

BELJING NORMAL UNIVERSITY
SCHOOL OF MATHEMATICS

Template

appleDog

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1 头文件

1.1 模板

```

1 // created on Lucian Xu's Laptop
2
3 #include <bits/stdc++.h>
4
5 #define typet typename T
6 #define typeu typename U
7 #define types typename... Ts
8 #define tempt template <typet>
9 #define tempu template <typeu>
10 #define temps template <types>
11 #define tandu template <typet, typeu>
12
13 using UI = unsigned int;
14 using ULL = unsigned long long;
15 using LL = long long;
16 using ULL = unsigned long long;
17 using i128 = __int128;
18 using PII = std::pair<int, int>;
19 using PIL = std::pair<int, LL>;
20 using PLI = std::pair<LL, int>;
21 using PLL = std::pair<LL, LL>;
22 using vi = std::vector<int>;
23 using vvi = std::vector<vi>;
24 using vl = std::vector<LL>;
25 using vvl = std::vector<vl>;
26 using vpi = std::vector<PII>;
27
28 #define ff first
29 #define ss second
30 #define all(v) v.begin(), v.end()
31 #define rall(v) v.rbegin(), v.rend()
32
33 #ifdef LOCAL
34 #include "debug.h"
35 #else
36 #define debug(...) \
37     do { \
38     } while (false)
39 #endif
40
41 constexpr int mod = 998244353;
42 constexpr int inv2 = (mod + 1) / 2;
43 constexpr int inf = 0x3f3f3f3f;
44 constexpr LL INF = 1e18;
45 constexpr double pi = 3.141592653589793;
46 constexpr double eps = 1e-6;
47
48 constexpr int lowbit(int x) { return x & -x; }
49 tandu bool Max(T& x, const U& y) { return x < y ? x = y, true : false; }
50 tandu bool Min(T& x, const U& y) { return x > y ? x = y, true : false; }
51
52 template <int P>
53 struct Mint {
54     int v = 0;
55
56     // reflection
57     template <typet = int>
58     constexpr operator T() const {
59         return v;
60     }
61
62     // constructor //
63     constexpr Mint() = default;
64     template <typet>
65     constexpr Mint(T x) : v(x % P) {}
66
67     // io //
68     friend std::istream& operator>>(std::istream& is, Mint& x) {
69         LL y;
70         is >> y;
71         x = y;
72         return is;
73     }
74     friend std::ostream& operator<<(std::ostream& os, Mint x) { return os << x.v; }
75
76     // comparision //
77     friend constexpr bool operator==(Mint lhs, Mint rhs) { return lhs.v == rhs.v; }
78     friend constexpr bool operator!=(Mint lhs, Mint rhs) { return lhs.v != rhs.v; }
79     friend constexpr bool operator<(Mint lhs, Mint rhs) { return lhs.v < rhs.v; }

```



```

80 friend constexpr bool operator<=(Mint lhs, Mint rhs) { return lhs.v <= rhs.v; }
81 friend constexpr bool operator>(Mint lhs, Mint rhs) { return lhs.v > rhs.v; }
82 friend constexpr bool operator>=(Mint lhs, Mint rhs) { return lhs.v >= rhs.v; }
83
84 // arithmetic //
85 friend constexpr Mint operator+(Mint lhs, Mint rhs) {
86     return lhs.v + rhs.v <= P ? lhs.v + rhs.v : lhs.v - P + rhs.v;
87 }
88 friend constexpr Mint operator-(Mint lhs, Mint rhs) {
89     return lhs.v < rhs.v ? lhs.v + P - rhs.v : lhs.v - rhs.v;
90 }
91 friend constexpr Mint operator*(Mint lhs, Mint rhs) {
92     return static_cast<LL>(lhs.v) * rhs.v % P;
93 }
94 constexpr Mint operator+=(Mint rhs) { return v = v + rhs; }
95 constexpr Mint operator-=(Mint rhs) { return v = v - rhs; }
96 constexpr Mint operator*=(Mint rhs) { return v = v * rhs; }
97 friend constexpr Mint operator&(Mint lhs, Mint rhs) { return lhs.v & rhs.v; }
98 friend constexpr Mint operator|(Mint lhs, Mint rhs) { return lhs.v | rhs.v; }
99 friend constexpr Mint operator^(Mint lhs, Mint rhs) { return lhs.v ^ rhs.v; }
100 friend constexpr Mint operator>>(Mint lhs, Mint rhs) { return lhs.v >> rhs.v; }
101 friend constexpr Mint operator<<(Mint lhs, Mint rhs) { return lhs.v << rhs.v; }
102 constexpr Mint operator&=(Mint rhs) { return v = v & rhs; }
103 constexpr Mint operator|=(Mint rhs) { return v = v | rhs; }
104 constexpr Mint operator^=(Mint rhs) { return v = v ^ rhs; }
105 constexpr Mint operator>>=(Mint rhs) { return v = v >> rhs; }
106 constexpr Mint operator<<=(Mint rhs) { return v = v << rhs; }
107 friend constexpr Mint power(Mint a, Mint n) {
108     Mint ans = 1;
109     while (n) {
110         if (n & 1) ans *= a;
111         a *= a;
112         n >>= 1;
113     }
114     return ans;
115 }
116 friend constexpr Mint inv(Mint rhs) { return power(rhs, P - 2); }
117 friend constexpr Mint operator/(Mint lhs, Mint rhs) { return lhs * inv(rhs); }
118 constexpr Mint operator/=(Mint rhs) { return v = v / rhs; }
119 };
120 using Z = Mint<998244353>;
121
122 int main() {
123     std::ios::sync_with_stdio(false);
124     std::cin.tie(0);
125     std::cout.tie(0);
126
127     int t = 1;
128     std::cin >> t;
129     while (t--) {
130
131     }
132     return 0;
133 }

```

短一点的 \mathbb{F}_p 上的运算.

```

1  constexpr int add(int x, int y) { return x + y < mod ? x + y : x - mod + y; }
2  constexpr int sub(int x, int y) { return x < y ? mod + x - y : x - y; }
3  constexpr int mul(LL x, int y) { return x * y % mod; }
4  constexpr void Add(int& x, int y) { x = add(x, y); }
5  constexpr void Sub(int& x, int y) { x = sub(x, y); }
6  constexpr void Mul(int& x, int y) { x = mul(x, y); }
7  constexpr int pow(int x, int y, int z = 1) {
8      for (; y; y /= 2) {
9          if (y & 1) Mul(z, x);
10         Mul(x, x);
11     }
12     return z;
13 }
14 temps constexpr int add(Ts... x) {
15     int y = 0;
16     (... , Add(y, x));
17     return y;
18 }
19 temps constexpr int mul(Ts... x) {
20     int y = 1;
21     (... , Mul(y, x));
22     return y;
23 }

```

1.2 debug.h 文件

```

1  tandu std::ostream& operator<<(std::ostream& os, const std::pair<T, U>& p) {
2      return os << '<' << p.ff << ',' << p.ss << endl;
3  }
4
5  template <
6      typename T, typename U = decltype(std::begin(std::declval<T>())),
7      typename It = std::enable_if_t<!std::is_same_v<T, std::string>>>
8  std::ostream& operator<<(std::ostream& os, const T& c) {
9      auto it = std::begin(c);
10     if (it == std::end(c)) return os << "{}";
11     for (os << '{' << *it; ++it != std::end(c); os << ',' << *it)
12         ;
13     return os << '}';
14 }
15
16 #define debug(arg...) \
17     do { \
18         std::cerr << "[" #arg "]" :"; \
19         dbg(arg); \
20     } while (false)
21
22 temps void dbg(Ts... args) {
23     (... , (std::cerr << ' ' << args));
24     std::cerr << endl;
25 }

```

md5: c29c0bb4ac2d5e2bb3fbd3ea57ecdadb

By MAOoo.

```

1  #include <bits/stdc++.h>
2
3  #define debug(arg...) \
4      do { \
5          std::cerr << "[" #arg "]" :"; \
6          dbg(arg); \
7      } while (false)
8
9  template <typename T, typename U>
10 std::ostream& operator<<(std::ostream& os, const std::pair<T, U>& p);
11 template <typename T, typename U, typename It>
12 std::ostream& operator<<(std::ostream& os, const T& a);
13 template <typename... Ts>
14 std::ostream& operator<<(std::ostream& os, const std::tuple<Ts...>& t);
15
16 template <typename T, typename U>
17 std::ostream& operator<<(std::ostream& os, const std::pair<T, U>& p) {
18     return os << '<' << p.first << ',' << p.second << '>';
19 }
20
21 template <
22     typename T, typename U = std::enable_if_t<!std::is_same_v<T, std::string>>,
23     typename It = decltype(std::begin(std::declval<T>()))>
24 std::ostream& operator<<(std::ostream& os, const T& a) {
25     constexpr bool flag = std::is_same_v<
26         typename std::iterator_traits<It>::iterator_category, std::random_access_iterator_tag>;
27     constexpr char L = flag ? '[' : '{';
28     constexpr char R = flag ? ']' : '}';
29     auto it = std::begin(a);
30     if (it == std::end(a)) return os << L << R;
31     for (os << L << *it++; it != std::end(a); it++) os << ',' << *it;
32     return os << R;
33 }
34
35 template <typename T>
36 std::ostream& operator<<(std::ostream& os, std::priority_queue<T> a) {
37     std::vector<T> b;
38     for (b.reserve(a.size()); not a.empty(); a.pop()) {
39         b.push_back(a.top());
40     }
41     return os << b;
42 }
43
44 template <typename Tuple, std::size_t... Is>
45 void print_tuple_impl(std::ostream& os, const Tuple& t, std::index_sequence<Is...>) {
46     ((os << (Is == 0 ? '<' : ',') << std::get<Is>(t), ...));
47     os << '>';
48 }
49
50 template <typename... Ts>
51 std::ostream& operator<<(std::ostream& os, const std::tuple<Ts...>& t) {

```

```
52     print_tuple_impl(os, t, std::index_sequence_for<Ts...>{});
53     return os;
54 }
55
56 template <typename... Ts>
57 void dbg(Ts... args) {
58     (... , (std::cerr << ' ' << args));
59     std::cerr << endl;
60 }
```

2 数据结构

2.1 栈

2.1.1 单调栈

维护单调下降序列.

```
1 for (int i = 1; i <= n; i++){
2     while (!stk.empty() and stk.back() > a[i]) {
3         stk.pop_back();
4     }
5     stk.push_back(a[i]);
6 }
```

2.2 队列

2.2.1 单调队列 (滑动窗口)

维护长度不超过 k 的单调下降的序列.

```
1 std::deque<int> q;
2 for (int i = 1; i <= n; i++) {
3     while (!q.empty() and a[q.back()] >= a[i]) q.pop_back();
4     if (!q.empty() and i - q.front() >= k) q.pop_front();
5     q.push_back(i);
6 }
```

2.3 DSU

```
1 vi fa(n + 1);
2 std::iota(all(fa), 0);
3 std::function<void(int)> find = [&] (int x) -> int{
4     return x == fa[x] ? x : fa[x] = find(fa[x]);
5 };
6 auto merge = [&] (int x, int y) -> void{
7     x = find(x), y = find(y);
8     if (x == y) return;
9     // operations //
10    fa[y] = x;
11 }
```

2.4 ST 表

用于解决可重复贡献问题的数据结构.

可重复问题是指对运算 opt , 满足 $x \text{ opt } x = x$.

2.4.1 一维 ST 表

以最大值为例.

```
1 // ST //
2 vvi f(n + 1, vi(30));
3 vi Log2(n + 1);
4 auto ST_init = [&] () -> void {
5     Log2[1] = 0;
6     for (int i = 1; i <= n; i++) {
7         f[i][0] = a[i];
8         if (i > 1) Log2[i] = Log2[i / 2] + 1;
9     }
10 }
```

```

10     int t = Log2[n];
11     for (int j = 1; j <= t; j++) {
12         for (int i = 1; i <= n - (1 << j) + 1; i++) {
13             f[i][j] = std::max(f[i][j - 1], f[i + (1 << (j - 1))][j - 1]);
14         }
15     }
16 };
17
18 auto ST_query = [&](int l, int r) -> int {
19     int t = Log2[r - l + 1];
20     return std::max(f[l][t], f[r - (1 << t) + 1][t]);
21 };

```

2.4.2 二维 ST 表

```

1 // ST //
2 std::vector f(n + 1, std::vector<std::array<std::array<int, 30>, 30>>(m + 1));
3 vi Log2(n + 1);
4 auto ST_init = [&]() -> void {
5     for (int i = 2; i <= std::max(n, m); i++) {
6         Log2[i] = Log2[i / 2] + 1;
7     }
8     for (int i = 2; i <= n; i++) {
9         for (int j = 2; j <= m; j++) {
10             f[i][j][0][0] = a[i][j];
11         }
12     }
13     for (int ki = 0; ki <= Log2[n]; ki++) {
14         for (int kj = 0; kj <= Log2[m]; kj++) {
15             if (!ki && !kj) continue;
16             for (int i = 1; i <= n - (1 << ki) + 1; i++) {
17                 for (int j = 1; j <= m - (1 << kj) + 1; j++) {
18                     if (ki) {
19                         f[i][j][ki][kj] =
20                             std::max(f[i][j][ki - 1][kj], f[i + (1 << (ki - 1))][j][ki - 1][kj]);
21                     } else {
22                         f[i][j][ki][kj] =
23                             std::max(f[i][j][ki][kj - 1], f[i][j + (1 << (kj - 1))][ki][kj - 1]);
24                     }
25                 }
26             }
27         }
28     }
29 };
30
31 auto ST_query = [&](int x1, int y1, int x2, int y2) -> int {
32     int ki = Log2[x2 - x1 + 1], kj = Log2[y2 - y1 + 1];
33     int t1 = f[x1][y1][ki][kj];
34     int t2 = f[x2 - (1 << ki) + 1][y1][ki][kj];
35     int t3 = f[x1][y2 - (1 << kj) + 1][ki][kj];
36     int t4 = f[x2 - (1 << ki) + 1][y2 - (1 << kj) + 1][ki][kj];
37     return std::max({t1, t2, t3, t4});
38 };

```

2.5 树状数组

2.5.1 单点修改, 区间查询

单点修改: a_x 加上 k . 区间查询: a_1 至 a_x 的和.

```

1 // BIT //
2 vi tr(n + 1);
3 auto add = [&](int x, int k) -> void {
4     while(x <= n){
5         tr[x] += k;
6         x += lowbit(x);
7     }
8 };
9
10 auto query = [&](int x) -> int {
11     int ans = 0;
12     while(x){
13         ans += tr[x];
14         x -= lowbit(x);
15     }
16     return ans;

```

```
17 |};
```

2.5.2 区间修改, 单点查询

设数组 b 为数组 a 的差分数组, 维护数组 b .

区间修改: a_l 至 a_r 每个数加 k . 单点查询: 查询 s_n 的值.

```
1 add(l, k);
2 add(r + 1, -k);
3 query(n)
```

2.5.3 区间修改, 区间查询

设数组 b 为数组 a 的差分数组, c_1 维护 b_i , c_2 维护 $i \times b_i$.

区间修改: a_l 至 a_r 每个数加 k . 区间查询: a_1 至 a_x 的和.

```
1 add(l, k);
2 add(r + 1, -k);
3 add(l, 1 * k);
4 add(r + 1, -(r + 1) * k);
5 ans = query(x) * (x + 1) - query(x);
```

2.6 线段树

包括 *build*, *push_up*, *push_down*, *modify*, *query* 五个函数.

2.6.1 区间修改 (带 *add* 的 *lazy_tag*)

n 个数, m 次操作, 操作分为:

- 1 $x\ y\ k$: 将区间 $[x, y]$ 中的数每个加上 k .
- 2 $x\ y$: 输出区间 $[x, y]$ 中数的和.

```
1 // Problem: P3372 【模板】线段树 1
2 struct Info {
3     LL sum = 0;
4
5     Info(LL _sum = 0) : sum(_sum) {}
6
7     Info operator+(const Info& b) const { return Info(sum + b.sum); }
8 };
9
10 struct Tag {
11     LL add = 0;
12
13     Tag(LL _add = 0) : add(_add) {}
14
15     bool operator==(const Tag& b) const { return add == b.add; }
16 };
17
18 void infoApply(Info& a, int l, int r, const Tag& tag) { a.sum += 1ll * (r - l + 1) * tag.add; }
19
20 void tagApply(Tag& a, int l, int r, const Tag& tag) { a.add += tag.add; }
21
22 template <class Info, class Tag>
23 class segTree {
24 #define ls i << 1
25 #define rs i << 1 | 1
26 #define mid ((l + r) >> 1)
27 #define lson ls, l, mid
28 #define rson rs, mid + 1, r
29
30     int n;
31     std::vector<Info> info;
```

```

32     std::vector<Tag> tag;
33
34 public:
35     segTree(const std::vector<Info>& init) : n(init.size() - 1) {
36         assert(n > 0);
37         info.resize(4 << std::lg(n));
38         tag.resize(4 << std::lg(n));
39         auto build = [&](auto dfs, int i, int l, int r) {
40             if (l == r) {
41                 info[i] = init[l];
42                 return;
43             }
44             dfs(dfs, lson);
45             dfs(dfs, rson);
46             push_up(i);
47         };
48         build(build, 1, 1, n);
49     }
50
51
52 private:
53     void push_up(int i) { info[i] = info[ls] + info[rs]; }
54
55
56     template <class... T>
57     void apply(int i, int l, int r, const T&... val) {
58         ::infoApply(info[i], l, r, val...);
59         ::tagApply(tag[i], l, r, val...);
60     }
61
62     void push_down(int i, int l, int r) {
63         if (tag[i] == Tag{}) return;
64         apply(lson, tag[i]);
65         apply(rson, tag[i]);
66         tag[i] = {};
67     }
68
69 public:
70     template <class... T>
71     void rangeMerge(int ql, int qr, const T&... val) {
72         auto dfs = [&](auto dfs, int i, int l, int r) {
73             if (qr < l or r < ql) return;
74             if (ql <= l and r <= qr) {
75                 apply(i, l, r, val...);
76                 return;
77             }
78             push_down(i, l, r);
79             dfs(dfs, lson);
80             dfs(dfs, rson);
81             push_up(i);
82         };
83         dfs(dfs, 1, 1, n);
84     }
85
86     Info rangeQuery(int ql, int qr) {
87         Info res{};
88         auto dfs = [&](auto dfs, int i, int l, int r) {
89             if (qr < l or r < ql) return;
90             if (ql <= l and r <= qr) {
91                 res = res + info[i];
92                 return;
93             }
94             push_down(i, l, r);
95             dfs(dfs, lson);
96             dfs(dfs, rson);
97         };
98         dfs(dfs, 1, 1, n);
99         return res;
100     }
101
102 #undef rson
103 #undef lson
104 #undef mid
105 #undef rs
106 #undef ls
107 };
108
109 int main() {
110     std::ios::sync_with_stdio(false);
111     std::cin.tie(0);
112     std::cout.tie(0);
113
114     int n, m;
115     std::cin >> n >> m;
116     std::vector<Info> a(n + 1);
117     for (int i = 1; i <= n; i++) std::cin >> a[i].sum;
118     static segTree<Info, Tag> tr(a);

