup_{n \rightarrow \infty} a_n$	$\lim_{n \rightarrow \infty} \sup \{a_i \mid i \geq n, i \in \mathbb{N}\}$ .
$\binom{n}{k}$	Combinations: Size $k$ subsets of a size $n$ set.
$\begin{bmatrix} n \\ k \end{bmatrix}$	Stirling numbers (1st kind): Arrangements of an $n$ element set into $k$ cycles.
$\{n\}_k$	Stirling numbers (2nd kind): Partitions of an $n$ element set into $k$ non-empty sets.
$\langle k \rangle$	1st order Eulerian numbers: Permutations $\pi_1 \pi_2 \dots \pi_n$ on $\{1, 2, \dots, n\}$ with $k$ ascents.
$\llbracket k \rrbracket$	2nd order Eulerian numbers.
$C_n$	Catalan Numbers: Binary trees with $n + 1$ vertices.

14. $\begin{bmatrix} n \\ 1 \end{bmatrix} = (n-1)!$ ,	15. $\begin{bmatrix} n \\ 2 \end{bmatrix} = (n-1)!H_{n-1}$ ,	16. $\begin{bmatrix} n \\ n \end{bmatrix} = 1$ ,	17. $\begin{bmatrix} n \\ k \end{bmatrix} \geq \left\{ \begin{matrix} n \\ k \end{matrix} \right\}$ ,
18. $\begin{bmatrix} n \\ k \end{bmatrix} = (n-1) \begin{bmatrix} n-1 \\ k \end{bmatrix} + \begin{bmatrix} n-1 \\ k-1 \end{bmatrix}$ ,	19. $\left\{ \begin{matrix} n \\ n-1 \end{matrix} \right\} = \begin{bmatrix} n \\ n-1 \end{bmatrix} = \binom{n}{2}$ ,	20. $\sum_{k=0}^n \begin{bmatrix} n \\ k \end{bmatrix} = n!$ ,	21. $C_n = \frac{1}{n+1} \binom{2n}{n}$ ,
22. $\left\langle \begin{matrix} n \\ 0 \end{matrix} \right\rangle = \left\langle \begin{matrix} n \\ n-1 \end{matrix} \right\rangle = 1$ ,	23. $\left\langle \begin{matrix} n \\ k \end{matrix} \right\rangle = \left\langle \begin{matrix} n \\ n-1-k \end{matrix} \right\rangle$ ,	24. $\left\langle \begin{matrix} n \\ k \end{matrix} \right\rangle = (k+1) \left\langle \begin{matrix} n-1 \\ k \end{matrix} \right\rangle + (n-k) \left\langle \begin{matrix} n-1 \\ k-1 \end{matrix} \right\rangle$ ,	
25. $\left\langle \begin{matrix} 0 \\ k \end{matrix} \right\rangle = \begin{cases} 1 & \text{if } k=0, \\ 0 & \text{otherwise} \end{cases}$ ,	26. $\left\langle \begin{matrix} n \\ 1 \end{matrix} \right\rangle = 2^n - n - 1$ ,	27. $\left\langle \begin{matrix} n \\ 2 \end{matrix} \right\rangle = 3^n - (n+1)2^n + \binom{n+1}{2}$ ,	
28. $x^n = \sum_{k=0}^n \left\langle \begin{matrix} n \\ k \end{matrix} \right\rangle (x+k)$ ,	29. $\left\langle \begin{matrix} n \\ m \end{matrix} \right\rangle = \sum_{k=0}^m \binom{n+1}{k} (m+1-k)^n (-1)^k$ ,	30. $m! \left\{ \begin{matrix} n \\ m \end{matrix} \right\} = \sum_{k=0}^n \left\langle \begin{matrix} n \\ k \end{matrix} \right\rangle \binom{k}{n-m}$ ,	
31. $\left\langle \begin{matrix} n \\ m \end{matrix} \right\rangle = \sum_{k=0}^n \left\{ \begin{matrix} n \\ k \end{matrix} \right\} \binom{n-k}{m} (-1)^{n-k-m} k!$ ,	32. $\left\langle \begin{matrix} n \\ 0 \end{matrix} \right\rangle = 1$ ,	33. $\left\langle \begin{matrix} n \\ n \end{matrix} \right\rangle = 0$ for $n \neq 0$ ,	
34. $\left\langle \begin{matrix} n \\ k \end{matrix} \right\rangle = (k+1) \left\langle \begin{matrix} n-1 \\ k \end{matrix} \right\rangle + (2n-1-k) \left\langle \begin{matrix} n-1 \\ k-1 \end{matrix} \right\rangle$ ,		35. $\sum_{k=0}^n \left\langle \begin{matrix} n \\ k \end{matrix} \right\rangle = \frac{(2n)^{\underline{n}}}{2^n}$ ,	
36. $\left\{ \begin{matrix} x \\ x-n \end{matrix} \right\} = \sum_{k=0}^n \left\langle \begin{matrix} n \\ k \end{matrix} \right\rangle \binom{x+n-1-k}{2n}$ ,		37. $\left\{ \begin{matrix} n+1 \\ m+1 \end{matrix} \right\} = \sum_k \binom{n}{k} \left\{ \begin{matrix} k \\ m \end{matrix} \right\} = \sum_{k=0}^n \left\{ \begin{matrix} k \\ m \end{matrix} \right\} (m+1)^{n-k}$ ,	

1. $\binom{n}{k} = \frac{n!}{(n-k)!k!}$ ,	2. $\sum_{k=0}^n \binom{n}{k} = 2^n$ ,	3. $\binom{n}{k} = \binom{n}{n-k}$ ,
4. $\binom{n}{k} = \frac{n}{k} \binom{n-1}{k-1}$ ,	5. $\binom{n}{k} = \binom{n-1}{k} + \binom{n-1}{k-1}$ ,	
6. $\binom{n}{m} \binom{m}{k} = \binom{n}{k} \binom{n-k}{m-k}$ ,	7. $\sum_{k=0}^n \binom{r+k}{k} = \binom{r+n+1}{n}$ ,	
8. $\sum_{k=0}^n \binom{k}{m} = \binom{n+1}{m+1}$ ,	9. $\sum_{k=0}^n \binom{r}{k} \binom{s}{n-k} = \binom{r+s}{n}$ ,	
10. $\binom{n}{k} = (-1)^k \binom{k-n-1}{k}$ ,	11. $\left\{ \begin{matrix} n \\ 1 \end{matrix} \right\} = \left\{ \begin{matrix} n \\ n \end{matrix} \right\} = 1$ ,	
12. $\left\{ \begin{matrix} n \\ 2 \end{matrix} \right\} = 2^{n-1} - 1$ ,	13. $\left\{ \begin{matrix} n \\ k \end{matrix} \right\} = k \left\{ \begin{matrix} n-1 \\ k \end{matrix} \right\} + \left\{ \begin{matrix} n-1 \\ k-1 \end{matrix} \right\}$ ,	

Harmonic series:	
$H_n = \sum_{i=1}^n \frac{1}{i}$ ,	$\sum_{i=1}^n iH_i = \frac{n(n+1)}{2} H_n - \frac{n(n-1)}{4}$ .
$\sum_{i=1}^n H_i = (n+1)H_n - n$ ,	$\sum_{i=1}^n \binom{i}{m} H_i = \binom{n+1}{m+1} \left( H_{n+1} - \frac{1}{m+1} \right)$ .
Geometric series:	
$\sum_{i=0}^n c^i = \frac{c^{n+1} - 1}{c - 1}, \quad c \neq 1$ ,	$\sum_{i=0}^{\infty} c^i = \frac{1}{1-c}, \quad  c  < 1$ ,
$\sum_{i=0}^n ic^i = \frac{nc^{n+2} - (n+1)c^{n+1} + c}{(c-1)^2} + c$ ,	$\sum_{i=0}^{\infty} ic^i = \frac{c}{(1-c)^2}, \quad  c  < 1$ .

coprime  $(k+1)$ -tuple together with  $n$ . It is a generalization of Euler's totient,  $\phi(n) = J_1(n)$ .

$$J_k(n) = n^k \prod_{p|n} \left(1 - \frac{1}{p^k}\right)$$

$$\sum_{d|n} J_k(d) = n^k$$

$$\sum_{d|n} \varphi(d) = n$$

$$\varphi(n) = \sum_{d|n} \mu(d) \cdot \frac{n}{d} = n \sum_{d|n} \frac{\mu(d)}{d}$$

- $a | b \implies \varphi(a) | \varphi(b)$
- $n | \varphi(a^n - 1)$  for  $a, n > 1$
- $\varphi(mn) = \varphi(m)\varphi(n) \cdot \frac{d}{\varphi(d)}$  where  $d = \gcd(m, n)$

Note the special cases

- $\varphi(2m) = \begin{cases} 2\varphi(m) & \text{if } m \text{ is even} \\ \varphi(m) & \text{if } m \text{ is odd} \end{cases}$
- $\varphi(n^m) = n^{m-1}\varphi(n)$
- $\varphi(\text{lcm}(m, n)) \cdot \varphi(\gcd(m, n)) = \varphi(m) \cdot \varphi(n)$   
Compare this to the formula
- $\text{lcm}(m, n) \cdot \gcd(m, n) = m \cdot n$   
(See [least common multiple](#).)
- $\varphi(n)$  is even for  $n \geq 3$ . Moreover, if  $n$  has  $r$  distinct odd prime factors,  $2^r | \varphi(n)$

```

    ///n / x yields the same value for i <= x <= la.
}
return 0;
}