```

```

119 |
120 |     while (m--) {
121 |         int op, k, l, r;
122 |         std::cin >> op >> l >> r;
123 |         if (op == 1) {
124 |             std::cin >> k;
125 |             tr.rangeMerge(l, r, Tag(k));
126 |         } else {
127 |             std::cout << tr.rangeQuery(l, r).sum << endl;
128 |         }
129 |     }
130 |
131 |     return 0;
132 | }

```

2.6.2 区间修改 (带 *add* 和 *mul* 的 *lazy_tag*)

n 个数, m 次操作, 操作分为:

- 1 $x\ y\ k$: 将区间 $[x, y]$ 中的数每个乘以 k .
- 2 $x\ y\ k$: 将区间 $[x, y]$ 中的数每个加上 k .
- 3 $x\ y$: 输出区间 $[x, y]$ 中数的和. (对 p 取模)

```

1  // Problem: P3373 【模板】线段树 2
2
3  struct Info {
4      LL sum = 0;
5
6      Info(LL _sum = 0) : sum(_sum) {}
7
8      Info operator+(const Info& b) const { return Info(add(sum + b.sum)); }
9  };
10
11 struct Tag {
12     LL add = 0, mul = 1;
13
14     Tag(LL _add = 0, LL _mul = 1) : add(_add), mul(_mul) {}
15
16     bool operator==(const Tag& b) const { return add == b.add and mul == b.mul; }
17 };
18
19 void infoApply(Info& a, int l, int r, const Tag& tag) {
20     a.sum = add(mul(a.sum, tag.mul), mul((r - l + 1), tag.add));
21 }
22
23 void tagApply(Tag& a, int l, int r, const Tag& tag) {
24     a.add = add(mul(a.add, tag.mul), tag.add);
25     a.mul = mul(a.mul, tag.mul);
26 }
27
28 template <class Info, class Tag>
29 class segTree {
30 #define ls i << 1
31 #define rs i << 1 | 1
32 #define mid ((l + r) >> 1)
33 #define lson ls, l, mid
34 #define rson rs, mid + 1, r
35
36     int n;
37     std::vector<Info> info;
38     std::vector<Tag> tag;
39
40 public:
41     segTree(const std::vector<Info>& init) : n(init.size() - 1) {
42         assert(n > 0);
43         info.resize(4 << std::lg(n));
44         tag.resize(4 << std::lg(n));
45         auto build = [&](auto dfs, int i, int l, int r) {
46             if (l == r) {
47                 info[i] = init[l];
48                 return;
49             }
50             dfs(dfs, lson);
51             dfs(dfs, rson);
52             push_up(i);
53         };
54         build(build, 1, 1, n);
55     }
56 }

```



```

57
58 private:
59 void push_up(int i) { info[i] = info[ls] + info[rs]; }
60
61
62 template <class... T>
63 void apply(int i, int l, int r, const T&... val) {
64     ::infoApply(info[i], l, r, val...);
65     ::tagApply(tag[i], l, r, val...);
66 }
67
68 void push_down(int i, int l, int r) {
69     if (tag[i] == Tag{}) return;
70     apply(lson, tag[i]);
71     apply(rson, tag[i]);
72     tag[i] = {};
73 }
74
75 public:
76 template <class... T>
77 void rangeMerge(int ql, int qr, const T&... val) {
78     auto dfs = [&](auto dfs, int i, int l, int r) {
79         if (qr < l or r < ql) return;
80         if (ql <= l and r <= qr) {
81             apply(i, l, r, val...);
82             return;
83         }
84         push_down(i, l, r);
85         dfs(dfs, lson);
86         dfs(dfs, rson);
87         push_up(i);
88     };
89     dfs(dfs, 1, 1, n);
90 }
91
92 Info rangeQuery(int ql, int qr) {
93     Info res{};
94     auto dfs = [&](auto dfs, int i, int l, int r) {
95         if (qr < l or r < ql) return;
96         if (ql <= l and r <= qr) {
97             res = res + info[i];
98             return;
99         }
100         push_down(i, l, r);
101         dfs(dfs, lson);
102         dfs(dfs, rson);
103     };
104     dfs(dfs, 1, 1, n);
105     return res;
106 }
107
108 #undef rson
109 #undef lson
110 #undef mid
111 #undef rs
112 #undef ls
113 };
114
115 int main() {
116     std::ios::sync_with_stdio(false);
117     std::cin.tie(0);
118     std::cout.tie(0);
119
120     int n, m, p;
121     std::cin >> n >> m >> p;
122     std::vector<Info> a(n + 1);
123     for (int i = 1; i <= n; i++) std::cin >> a[i].sum;
124     static segTree<Info, Tag> tr(a);
125
126     while (m--) {
127         int op, k, l, r;
128         std::cin >> op >> l >> r;
129         if (op == 1) {
130             std::cin >> k;
131             tr.rangeMerge(l, r, Tag(0, k));
132         } else if (op == 2) {
133             std::cin >> k;
134             tr.rangeMerge(l, r, Tag(k, 1));
135         } else {
136             std::cout << tr.rangeQuery(l, r).sum << endl;
137         }
138     }
139
140     return 0;
141 }

```

2.7 线段树 2.0 (23.05.12)

以维护区间最大值和带加法修改的区间和为例.

需要修改的内容: Info 和 Tag 两个 struct 以及 infoApply 和 tagApply 两个函数.

```

1 struct Info {
2     // 重载 operator+ //
3 };
4
5 struct Tag {
6     // 重载 operator== //
7 };
8
9 void infoApply(Info& a, int l, int r, const Tag& tag) {
10
11 }
12
13 void tagApply(Tag& a, int l, int r, const Tag& tag) {
14
15 }
16
17 template <class Info, class Tag>
18 class segTree {
19 #define ls i << 1
20 #define rs i << 1 | 1
21 #define mid ((l + r) >> 1)
22 #define lson ls, l, mid
23 #define rson rs, mid + 1, r
24
25     int n;
26     std::vector<Info> info;
27     std::vector<Tag> tag;
28
29 public:
30     segTree(const std::vector<Info>& init) : n(init.size() - 1) {
31         assert(n > 0);
32         info.resize(4 << std::lg(n));
33         tag.resize(4 << std::lg(n));
34         auto build = [&](auto dfs, int i, int l, int r) {
35             if (l == r) {
36                 info[i] = init[l];
37                 return;
38             }
39             dfs(dfs, lson);
40             dfs(dfs, rson);
41             push_up(i);
42         };
43         build(build, 1, 1, n);
44     }
45
46 private:
47     void push_up(int i) { info[i] = info[ls] + info[rs]; }
48
49
50
51     template <class... T>
52     void apply(int i, int l, int r, const T&... val) {
53         ::infoApply(info[i], l, r, val...);
54         ::tagApply(tag[i], l, r, val...);
55     }
56
57     void push_down(int i, int l, int r) {
58         if (tag[i] == Tag{}) return;
59         apply(lson, tag[i]);
60         apply(rson, tag[i]);
61         tag[i] = {};
62     }
63
64 public:
65     template <class... T>
66     void rangeApply(int ql, int qr, const T&... val) {
67         auto dfs = [&](auto dfs, int i, int l, int r) {
68             if (qr < l or r < ql) return;
69             if (ql <= l and r <= qr) {
70                 apply(i, l, r, val...);
71                 return;
72             }
73             push_down(i, l, r);
74             dfs(dfs, lson);
75             dfs(dfs, rson);
76             push_up(i);
77         };
78         dfs(dfs, 1, 1, n);
79     }

```

```

80
81 Info rangeAsk(int ql, int qr) {
82     Info res{};
83     auto dfs = [&](auto dfs, int i, int l, int r) {
84         if (qr < l or r < ql) return;
85         if (ql <= l and r <= qr) {
86             res = res + info[i];
87             return;
88         }
89         push_down(i, l, r);
90         dfs(dfs, lson);
91         dfs(dfs, rson);
92     };
93     dfs(dfs, 1, 1, n);
94     return res;
95 }
96
97 #undef rson
98 #undef lson
99 #undef mid
100 #undef rs
101 #undef ls
102 };

```

2.7.1 动态开点权值线段树

如果要实现 *push_up* 函数, 记得先开点再操作.

```

1 // Problem: 洛谷: P3369 【模板】普通平衡树
2
3 struct node {
4     int id, l, r;
5     int ls, rs;
6     int sum;
7
8     node(int _id, int _l, int _r) : id(_id), l(_l), r(_r) {
9         ls = rs = 0;
10        sum = 0;
11    }
12 };
13
14
15 // Segment tree //
16 int idx = 1;
17 std::vector<node> tree = {node{0, 0, 0}};
18
19 auto new_node = [&](int l, int r) -> int {
20     tree.push_back(node(idx, l, r));
21     return idx++;
22 };
23
24 auto push_up = [&](int u) -> void {
25     tree[u].sum = 0;
26     if (tree[u].ls) tree[u].sum += tree[tree[u].ls].sum;
27     if (tree[u].rs) tree[u].sum += tree[tree[u].rs].sum;
28 };
29
30 auto build = [&]() { new_node(-10000000, 10000000); };
31
32 std::function<void(int, int, int, int)> insert = [&](int u, int l, int r, int x) {
33     if (l == r) {
34         tree[u].sum++;
35         return;
36     }
37     int mid = (l + r - 1) / 2;
38     if (x <= mid) {
39         if (!tree[u].ls) tree[u].ls = new_node(l, mid);
40         insert(tree[u].ls, l, mid, x);
41     } else {
42         if (!tree[u].rs) tree[u].rs = new_node(mid + 1, r);
43         insert(tree[u].rs, mid + 1, r, x);
44     }
45     push_up(u);
46 };
47
48 std::function<void(int, int, int, int)> remove = [&](int u, int l, int r, int x) {
49     if (l == r) {
50         if (tree[u].sum) tree[u].sum--;
51         return;
52     }
53     int mid = (l + r - 1) / 2;
54     if (x <= mid) {
55         if (!tree[u].ls) return;

```

```

56     remove(tree[u].ls, l, mid, x);
57 } else {
58     if (!tree[u].rs) return;
59     remove(tree[u].rs, mid + 1, r, x);
60 }
61 push_up(u);
62 };
63
64 std::function<int(int, int, int, int)> get_rank_by_key = [&](int u, int l, int r, int x) -> int {
65     if (l == r) {
66         return 1;
67     }
68     int mid = (l + r - 1) / 2;
69     int ans = 0;
70     if (x <= mid) {
71         if (!tree[u].ls) return 1;
72         ans = get_rank_by_key(tree[u].ls, l, mid, x);
73     } else {
74         if (!tree[u].rs) return tree[tree[u].ls].sum + 1;
75         if (!tree[u].ls) {
76             ans = get_rank_by_key(tree[u].rs, mid + 1, r, x);
77         } else {
78             ans = get_rank_by_key(tree[u].rs, mid + 1, r, x) + tree[tree[u].ls].sum;
79         }
80     }
81     return ans;
82 };
83
84 std::function<int(int, int, int, int)> get_key_by_rank = [&](int u, int l, int r, int x) -> int {
85     if (l == r) {
86         return 1;
87     }
88     int mid = (l + r - 1) / 2;
89     if (tree[u].ls) {
90         if (x <= tree[tree[u].ls].sum) {
91             return get_key_by_rank(tree[u].ls, l, mid, x);
92         } else {
93             return get_key_by_rank(tree[u].rs, mid + 1, r, x - tree[tree[u].ls].sum);
94         }
95     } else {
96         return get_key_by_rank(tree[u].rs, mid + 1, r, x);
97     }
98 };
99
100 std::function<int(int)> get_prev = [&](int x) -> int {
101     int rank = get_rank_by_key(1, -10000000, 10000000, x) - 1;
102     debug(rank);
103     return get_key_by_rank(1, -10000000, 10000000, rank);
104 };
105
106 std::function<int(int)> get_next = [&](int x) -> int {
107     debug(x + 1);
108     int rank = get_rank_by_key(1, -10000000, 10000000, x + 1);
109     debug(rank);
110     return get_key_by_rank(1, -10000000, 10000000, rank);
111 };

```

2.7.2 (权值) 线段树合并

```

1 // Problem: 洛谷: P4556 [Vani有约会]雨天的尾巴 / 【模板】线段树合并
2
3 struct node {
4     int l, r, id;
5     int ls, rs;
6     int cnt, ans;
7
8     node(int _id, int _l, int _r) : id(_id), l(_l), r(_r) {
9         ls = rs = 0;
10        cnt = ans = 0;
11    }
12 };
13
14 int main() {
15     std::ios::sync_with_stdio(false);
16     std::cin.tie(0);
17     std::cout.tie(0);
18
19     int n, m;
20     std::cin >> n >> m;
21     vvi e(n + 1);
22     vi ans(n + 1);
23     for (int i = 1; i < n; i++) {
24         int u, v;

```

```

25     std::cin >> u >> v;
26     e[u].push_back(v);
27     e[v].push_back(u);
28 }
29
30 // Segment tree //
31 int idx = 1;
32 vi rt(n + 1);
33 std::vector<node> tree = {node{0, 0, 0}};
34
35 auto new_node = [&](int l, int r) -> int {
36     tree.push_back(node(idx, l, r));
37     return idx++;
38 };
39
40 auto push_up = [&](int u) -> void {
41     if (!tree[u].ls) {
42         tree[u].cnt = tree[tree[u].rs].cnt;
43         tree[u].ans = tree[tree[u].rs].ans;
44     } else if (!tree[u].rs) {
45         tree[u].cnt = tree[tree[u].ls].cnt;
46         tree[u].ans = tree[tree[u].ls].ans;
47     } else {
48         if (tree[tree[u].rs].cnt > tree[tree[u].ls].cnt) {
49             tree[u].cnt = tree[tree[u].rs].cnt;
50             tree[u].ans = tree[tree[u].rs].ans;
51         } else {
52             tree[u].cnt = tree[tree[u].ls].cnt;
53             tree[u].ans = tree[tree[u].ls].ans;
54         }
55     }
56 };
57
58 std::function<void(int, int, int, int, int)> modify = [&](int u, int l, int r, int x, int k) {
59     if (l == r) {
60         tree[u].cnt += k;
61         tree[u].ans = 1;
62         return;
63     }
64     int mid = (l + r) >> 1;
65     if (x <= mid) {
66         if (!tree[u].ls) tree[u].ls = new_node(l, mid);
67         modify(tree[u].ls, l, mid, x, k);
68     } else {
69         if (!tree[u].rs) tree[u].rs = new_node(mid + 1, r);
70         modify(tree[u].rs, mid + 1, r, x, k);
71     }
72     push_up(u);
73 };
74
75 std::function<int(int, int, int, int)> merge = [&](int u, int v, int l, int r) -> int {
76     // v 的信息传递给 u //
77     if (!u) return v;
78     if (!v) return u;
79     if (l == r) {
80         tree[u].cnt += tree[v].cnt;
81         return u;
82     }
83     int mid = (l + r) >> 1;
84     tree[u].ls = merge(tree[u].ls, tree[v].ls, l, mid);
85     tree[u].rs = merge(tree[u].rs, tree[v].rs, mid + 1, r);
86     push_up(u);
87     return u;
88 };
89
90 // LCA //
91
92 for (int i = 1; i <= n; i++) {
93     rt[i] = idx;
94     new_node(1, 100000);
95 }
96
97 for (int i = 1; i <= m; i++) {
98     int u, v, w;
99     std::cin >> u >> v >> w;
100     int lca = LCA(u, v);
101     modify(rt[u], 1, 100000, w, 1);
102     modify(rt[v], 1, 100000, w, 1);
103     modify(rt[lca], 1, 100000, w, -1);
104     if (father[lca][0]) {
105         modify(rt[father[lca][0]], 1, 100000, w, -1);
106     }
107 }
108
109 // dfs //
110 std::function<void(int, int)> Dfs = [&](int u, int fa) {
111     for (auto v : e[u]) {

```

```

112         if (v == fa) continue;
113         Dfs(v, u);
114         merge(rt[u], rt[v], 1, 100000);
115     }
116     ans[u] = tree[rt[u]].ans;
117     if (tree[rt[u]].cnt == 0) ans[u] = 0;
118 };
119
120 Dfs(1, 0);
121
122 for (int i = 1; i <= n; i++) {
123     std::cout << ans[i] << endl;
124 }
125
126 return 0;
127 }

```

2.8 划分树

n 个数, q 次查询, 每次查询区间 $[l, r]$ 中的第 k 大数.

```

1  int n, q, k, l, r;
2  int tree[20][N], toleft[20][N], sorted[N];
3
4  void build(int dep, int l, int r) {
5      if (l == r) return;
6      int mid = (l + r) >> 1;
7      int cnt = mid - l + 1;
8      for (int i = l; i <= r; i++) {
9          if (tree[dep][i] < sorted[mid]) cnt--;
10     }
11     int ls = l, rs = mid + 1;
12     for (int i = l; i <= r; i++) {
13         int flag = 0;
14         if (tree[dep][i] < sorted[mid] || (tree[dep][i] == sorted[mid] && cnt > 0)) {
15             flag = 1;
16             tree[dep + 1][ls++] = tree[dep][i];
17             if (tree[dep][i] == sorted[mid]) cnt--;
18         } else
19             tree[dep + 1][rs++] = tree[dep][i];
20         toleft[dep][i] = toleft[dep][i - 1] + flag;
21     }
22     build(dep + 1, l, mid), build(dep + 1, mid + 1, r);
23 }
24
25 int query(int dep, int ql, int qr, int l, int r, int k) {
26     if (l == r) return tree[dep][l];
27     int mid = (l + r) >> 1;
28     int x = toleft[dep][ql - 1] - toleft[dep][l - 1];
29     int y = toleft[dep][qr] - toleft[dep][l - 1];
30     int rx = ql - l - x, ry = qr - l - y, len = y - x;
31     if (len >= k)
32         return query(dep + 1, l + x, l + y - 1, l, mid, k);
33     else
34         return query(dep + 1, mid + rx + 1, mid + ry + 1, mid + 1, r, k - len);
35 }
36
37 int main() {
38     std::ios::sync_with_stdio(false);
39     std::cin.tie(0);
40     std::cout.tie(0);
41
42     std::cin >> n >> q;
43     rep(i, 1, n) std::cin >> sorted[i], tree[1][i] = sorted[i];
44     std::sort(sorted + 1, sorted + n + 1);
45     build(1, 1, n);
46     while (q--) {
47         std::cin >> l >> r >> k;
48         std::cout << query(1, l, r, 1, n, k) << endl;
49     }
50     return 0;
51 }

```

2.9 可持久化线段树

2.9.1 第 1 个例题

n 个数, m 次操作, 操作分别为:

- v_i 1 loc_i $value_i$: 将第 v_i 个版本的 $a[loc_i]$ 修改为 $value_i$
- v_i 2 loc_i : 拷贝第 v_i 个版本, 并查询该版本的 $a[loc_i]$

```

1 // 洛谷 P3919 【模板】可持久化线段树 1(可持久化数组)
2
3 struct node {
4     int l, r, key;
5 };
6
7 int main() {
8     std::ios::sync_with_stdio(false);
9     std::cin.tie(0);
10    std::cout.tie(0);
11
12    int n, m;
13    std::cin >> n >> m;
14    vi a(n + 1);
15    for (int i = 1; i <= n; i++) {
16        std::cin >> a[i];
17    }
18
19    // hjt segment tree //
20    int idx = 0;
21    vi root(m + 1);
22    std::vector<node> tr(n * 25);
23
24    std::function<int(int, int)> build = [&](int l, int r) -> int {
25        int p = ++idx;
26        if (l == r) {
27            tr[p].key = a[l];
28            return p;
29        }
30        int mid = (l + r) >> 1;
31        tr[p].l = build(l, mid);
32        tr[p].r = build(mid + 1, r);
33        return p;
34    };
35
36    std::function<int(int, int, int, int, int)> modify = [&](int p, int l, int r, int k,
37                                                            int x) -> int {
38        int q = ++idx;
39        tr[q].l = tr[p].l, tr[q].r = tr[p].r;
40        if (tr[q].l == tr[q].r) {
41            tr[q].key = x;
42            return q;
43        }
44        int mid = (l + r) >> 1;
45        if (k <= mid) {
46            tr[q].l = modify(tr[q].l, l, mid, k, x);
47        } else {
48            tr[q].r = modify(tr[q].r, mid + 1, r, k, x);
49        }
50        return q;
51    };
52
53    std::function<int(int, int, int, int)> query = [&](int p, int l, int r, int k) -> int {
54        if (tr[p].l == tr[p].r) {
55            return tr[p].key;
56        }
57        int mid = (l + r) >> 1;
58        if (k <= mid) {
59            return query(tr[p].l, l, mid, k);
60        } else {
61            return query(tr[p].r, mid + 1, r, k);
62        }
63    };
64
65    root[0] = build(1, n);
66
67    for (int i = 1; i <= m; i++) {
68        int op, ver, k, x;
69        std::cin >> ver >> op;
70        if (op == 1) {
71            std::cin >> k >> x;
72            root[i] = modify(root[ver], 1, n, k, x);
73        } else {

```

```

74         std::cin >> k;
75         root[i] = root[ver];
76         std::cout << query(root[ver], 1, n, k) << endl;
77     }
78 }
79
80 return 0;
81 }

```

指针写法 (可惜洛谷上 #2 点会 *MLE*, 更新数据后变成 *TLE* 了)

```

1  int n, m, k, x, vi, op, a[N];
2
3  struct node {
4      node *ch[2];
5      int key;
6
7      node() {
8          key = 0;
9          ch[0] = ch[1] = nullptr;
10     }
11
12     node(node *_node) {
13         key = _node->key;
14         ch[0] = _node->ch[0], ch[1] = _node->ch[1];
15     }
16 };
17
18 struct segment_tree {
19     node *root[N];
20
21     node *build(int l, int r) {
22         node *new_node;
23         new_node = new node();
24         if (l == r) {
25             new_node->key = a[l];
26             return new_node;
27         }
28         int mid = (l + r) >> 1;
29         new_node->ch[0] = build(l, mid);
30         new_node->ch[1] = build(mid + 1, r);
31         return new_node;
32     }
33
34     // a[k] 改成 x //
35     node *modify(node *p, int l, int r, int k, int x) {
36         node *new_node;
37         new_node = new node(p);
38         if (l == r) {
39             new_node->key = x;
40             return new_node;
41         }
42         int mid = (l + r) >> 1;
43         if (k <= mid)
44             new_node->ch[0] = modify(new_node->ch[0], l, mid, k, x);
45         else
46             new_node->ch[1] = modify(new_node->ch[1], mid + 1, r, k, x);
47         return new_node;
48     }
49
50     // 询问 p 为根节点的版本的 a[k] //
51     int query(node *p, int l, int r, int k) {
52         if (l == r) {
53             return p->key;
54         }
55         int mid = (l + r) >> 1;
56         if (k <= mid)
57             return query(p->ch[0], l, mid, k);
58         else
59             return query(p->ch[1], mid + 1, r, k);
60     }
61 };
62
63 segment_tree tr;
64
65 int main() {
66     ios::sync_with_stdio(false);
67     cin.tie(0);
68     cout.tie(0);
69
70     cin >> n >> m;
71     rep(i, 1, n) cin >> a[i];
72     tr.root[0] = tr.build(1, n);
73     rep(i, 1, m) {
74         cin >> vi >> op;

```



```

75     if (op == 1) {
76         cin >> k >> x;
77         tr.root[i] = tr.modify(tr.root[vi], 1, n, k, x);
78     } else {
79         cin >> k;
80         tr.root[i] = tr.root[vi];
81         cout << tr.query(tr.root[vi], 1, n, k) << endl;
82     }
83 }
84 return 0;
85 }

```

2.9.2 第 2 个例题

长度为 n 的序列 a , m 次查询, 每次查询 $[l, r]$ 中的第 k 小值.

```

1 // 洛谷P3834 【模板】可持久化线段树 2
2
3 struct node {
4     int l, r, cnt;
5 };
6
7 int main() {
8     std::ios::sync_with_stdio(false);
9     std::cin.tie(0);
10    std::cout.tie(0);
11
12    int n, m;
13    std::cin >> n >> m;
14    vi a(n + 1), v;
15    for (int i = 1; i <= n; i++) {
16        std::cin >> a[i];
17        v.push_back(a[i]);
18    }
19    std::sort(all(v));
20    v.erase(unique(all(v)), v.end());
21    auto find = [&](int x) -> int { return std::lower_bound(all(v), x) - v.begin() + 1; };
22
23    // hjt segment tree //
24    std::vector<node>(n * 25);
25    vi root(n + 1);
26    int idx = 0;
27
28    std::function<int(int, int)> build = [&](int l, int r) -> int {
29        int p = ++idx;
30        if (l == r) return p;
31        int mid = (l + r) >> 1;
32        tr[p].l = build(l, mid), tr[p].r = build(mid + 1, r);
33        return p;
34    };
35
36    std::function<int(int, int, int, int)> modify = [&](int p, int l, int r, int x) -> int {
37        int q = ++idx;
38        tr[q] = tr[p];
39        if (tr[q].l == tr[q].r) {
40            tr[q].cnt++;
41            return q;
42        }
43        int mid = (l + r) >> 1;
44        if (x <= mid) {
45            tr[q].l = modify(tr[q].l, l, mid, x);
46        } else {
47            tr[q].r = modify(tr[q].r, mid + 1, r, x);
48        }
49        tr[q].cnt = tr[tr[q].l].cnt + tr[tr[q].r].cnt;
50        return q;
51    };
52
53    std::function<int(int, int, int, int, int)> query = [&](int p, int q, int l, int r,
54        int x) -> int {
55        if (l == r) return l;
56        int cnt = tr[tr[p].l].cnt - tr[tr[q].l].cnt;
57        int mid = (l + r) >> 1;
58        if (x <= cnt) {
59            return query(tr[p].l, tr[q].l, l, mid, x);
60        } else {
61            return query(tr[p].r, tr[q].r, mid + 1, r, x - cnt);
62        }
63    };
64
65    root[0] = build(1, v.size());
66

```

```

67 |
68 |     for (int i = 1; i <= n; i++) {
69 |         root[i] = modify(root[i - 1], 1, v.size(), find(a[i]));
70 |     }
71 |     for (int i = 1; i <= m; i++) {
72 |         int l, r, k;
73 |         std::cin >> l >> r >> k;
74 |         std::cout << v[query(root[r], root[l - 1], 1, v.size(), k) - 1] << endl;
75 |     }
76 |
77 |     return 0;
78 | }

```

指针写法

```

1 | int n, m, a[N];
2 | vector<int> v;
3 |
4 | int find(int x) { return lower_bound(all(v), x) - v.begin() + 1; }
5 |
6 | struct node {
7 |     node *ch[2];
8 |     int cnt;
9 |
10 |    node() {
11 |        cnt = 0;
12 |        ch[0] = ch[1] = nullptr;
13 |    }
14 |
15 |    node(node *_node) {
16 |        cnt = _node->cnt;
17 |        ch[0] = _node->ch[0], ch[1] = _node->ch[1];
18 |    }
19 | };
20 |
21 | struct segment_tree {
22 |     node *root[N];
23 |
24 |     node *build(int l, int r) {
25 |         node *new_node;
26 |         new_node = new node();
27 |         if (l == r) {
28 |             return new_node;
29 |         }
30 |         int mid = (l + r) >> 1;
31 |         new_node->ch[0] = build(l, mid);
32 |         new_node->ch[1] = build(mid + 1, r);
33 |         return new_node;
34 |     }
35 |
36 |     node *modify(node *p, int l, int r, int x) {
37 |         node *new_node;
38 |         new_node = new node(p);
39 |         if (l == r) {
40 |             new_node->cnt++;
41 |             return new_node;
42 |         }
43 |         int mid = (l + r) >> 1;
44 |         if (x <= mid)
45 |             new_node->ch[0] = modify(new_node->ch[0], l, mid, x);
46 |         else
47 |             new_node->ch[1] = modify(new_node->ch[1], mid + 1, r, x);
48 |         new_node->cnt = new_node->ch[0]->cnt + new_node->ch[1]->cnt;
49 |         return new_node;
50 |     }
51 |
52 |     int query(node *p, node *q, int l, int r, int x) {
53 |         if (l == r) {
54 |             return l;
55 |         }
56 |         int cnt = p->ch[0]->cnt - q->ch[0]->cnt;
57 |         int mid = (l + r) >> 1;
58 |         if (x <= cnt)
59 |             return query(p->ch[0], q->ch[0], l, mid, x);
60 |         else
61 |             return query(p->ch[1], q->ch[1], mid + 1, r, x - cnt);
62 |     }
63 | };
64 |
65 | segment_tree tr;
66 |
67 | int main() {
68 |     ios::sync_with_stdio(false);
69 |     cin.tie(0);
70 |     cout.tie(0);
71 |

```

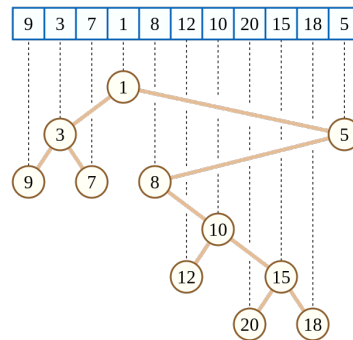
```

72     cin >> n >> m;
73     rep(i, 1, n) {
74         cin >> a[i];
75         v.p_b(a[i]);
76     }
77
78     sort(all(v));
79     v.erase(unique(all(v)), v.end());
80
81     tr.root[0] = tr.build(1, v.size());
82     rep(i, 1, n) { tr.root[i] = tr.modify(tr.root[i - 1], 1, v.size(), find(a[i])); }
83     rep(i, 1, m) {
84         int l, r, k;
85         cin >> l >> r >> k;
86         cout << v[tr.query(tr.root[r], tr.root[l - 1], 1, v.size(), k) - 1] << endl;
87     }
88     return 0;
89 }

```

2.10 笛卡尔树

一种特殊的平衡树, 用元素的值作为平衡点节点的 *val*, 元素的下标作为 *key*.



```

1 // cartesian tree //
2 vi ls(n + 1), rs(n + 1), stk(n + 1);
3 int top = 1;
4 for (int i = 1; i <= n; i++) {
5     int k = top;
6     while (k and a[stk[k]] > a[i]) k--;
7     if (k) rs[stk[k]] = i;
8     if (k < top) ls[i] = stk[k + 1];
9     stk[++k] = i;
10    top = k;
11 }

```

2.11 Treap

n 次操作, 操作分为如下 6 种:

- 插入数 x
- 删除数 x (若有多个相同的数, 只删除一个)
- 查询数 x 的排名 (排名定义为小于 x 的数的个数 + 1)
- 查询数 x 的排名
- 求 x 的前驱 (前驱定义为小于 x 的最大数)
- 求 x 的后继 (后继定义为大于 x 的最小数)

2.11.1 旋转 Treap

```

1 // Problem: 洛谷: P3369 【模板】普通平衡树
2
3 int n, root, idx;
4
5 struct node {
6     int l, r;
7     int key, val;
8     int cnt, size;
9 } treap[N];
10
11 void push_up(int p) {
12     treap[p].size = treap[treap[p].l].size + treap[treap[p].r].size + treap[p].cnt;
13 }
14
15 int get_node(int key) {
16     treap[++idx].key = key;
17     treap[idx].val = rand();
18     treap[idx].cnt = treap[idx].size = 1;
19     return idx;
20 }
21
22 void zig(int &p) {
23     // 右旋 //
24     int q = treap[p].l;
25     treap[p].l = treap[q].r, treap[q].r = p, p = q;
26     push_up(treap[p].r), push_up(p);
27 }
28
29 void zag(int &p) {
30     // 左旋 //
31     int q = treap[p].r;
32     treap[p].r = treap[q].l, treap[q].l = p, p = q;
33     push_up(treap[p].l), push_up(p);
34 }
35
36 void build() {
37     get_node(-inf), get_node(inf);
38     root = 1, treap[1].r = 2;
39     push_up(root);
40     if (treap[1].val < treap[2].val) zag(root);
41 }
42
43 void insert(int &p, int key) {
44     if (!p) {
45         p = get_node(key);
46     } else if (treap[p].key == key) {
47         treap[p].cnt++;
48     } else if (treap[p].key > key) {
49         insert(treap[p].l, key);
50         if (treap[treap[p].l].val > treap[p].val) zig(p);
51     } else {
52         insert(treap[p].r, key);
53         if (treap[treap[p].r].val > treap[p].val) zag(p);
54     }
55     push_up(p);
56 }
57
58 void remove(int &p, int key) {
59     if (!p) return;
60     if (treap[p].key == key) {
61         if (treap[p].cnt > 1) {
62             treap[p].cnt--;
63         } else if (treap[p].l || treap[p].r) {
64             if (!treap[p].r || treap[treap[p].l].val > treap[treap[p].r].val) {
65                 zig(p);
66                 remove(treap[p].r, key);
67             } else {
68                 zag(p);
69                 remove(treap[p].l, key);
70             }
71         } else {
72             p = 0;
73         }
74     } else if (treap[p].key > key) remove(treap[p].l, key);
75     else remove(treap[p].r, key);
76     push_up(p);
77 }
78
79 int get_rank_by_key(int p, int key) {
80     // 通过数值找排名 //
81     if (!p) return 0;
82     if (treap[p].key == key) return treap[treap[p].l].size;
83     if (treap[p].key > key) return get_rank_by_key(treap[p].l, key);
84 }

```

```

87     return treap[treap[p].l].size + treap[p].cnt + get_rank_by_key(treap[p].r, key);
88 }
89
90 int get_key_by_rank(int p, int rank) {
91     // 通过排名找数值 //
92     if (!p) return inf;
93     if (treap[treap[p].l].size >= rank) return get_key_by_rank(treap[p].l, rank);
94     if (treap[treap[p].l].size + treap[p].cnt >= rank) return treap[p].key;
95     return get_key_by_rank(treap[p].r, rank - treap[treap[p].l].size - treap[p].cnt);
96 }
97
98 int get_prev(int p, int key) {
99     // 找前驱 //
100    if (!p) return -inf;
101    if (treap[p].key >= key) return get_prev(treap[p].l, key);
102    return max(treap[p].key, get_prev(treap[p].r, key));
103 }
104
105 int get_next(int p, int key) {
106     // 找后继 //
107     if (!p) return inf;
108     if (treap[p].key <= key) return get_next(treap[p].r, key);
109     return min(treap[p].key, get_next(treap[p].l, key));
110 }
111
112 int main() {
113     ios::sync_with_stdio(false);
114     cin.tie(0);
115     cout.tie(0);
116
117     cin >> n;
118     build();
119     rep(i, 1, n) {
120         int op, x;
121         cin >> op >> x;
122         if (op == 1) {
123             insert(root, x);
124         } else if (op == 2) {
125             remove(root, x);
126         } else if (op == 3) {
127             cout << get_rank_by_key(root, x) << endl;
128         } else if (op == 4) {
129             cout << get_key_by_rank(root, x + 1) << endl;
130         } else if (op == 5) {
131             cout << get_prev(root, x) << endl;
132         } else {
133             cout << get_next(root, x) << endl;
134         }
135     }
136     return 0;
137 }

```

2.11.2 无旋 Treap

```

1  // created on Laptop of Lucian Xu
2
3  struct node {
4      node *ch[2];
5      int key, val;
6      int cnt, size;
7
8      node(int _key) : key(_key), cnt(1), size(1) {
9          ch[0] = ch[1] = nullptr;
10         val = rand();
11     }
12
13     // node(node *_node) {
14     //     key = _node->key, val = _node->val, cnt = _node->cnt, size = _node->size;
15     // }
16
17     inline void push_up() {
18         size = cnt;
19         if (ch[0] != nullptr) size += ch[0]->size;
20         if (ch[1] != nullptr) size += ch[1]->size;
21     }
22 };
23
24 struct treap {
25     #define _2 second.first
26     #define _3 second.second
27
28     node *root;
29