```

## Mobius Function and Inversion

### Notes

- For any positive integer  $n$ , define  $\mu(n)$  as the sum of the primitive  $n$ th roots of unity. It has values in  $\{-1, 0, 1\}$  depending on the factorization of  $n$  into prime factors:
  - ✓  $\mu(n) = 1$  if  $n$  is a square-free positive integer with an even number of prime factors.
  - ✓  $\mu(n) = -1$  if  $n$  is a square-free positive integer with an odd number of prime factors.
  - ✓  $\mu(n) = 0$  if  $n$  has a squared prime factor.
- Here, a root of unity, occasionally called a de Moivre number, is any complex number that gives 1 when raised to some positive integer power  $n$ .
- An  $n$ th root of unity, where  $n$  is a positive integer (i.e.  $n = 1, 2, 3, \dots$ ), is a number  $z$  (maybe complex) satisfying the equation  $z^n = 1$ .
- An  $n$ th root of unity is said to be primitive if it is not a  $k$ th root of unity for some smaller  $k$ , that is if

$$z^n = 1 \quad \text{and} \quad z^k \neq 1 \quad \text{for } k = 1, 2, 3, \dots, n-1.$$

- It is a multiplicative function.

$$\sum_{d|n} \mu(d) = \begin{cases} 1 & \text{if } n = 1, \\ 0 & \text{if } n > 1. \end{cases}$$

$$\varphi(n) = \sum_{d|n} d \mu\left(\frac{n}{d}\right)$$

$$\sum_{d|n} \frac{\mu^2(d)}{\varphi(d)} = \frac{n}{\varphi(n)}$$

$$\sum_{\substack{1 \leq k \leq n \\ \gcd(k, n) = 1}} k = \frac{1}{2} n \varphi(n) \quad \text{for } n > 1$$

$$\frac{\varphi(n)}{n} = \frac{\varphi(\text{rad}(n))}{\text{rad}(n)} \quad \text{where,}$$

$$\text{rad}(n) = \prod_{\substack{p|n \\ p \text{ prime}}} p$$

$$\left\lfloor \frac{n}{\varphi(n)} \right\rfloor \text{ is periodic. } 1, 2, 1, 2, 1, 3, 1, 2, 1, 2, 1, 3, \dots$$

$$\sum_{\substack{1 \leq k \leq n \\ \gcd(k, n) = 1}} \gcd(k-1, n) = \varphi(n) d(n)$$

- where  $d(n)$  is number of divisors.
- same equation for  $\gcd(ak-1, n)$  where  $a$  and  $n$  are coprime.
- for every  $n$  there is at least one other integer  $m \neq n$  such that  $\phi(m) = \phi(n)$ .

### Divisor function

$$\sigma_x(n) = \sum_{d|n} d^x$$

- It is multiplicative i.e. if  $\gcd(a, b) = 1 \implies \sigma_x(ab) = \sigma_x(a)\sigma_x(b)$ .

$$\begin{aligned} \sum_{i=1}^n [\gcd(i, n) = k] &= \varphi\left(\frac{n}{k}\right) \\ \sum_{k=1}^n \gcd(k, n) &= \sum_{d|n} d \cdot \varphi\left(\frac{n}{d}\right) \\ \sum_{k=1}^n \frac{1}{\gcd(k, n)} &= \sum_{d|n} \frac{1}{d} \cdot \varphi\left(\frac{n}{d}\right) = \frac{1}{n} \sum_{d|n} d \cdot \varphi(d) \\ \sum_{k=1}^n \frac{k}{\gcd(k, n)} &= \frac{n}{2} \cdot \sum_{d|n} \frac{1}{d} \cdot \varphi\left(\frac{n}{d}\right) = \frac{n}{2} \cdot \frac{1}{n} \cdot \sum_{d|n} d \cdot \varphi(d) \\ \sum_{k=1}^n \frac{n}{\gcd(k, n)} &= 2 \cdot \sum_{k=1}^n \frac{k}{\gcd(k, n)} - 1, \text{ for } n > 1 \end{aligned}$$

- Given several integers, with integer  $x$  appears  $c_x$  times, and some fixed integer  $m$ . It is asked that how many integers that are co-prime to  $m$ , so,

$$\sum_{i=1}^n c_i [\gcd(i, m) = 1] = \sum_{d|m} \mu(d) \sum_{i=1}^{\lfloor n/d \rfloor} c_{id}$$