```

```

30 pair<node *, node *> split(node *p, int key) {
31     if (p == nullptr) return {nullptr, nullptr};
32     if (p->key <= key) {
33         auto temp = split(p->ch[1], key);
34         p->ch[1] = temp.first;
35         p->push_up();
36         return {p, temp.second};
37     } else {
38         auto temp = split(p->ch[0], key);
39         p->ch[0] = temp.second;
40         p->push_up();
41         return {temp.first, p};
42     }
43 }
44
45 pair<node *, pair<node *, node *> > split_by_rank(node *p, int rank) {
46     if (p == nullptr) return {nullptr, {nullptr, nullptr}};
47     int ls_size = p->ch[0] == nullptr ? 0 : p->ch[0]->size;
48     if (rank <= ls_size) {
49         auto temp = split_by_rank(p->ch[0], rank);
50         p->ch[0] = temp._3;
51         p->push_up();
52         return {temp.first, {temp._2, p}};
53     } else if (rank <= ls_size + p->cnt) {
54         node *lt = p->ch[0];
55         node *rt = p->ch[1];
56         p->ch[0] = p->ch[1] = nullptr;
57         return {lt, {p, rt}};
58     } else {
59         auto temp = split_by_rank(p->ch[1], rank - ls_size - p->cnt);
60         p->ch[1] = temp.first;
61         p->push_up();
62         return {p, {temp._2, temp._3}};
63     }
64 }
65
66 node *merge(node *u, node *v) {
67     if (u == nullptr && v == nullptr) return nullptr;
68     if (u != nullptr && v == nullptr) return u;
69     if (v != nullptr && u == nullptr) return v;
70     if (u->val < v->val) {
71         u->ch[1] = merge(u->ch[1], v);
72         u->push_up();
73         return u;
74     } else {
75         v->ch[0] = merge(u, v->ch[0]);
76         v->push_up();
77         return v;
78     }
79 }
80
81 void insert(int key) {
82     auto temp = split(root, key);
83     auto l_tr = split(temp.first, key - 1);
84     node *new_node;
85     if (l_tr.second == nullptr) {
86         new_node = new node(key);
87     } else {
88         l_tr.second->cnt++;
89         l_tr.second->push_up();
90     }
91     node *l_tr_combined = merge(l_tr.first, l_tr.second == nullptr ? new_node : l_tr.second);
92     root = merge(l_tr_combined, temp.second);
93 }
94
95 void remove(int key) {
96     auto temp = split(root, key);
97     auto l_tr = split(temp.first, key - 1);
98     if (l_tr.second->cnt > 1) {
99         l_tr.second->cnt--;
100         l_tr.second->push_up();
101         l_tr.first = merge(l_tr.first, l_tr.second);
102     } else {
103         if (temp.first == l_tr.second) temp.first = nullptr;
104         delete l_tr.second;
105         l_tr.second = nullptr;
106     }
107     root = merge(l_tr.first, temp.second);
108 }
109
110 int get_rank_by_key(node *p, int key) {
111     auto temp = split(p, key - 1);
112     int ret = (temp.first == nullptr ? 0 : temp.first->size) + 1;
113     root = merge(temp.first, temp.second);
114     return ret;
115 }
116

```

```

117 int get_key_by_rank(node *p, int rank) {
118     auto temp = split_by_rank(p, rank);
119     int ret = temp._2->key;
120     root = merge(temp.first, merge(temp._2, temp._3));
121     return ret;
122 }
123
124 int get_prev(int key) {
125     auto temp = split(root, key - 1);
126     int ret = get_key_by_rank(temp.first, temp.first->size);
127     root = merge(temp.first, temp.second);
128     return ret;
129 }
130
131 int get_nex(int key) {
132     auto temp = split(root, key);
133     int ret = get_key_by_rank(temp.second, 1);
134     root = merge(temp.first, temp.second);
135     return ret;
136 }
137 };
138
139 treap tr;
140
141 int main() {
142     ios::sync_with_stdio(false);
143     cin.tie(0);
144     cout.tie(0);
145
146     srand(time(0));
147
148     int n;
149     cin >> n;
150     while (n-->0) {
151         int op, x;
152         cin >> op >> x;
153         if (op == 1) {
154             tr.insert(x);
155         } else if (op == 2) {
156             tr.remove(x);
157         } else if (op == 3) {
158             cout << tr.get_rank_by_key(tr.root, x) << endl;
159         } else if (op == 4) {
160             cout << tr.get_key_by_rank(tr.root, x) << endl;
161         } else if (op == 5) {
162             cout << tr.get_prev(x) << endl;
163         } else {
164             cout << tr.get_nex(x) << endl;
165         }
166     }
167     return 0;
168 }

```

2.11.3 用 01 Trie 实现

使用 01 Trie 只能存在非负数.

速度能快不少, 但只能单点操作, 而且有点费空间.

```

1 // 洛谷 P3369 【模板】普通平衡树
2
3 struct Treap {
4     int id = 1, maxlog = 25;
5     int ch[N * 25][2], siz[N * 25];
6
7     int newnode() {
8         id++;
9         ch[id][0] = ch[id][1] = siz[id] = 0;
10        return id;
11    }
12
13    void merge(int key, int cnt) {
14        int u = 1;
15        for (int i = maxlog - 1; i >= 0; i--) {
16            int v = (key >> i) & 1;
17            if (!ch[u][v]) ch[u][v] = newnode();
18            u = ch[u][v];
19            siz[u] += cnt;
20        }
21    }
22
23    int get_key_by_rank(int rank) {

```

```

24     int u = 1, key = 0;
25     for (int i = maxlog - 1; i >= 0; i--) {
26         if (siz[ch[u][0]] >= rank) {
27             u = ch[u][0];
28         } else {
29             key |= (1 << i);
30             rank -= siz[ch[u][0]];
31             u = ch[u][1];
32         }
33     }
34     return key;
35 }
36
37 int get_rank_by_key(int rank) {
38     int key = 0;
39     int u = 1;
40     for (int i = maxlog - 1; i >= 0; i--) {
41         if ((rank >> i) & 1) {
42             key += siz[ch[u][0]];
43             u = ch[u][1];
44         } else {
45             u = ch[u][0];
46         }
47         if (!u) break;
48     }
49     return key;
50 }
51
52 int get_prev(int x) { return get_key_by_rank(get_rank_by_key(x)); }
53 int get_next(int x) { return get_key_by_rank(get_rank_by_key(x + 1) + 1); }
54 } treap;
55
56 const int num = 1e7;
57 int n, op, x;
58
59 int main() {
60     std::ios::sync_with_stdio(false);
61     std::cin.tie(0);
62     std::cout.tie(0);
63
64     std::cin >> n;
65     for (int i = 1; i <= n; i++) {
66         std::cin >> op >> x;
67         if (op == 1) {
68             treap.merge(x + num, 1);
69         } else if (op == 2) {
70             treap.merge(x + num, -1);
71         } else if (op == 3) {
72             std::cout << treap.get_rank_by_key(x + num) + 1 << endl;
73         } else if (op == 4) {
74             std::cout << treap.get_key_by_rank(x) - num << endl;
75         } else if (op == 5) {
76             std::cout << treap.get_prev(x + num) - num << endl;
77         } else if (op == 6) {
78             std::cout << treap.get_next(x + num) - num << endl;
79         }
80     }
81     return 0;
82 }

```

2.12 Splay

2.12.1 文艺平衡树

初始为 1 到 n 的序列, m 次操作, 每次将序列下标为 $[l \sim r]$ 的区间翻转.

```

1 // 洛谷 P3391 【模板】文艺平衡树
2
3 struct node {
4     int ch[2], fa, key;
5     int siz, flag;
6
7     void init(int _fa, int _key) { fa = _fa, key = _key, siz = 1; }
8 };
9
10 struct splay {
11     node tr[N];
12     int n, root, idx;
13
14     bool get(int u) { return u == tr[tr[u].fa].ch[1]; }
15 }

```



```

16 void pushup(int u) { tr[u].siz = tr[tr[u].ch[0]].siz + tr[tr[u].ch[1]].siz + 1; }
17
18 void pushdown(int u) {
19     if (tr[u].flag) {
20         std::swap(tr[u].ch[0], tr[u].ch[1]);
21         tr[tr[u].ch[0]].flag ^= 1, tr[tr[u].ch[1]].flag ^= 1;
22         tr[u].flag = 0;
23     }
24 }
25
26 void rotate(int x) {
27     int y = tr[x].fa, z = tr[y].fa;
28     int op = get(x);
29     tr[y].ch[op] = tr[x].ch[op ^ 1];
30     if (tr[x].ch[op ^ 1]) tr[tr[x].ch[op ^ 1]].fa = y;
31     tr[x].ch[op ^ 1] = y;
32     tr[y].fa = x, tr[x].fa = z;
33     if (z) tr[z].ch[y == tr[z].ch[1]] = x;
34     pushup(y), pushup(x);
35 }
36
37 void opt(int u, int k) {
38     for (int f = tr[u].fa; f != k; rotate(u)) {
39         if (tr[f].fa != k) rotate(get(u) == get(f) ? f : u);
40     }
41     if (k == 0) root = u;
42 }
43
44 void output(int u) {
45     pushdown(u);
46     if (tr[u].ch[0]) output(tr[u].ch[0]);
47     if (tr[u].key >= 1 && tr[u].key <= n) {
48         std::cout << tr[u].key << ' ';
49     }
50     if (tr[u].ch[1]) output(tr[u].ch[1]);
51 }
52
53 void insert(int key) {
54     idx++;
55     tr[idx].ch[0] = root;
56     tr[idx].init(0, key);
57     tr[root].fa = idx;
58     root = idx;
59     pushup(idx);
60 }
61
62 int kth(int k) {
63     int u = root;
64     while (1) {
65         pushdown(u);
66         if (tr[u].ch[0] && k <= tr[tr[u].ch[0]].siz) {
67             u = tr[u].ch[0];
68         } else {
69             k -= tr[tr[u].ch[0]].siz + 1;
70             if (k <= 0) {
71                 opt(u, 0);
72                 return u;
73             } else {
74                 u = tr[u].ch[1];
75             }
76         }
77     }
78 }
79
80 } splay;
81
82 int n, m, l, r;
83
84 int main() {
85     std::ios::sync_with_stdio(false);
86     std::cin.tie(0);
87     std::cout.tie(0);
88
89     std::cin >> n >> m;
90     splay.n = n;
91     splay.insert(-inf);
92     rep(i, 1, n) splay.insert(i);
93     splay.insert(inf);
94     rep(i, 1, m) {
95         std::cin >> l >> r;
96         l = splay.kth(l), r = splay.kth(r + 2);
97         splay.opt(l, 0), splay.opt(r, 1);
98         splay.tr[splay.tr[r].ch[0]].flag ^= 1;
99     }
100     splay.output(splay.root);
101
102     return 0;

```

103 | }

2.12.2 普通平衡树

n 次操作, 操作分为如下 6 种:

- 插入数 x
- 删除数 x (若有多个相同的数, 只删除一个)
- 查询数 x 的排名 (排名定义为小于 x 的数的个数 + 1)
- 查询排名为 x 的数
- 求 x 的前驱 (前驱定义为小于 x 的最大数)
- 求 x 的后继 (后继定义为大于 x 的最小数)

```

1 // 洛谷 P3369 【模板】普通平衡树
2
3 struct node {
4     int ch[2], fa, key, siz, cnt;
5
6     void init(int _fa, int _key) { fa = _fa, key = _key, siz = cnt = 1; }
7
8     void clear() { ch[0] = ch[1] = fa = key = siz = cnt = 0; }
9 };
10
11 struct splay {
12     node tr[N];
13     int n, root, idx;
14
15     bool get(int u) { return u == tr[tr[u].fa].ch[1]; }
16
17     void pushup(int u) { tr[u].siz = tr[tr[u].ch[0]].siz + tr[tr[u].ch[1]].siz + tr[u].cnt; }
18
19     void rotate(int x) {
20         int y = tr[x].fa, z = tr[y].fa;
21         int op = get(x);
22         tr[y].ch[op] = tr[x].ch[op ^ 1];
23         if (tr[x].ch[op ^ 1]) tr[tr[x].ch[op ^ 1]].fa = y;
24         tr[x].ch[op ^ 1] = y;
25         tr[y].fa = x, tr[x].fa = z;
26         if (z) tr[z].ch[y == tr[z].ch[1]] = x;
27         pushup(y), pushup(x);
28     }
29
30     void opt(int u, int k) {
31         for (int f = tr[u].fa; f != k; rotate(u)) {
32             if (tr[f].fa != k) {
33                 rotate(get(u) == get(f) ? f : u);
34             }
35         }
36         if (k == 0) root = u;
37     }
38
39     void insert(int key) {
40         if (!root) {
41             idx++;
42             tr[idx].init(0, key);
43             root = idx;
44             return;
45         }
46         int u = root, f = 0;
47         while (1) {
48             if (tr[u].key == key) {
49                 tr[u].cnt++;
50                 pushup(u), pushup(f);
51                 opt(u, 0);
52                 break;
53             }
54             f = u, u = tr[u].ch[tr[u].key < key];
55             if (!u) {
56                 idx++;
57                 tr[idx].init(f, key);
58                 tr[f].ch[tr[f].key < key] = idx;
59                 pushup(idx), pushup(f);
60                 opt(idx, 0);
61                 break;

```

```

62     }
63 }
64 }
65
66 // 返回节点编号 //
67 int kth(int rank) {
68     int u = root;
69     while (1) {
70         if (tr[u].ch[0] && rank <= tr[tr[u].ch[0]].siz) {
71             u = tr[u].ch[0];
72         } else {
73             rank -= tr[tr[u].ch[0]].siz + tr[u].cnt;
74             if (rank <= 0) {
75                 opt(u, 0);
76                 return u;
77             } else {
78                 u = tr[u].ch[1];
79             }
80         }
81     }
82 }
83
84 // 返回排名 //
85 int nlt(int key) {
86     int rank = 0, u = root;
87     while (1) {
88         if (tr[u].key > key) {
89             u = tr[u].ch[0];
90         } else {
91             rank += tr[tr[u].ch[0]].siz;
92             if (tr[u].key == key) {
93                 opt(u, 0);
94                 return rank + 1;
95             }
96             rank += tr[u].cnt;
97             if (tr[u].ch[1]) {
98                 u = tr[u].ch[1];
99             } else {
100                 return rank + 1;
101             }
102         }
103     }
104 }
105
106 int get_prev(int key) { return kth(nlt(key) - 1); }
107
108 int get_next(int key) { return kth(nlt(key) + 1); }
109
110 void remove(int key) {
111     nlt(key);
112     if (tr[root].cnt > 1) {
113         tr[root].cnt--;
114         pushup(root);
115         return;
116     }
117     int u = root, l = get_prev(key);
118     tr[tr[u].ch[1]].fa = l;
119     tr[l].ch[1] = tr[u].ch[1];
120     tr[u].clear();
121     pushup(root);
122 }
123
124 void output(int u) {
125     if (tr[u].ch[0]) output(tr[u].ch[0]);
126     std::cout << tr[u].key << ' ';
127     if (tr[u].ch[1]) output(tr[u].ch[1]);
128 }
129
130 } splay;
131
132 int n, op, x;
133
134 int main() {
135     std::ios::sync_with_stdio(false);
136     std::cin.tie(0);
137     std::cout.tie(0);
138
139     splay.insert(-inf), splay.insert(inf);
140
141     std::cin >> n;
142     for (int i = 1; i <= n; i++) {
143         std::cin >> op >> x;
144         if (op == 1) {
145             splay.insert(x);
146         } else if (op == 2) {
147             splay.remove(x);
148         } else if (op == 3) {

```

```

149     std::cout << splay.nlt(x) - 1 << endl;
150 } else if (op == 4) {
151     std::cout << splay.tr[splay.kth(x + 1)].key << endl;
152 } else if (op == 5) {
153     std::cout << splay.tr[splay.get_prev(x)].key << endl;
154 } else if (op == 6) {
155     std::cout << splay.tr[splay.get_next(x)].key << endl;
156 }
157 }
158
159 return 0;
160 }

```

2.13 树套树

2.13.1 线段树套线段树

n 个三维数对 (a_i, b_i, c_i) , 设 $f(i)$ 表示 $a_j \leq a_i$ 且 $b_j \leq b_i$ 且 $c_j \leq c_i$ 且 $i \neq j$ 的个数.

输出 $f(i)$ ($0 \leq i \leq n-1$) 的值.

```

1 // 洛谷 P3810 【模板】三维偏序( 陌上花开 )
2
3 struct node1 {
4     int l, r, root;
5 } tr1[N << 2];
6
7 struct node2 {
8     int ch[2], cnt;
9 } tr2[N << 7];
10
11 struct node {
12     int x, y, z, cnt;
13
14     bool operator==(const node& a) { return (x == a.x && y == a.y && z == a.z); }
15 } data[N];
16
17 bool cmp(node a, node b) {
18     if (a.x != b.x) return a.x < b.x;
19     if (a.y != b.y) return a.y < b.y;
20     return a.z < b.z;
21 }
22
23 int root_tot, n, m, ans[N], anss[N];
24
25 void build(int u, int l, int r) {
26     tr1[u].l = l, tr1[u].r = r;
27     if (l != r) {
28         int mid = (l + r) >> 1;
29         build(u << 1, l, mid);
30         build(u << 1 | 1, mid + 1, r);
31     }
32 }
33
34 void modify_2(int& u, int l, int r, int pos) {
35     if (u == 0) u = ++root_tot;
36     tr2[u].cnt++;
37     if (l == r) return;
38     int mid = (l + r) >> 1;
39     if (pos <= mid) {
40         modify_2(tr2[u].ch[0], l, mid, pos);
41     } else {
42         modify_2(tr2[u].ch[1], mid + 1, r, pos);
43     }
44 }
45
46 int query_2(int& u, int l, int r, int x, int y) {
47     if (u == 0) return 0;
48     if (x <= l && r <= y) return tr2[u].cnt;
49     int mid = (l + r) >> 1, ans = 0;
50     if (x <= mid) ans += query_2(tr2[u].ch[0], l, mid, x, y);
51     if (mid < y) ans += query_2(tr2[u].ch[1], mid + 1, r, x, y);
52     return ans;
53 }
54
55 void modify_1(int u, int l, int r, int t) {
56     modify_2(tr1[u].root, 1, m, data[t].z);
57     if (l == r) return;
58     int mid = (l + r) >> 1;

```

```

60     if (data[t].y <= mid) {
61         modify_1(u << 1, l, mid, t);
62     } else {
63         modify_1(u << 1 | 1, mid + 1, r, t);
64     }
65 }
66
67 int query_1(int u, int l, int r, int t) {
68     if (1 <= l && r <= data[t].y) return query_2(tr1[u].root, 1, m, 1, data[t].z);
69     int mid = (l + r) >> 1, ans = 0;
70     if (1 <= mid) ans += query_1(u << 1, l, mid, t);
71     if (mid < data[t].y) ans += query_1(u << 1 | 1, mid + 1, r, t);
72     return ans;
73 }
74
75 int main() {
76     std::ios::sync_with_stdio(false);
77     std::cin.tie(0);
78     std::cout.tie(0);
79
80     std::cin >> n >> m;
81     rep(i, 1, n) {
82         int x, y, z;
83         std::cin >> x >> y >> z;
84         data[i] = {x, y, z};
85     }
86     std::sort(data + 1, data + n + 1, cmp);
87     build(1, 1, m);
88     rep(i, 1, n) {
89         modify_1(1, 1, m, i);
90         ans[i] = query_1(1, 1, m, i);
91     }
92     per(i, n - 1, 1) {
93         if (data[i] == data[i + 1]) ans[i] = ans[i + 1];
94     }
95     rep(i, 1, n) anss[ans[i]]++;
96     rep(i, 1, n) std::cout << anss[i] << endl;
97
98     return 0;
99 }

```

2.13.2 线段树套平衡树

长度为 n 的序列和 m 此操作, 包含 5 种操作:

- $l\ r\ k$: 询问区间 $[l \sim r]$ 中数 k 的排名.
- $l\ r\ k$: 询问区间 $[l \sim r]$ 中排名为 k 的数.
- $pos\ k$: 将序列中 pos 位置的数修改为 k .
- $l\ r\ k$: 询问区间 $[l \sim r]$ 中数 k 的前驱.
- $l\ r\ k$: 询问区间 $[l \sim r]$ 中数 k 的后继.