The classic version states that if  $g$  and  $f$  are arithmetic functions satisfying

$$g(n) = \sum_{d|n} f(d) \quad \text{for every integer } n \geq 1$$

then

$$f(n) = \sum_{d|n} \mu(d) g\left(\frac{n}{d}\right) \quad \text{for every integer } n \geq 1$$

$$\begin{aligned} \sum_{d|n} \mu(d) &= [n = 1] \\ \sum_{i=1}^n \sum_{j=1}^n [\gcd(i, j) = 1] &= \sum_{d=1}^n \mu(d) \left\lfloor \frac{n}{d} \right\rfloor^2 \\ \sum_{i=1}^n \sum_{j=1}^n \gcd(i, j) &= \sum_{d=1}^n \varphi(d) \left\lfloor \frac{n}{d} \right\rfloor^2 \\ \text{if } F(n) &= \prod_{d|n} f(d), \text{ then } f(n) = \prod_{d|n} F\left(\frac{n}{d}\right)^{\mu(d)} \end{aligned}$$

### mobius function

```

int mob[N];
void mobius()

```

- Any three consecutive Fibonacci numbers are pairwise coprime, which means that, for every  $n$ ,  $\gcd(F_n, F_{n+1}) = \gcd(F_n, F_{n+2}) = \gcd(F_{n+1}, F_{n+2}) = 1$ .
- If  $p$  is a prime,
 
$$\begin{cases} p = 5 & \implies p | F_p, \\ p \equiv \pm 1 \pmod{5} & \implies p | F_{p-1} \\ p \equiv \pm 2 \pmod{5} & \implies p | F_{p+1} \end{cases}$$
- The only nontrivial square Fibonacci number is 144. Attila Pethő proved in 2001 that there is only a finite number of perfect power Fibonacci numbers. In 2006, Y. Bugeaud, M. Mignotte, and S. Siksek proved that 8 and 144 are the only such non-trivial perfect powers.
- If the members of the Fibonacci sequence are taken mod  $n$ , the resulting sequence is periodic with period at most  $6n$ .

### Sum of floors

$$\sum_{i=1}^n \left\lfloor \frac{n}{i} \right\rfloor = ?$$

```

int32_t main()
{
    BeatMeScanf;
    int i, j, k, n, m;
    cin >> n;
    ///complexity O(sqrt(n))
    for (int i = 1, last; i <= n; i = last + 1) {
        last = n / (n / i);
        debug(i, last, n/i);
    }
}

```

```

{
    for(int i=1; i<N; i++) mob[i]=3;
    mob[1]=1;
    for(int i=2; i<N; i++){
        if(mob[i]==3){
            mob[i]=-1;
            for(int j=2*i; j<N; j+=i) mob[j]=(mob[j]==3?-1:mob[j]*(-1));
            if(i<=(N-1)/i) for(int j=i*i; j<N; j+=i*i) mob[j]=0;
        }
    }
}

```

### GCD and LCM

$$\begin{aligned} \gcd(a, 0) &= a \\ \gcd(a, b) &= \gcd(b, a \bmod b) \end{aligned}$$

- Every common divisor of  $a$  and  $b$  is a divisor of  $\gcd(a, b)$ .
- If  $a$  divides the product  $b \cdot c$ , and  $\gcd(a, b) = d$ , then  $a/d$  divides  $c$ .
- If  $m$  is any integer, then  $\gcd(a + m \cdot b, b) = \gcd(a, b)$
- The gcd is a multiplicative function in the following sense: if  $a_1$  and  $a_2$  are relatively prime, then  $\gcd(a_1 \cdot a_2, b) = \gcd(a_1, b) \cdot \gcd(a_2, b)$ .
- $\gcd(a, b) \cdot \text{lcm}(a, b) = |a \cdot b|$
- $\gcd(a, \text{lcm}(b, c)) = \text{lcm}(\gcd(a, b), \gcd(a, c))$
- $\text{lcm}(a, \gcd(b, c)) = \gcd(\text{lcm}(a, b), \text{lcm}(a, c))$ .
- For non-negative integers  $a$  and  $b$ , where  $a$  and  $b$  are not both zero,
 
$$\gcd(n^a - 1, n^b - 1) = n^{\gcd(a, b)} - 1.$$

$$r_8(n) = 16 \sum_{d|n} (-1)^{n+d} d^3$$

### Gauss Circle Theorem

- The Gauss circle problem is the problem of determining how many integer lattice points there are in a circle centered at the origin and with radius  $r$ .
- Since the equation of this circle is given in Cartesian coordinates by  $x^2 + y^2 = r^2$ , the question is equivalently asking how many pairs of integers  $m$  and  $n$  there are such that  $m^2 + n^2 \leq r^2$
- If the answer for a given  $r$  is denoted by  $N(r)$  then
 
$$N(r) = 1 + 4 \sum_{i=0}^{\infty} \left( \left\lfloor \frac{r^2}{4i+1} \right\rfloor - \left\lfloor \frac{r^2}{4i+3} \right\rfloor \right)$$
- A much simpler sum appears if the sum of squares function  $r_2(n)$  is defined as the number of ways of writing the number  $n$  as the sum of two squares. Then

$$N(r) = \sum_{n=0}^{r^2} r_2(n).$$

### 3. Combinatorics

#### Notes

- $\sum_{0 \leq k \leq n} \binom{n-k}{k} = \text{Fib}_{n+1}$
- $\binom{n}{k} = \binom{n}{n-k}$
- $\binom{n}{k} + \binom{n}{k+1} = \binom{n+1}{k+1}$
- $k \binom{n}{k} = n \binom{n-1}{k-1}$

- $\binom{n}{k} = \frac{n}{k} \binom{n-1}{k-1}$
- $\sum_{i=0}^n \binom{n}{i} = 2^n$
- $\sum_{i \geq 0} \binom{n}{2i} = 2^{n-1}$
- $\sum_{i \geq 0} \binom{n}{2i+1} = 2^{n-1}$
- $\sum_{i=0}^k (-1)^i \binom{n}{i} = (-1)^k \binom{n-1}{k}$
- $\sum_{i=0}^k \binom{n+i}{i} = \binom{n+k+1}{k}$
- $\sum_{i=0}^k \binom{n+i}{n} = \binom{n+k+1}{k}$
- $\sum_{i=0}^k \binom{i}{n} = \binom{k+1}{n+1}$
- $1 \cdot \binom{n}{1} + 2 \cdot \binom{n}{2} + 3 \cdot \binom{n}{3} + \dots + n \cdot \binom{n}{n} = n \cdot 2^{n-1}$
- $1^2 \cdot \binom{n}{1} + 2^2 \cdot \binom{n}{2} + 3^2 \cdot \binom{n}{3} + \dots + n^2 \cdot \binom{n}{n} = (n+1) \cdot 2^{n-2}$
- Vandermonde's Identity:  $\sum_{k=0}^r \binom{m}{k} \binom{n}{r-k} = \binom{m+n}{r}$
- Hockey-Stick

$$n, r \in \mathbb{N}, n > r, \sum_{i=r}^n \binom{i}{r} = \binom{n+1}{r+1}$$

Identity:

$$\sum_{i=0}^k \binom{k}{i}^2 = \binom{2k}{k}$$

- $\sum_{k=0}^n \binom{n}{k} \binom{n}{n-k} = \binom{2n}{n}$
- $\sum_{k=q}^n \binom{n}{k} \binom{k}{q} = 2^{n-q} \binom{n}{q}$
- $\sum_{i=0}^n 3^i \binom{n}{i} = 4^n$
- $\sum_{i=0}^n \binom{2n}{i} = 2^{2n-1} + \frac{1}{2} \binom{2n}{n}$
- $\sum_{i=1}^n \binom{n}{i} \binom{n-1}{i-1} = \binom{2n-1}{n-1}$

- $\sum_{i=0}^n \binom{2n}{i}^2 = \frac{1}{2} \left\{ \binom{4n}{2n} + \binom{2n}{n}^2 \right\}$
- An integer  $n \geq 2$  is prime if and only if all the intermediate binomial coefficients  $\binom{n}{1}, \binom{n}{2}, \dots, \binom{n}{n-1}$  are divisible by  $n$ .
- $\binom{n+k}{k}$  divides  $\frac{\text{lcm}(n, n+1, \dots, n+k)}{n}$
- Kummer's theorem states that for given integers  $n \geq m \geq 0$  and a prime number  $p$ , the largest power of  $p$  dividing  $\binom{n}{m}$  is equal to the number of carries when  $m$  is added to  $n - m$  in base  $p$ .
- Number of different binary sequences of length  $n$  such that no two 0's are adjacent =  $\text{Fib}_{n+1}$
- Combination with repetition: Let's say we choose  $k$  elements from an  $n$ -element set, the order doesn't matter and each element can be chosen more than once. In that case, the number of different combinations is:  $\binom{n+k-1}{k}$
- Number of ways to divide  $n$  different persons in  $n/k$  equal groups i.e. each having size  $k$  is  $\binom{n-1}{k-1}$
- The number non-negative solution of the equation  $x_1 + x_2 + x_3 + \dots + x_k = n$  is  $\binom{n+k-1}{n}$
- Number of binary sequence of length  $n$  and with  $k$  '1' is  $\binom{n}{k}$
- The number of ordered pairs  $(a, b)$  of binary sequences of length  $n$ , such that the distance between them is  $k$ , can be

$$\binom{n}{k} \cdot 2^n$$

calculated as follows:  
The distance between  $a$  and  $b$  is the number of components that differs in  $a$  and  $b$  — for example, the distance between  $(0, 0, 1, 0)$  and  $(1, 0, 1, 1)$  is 2).