Treap 实现

```

1 // 洛谷 P3380 【模板】二逼平衡树(树套树)
2
3 int n, m, op, l, r, pos, key, root_tot;
4 int a[N];
5
6 struct node2 {
7     node2 *ch[2];
8     int key, val;
9     int cnt, size;
10
11     node2(int _key) : key(_key), cnt(1), size(1) {
12         ch[0] = ch[1] = nullptr;
13         val = rand();
14     }
15
16     // node2(node2 *_node2) {
17     //     key = _node2->key, val = _node2->val, cnt = _node2->cnt, size = _node2->size;
18     // }
19
20     inline void push_up() {
21         size = cnt;
22         if (ch[0] != nullptr) size += ch[0]->size;

```

```

23     if (ch[1] != nullptr) size += ch[1]->size;
24 }
25 };
26
27 struct treap {
28     ...
29 };
30
31 treap tr2[N << 4];
32
33 struct node1 {
34     int l, r, root;
35 } tr1[N << 4];
36
37 void build(int u, int l, int r) {
38     tr1[u] = {l, r, u};
39     root_tot = std::max(root_tot, u);
40     if (l == r) return;
41     int mid = (l + r) >> 1;
42     build(u << 1, l, mid), build(u << 1 | 1, mid + 1, r);
43 }
44
45 void modify(int u, int pos, int key) {
46     tr2[u].insert(key);
47     if (tr1[u].l == tr1[u].r) return;
48     int mid = (tr1[u].l + tr1[u].r) >> 1;
49     if (pos <= mid){
50         modify(u << 1, pos, key);
51     }
52     else{
53         modify(u << 1 | 1, pos, key);
54     }
55 }
56
57 int get_rank_by_key_in_interval(int u, int l, int r, int key) {
58     if (l <= tr1[u].l && tr1[u].r <= r) return tr2[u].get_rank_by_key(tr2[u].root, key) - 2;
59     int mid = (tr1[u].l + tr1[u].r) >> 1, ans = 0;
60     if (l <= mid) ans += get_rank_by_key_in_interval(u << 1, l, r, key);
61     if (mid < r) ans += get_rank_by_key_in_interval(u << 1 | 1, l, r, key);
62     return ans;
63 }
64
65 int get_key_by_rank_in_interval(int u, int l, int r, int rank) {
66     int L = 0, R = 1e8;
67     while (L < R) {
68         int mid = (L + R + 1) / 2;
69         if (get_rank_by_key_in_interval(1, l, r, mid) < rank){
70             L = mid;
71         }
72         else{
73             R = mid - 1;
74         }
75     }
76     return L;
77 }
78
79 void change(int u, int pos, int pre_key, int key) {
80     tr2[u].remove(pre_key);
81     tr2[u].insert(key);
82     if (tr1[u].l == tr1[u].r) return;
83     int mid = (tr1[u].l + tr1[u].r) >> 1;
84     if (pos <= mid){
85         change(u << 1, pos, pre_key, key);
86     }
87     else{
88         change(u << 1 | 1, pos, pre_key, key);
89     }
90 }
91
92 int get_prev_in_interval(int u, int l, int r, int key) {
93     if (l <= tr1[u].l && tr1[u].r <= r) return tr2[u].get_prev(key);
94     int mid = (tr1[u].l + tr1[u].r) >> 1, ans = -inf;
95     if (l <= mid) ans = std::max(ans, get_prev_in_interval(u << 1, l, r, key));
96     if (mid < r) ans = std::max(ans, get_prev_in_interval(u << 1 | 1, l, r, key));
97     return ans;
98 }
99
100 int get_nex_in_interval(int u, int l, int r, int key) {
101     if (l <= tr1[u].l && tr1[u].r <= r) return tr2[u].get_nex(key);
102     int mid = (tr1[u].l + tr1[u].r) >> 1, ans = inf;
103     if (l <= mid) ans = std::min(ans, get_nex_in_interval(u << 1, l, r, key));
104     if (mid < r) ans = std::min(ans, get_nex_in_interval(u << 1 | 1, l, r, key));
105     return ans;
106 }
107
108 int main() {
109     std::ios::sync_with_stdio(false);

```

```

110     std::cin.tie(0);
111     std::cout.tie(0);
112
113     srand(time(0));
114
115     std::cin >> n >> m;
116     build(1, 1, n);
117     rep(i, 1, n) {
118         std::cin >> a[i];
119         modify(1, i, a[i]);
120     }
121     rep(i, 1, root_tot) { tr2[i].insert(1), tr2[i].insert(-1); }
122     rep(i, 1, m) {
123         std::cin >> op;
124         if (op == 1) {
125             std::cin >> l >> r >> key;
126             std::cout << get_rank_by_key_in_interval(1, l, r, key) + 1 << endl;
127         } else if (op == 2) {
128             std::cin >> l >> r >> key;
129             std::cout << get_key_by_rank_in_interval(1, l, r, key) << endl;
130         } else if (op == 3) {
131             std::cin >> pos >> key;
132             change(1, pos, a[pos], key);
133             a[pos] = key;
134         } else if (op == 4) {
135             std::cin >> l >> r >> key;
136             std::cout << get_prev_in_interval(1, l, r, key) << endl;
137         } else if (op == 5) {
138             std::cin >> l >> r >> key;
139             std::cout << get_nex_in_interval(1, l, r, key) << endl;
140         }
141     }
142     return 0;
143 }
144

```

然而洛谷上的会 T 两个点, Loj 和 ACwing 上的能过.

Splay 实现

```

1 // 洛谷 P3380 【模板】二逼平衡树( 树套树 )
2
3 int n, m, op, l, r, pos, key, root_tot;
4 int a[N];
5
6 struct node{
7     int ch[2], fa, key, siz, cnt;
8
9     void init(int _fa, int _key){
10         fa = _fa, key = _key, siz = cnt = 1;
11     }
12
13     void clear(){
14         ch[0] = ch[1] = fa = key = siz = cnt = 0;
15     }
16 }tr[N * 30];
17
18 struct splay{
19
20     int idx;
21
22     bool get(int u){
23         return u == tr[tr[u].fa].ch[1];
24     }
25
26     void pushup(int u){
27         tr[u].siz = tr[tr[u].ch[0]].siz + tr[tr[u].ch[1]].siz + tr[u].cnt;
28     }
29
30     void rotate(int x){
31         int y = tr[x].fa, z = tr[y].fa;
32         int op = get(x);
33         tr[y].ch[op] = tr[x].ch[op ^ 1];
34         if(tr[x].ch[op ^ 1]) tr[tr[x].ch[op ^ 1]].fa = y;
35         tr[x].ch[op ^ 1] = y;
36         tr[y].fa = x, tr[x].fa = z;
37         if(z) tr[z].ch[y == tr[z].ch[1]] = x;
38         pushup(y), pushup(x);
39     }
40
41     void opt(int& root, int u, int k){
42         for(int f = tr[u].fa; f = tr[f].fa, f != k; rotate(u)){
43             if(tr[f].fa != k) rotate(get(u) == get(f) ? f : u);
44         }
45         if(k == 0) root = u;
46     }
47

```

```

46     }
47
48 void insert(int& root, int key){
49     if(tr[root].siz == 0){
50         idx++;
51         tr[idx].init(0, key);
52         root = idx;
53         return;
54     }
55     int u = root, f = 0;
56     while(1){
57         if(tr[u].key == key){
58             tr[u].cnt++;
59             pushup(u), pushup(f);
60             opt(root, u, 0);
61             break;
62         }
63         f = u, u = tr[u].ch[tr[u].key < key];
64         if(!u){
65             idx++;
66             tr[idx].init(f, key);
67             tr[f].ch[tr[f].key < key] = idx;
68             pushup(idx), pushup(f);
69             opt(root, idx, 0);
70             break;
71         }
72     }
73 }
74
75 int kth(int& root, int rank){
76     int u = root;
77     while(1){
78         if(tr[u].ch[0] && rank <= tr[tr[u].ch[0]].siz) u = tr[u].ch[0];
79         else{
80             rank -= tr[tr[u].ch[0]].siz + tr[u].cnt;
81             if(rank <= 0){
82                 opt(root, u, 0);
83                 return u;
84             }
85             else u = tr[u].ch[1];
86         }
87     }
88 }
89
90 int nlt(int& root, int key){
91     int rank = 0, u = root;
92     while(1){
93         if(tr[u].key > key) u = tr[u].ch[0];
94         else{
95             rank += tr[tr[u].ch[0]].siz;
96             if(tr[u].key == key){
97                 opt(root, u, 0);
98                 return rank + 1;
99             }
100             rank += tr[u].cnt;
101             if(tr[u].ch[1]) u = tr[u].ch[1];
102             else return rank + 1;
103         }
104     }
105 }
106
107 int get_prev(int& root, int key){
108     return kth(root, nlt(root, key) - 1);
109 }
110
111 int get_next(int& root, int key){
112     return kth(root, nlt(root, key + 1));
113 }
114
115 void remove(int& root, int key){
116     nlt(root, key);
117     if(tr[root].cnt > 1){
118         tr[root].cnt--;
119         pushup(root);
120         return;
121     }
122     int u = root, l = get_prev(root, key);
123     tr[tr[u].ch[1]].fa = l;
124     tr[l].ch[1] = tr[u].ch[1];
125     tr[u].clear();
126     pushup(root);
127 }
128
129 void output(int u){
130     if(tr[u].ch[0]) output(tr[u].ch[0]);
131     std::cout << tr[u].key << ' ';
132     if(tr[u].ch[1]) output(tr[u].ch[1]);

```



```

133     }
134
135 }splay;
136
137 struct node1{
138     int l, r, root;
139 }tr1[N * 4];
140
141 void build(int u, int l, int r){
142     tr1[u] = {l, r, u};
143     root_tot = splay.idx = std::max(root_tot, u);
144     if(l == r) return;
145     int mid = (l + r) >> 1;
146     build(u << 1, l, mid), build(u << 1 | 1, mid + 1, r);
147 }
148
149 void modify(int u, int pos, int key){
150     splay.insert(tr1[u].root, key);
151     if(tr1[u].l == tr1[u].r) return;
152     int mid = (tr1[u].l + tr1[u].r) >> 1;
153     if(pos <= mid) modify(u << 1, pos, key);
154     else modify(u << 1 | 1, pos, key);
155 }
156
157 int get_rank_by_key_in_interval(int u, int l, int r, int key){
158     if(l <= tr1[u].l && tr1[u].r <= r)
159         return splay.nlt(tr1[u].root, key) - 2;
160     int mid = (tr1[u].l + tr1[u].r) >> 1, ans = 0;
161     if(l <= mid) ans += get_rank_by_key_in_interval(u << 1, l, r, key);
162     if(mid < r) ans += get_rank_by_key_in_interval(u << 1 | 1, l, r, key);
163     return ans;
164 }
165
166 int get_key_by_rank_in_interval(int u, int l, int r, int rank){
167     int L = 0, R = 1e8;
168     while(L < R){
169         int mid = (L + R + 1) / 2;
170         if(get_rank_by_key_in_interval(1, l, r, mid) < rank) L = mid;
171         else R = mid - 1;
172     }
173     return L;
174 }
175
176 void change(int u, int pos, int pre_key, int key){
177     splay.remove(tr1[u].root, pre_key);
178     splay.insert(tr1[u].root, key);
179     if(tr1[u].l == tr1[u].r) return;
180     int mid = (tr1[u].l + tr1[u].r) >> 1;
181     if(pos <= mid) change(u << 1, pos, pre_key, key);
182     else change(u << 1 | 1, pos, pre_key, key);
183 }
184
185 int get_prev_in_interval(int u, int l, int r, int key){
186     if(l <= tr1[u].l && tr1[u].r <= r)
187         return tr[splay.get_prev(tr1[u].root, key)].key;
188     int mid = (tr1[u].l + tr1[u].r) >> 1, ans = -inf;
189     if(l <= mid) ans = std::max(ans, get_prev_in_interval(u << 1, l, r, key));
190     if(mid < r) ans = std::max(ans, get_prev_in_interval(u << 1 | 1, l, r, key));
191     return ans;
192 }
193
194
195 int get_next_in_interval(int u, int l, int r, int key){
196     if(l <= tr1[u].l && tr1[u].r <= r)
197         return tr[splay.get_next(tr1[u].root, key)].key;
198     int mid = (tr1[u].l + tr1[u].r) >> 1, ans = inf;
199     if(l <= mid) ans = std::min(ans, get_next_in_interval(u << 1, l, r, key));
200     if(mid < r) ans = std::min(ans, get_next_in_interval(u << 1 | 1, l, r, key));
201     return ans;
202 }
203
204 int main(){
205     std::ios::sync_with_stdio(false);
206     std::cin.tie(0);
207     std::cout.tie(0);
208
209     srand(time(0));
210
211     std::cin >> n >> m;
212     build(1, 1, n);
213     rep(i, 1, n){
214         std::cin >> a[i];
215         modify(1, i, a[i]);
216     }
217     rep(i, 1, root_tot){
218         splay.insert(tr1[i].root, inf), splay.insert(tr1[i].root, -inf);
219     }

```

```
220 }
221 rep(i, 1, m){
222     std::cin >> op;
223     if(op == 1){
224         std::cin >> l >> r >> key;
225         std::cout << get_rank_by_key_in_interval(1, l, r, key) + 1 << endl;
226     }
227     else if(op == 2){
228         std::cin >> l >> r >> key;
229         std::cout << get_key_by_rank_in_interval(1, l, r, key) << endl;
230     }
231     else if(op == 3){
232         std::cin >> pos >> key;
233         change(1, pos, a[pos], key);
234         a[pos] = key;
235     }
236     else if(op == 4){
237         std::cin >> l >> r >> key;
238         std::cout << get_prev_in_interval(1, l, r, key) << endl;
239     }
240     else if(op == 5){
241         std::cin >> l >> r >> key;
242         std::cout << get_next_in_interval(1, l, r, key) << endl;
243     }
244 }
245
246 return 0;
247 }
```

然而洛谷吸氧能过, ACwing 能过, Loj T 一堆.

3 字符串

3.1 字典树

3.1.1 普通字典树 (单词匹配)

```

1 // trie //
2 int cnt;
3 std::vector<std::array<int, 26>> trie(n + 1);
4 vi exist(n + 1);
5
6 auto insert = [&](string s) -> void {
7     int p = 0;
8     for (int i = 0; i < s.size() - 1; i++) {
9         int c = s[i] - 'a';
10        if (!trie[p][c]) trie[p][c] = ++cnt;
11        p = trie[p][c];
12    }
13    exist[p] = true;
14 };
15
16 auto find = [&](string s) -> bool {
17     int p = 0;
18     for (int i = 0; i < s.size() - 1; i++) {
19         int c = s[i] - 'a';
20         if (!trie[p][c]) return false;
21         p = trie[p][c];
22     }
23     return exist[p];
24 };
25

```

3.1.2 01 字典树 (求最大异或值)

给定 n 个数, 取两个数进行异或运算, 求最大异或值.

```

1 // trie //
2 int cnt = 0;
3 std::vector<std::array<int, 2>> trie(N);
4
5 auto insert = [&](int x) -> void {
6     int p = 0;
7     for (int i = 30; i >= 0; i--) {
8         int c = (x >> i) & 1;
9         if (!trie[p][c]) trie[p][c] = ++cnt;
10        p = trie[p][c];
11    }
12 };
13
14 auto find = [&](int x) -> int {
15     int sum = 0, p = 0;
16     for (int i = 30; i >= 0; i--) {
17         int c = (x >> i) & 1;
18         if (trie[p][c ^ 1]) {
19             p = trie[p][c ^ 1];
20             sum += (1 << i);
21         } else {
22             p = trie[p][c];
23         }
24     }
25     return sum;
26 };

```

3.1.3 字典树合并

来自浙大城市学院 2023 校赛 E 题.