#### Catalan numbers

- $C_n = \frac{1}{n+1} \binom{2n}{n}$
- $C_0 = 1, C_1 = 1$  and  $C_n = \sum_{k=0}^{n-1} C_k C_{n-1-k}$
- 1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786
- Number of correct bracket sequence consisting of  $n$  opening and  $n$  closing brackets.
- The number of ways to completely parenthesize  $n+1$  factors.
- The number of triangulations of a convex polygon with  $n+2$  sides (i.e. the number of partitions of polygon into disjoint triangles by using the diagonals).
- The number of ways to connect the  $2n$  points on a circle to form  $n$  disjoint i.e. non-intersecting chords.
- The number of monotonic lattice paths from point  $(0,0)$  to point  $(n,n)$  in a square lattice of size  $n \times n$ , which do not pass above the main diagonal (i.e. connecting  $(0,0)$  to  $(n,n)$ ).
- Number of permutations of length  $n$  that can be stack sorted (i.e. it can be shown that the

rearrangement is stack sorted if and only if there is no such index  $i < j < k$ , such that  $a_k < a_i < a_j$ ).

- ✓ The number of **non-crossing partitions** of a set of  $n$  elements.
- ✓ The number of rooted full binary trees with  $n+1$  leaves (vertices are not numbered). A rooted binary tree is full if every vertex has either two children or no children.
- ✓ The number of Dyck words of length  $2n$ . A Dyck word is a string consisting of  $n$  X's and  $n$  Y's such that no initial segment of the string has more Y's than X's. For example, the following are the Dyck words of length 6: XXXYYY XYXXYY XYXYXY XYYXXY XXYXXY.
- ✓ The number of different ways a convex polygon with  $n+2$  sides can be cut into triangles by connecting vertices with straight lines (a form of Polygon triangulation)
- ✓ Number of permutations of  $\{1, \dots, n\}$  that avoid the pattern 123 (or any of the other patterns of length 3); that is, the number of permutations with no three-term increasing subsequence. For  $n = 3$ , these permutations are 132, 213, 231, 312 and 321. For  $n = 4$ , they are 1432, 2143, 2413, 2431, 3142, 3214, 3241, 3412, 3421, 4132, 4213, 4231, 4312 and 4321
- ✓ Number of ways to tile a staircase shape of height  $n$  with  $n$  rectangles.

$$\checkmark N(n, k) = \frac{1}{n} \binom{n}{k} \binom{n}{k-1}$$

- ✓ The number of expressions containing  $n$  pairs of parentheses, which are correctly matched and which contain  $k$  distinct nestings. For instance,  $N(4, 2) = 6$  as with four pairs of parentheses six sequences can be created which each contain two times the sub-pattern '()':

$()(())() (())()() (())(()) ((()))() ((()))() ((()))()$

- ✓ The number of paths from  $(0, 0)$  to  $(2n, 0)$ , with steps only northeast and southeast, not straying below the  $x$ -axis, with  $k$  peaks. And sum of all number of peaks is Catalan number.

#### Stirling numbers of the first kind

- ✓ The Stirling numbers of the first kind count permutations according to their number of cycles (counting fixed points as cycles of length one).
- ✓  $S(n, k)$  counts the number of permutations of  $n$  elements with  $k$  disjoint cycles.
- ✓  $S(n, k) = (n-1) * S(n-1, k) + S(n-1, k-1)$ , where  $S(0, 0) = 1, S(n, 0) = S(0, n) = 0$
- ✓  $\sum_{k=0}^n S(n, k) = n!$



### Stirling numbers of the second kind

- ✓ Stirling number of the second kind is the number of ways to **partition a set** of  $n$  objects into  $k$  non-empty subsets.
- ✓  $S(n, k) = k * S(n-1, k) + S(n-1, k-1)$ ,  
where  $S(0, 0) = 1, S(n, 0) = S(0, n) = 0$
- ✓  $S(n, 2) = 2^{n-1} - 1$
- ✓  $S(n, k) * k!$  = number of ways to color  $n$  nodes using colors from 1 to  $k$  such that each color is used at least once.

### Bell number

- ✓ Counts the number of partitions of a set.
- ✓  $B_{n+1} = \sum_{k=0}^n \binom{n}{k} * B_k$
- ✓  $B_n = \sum_{k=0}^n S(n, k)$ , where  $S(n, k)$  is stirling number of second kind.
- ✓ The number of multiplicative partitions of a **squarefree** number with  $i$  prime factors is the  $i$ -th Bell number,  $B_i$ .
- ✓ If a deck of  $n$  cards is shuffled by repeatedly removing the top card and reinserting it anywhere in the deck (including its original position at the top of the deck), with exactly  $n$  repetitions of this operation, then there are  $n^n$  different shuffles that can be performed. Of these, the number that return the deck to its original sorted order is exactly  $B_n$ . Thus, the probability that the deck is in its original order after shuffling it in this way is  $B_n/n^n$ .