给定一棵根为 1 的树, 每个点的点权为 w_i . 一共 q 次询问, 每次给出一对 u, v , 询问以 v 为根的子树上的点与 u 的权值最大异或值.

```

1  int main() {
2      std::ios::sync_with_stdio(false);
3      std::cin.tie(0);
4      std::cout.tie(0);
5
6      int n, m;
7      std::cin >> n;
8      vi w(n + 1);
9      for (int i = 1; i <= n; i++) {
10         std::cin >> w[i];
11     }
12
13     vvi e(n + 1);
14     for (int i = 1; i < n; i++) {
15         int u, v;
16         std::cin >> u >> v;
17         e[u].push_back(v);
18         e[v].push_back(u);
19     }
20
21     // 离线询问 //
22     std::cin >> m;
23     std::vector<vpi> q(n + 1);
24     vi ans(m + 1);
25     for (int i = 1; i <= m; i++) {
26         int u, v;
27         std::cin >> u >> v;
28         q[v].emplace_back(u, i);
29     }
30
31     // 01 trie //
32     std::vector<std::array<int, 2>> tr(1);
33
34     auto new_node = [&]() -> int {
35         tr.emplace_back();
36         return tr.size() - 1;
37     };
38
39     vi id(n + 1);
40
41     auto insert = [&](int root, int x) {
42         int p = root;
43         for (int i = 29; i >= 0; i--) {
44             int c = x >> i & 1;
45             if (!tr[p][c]) tr[p][c] = new_node();
46             p = tr[p][c];
47         }
48     };
49
50     auto query = [&](int root, int x) -> int {
51         int ans = 0, p = root;
52         for (int i = 29; i >= 0; i--) {
53             int c = x >> i & 1;
54             if (tr[p][c ^ 1]) {
55                 p = tr[p][c ^ 1];
56                 ans += (1 << i);
57             } else {
58                 p = tr[p][c];
59             }
60         }
61         return ans;
62     };
63
64     std::function<int(int, int)> merge = [&](int a, int b) -> int {
65         // b 的信息挪到 a 上 //
66         if (!a) return b;
67         if (!b) return a;
68         tr[a][0] = merge(tr[a][0], tr[b][0]);
69         tr[a][1] = merge(tr[a][1], tr[b][1]);
70         return a;
71     };
72
73     std::function<void(int, int)> dfs = [&](int u, int fa) {
74         id[u] = new_node();
75         insert(id[u], w[u]);
76         for (auto v : e[u]) {
77             if (v == fa) continue;
78             dfs(v, u);
79             id[u] = merge(id[u], id[v]);
80         }
81         for (auto [v, i] : q[u]) {
82             ans[i] = query(id[u], w[v]);
83         }
84     };
85     dfs(1, 0);
86
87     for (int i = 1; i <= m; i++) std::cout << ans[i] << endl;

```

```

88 |
89 |     return 0;
90 | }

```

3.2 KMP

这一节的 *string* 都是从 0 开始计数.

3.2.1 计算 *next* 数组

```

1  auto get_next = [&](string s) -> vi {
2      int n = s.length();
3      vi next(n);
4      for (int i = 1; i < n; i++) {
5          int j = next[i - 1];
6          while (j > 0 and s[i] != s[j]) j = next[j - 1];
7          if (s[i] == s[j]) j++;
8          next[i] = j;
9      }
10     return next;
11 };

```

3.2.2 在文本串中匹配模式串

求出 s 在 t 中所有出现的位置.

用脏字符连接文本串与模式串跑 KMP 即可.

3.2.3 字符串的最小周期

如果周期大于 1, $n - \text{next}[n - 1]$ 是最小周期.

如果周期为 1, 满足条件:

1. $\text{next}[n - 1] = n$;
2. $\text{next}[n - 1] \neq n$, 但计算出来的并不是循环节, 暴力判断一下.

3.3 Z 函数

这一节的 *string* 都是从 0 开始计数.

3.3.1 计算 z 数组

```

1  auto z_function = [&](const std::string& s) -> vi {
2      int n = s.size();
3      vi z(n);
4      for (int i = 1, l = 0, r = 0; i < n; i++) {
5          if (i <= r and z[i - l] < r - i + 1) {
6              z[i] = z[i - l];
7          } else {
8              z[i] = std::max(0, r - i + 1);
9              while (z[i] + i < n and s[z[i]] == s[i + z[i]]) z[i]++;
10             if (z[i] + i - 1 > r) {
11                 l = i;
12                 r = z[i] + i - 1;
13             }
14         }
15     }
16     return z;
17 };

```

4 数学 - 多项式

4.1 FFT

```

1  const int sz = 1 << 23;
2  int rev[sz];
3  int rev_n;
4  void set_rev(int n) {
5      if (n == rev_n) return;
6      for (int i = 0; i < n; i++) rev[i] = (rev[i / 2] | (i & 1) * n) / 2;
7      rev_n = n;
8  }
9  tempt void butterfly(T* a, int n) {
10     set_rev(n);
11     for (int i = 0; i < n; i++) {
12         if (i < rev[i]) std::swap(a[i], a[rev[i]]);
13     }
14 }
15
16 namespace Comp {
17
18 long double pi = 3.141592653589793238;
19
20 tempt struct complex {
21     T x, y;
22     complex(T x = 0, T y = 0) : x(x), y(y) {}
23     complex operator+(const complex& b) const { return complex(x + b.x, y + b.y); }
24
25     complex operator-(const complex& b) const { return complex(x - b.x, y - b.y); }
26
27     complex operator*(const complex& b) const {
28         return complex<T>(x * b.x - y * b.y, x * b.y + y * b.x);
29     }
30     complex operator~() const { return complex(x, -y); }
31     static complex unit(long double rad) { return complex(std::cos(rad), std::sin(rad)); }
32 };
33
34 } // namespace Comp
35
36 struct fft_t {
37     typedef Comp::complex<double> complex;
38     complex wn[sz];
39
40     fft_t() {
41         for (int i = 0; i < sz / 2; i++) {
42             wn[sz / 2 + i] = complex::unit(2 * Comp::pi * i / sz);
43         }
44         for (int i = sz / 2 - 1; i; i--) wn[i] = wn[i * 2];
45     }
46
47     void operator()(complex* a, int n, int type) {
48         if (type == -1) std::reverse(a + 1, a + n);
49         butterfly(a, n);
50         for (int i = 1; i < n; i *= 2) {
51             const complex* w = wn + i;
52             for (complex* b = a, t; b != a + n; b += i + 1) {
53                 t = b[i];
54                 b[i] = *b - t;
55                 *b = *b + t;
56                 for (int j = 1; j < i; j++) {
57                     t = (++b)[i] * w[j];
58                     b[i] = *b - t;
59                     *b = *b + t;
60                 }
61             }
62         }
63         if (type == 1) return;
64         for (int i = 0; i < n * 2; i++) ((double*) a)[i] /= n;
65     }
66 } FFT;
67
68 typedef decltype(FFT)::complex complex;

```

4.1.1 FFT

```

1  vi fft(const vi& f, const vi& g) {
2      static complex ff[sz];
3      int n = f.size(), m = g.size();

```

```

4   vi h(n + m - 1);
5   if (std::min(n, m) <= 50) {
6       for (int i = 0; i < n; i++) {
7           for (int j = 0; j < m; ++j) {
8               h[i + j] += f[i] * g[j];
9           }
10      }
11      return h;
12  }
13  int c = 1;
14  while (c + 1 < n + m) c *= 2;
15  std::memset(ff, 0, sizeof(decltype(*(ff))) * (c));
16  for (int i = 0; i < n; i++) ff[i].x = f[i];
17  for (int i = 0; i < m; i++) ff[i].y = g[i];
18  FFT(ff, c, 1);
19  for (int i = 0; i < c; i++) ff[i] = ff[i] * ff[i];
20  FFT(ff, c, -1);
21  for (int i = 0; i + 1 < n + m; i++) h[i] = std::llround(ff[i].y / 2);
22  return h;
23 }

```

4.1.2 拆系数 FFT

注意改头文件模板的 mod 数.

```

1   vi mtt(const vi& f, const vi& g) {
2       static complex ff[3][sz], gg[2][sz];
3       static int s[3] = {1, 31623, 31623 * 31623};
4       int n = f.size(), m = g.size();
5       vi h(n + m - 1);
6       if (std::min(n, m) <= 50) {
7           for (int i = 0; i < n; ++i) {
8               for (int j = 0; j < m; ++j) {
9                   Add(h[i + j], mul(f[i], g[j]));
10              }
11          }
12          return h;
13      }
14      int c = 1;
15      while (c + 1 < n + m) c *= 2;
16      for (int i = 0; i < 2; ++i) {
17          std::memset(ff[i], 0, sizeof(decltype(*(ff[i]))) * (c));
18          std::memset(gg[i], 0, sizeof(decltype(*(gg[i]))) * (c));
19          for (int j = 0; j < n; ++j) ff[i][j].x = f[j] / s[i] % s[1];
20          for (int j = 0; j < m; ++j) gg[i][j].x = g[j] / s[i] % s[1];
21          FFT(ff[i], c, 1);
22          FFT(gg[i], c, 1);
23      }
24      for (int i = 0; i < c; ++i) {
25          ff[2][i] = ff[1][i] * gg[1][i];
26          ff[1][i] = ff[1][i] * gg[0][i];
27          gg[1][i] = ff[0][i] * gg[1][i];
28          ff[0][i] = ff[0][i] * gg[0][i];
29      }
30      for (int i = 0; i < 3; ++i) {
31          FFT(ff[i], c, -1);
32          for (int j = 0; j + 1 < n + m; ++j) {
33              Add(h[j], mul(std::llround(ff[i][j].x) % mod, s[i]));
34          }
35      }
36      FFT(gg[1], c, -1);
37      for (int i = 0; i + 1 < n + m; ++i) {
38          Add(h[i], mul(std::llround(gg[1][i].x) % mod, s[1]));
39      }
40      return h;
41  }

```

4.2 NTT 全家桶

```

1   class polynomial : public vi {
2   public:
3       polynomial() = default;
4       polynomial(const vi& v) : vi(v) {}
5       polynomial(vi&& v) : vi(std::move(v)) {}
6
7       int degree() { return size() - 1; }
8
9       void clearzero() {

```

```

10     while (size() && !back()) pop_back();
11 }
12 };
13
14
15 polynomial& operator+=(polynomial& a, const polynomial& b) {
16     a.resize(std::max(a.size(), b.size()), 0);
17     for (int i = 0; i < b.size(); i++) {
18         Add(a[i], b[i]);
19     }
20     a.clearzero();
21     return a;
22 }
23
24 polynomial operator+(const polynomial& a, const polynomial& b) {
25     polynomial ans = a;
26     return ans += b;
27 }
28
29 polynomial& operator-=(polynomial& a, const polynomial& b) {
30     a.resize(std::max(a.size(), b.size()), 0);
31     for (int i = 0; i < b.size(); i++) {
32         Sub(a[i], b[i]);
33     }
34     a.clearzero();
35     return a;
36 }
37
38 polynomial operator-(const polynomial& a, const polynomial& b) {
39     polynomial ans = a;
40     return ans -= b;
41 }
42
43 class ntt_t {
44 public:
45     static const int maxbit = 22;
46     static const int sz = 1 << maxbit;
47     static const int mod = 998244353;
48     static const int g = 3;
49
50     std::array<int, sz + 10> w;
51     std::array<int, maxbit + 10> len_inv;
52
53     ntt_t() {
54         int wn = pow(g, (mod - 1) >> maxbit);
55         w[0] = 1;
56         for (int i = 1; i <= sz; i++) {
57             w[i] = mul(w[i - 1], wn);
58         }
59         len_inv[maxbit] = pow(sz, mod - 2);
60         for (int i = maxbit - 1; ~i; i--) {
61             len_inv[i] = add(len_inv[i + 1], len_inv[i + 1]);
62         }
63     }
64
65     void operator()(vi& v, int& n, int type) {
66         int bit = 0;
67         while ((1 << bit) < n) bit++;
68         int tot = (1 << bit);
69         v.resize(tot, 0);
70         vi rev(tot);
71         n = tot;
72         for (int i = 0; i < tot; i++) {
73             rev[i] = rev[i >> 1] >> 1;
74             if (i & 1) {
75                 rev[i] |= tot >> 1;
76             }
77         }
78         for (int i = 0; i < tot; i++) {
79             if (i < rev[i]) {
80                 std::swap(v[i], v[rev[i]]);
81             }
82         }
83         for (int midd = 0; (1 << midd) < tot; midd++) {
84             int mid = 1 << midd;
85             int len = mid << 1;
86             for (int i = 0; i < tot; i += len) {
87                 for (int j = 0; j < mid; j++) {
88                     int w0 = v[i + j];
89                     int w1 = mul(
90                         w[type == 1 ? (j << maxbit - midd - 1) : (len - j << maxbit - midd - 1)],
91                         v[i + j + mid]);
92                     v[i + j] = add(w0, w1);
93                     v[i + j + mid] = sub(w0, w1);
94                 }
95             }
96         }
97     }
98 }

```



```

97         if (type == -1) {
98             for (int i = 0; i < tot; i++) {
99                 v[i] = mul(v[i], len_inv[bit]);
100             }
101         }
102     }
103 } NTT;

```

4.2.1 乘法

```

1 polynomial& operator*=(polynomial& a, const polynomial& b) {
2     if (!a.size() || !b.size()) {
3         a.resize(0);
4         return a;
5     }
6     polynomial tmp = b;
7     int deg = a.size() + b.size() - 1;
8     int temp = deg;
9
10    // 项数较小直接硬算
11
12    if ((LL) a.size() * (LL) b.size() <= (LL) deg * 50LL) {
13        tmp.resize(0);
14        tmp.resize(deg, 0);
15        for (int i = 0; i < a.size(); i++) {
16            for (int j = 0; j < b.size(); j++) {
17                tmp[i + j] = add(tmp[i + j], mul(a[i], b[j]));
18            }
19        }
20        a = tmp;
21        return a;
22    }
23
24    // 项数较多跑 NTT
25
26    NTT(a, deg, 1);
27    NTT(tmp, deg, 1);
28    for (int i = 0; i < deg; i++) {
29        Mul(a[i], tmp[i]);
30    }
31    NTT(a, deg, -1);
32    a.resize(temp);
33    return a;
34 }
35
36 polynomial operator*(const polynomial& a, const polynomial& b) {
37     polynomial ans = a;
38     return ans *= b;
39 }

```

4.2.2 逆

```

1 polynomial inverse(const polynomial& a) {
2     polynomial ans({pow(a[0], mod - 2)});
3     polynomial temp;
4     polynomial tempa;
5     int deg = a.size();
6     for (int i = 0; (1 << i) < deg; i++) {
7         tempa.resize(0);
8         tempa.resize(1 << i << 1, 0);
9         for (int j = 0; j != tempa.size() and j != deg; j++) {
10             tempa[j] = a[j];
11         }
12         temp = ans * (polynomial({2}) - tempa * ans);
13         if (temp.size() > (1 << i << 1)) {
14             temp.resize(1 << i << 1, 0);
15         }
16         temp.clearzero();
17         std::swap(temp, ans);
18     }
19     ans.resize(deg);
20     return ans;
21 }

```

4.2.3 log

```

1 polynomial differential(const polynomial& a) {
2     if (!a.size()) {
3         return a;
4     }
5     polynomial ans(vi(a.size() - 1));
6     for (int i = 1; i < a.size(); i++) {
7         ans[i - 1] = mul(a[i], i);
8     }
9     return ans;
10 }
11
12 polynomial integral(const polynomial& a) {
13     polynomial ans(vi(a.size() + 1));
14     for (int i = 0; i < a.size(); i++) {
15         ans[i + 1] = mul(a[i], pow(i + 1, mod - 2));
16     }
17     return ans;
18 }
19
20 polynomial ln(const polynomial& a) {
21     int deg = a.size();
22     polynomial da = differential(a);
23     polynomial inva = inverse(a);
24     polynomial ans = integral(da * inva);
25     ans.resize(deg);
26     return ans;
27 }

```

4.2.4 exp

```

1 polynomial exp(const polynomial& a) {
2     polynomial ans({1});
3     polynomial temp;
4     polynomial tempa;
5     polynomial tempaa;
6     int deg = a.size();
7     for (int i = 0; (1 << i) < deg; i++) {
8         tempa.resize(0);
9         tempa.resize(1 << i << 1, 0);
10        for (int j = 0; j != tempa.size() and j != deg; j++) {
11            tempa[j] = a[j];
12        }
13        tempaa = ans;
14        tempaa.resize(1 << i << 1);
15        temp = ans * (tempa + polynomial({1}) - ln(tempaa));
16        if (temp.size() > (1 << i << 1)) {
17            temp.resize(1 << i << 1, 0);
18        }
19        temp.clearzero();
20        std::swap(temp, ans);
21    }
22    ans.resize(deg);
23    return ans;
24 }

```

4.2.5 sqrt

```

1 polynomial sqrt(polynomial& a) {
2     polynomial ans({cipolla(a[0])});
3     if (ans[0] == -1) return ans;
4     polynomial temp;
5     polynomial tempa;
6     polynomial tempaa;
7     int deg = a.size();
8     for (int i = 0; (1 << i) < deg; i++) {
9         tempa.resize(0);
10        tempa.resize(1 << i << 1, 0);
11        for (int j = 0; j != tempa.size() and j != deg; j++) {
12            tempa[j] = a[j];
13        }
14        tempaa = ans;
15        tempaa.resize(1 << i << 1);
16        temp = (tempa * inverse(tempaa) + ans) * inv2;
17        if (temp.size() > (1 << i << 1)) {
18            temp.resize(1 << i << 1, 0);

```

```

19     }
20     temp.clearzero();
21     std::swap(temp, ans);
22 }
23 ans.resize(deg);
24 return ans;
25 }
26
27 // 特判 //
28
29 int cnt = 0;
30 for (int i = 0; i < a.size(); i++) {
31     if (a[i] == 0) {
32         cnt++;
33     } else {
34         break;
35     }
36 }
37 if (cnt) {
38     if (cnt == n) {
39         for (int i = 0; i < n; i++) {
40             std::cout << "0 ";
41         }
42         std::cout << endl;
43         return 0;
44     }
45     if (cnt & 1) {
46         std::cout << "-1" << endl;
47         return 0;
48     }
49     polynomial b(vi(a.size() - cnt));
50     for (int i = cnt; i < a.size(); i++) {
51         b[i - cnt] = a[i];
52     }
53     a = b;
54 }
55 a.resize(n - cnt / 2);
56 a = sqrt(a);
57 if (a[0] == -1) {
58     std::cout << "-1" << endl;
59     return 0;
60 }
61 reverse(all(a));
62 a.resize(n);
63 reverse(all(a));

```

4.3 FWT

4.3.1 与

$$C_i = \sum_{i=j \& k} A_j B_k$$

分治过程

$$\text{FWT}[A] = \text{merge}(\text{FWT}[A_0] + \text{FWT}[A_1], \text{FWT}[A_1]),$$

$$\text{UFWT}[A'] = \text{merge}(\text{UFWT}[A'_0] - \text{UFWT}[A'_1], \text{UFWT}[A'_1]).$$

```

1 // mod 998244353 //
2 auto FWT_and = [&](vi v, int type) -> vi {
3     int n = v.size();
4     for (int mid = 1; mid < n; mid <= 1) {
5         for (int block = mid < 1, j = 0; j < n; j += block) {
6             for (int i = j; i < j + mid; i++) {
7                 LL x = v[i], y = v[i + mid];
8                 if (type == 1) {
9                     v[i] = add(x, y);
10                } else {
11                    v[i] = sub(x, y);
12                }
13            }
14        }
15    }
16    return v;
17 };

```

4.3.2 或

$$C_i = \sum_{i=j|k} A_j B_k$$

分治过程

$$\text{FWT}[A] = \text{merge}(\text{FWT}[A_0], \text{FWT}[A_0] + \text{FWT}[A_1]),$$

$$\text{UFWT}[A'] = \text{merge}(\text{UFWT}[A'_0], -\text{UFWT}[A'_0] + \text{UFWT}[A'_1]).$$

```

1 // mod 998244353 //
2 auto FWT_or = [&](vi v, int type) -> vi {
3     int n = v.size();
4     for (int mid = 1; mid < n; mid <= 1) {
5         for (int block = mid << 1, j = 0; j < n; j += block) {
6             for (int i = j; i < j + mid; i++) {
7                 LL x = v[i], y = v[i + mid];
8                 if (type == 1) {
9                     v[i + mid] = add(x, y);
10                } else {
11                    v[i + mid] = sub(y, x);
12                }
13            }
14        }
15    }
16    return v;
17 };

```

4.3.3 异或

$$C_i = \sum_{i=j \text{ xor } k} A_j B_k$$

分治过程

$$\text{FWT}[A] = \text{merge}(\text{FWT}[A_0] + \text{FWT}[A_1], \text{FWT}[A_0] - \text{FWT}[A_1]),$$

$$\text{UFWT}[A'] = \text{merge}\left(\frac{\text{UFWT}[A'_0] + \text{UFWT}[A'_1]}{2}, \frac{\text{UFWT}[A'_0] - \text{UFWT}[A'_1]}{2}\right).$$

```

1 // mod 998244353 //
2 auto FWT_xor = [&](vi v, int type) -> vi {
3     int n = v.size();
4     for (int mid = 1; mid < n; mid <= 1) {
5         for (int block = mid << 1, j = 0; j < n; j += block) {
6             for (int i = j; i < j + mid; i++) {
7                 LL x = v[i], y = v[i + mid];
8                 v[i] = add(x, y);
9                 v[i + mid] = sub(x, y);
10                if (type == -1) {
11                    Mul(v[i], inv2);
12                    Mul(v[i + mid], inv2);
13                }
14            }
15        }
16    }
17    return v;
18 };

```

统一地,

```

1 a = FWT(a, 1), b = FWT(b, 1);
2 for (int i = 0; i < (1 << n); i++) {
3     c[i] = mul(a[i], b[i]);
4 }
5 c = FWT(c, -1);

```

4.4 拉格朗日插值

4.4.1 一般的插值

给出一个多项式 $f(x)$ 上的 n 个点 (x_i, y_i) , 求 $f(k)$.

拉格朗日插值的结果是

$$f(x) = \sum_{i=1}^n y_i \prod_{j \neq i} \frac{x - x_j}{x_i - x_j},$$

直接带入 k 并且取模即可, 时间复杂度 $O(n^2)$.

```

1 int ans = 0;
2 for (int i = 1; i <= n; i++) {
3     LL s1 = y[i] % mod, s2 = 1LL;
4     for (int j = 1; j <= n; j++) {
5         if (i != j) {
6             Mul(s1, (k - x[j]));
7             Mul(s2, (x[i] - x[j]));
8         }
9     }
10    Add(ans, mul(s1, pow(s2, mod - 2)));
11 }

```

4.4.2 坐标连续的插值

给出的点是 (i, y_i) .

$$\begin{aligned}
 f(x) &= \sum_{i=1}^n y_i \prod_{j \neq i} \frac{x - x_j}{x_i - x_j} \\
 &= \sum_{i=1}^n y_i \prod_{j \neq i} \frac{x - j}{i - j} \\
 &= \sum_{i=1}^n y_i \cdot \frac{\prod_{j=1}^n (x - j)}{(x - i)(-1)^{n+1-i}(i - 1)!(n + 1 - i)!} \\
 &= \left(\prod_{j=1}^n (x - j) \right) \left(\sum_{i=1}^n \frac{(-1)^{n+1-i} y_i}{(x - i)(i - 1)!(n + 1 - i)!} \right),
 \end{aligned}$$

时间复杂度为 $O(n)$.

5 数学 - 数论

5.1 欧几里得算法

5.1.1 欧几里得算法

5.1.2 扩展欧几里得算法

```

1 std::function<void(LL, LL, LL&, LL&)> exgcd = [&](LL a, LL b, LL& x, LL& y) -> void {
2     LL x1 = 1, x2 = 0, x3 = 0, x4 = 1;
3     while (b != 0) {
4         LL c = a / b;
5         std::tie(x1, x2, x3, x4, a, b) =
6             std::make_tuple(x3, x4, x1 - x3 * c, x2 - x4 * c, b, a - b * c);
7     }
8     x = x1, y = x2;
9 };

```

5.1.3 类欧几里得算法

一般形式: 求 $f(a, b, c, n) = \sum_{i=0}^n \lfloor \frac{ai+b}{c} \rfloor$.

$f(a, b, c, n)$ 可以单独求.

$$f(a, b, c, n) = nm - f(c, c - b - 1, a, m - 1)$$

```

1 LL f(LL a, LL b, LL c, LL n) {
2     if (a == 0) return ((b / c) * (n + 1));
3     if (a >= c || b >= c)
4         return f(a % c, b % c, c, n) + (a / c) * n * (n + 1) / 2 + (b / c) * (n + 1);
5     LL m = (a * n + b) / c;
6     LL v = f(c, c - b - 1, a, m - 1);
7     return n * m - v;
8 }

```

更进一步, 求: $g(a, b, c, n) = \sum_{i=0}^n i \lfloor \frac{ai+b}{c} \rfloor$ 以及 $h(a, b, c, n) = \sum_{i=0}^n \lfloor \frac{ai+b}{c} \rfloor^2$

直接记吧.

$$g(a, b, c, n) = \lfloor \frac{mn(n+1) - f(c, c-b-1, a, m-1) - h(c, c-b-1, a, m-1)}{2} \rfloor$$

$$h(a, b, c, n) = nm(m+1) - 2f(c, c-b-1, a, m-1) - 2g(c, c-b-1, a, m-1) - f(a, b, c, n)$$

```

1 const int inv2 = 499122177, inv6 = 166374059;    // 2和6的逆元 //
2
3 LL f(LL a, LL b, LL c, LL n);
4 LL g(LL a, LL b, LL c, LL n);
5 LL h(LL a, LL b, LL c, LL n);
6
7 struct data {
8     LL f, g, h;
9 };
10
11 data calc(LL a, LL b, LL c, LL n) {
12     LL ac = a / c, bc = b / c, m = (a * n + b) / c, n1 = n + 1, n21 = n * 2 + 1;
13     data d;
14     if (a == 0) {
15         d.f = bc * n1 % mod;
16         d.g = bc * n % mod * n1 % mod * inv2 % mod;
17         d.h = bc * bc % mod * n1 % mod;
18         return d;
19     }
20     if (a >= c || b >= c) {
21         d.f = n * n1 % mod * inv2 % mod * ac % mod + bc * n1 % mod;
22         d.g =
23             ac * n % mod * n1 % mod * n21 % mod * inv6 % mod + bc * n % mod * n1 % mod * inv2 % mod;
24         d.h = ac * ac % mod * n % mod * n1 % mod * n21 % mod * inv6 % mod +
25             bc * bc % mod * n1 % mod + ac * bc % mod * n % mod * n1 % mod;
26         d.f %= mod, d.g %= mod, d.h %= mod;
27         data e = calc(a % c, b % c, c, n);

```

```

28     d.h += e.h + 2 * bc % mod * e.f % mod + 2 * ac % mod * e.g % mod;
29     d.g += e.g, d.f += e.f;
30     d.f %= mod, d.g %= mod, d.h %= mod;
31     return d;
32 }
33 data e = calc(c, c - b - 1, a, m - 1);
34 d.f = n * m % mod - e.f, d.f = (d.f % mod + mod) % mod;
35 d.g = m * n % mod * n1 % mod - e.h - e.f, d.g = (d.g * inv2 % mod + mod) % mod;
36 d.h = n * m % mod * (m + 1) % mod - 2 * e.g - 2 * e.f - d.f;
37 d.h = (d.h % mod + mod) % mod;
38 return d;
39 }

```

5.2 快速幂

```

1 auto quick_power = [&](LL a, LL n, LL mod) -> LL {
2     LL ans = 1;
3     while (n != 0) {
4         if (n & 1) ans = ans * a % mod;
5         a = a * a % mod;
6         n >>= 1;
7     }
8     return ans;
9 };

```

5.3 逆元

5.3.1 费马小定理

p 为素数, 有 $a^{-1} \equiv a^{p-2} \pmod{p}$.

5.3.2 扩展欧几里得

```

1 auto inv = [&](LL a, LL p) -> LL {
2     if (std::gcd(a, p) != 1) return -1;
3     LL x, y;
4     exgcd(a, p, x, y);
5     return (x % p + p) % p;
6 }

```

5.3.3 线性递推

$$a^{-1} \equiv -\left\lfloor \frac{p}{a} \right\rfloor \times (p \% a)^{-1}.$$

```

1 vi inv(n + 1);
2 auto sieve_inv = [&](int n) -> void {
3     inv[1] = 1;
4     for (int i = 2; i <= n; i++) {
5         inv[i] = mul(sub(p, p / i), inv[p % i]);
6     }
7 }

```

5.4 欧拉函数

设 $n = \prod_{i=1}^s p_i^{k_i}$, 则 $\varphi(n) = n \cdot \prod_{i=1}^s (1 - \frac{1}{p_i})$.

5.4.1 某个数的欧拉函数值

```

1 auto phi = [&](int n) -> int {
2     int ans = n;

```

```

3   for (int i = 2; i * i <= n; i++) {
4       if (n % i != 0) continue;
5       ans = ans / i * (i - 1);
6       while (n % i == 0) n /= i;
7   }
8   if (n > 1) ans = ans / n * (n - 1);
9   return ans;
10 };

```

5.4.2 欧拉定理

若 $\gcd(a, p) = 1$, 则 $a^{\varphi(p)} \equiv 1 \pmod{p}$.

5.4.3 扩展欧拉定理

若 $\gcd(a, p) \neq 1$, 则 $a^b = \begin{cases} a^b & b \leq \varphi(p) \\ a^{b \% \varphi(p) + \varphi(p)} \pmod{p} & b > \varphi(p) \end{cases}$.

5.5 中国剩余定理

求解

$$\begin{cases} N \equiv a_1 \pmod{m_1} \\ N \equiv a_2 \pmod{m_2} \\ \dots \\ N \equiv a_n \pmod{m_n} \end{cases}$$

有 $N \equiv \sum_{i=1}^k a_i \times \text{inv}\left(\frac{M}{m_i}, m_i\right) \times \left(\frac{M}{m_i}\right) \pmod{M}$

前提: 模数为两两不同的素数

```

1   auto crt = [&](int n, const vi& a, const vi& m) -> int{
2       LL ans = 0, M = 1;
3       for(int i = 1; i <= n; i++) M *= m[i];
4       for(int i = 1; i <= n; i++){
5           ans = (ans + a[i] * inv(M / m[i], m[i]) * (M / m[i])) % M;
6       }
7       return (ans % M + M) % M;
8   };

```

5.5.1 扩展中国剩余定理

```

1   auto excrt = [&](int n, const vi& a, const vi& m) -> LL{
2       LL A = a[1], M = m[1];
3       for (int i = 2; i <= n; i++) {
4           LL x, y, d = std::gcd(M, m[i]);
5           exgcd(M, m[i], x, y);
6           LL mod = M / d * m[i];
7           x = x * (a[i] - A) / d % (m[i] / d);
8           A = ((M * x + A) % mod + mod) % mod;
9           M = mod;
10      }
11      return A;
12  };

```


5.6 数论分块

5.6.1 分块的逻辑

下取整 $\lfloor \frac{n}{g} \rfloor = k$ 的分块 ($g \leq n$).

```
1 for(int l = 1, r, k; l <= n; l = r + 1){
2     k = n / l;
3     r = n / (n / l);
4     debug(l, r, k);
5 }
```

$k = \lfloor \frac{n}{g} \rfloor$ 从大到小遍历 $\lfloor \frac{n}{g} \rfloor$ 的所有取值, $[l, r]$ 对应的是 g 取值的区间.

下面是 debug 结果.

```
1 // n = 11
2 [l, r, k] : 1 1 11
3 [l, r, k] : 2 2 5
4 [l, r, k] : 3 3 3
5 [l, r, k] : 4 5 2
6 [l, r, k] : 6 11 1
```

上取整 $\lceil \frac{n}{g} \rceil = k$ 的分块 ($g < n$).

```
1 for(int l = 1, r, k; l < n; l = r + 1){
2     k = (n + l - 1) / l;
3     r = (n + k - 2) / (k - 1) - 1;
4     debug(l, r, k);
5 }
```

$k = \lceil \frac{n}{g} \rceil$ 从大到小遍历 $\lceil \frac{n}{g} \rceil$ 的所有取值, $[l, r]$ 对应的是 g 取值的区间.

下面是 debug 结果.

```
1 // n = 11
2 [l, r, k] : 1 1 11
3 [l, r, k] : 2 2 6
4 [l, r, k] : 3 3 4
5 [l, r, k] : 4 5 3
6 [l, r, k] : 6 10 2
```

5.6.2 一般形式

设 s 为 f 的前缀.

$$\sum_{i=1}^n f(i) \lfloor \frac{n}{i} \rfloor.$$

```
1 for (int l = 1, r; l <= n; l = r + 1) {
2     r = n / (n / l);
3     ans += (s[r] - s[l - 1]) * (n / l);
4 }
```

$$\sum_{i=1}^n f(i) \lfloor \frac{a}{i} \rfloor \lfloor \frac{b}{i} \rfloor.$$

```
1 for (int l = 1, r, r1, r2; l <= n; l = r + 1) {
2     if (a / l) {
3         r1 = a / (a / l);
4     } else {
5         r1 = n;
6     }
7     if (b / l) {
8         r2 = b / (b / l);
9     } else {
10        r2 = n;
11    }
12    r = min(min(r1, r2), n);
13    ans += (s[r] - s[l - 1]) * (a / l) * (b / l);
14 }
```

5.7 威尔逊定理

5.8 卢卡斯定理

5.8.1 卢卡斯定理

用于求大组合数, 并且模数是一个不大的素数.

$$\binom{n}{m} \bmod p = \binom{\lfloor n/p \rfloor}{\lfloor m/p \rfloor} \cdot \binom{n \bmod p}{m \bmod p} \bmod p.$$

其中 $\binom{\lfloor n/p \rfloor}{\lfloor m/p \rfloor}$ 可以继续用卢卡斯定理计算, $\binom{n \bmod p}{m \bmod p}$ 可以直接计算.

当 $m = 0$ 的时候, 返回 1.

p 不会太大, 一般在 10^5 左右.

```

1 auto C = [&](LL n, LL m, LL p) -> LL {
2     if (n < m) return 0;
3     if (m == 0) return 1;
4     return ((fac[n] * inv_fac[m]) % p * inv_fac[n - m]) % p;
5 };
6
7 auto lucas = [&](auto&& self, LL n, LL m, LL p) -> LL {
8     if (n < m) return 0;
9     if (m == 0) return 1;
10    return (C(n % p, m % p, p) * self(self, n / p, m / p, p)) % p;
11 }

```

5.8.2 素数在组合数中的次数

Legengre 给出一种 $n!$ 中素数 p 的幂次的计算方式为: $\sum_{1 \leq j} \lfloor \frac{n}{p^j} \rfloor$.

另一种计算方式利用 p 进制下各位数字和: $v_p(n!) = \frac{n - S_p(n)}{p-1}$.

则有 $v_p(C_m^n) = \frac{S_p(n) + S_p(m-n) - S_p(m)}{p-1}$.

5.8.3 扩展卢卡斯定理

计算 $\binom{n}{m} \bmod M$, 其中 M 可能为合数, 分为三步:

第一部分: CRT.

原问题变成求:

$$\left\{ \begin{array}{l} \binom{n}{m} \equiv a_1 \bmod p_1^{\alpha_1} \\ \binom{n}{m} \equiv a_2 \bmod p_2^{\alpha_2} \\ \dots \\ \binom{n}{m} \equiv a_k \bmod p_k^{\alpha_k} \end{array} \right.$$

在求出 a_i 之后就可以利用 CRT 求出答案.

第二部分: 移除分子分母中的素数.

问题转换成求解 $\binom{n}{m} \bmod q^k$, 等价于求

$$\frac{\frac{n!}{q^x}}{\frac{m!}{q^y} \frac{(n-m)!}{q^z}} q^{x-y-z} \bmod q^k$$

其中 x 表示 $n!$ 中 q 的次数, y, z 同理.

第三部分: 威尔逊定理的推论.