### Lucas Theorem

- ✓ If  $p$  is prime the  $\binom{p^a}{k} \equiv 0 \pmod{p}$
- ✓ For non-negative integers  $m$  and  $n$  and a prime  $p$ , the following congruence relation holds:

$$\binom{m}{n} \equiv \prod_{i=0}^k \binom{m_i}{n_i} \pmod{p},$$

where,  
 $m = m_k p^k + m_{k-1} p^{k-1} + \dots + m_1 p + m_0$ ,  
 and  
 $n = n_k p^k + n_{k-1} p^{k-1} + \dots + n_1 p + n_0$   
 are the base  $p$  expansions of  $m$  and  $n$  respectively. This uses the convention that  $\binom{m}{n} = 0$ , when  $m < n$ .

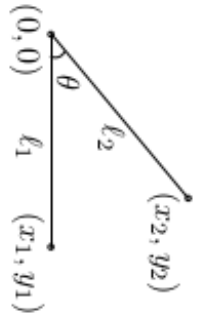
### Derangement

- ✓ A derangement is a permutation of the elements of a set, such that no element appears in its original position.
- ✓  $d(n) = (n-1) * (d(n-1) + d(n-2))$ ,  
where  $d(0) = 1, d(1) = 0$
- ✓  $d(n) = \left\lfloor \frac{n!}{e} \right\rfloor, n \geq 1$

### 4. Burnside Lemma

The task is to count the number of different necklaces from  $n$  beads, each of which can be painted in one of the  $k$  colors. When comparing two necklaces, they can be rotated, but not reversed (i.e. a cyclic shift is permitted).  
 Solution:

Identities Cont.		Trees
38. $\binom{n+1}{m+1} = \sum_k \binom{n}{k} \binom{k}{m} = \sum_{k=0}^n \binom{k}{m} n^{\overline{n-k}} = n! \sum_{k=0}^n \frac{1}{k!} \binom{k}{m}$ ,	39. $\left[ \begin{matrix} x \\ x-n \end{matrix} \right] = \sum_{k=0}^n \left\langle \begin{matrix} n \\ k \end{matrix} \right\rangle \binom{x+k}{2n}$ ,	Every tree with $n$ vertices has $n-1$ edges.
40. $\left\{ \begin{matrix} n \\ m \end{matrix} \right\} = \sum_k \binom{n}{k} \left\{ \begin{matrix} k+1 \\ m+1 \end{matrix} \right\} (-1)^{n-k}$ ,	41. $\left[ \begin{matrix} n \\ m \end{matrix} \right] = \sum_k \left[ \begin{matrix} n+1 \\ k+1 \end{matrix} \right] \binom{k}{m} (-1)^{m-k}$ ,	Kraft inequality: If the depths of the leaves of a binary tree are $d_1, \dots, d_n$ :
42. $\left\{ \begin{matrix} m+n+1 \\ m \end{matrix} \right\} = \sum_{k=0}^m k \left\{ \begin{matrix} n+k \\ k \end{matrix} \right\}$ ,	43. $\left[ \begin{matrix} m+n+1 \\ m \end{matrix} \right] = \sum_{k=0}^m k(n+k) \left[ \begin{matrix} n+k \\ k \end{matrix} \right]$ ,	$\sum_{i=1}^n 2^{-d_i} \leq 1$ ,
44. $\binom{n}{m} = \sum_k \left\{ \begin{matrix} n+1 \\ k+1 \end{matrix} \right\} \left[ \begin{matrix} k \\ m \end{matrix} \right] (-1)^{m-k}$ ,	45. $(n-m)! \binom{n}{m} = \sum_k \left[ \begin{matrix} n+1 \\ k+1 \end{matrix} \right] \left\{ \begin{matrix} k \\ m \end{matrix} \right\} (-1)^{m-k}$ , for $n \geq m$ ,	and equality holds only if every internal node has 2 sons.
46. $\left\{ \begin{matrix} n \\ n-m \end{matrix} \right\} = \sum_k \binom{m-n}{m+k} \binom{m+n}{n+k} \left[ \begin{matrix} m+k \\ k \end{matrix} \right]$ ,	47. $\left[ \begin{matrix} n \\ n-m \end{matrix} \right] = \sum_k \binom{m-n}{m+k} \binom{m+n}{n+k} \left\{ \begin{matrix} m+k \\ k \end{matrix} \right\}$ ,	
48. $\left\{ \begin{matrix} n \\ \ell+m \end{matrix} \right\} \binom{\ell+m}{\ell} = \sum_k \left\{ \begin{matrix} k \\ \ell \end{matrix} \right\} \left\{ \begin{matrix} n-k \\ m \end{matrix} \right\} \binom{n}{k}$ ,	49. $\left[ \begin{matrix} n \\ \ell+m \end{matrix} \right] \binom{\ell+m}{\ell} = \sum_k \left[ \begin{matrix} k \\ \ell \end{matrix} \right] \left[ \begin{matrix} n-k \\ m \end{matrix} \right] \binom{n}{k}$ .	

Geometry
<p>Projective coordinates: triples <math>(x, y, z)</math>, not all <math>x, y</math> and <math>z</math> zero.</p> <p><math>(x, y, z) = (cx, cy, cz) \quad \forall c \neq 0</math>.</p> <p>Cartesian Projective</p> <p><math>(x, y) \quad (x, y, 1)</math></p> <p><math>y = mx + b \quad (m, -1, b)</math></p> <p><math>x = c \quad (1, 0, -c)</math></p> <p>Distance formula, <math>L_p</math> and <math>L_\infty</math> metric:</p> <p><math>\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2}</math>,</p> <p><math>\left[  x_1 - x_0 ^p +  y_1 - y_0 ^p \right]^{1/p}</math>,</p> <p><math>\lim_{p \rightarrow \infty} \left[  x_1 - x_0 ^p +  y_1 - y_0 ^p \right]^{1/p}</math>.</p> <p>Area of triangle <math>(x_0, y_0), (x_1, y_1)</math> and <math>(x_2, y_2)</math>:</p> <p><math>\frac{1}{2} \text{abs} \begin{vmatrix} x_1 - x_0 &amp; y_1 - y_0 \\ x_2 - x_0 &amp; y_2 - y_0 \end{vmatrix}</math>.</p> <p>Angle formed by three points:</p>  <p><math>\cos \theta = \frac{(x_1, y_1) \cdot (x_2, y_2)}{l_1 l_2}</math>.</p> <p>Line through two points <math>(x_0, y_0)</math> and <math>(x_1, y_1)</math>:</p> <p><math>\begin{vmatrix} x &amp; y &amp; 1 \\ x_0 &amp; y_0 &amp; 1 \\ x_1 &amp; y_1 &amp; 1 \end{vmatrix} = 0</math>.</p> <p>Area of circle, volume of sphere:</p> <p><math>A = \pi r^2, \quad V = \frac{4}{3} \pi r^3</math>.</p>



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

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

## Combinatorial (5)

### 5.1 Permutations

#### 5.1.1 Factorial

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

#### IntPerm.h

**Description:** Permutation  $\rightarrow$  integer conversion. (Not order preserving.)

**Time:**  $O(n)$

6 lines

```
int permToInt(vi& v) {
    int use = 0, i = 0, r = 0;
    trav(x,v) r=r * ++i + __builtin_popcount(use & ~(1 << x)),
        use |= 1 << x; // (note: minus, not ~!)
    return r;
} // hash-cpp-all = elb8eaea02324af14a3da94f409019b8
```

#### 5.1.2 Cycles

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

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

#### 5.1.3 Derangements

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

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

#### 5.1.4 Burnside's lemma

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

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

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

Sums of powers:

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

Euler-Maclaurin formula for infinite sums:

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

#### 5.3.2 Stirling numbers of the first kind

Number of permutations on  $n$  items with  $k$  cycles.

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

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

$$c(8, k) =$$

$$8, 0, 5040, 13068, 13132, 6769, 1960, 322, 28, 1$$

$$c(n, 2) =$$

$$0, 0, 1, 3, 11, 50, 274, 1764, 13068, 109584, \dots$$

#### 5.3.3 Eulerian numbers

Number of permutations  $\pi \in S_n$  in which exactly  $k$  elements are greater than the previous element.  $k$   $j$ :s s.t.

$\pi(j) > \pi(j+1)$ ,  $k+1$   $j$ :s s.t.  $\pi(j) \geq j$ ,  $k$   $j$ :s s.t.

$\pi(j) > j$ .

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

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

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

#### 5.3.4 Stirling numbers of the second kind

Partitions of  $n$  distinct elements into exactly  $k$  groups.

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

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

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

#### 5.3.5 Bell numbers

Total number of partitions of  $n$  distinct elements.

$B(n) = 1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, \dots$  For  $p$  prime,

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

#### 5.3.6 Labeled unrooted trees

# on  $n$  vertices:  $n^{n-2}$

# on  $k$  existing trees of size  $n_i$ :  $n_1 n_2 \dots n_k n^{k-2}$

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

#### 5.3.7 Catalan numbers

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

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

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

- 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.