问题转换为求 $\frac{n!}{q^x} \bmod q^k$, 可以利用威尔逊定理的推论.

```

1 // Problem: 洛谷: P4720 【模板】扩展卢卡斯定理/exLucas
2
3 LL n, m, p;
4 LL fac[N], inv_fac[N];
5
6 LL quick_power(LL a, LL n, LL p){
7     LL ans = 1;
8     while(n != 0){
9         if(n & 1) ans = (ans * a) % p;
10        a = (a * a) % p;
11        n >>= 1;
12    }
13    return ans;
14 }
15
16 void exgcd(LL a, LL b, LL &x, LL &y) {
17     LL x1 = 1, x2 = 0, x3 = 0, x4 = 1;
18     while(b != 0){
19         LL c = a / b;
20         tie(x1, x2, x3, x4, a, b) =
21             make_tuple(x3, x4, x1 - x3 * c, x2 - x4 * c, b, a - b * c);
22     }
23     x = x1, y = x2;
24 }
25
26 LL mul_inv(LL a, LL p){
27     LL x, y;
28     exgcd(a, p, x, y);
29     return (x % p + p) % p;
30 }
31
32 LL func(LL n, LL pi, LL pk){
33     if(!n) return 1;
34     LL ans = 1;
35     for(LL i = 2; i <= pk; i++){
36         if(i % pi) ans = ans * i % p;
37     }
38     ans = quick_power(ans, n / pk, pk);
39     for(LL i = 2; i <= n % pk; i++){
40         if(i % pi) ans = ans * i % pk;
41     }
42     return ans * func(n / pi, pi, pk) % pk;
43 }
44
45 LL multiLucas(LL n, LL m, LL pi, LL pk){
46     int cnt = 0;
47     for(LL i = n; i; i /= pi) cnt += i / pi;
48     for(LL i = m; i; i /= pi) cnt -= i / pi;
49     for(LL i = n - m; i; i /= pi) cnt -= i / pi;
50     return quick_power(pi, cnt, pk) * func(n, pi, pk) % pk
51         * mul_inv(func(m, pi, pk), pk) % pk * mul_inv(func(n - m, pi, pk), pk) % pk;
52 }
53
54 LL CRT(LL a[], LL m[], LL k){
55     LL ans = 0;
56     for(int i = 1; i <= k; i++){
57         ans = (ans + a[i] * mul_inv(p / m[i], m[i]) * (p / m[i])) % p;
58     }
59     return (ans % p + p) % p;
60 }
61
62 LL exLucas(LL n, LL m, LL p){
63     int cnt = 0;
64     LL prime[20], a[20];
65     for(LL i = 2; i * i <= p; i++){
66         if(p % i == 0){
67             prime[++cnt] = i;
68             while(p % i == 0) p /= i;
69             a[cnt] = multiLucas(n, m, i, prime[cnt]);
70         }
71     }
72     return CRT(a, prime, cnt);
73 }

```

```

72 |     if(p > 1) prime[++cnt] = p, a[cnt] = multiLucas(n, m, p, p);
73 |     return CRT(a, prime, cnt);
74 | }
75 |
76 | int main(){
77 |
78 |     ios::sync_with_stdio(false);
79 |     cin.tie(0);
80 |     cout.tie(0);
81 |
82 |     cin >> n >> m >> p;
83 |     cout << exLucas(n, m, p) << endl;
84 |
85 |     return 0;
86 | }

```

5.9 裴蜀定理

5.9.1 裴蜀定理

设 x, y 是不全为零的整数, 则存在整数 a, b 使得 $ax + by = \gcd(x, y)$.

5.9.2 推论

若 $\gcd(a, b) = 1, x, y \in \mathbb{N}, ax + by = n$, 则称 a, b 可以表示 n .

记 $C = ad - a - b$, 则 n 与 $C - n$ 中有且仅有一个可以被 a, b 表示.

当 $n < ab$ 时, 不大于 n 的能被表示的非负整数的个数是 $\sum_{i=1}^{\lfloor \frac{n}{a} \rfloor} \lfloor \frac{n - ia}{b} \rfloor$, 可以用类欧几里得算法可求解.

5.10 升幂定理

简记为 LTE, 分为模为奇素数和模为 2 两部分, 简记为 LTF_p 和 LTF_2 .

将素数 p 在整数 n 中的个数记为 $v_p(n)$.

5.10.1 模为奇素数

如果 $n \in \mathbb{N}_+, a, b \not\equiv 0 \pmod{p}, a \equiv b \pmod{p}$,

则 $v_p(a^n - b^n) = v_p(a - b) + v_p(n)$

5.10.2 模为 2

如果 $n \in \mathbb{Z}_+, a, b$ 为奇数,

则
$$v_2(a^n - b^n) = \begin{cases} v_2(a - b) & n \text{ is odd,} \\ v_2(a - b) + v_2(a + b) + v_2(n) - 1 & n \text{ is even.} \end{cases}$$

5.11 筛法汇总

5.11.1 素数筛

```

1 | int n;
2 | vi prime;
3 | std::vector<bool> is_prime(n + 1);
4 | void Euler_sieve(int n){

```

```

5     for(int i = 2; i <= n; i++){
6         if(!is_prime[i]) prime.push_back(i);
7         for(auto p : prime){
8             if(i * p > n) break;
9             is_prime[i * p] = 1;
10            if(i % p == 0) break;
11        }
12    }
13 }
14 // is_prime 为 true 的时候是合数 //

```

5.11.2 欧拉函数 $\varphi(n)$

```

1 int n;
2 vi phi(n + 1), prime;
3 std::vector<bool> is_prime(n + 1);
4 void phi_sieve(int n){
5     for(int i = 2; i <= n; i++){
6         if(!is_prime[i]){
7             prime.push_back(i);
8             phi[i] = i - 1;
9         }
10        for(auto p : prime){
11            if(i * p > n) break;
12            is_prime[i * p] = 1;
13            if(i % p){
14                phi[i * p] = phi[i] * phi[p];
15            }
16            else{
17                phi[i * p] = phi[i] * p;
18                break;
19            }
20        }
21    }
22 }
23 // is_prime 为 true 的时候是合数 //

```

5.11.3 莫比乌斯函数 $\mu(n)$

```

1 int n;
2 vi mu(n + 1), prime;
3 std::vector<bool> is_prime(n + 1);
4 void mu_sieve(int n){
5     mu[1] = 1;
6     for(int i = 2; i <= n; i++){
7         if(!is_prime[i]){
8             prime.push_back(i);
9             mu[i] = -1;
10        }
11        for(auto p : prime){
12            if(i * p > n) break;
13            is_prime[i * p] = 1;
14            if(i % p){
15                mu[i * p] = -mu[i];
16            }
17            else{
18                mu[i * p] = 0;
19                break;
20            }
21        }
22    }
23    // is_prime 为 true 的时候是合数 //
24 }

```

5.11.4 因数求和 $d(n)$

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

```

1 int n;
2 vi d(n + 1), g(n + 1), prime;
3 std::vector<bool> is_prime(n + 1);
4 void d_sieve(int n){
5     d[1] = g[1] = 1;

```

```

6   for(int i = 2; i <= n; i++){
7       if(!is_prime[i]){
8           prime.push_back(i);
9           d[i] = g[i] = i + 1;
10      }
11      for(auto p : prime){
12          if(i * p > n) break;
13          is_prime[i * p] = 1;
14          if(i % p){
15              g[i * p] = p + 1;
16              d[i * p] = d[i] * d[p];
17          }
18          else{
19              g[i * p] = d[i] * p + 1;
20              d[i * p] = d[i] / g[i] * g[i * p];
21              break;
22          }
23      }
24  }
25  // is_prime 为 true 的时候是合数 //
26 }

```

5.12 莫比乌斯反演

5.12.1 莫比乌斯函数

$$\mu(n) = \begin{cases} 1 & n = 1, \\ 0 & n \text{ 含有平方因子}, \\ (-1)^k & k \text{ 为 } n \text{ 的本质不同素因子个数}. \end{cases}$$

几个性质:

- $\sum_{d|n} \mu(d) = \begin{cases} 1 & n = 1 \\ 0 & n \neq 1 \end{cases}$,
- $\varphi(n) = \sum_{d|n} d \cdot \mu(\frac{n}{d})$.

一个简单易写的 $O(n \log n)$ 求法.

```

1 mu[1] = 1;
2 for(int i = 1; i <= N; i++){
3     for(int j = i + i; j <= N; j += i){
4         mu[j] -= mu[i];
5     }
6 }

```

5.12.2 莫比乌斯反演

设 $f(n)$, $F(n)$.

- $F(n) = \sum_{d|n} f(d)$, 则 $f(n) = \sum_{d|n} \mu(d) F(\frac{n}{d})$.
- $F(n) = \sum_{n|d} f(d)$, 则 $f(n) = \sum_{n|d} \mu(\frac{d}{n}) F(d)$.

5.12.3 例子

$$\sum_{i=1}^n \sum_{j=1}^m [\gcd(i, j) = k] = \sum_{d=1}^{\min\{\lfloor \frac{n}{k} \rfloor, \lfloor \frac{m}{k} \rfloor\}} \mu(d) \lfloor \frac{n}{kd} \rfloor \lfloor \frac{m}{kd} \rfloor.$$

5.13 BSGS

5.13.1 BSGS

在 $\gcd(a, p) = 1$ 的前提下求解满足 $a^x \equiv b \pmod{p}$ 的 x .

时间复杂度 $O(\sqrt{p})$.

```

1 auto BSGS = [&](LL a, LL b, LL p) -> LL {
2     if (1 % p == b % p) return 0;
3     LL k = sqrt(p) + 1;
4     unordered_map<LL, LL> hash(2 * k);
5     for (LL i = 0, j = b % p; i < k; i++) {
6         hash[j] = i;
7         j = j * a % p;
8     }
9     LL ak = 1;
10    for (int i = 1; i <= k; i++) ak = ak * a % p;
11    for (int i = 1, j = ak; i <= k; i++) {
12        if (hash.count(j)) return (LL) i * k - hash[j];
13        j = (LL) j * ak % p;
14    }
15    return -inf;
16 };

```

5.13.2 扩展 BSGS

$(a, p) \neq 1$ 的情形.

```

1 std::function<LL(LL, LL, LL)> exBSGS = [&](LL a, LL b, LL p) -> LL {
2     b = (b % p + p) % p;
3     if ((LL) 1 % p == b % p) return 0;
4     LL x, y, d;
5     exgcd(a, p, x, y, d);
6     if (d > 1) {
7         if (b % d != 0) return -inf;
8         LL d1;
9         exgcd(a / d, p / d, x, y, d1);
10        return exBSGS(a, b / d * x % (p / d), p / d) + 1;
11    }
12    return BSGS(a, b, p);
13 }

```

5.14 Miller-Rabin 素数检验

```

1 vector<int> test = {2, 7, 61};
2 // vector<LL> test = {2, 325, 9375, 28178, 450775, 9780504, 1795265022};
3
4 auto miller_rabin = [&](LL n) -> bool {
5     if (n <= 3) return n == 2 || n == 3;
6     LL a = n - 1, b = 0;
7     while (!(a & 1)) a >>= 1, b++;
8     for (auto x : test) {
9         v = quick_power(x, a, n);
10        if (v == 1 || v == n - 1) continue;
11        for (j = 0; j < b; j++) {
12            if (v == n - 1) break;
13            v = (i28) v * v % n;
14        }
15        if (j >= b) return false;
16    }
17    return true;
18 };

```

```

1 // by 林泽瀚 //
2 vl vv = {2, 3, 5, 7, 11, 13, 17, 23, 29};
3
4 auto miller_rabin = [&](LL n) -> bool {
5     auto test = [&](LL n, int a) {
6         if (n == a) return true;
7         if (n % 2 == 0) return false;
8         LL d = (n - 1) >> __builtin_ctzll(n - 1);

```

```

9      LL r = quick_power(a, d, n);
10     while (d < n - 1 and r != 1 and r != n - 1) {
11         d <<= 1;
12         r = (i128) r * r % n;
13     }
14     return r == n - 1 or d & 1;
15 };
16 if (n == 2 or n == 3) return true;
17 for (auto p : vv) {
18     if (test(n, p) == 0) return false;
19 }
20 return true;
21 }

```

5.15 Pollard-Rho 算法

能在 $O(n^{\frac{1}{4}})$ 的时间内随机出一个 n 的非平凡因数。

5.15.1 倍增实现

```

1 auto pollard_rho = [&](LL x) -> LL{
2     LL s = 0, t = 0, val = 1;
3     LL c = rand() % (x - 1) + 1;
4     for(int goal = 1;; goal <<= 1, s = t, val = 1){
5         for(int step = 1; step <= goal; step++){
6             t = ((i128) t * t + c) % x;
7             val = (i128) val * abs(t - s) % x;
8             if(step % 127 == 0){
9                 LL d = std::gcd(val, x);
10                if(d > 1) return d;
11            }
12        }
13        LL d = std::gcd(val, x);
14        if(d > 1) return d;
15    }
16 };

```

5.15.2 利用 Miller-Rabin 和 Pollard-Rho 进行素因数分解

```

1 auto factorize = [&](LL a) -> vl{
2     vl ans, stk;
3     for (auto p : prime) {
4         if (p > 1000) break;
5         while (a % p == 0) {
6             ans.push_back(p);
7             a /= p;
8         }
9         if (a == 1) return ans;
10    }
11    // 先筛小素数, 再跑 Pollard-Rho //
12    stk.push_back(a);
13    while (!stk.empty()) {
14        LL b = stk.back();
15        stk.pop_back();
16        if (miller_rabin(b)) {
17            ans.push_back(b);
18            continue;
19        }
20        LL c = b;
21        while (c >= b) c = pollard_rho(b);
22        stk.push_back(c);
23        stk.push_back(b / c);
24    }
25    return ans;
26 };

```

5.16 二次剩余

5.16.1 Cipolla 算法


```

1 int cipolla(int x) {
2     std::srand(time(0));
3     auto check = [&](int x) -> bool { return pow(x, (mod - 1) / 2) == 1; };
4     if (!x) return 0;
5     if (!check(x)) return -1;
6     int a, b;
7     while (1) {
8         a = rand() % mod;
9         b = sub(mul(a, a), x);
10        if (!check(b)) break;
11    }
12    PII t = {a, 1};
13    PII ans = {1, 0};
14    auto mulp = [&](PII x, PII y) -> PII {
15        auto [x1, x2] = x;
16        auto [y1, y2] = y;
17        int c = add(mul(x1, y1), mul(x2, y2, b));
18        int d = add(mul(x1, y2), mul(x2, y1));
19        return {c, d};
20    };
21    for (int i = (mod + 1) / 2; i; i >>= 1) {
22        if (i & 1) ans = mulp(ans, t);
23        t = mulp(t, t);
24    }
25    return std::min(ans.ff, mod - ans.ff);
26 }

```

6 数学 - 组合数学

6.1 斯特林数

6.1.1 第一类 Stirling 数

记作 $s(n, k)$ 或者 $\left[\begin{smallmatrix} n \\ k \end{smallmatrix} \right]$.

表示将 n 个两两不同的元素划分成 k 个圆排列的方案数.

递推式

$$s(n, k) = s(n-1, k-1) + (n-1) s(n-1, k), \text{ where } s(n, 0) = [n=0].$$

6.1.2 第二类 Stirling 数

记作 $S(n, k)$ 或者 $\left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\}$.

表示将 n 个两两不同的元素划分为 k 个互不相交的非空子集的方案数.

递推式

$$S(n, k) = S(n-1, k-1) + k S(n-1, k), \text{ where } S(n, 0) = [n=0].$$

7 数学 - 复数

```

1  tandu struct Comp {
2      T a, b;
3
4      Comp(T _a = 0, T _b = 0) { a = _a, b = _b; }
5
6      Comp operator+(const Comp& x) const { return Comp(a + x.a, b + x.b); }
7
8      Comp operator-(const Comp& x) const { return Comp(a - x.a, b - x.b); }
9
10     Comp operator*(const Comp& x) const { return Comp(a * x.a - b * x.b, a * x.b + b * x.a); }
11
12     bool operator==(const Comp& x) const { return a == x.a and b == x.b; }
13
14     T real() { return a; }
15
16     T imag() { return b; }
17
18     U norm() { return (U) a * a + (U) b * b; }
19
20     Comp conj() { return Comp(a, -b); }
21
22     Comp operator/(const Comp& x) const {
23         Comp y = x;
24         Comp c = Comp(a, b) * y.conj();
25         T d = y.norm();
26         return Comp(c.a / d, c.b / d);
27     }
28 };
29
30 typedef Comp<LL, LL> complex;
31
32 complex gcd(complex a, complex b) {
33     LL d = b.norm();
34     if (d == 0) return a;
35     std::vector<complex> v(4);
36     complex c = a * b.conj();
37     auto fdiv = [&](LL a, LL b) -> LL { return a / b - ((a ^ b) < 0 && (a % b)); };
38     v[0] = complex(fdiv(c.real(), d), fdiv(c.imag(), d));
39     v[1] = v[0] + complex(1, 0);
40     v[2] = v[0] + complex(0, 1);
41     v[3] = v[0] + complex(1, 1);
42     for (auto& x : v) {
43         x = a - x * b;
44     }
45     std::sort(all(v), [&](complex a, complex b) { return a.norm() < b.norm(); });
46     return gcd(b, v[0]);
47 };

```

8 数学 - 线性代数

8.1 行列式

模 998244353.

```

1 auto det = [&](int n, vvi e) -> int {
2     int ans = 1;
3     for (int i = 1; i <= n; i++) {
4         if (a[i][i] == 0) {
5             for (int j = i + 1; j <= n; j++) {
6                 if (a[j][i] != 0) {
7                     for (int k = i; k <= n; k++) {
8                         std::swap(a[i][k], a[j][k]);
9                     }
10                    ans = sub(mod, ans);
11                    break;
12                }
13            }
14        }
15        if (a[i][i] == 0) return 0;
16        Mul(ans, a[i][i]);
17        int x = pow(a[i][i], mod - 2);
18        for (int k = i; k <= n; k++) {
19            Mul(a[i][k], x);
20        }
21        for (int j = i + 1; j <= n; j++) {
22            int x = a[j][i];
23            for (int k = i; k <= n; k++) {
24                Sub(a[j][k], mul(a[i][k], x));
25            }
26        }
27    }
28    return ans;
29 };

```

8.2 矩阵乘法

$A_{n \times m}$ 乘 $B_{m \times k}$ 并模 998244353.

```

1 auto matrix_mul = [&](int n, int m, int k, vvi a, vvi b) -> vvi {
2     vvi c(n + 1, vi(k + 1));
3     for (int i = 1; i <= n; i++) {
4         for (int l = 1; l <= m; l++) {
5             int x = a[i][l];
6             for (int j = 1; j <= k; j++) {
7                 Add(c[i][j], mul(x, b[l][j]));
8             }
9         }
10    }
11    return c;
12 };

```

9 博弈论

9.1 Nim 游戏

若 Nim 和为 0，则先手必败.

暴力打表.

```
1 vi SG(100, -1); /* 记忆化 */
2 std::function<int(int)> sg = [&](int x) -> int {
3     if (/* 为最终态 */ return SG[x] = 0;
4     if (SG[x] != -1) return SG[x];
5     vi st;
6     for (/* 枚举所有可达的状态 y */) {
7         st.push_back(sg(y));
8     }
9     std::sort(all(st));
10    st.erase(unique(all(st), st.end()));
11    for (int i = 0; i < st.size(); i++) {
12        if (st[i] != i) return SG[x] = i;
13    }
14    return SG[x] = st.size();
15 };
```

9.2 anti-Nim 游戏

若

- 所有堆的石子均为一个, 且 Nim 和不为 0,
- 至少有一堆石子超过一个, 且 Nim 和为 0,

则先手必败.

10 线性规划

10.1 单纯形算法

```

1 // by jiangly //
2 std::vector<double> solve(const std::vector<std::vector<double>> &a,
3                           const std::vector<double> &b, const std::vector<double> &c) {
4     int n = (int)a.size(), m = (int)a[0].size() + 1;
5     std::vector<std::vector<double>> value(n + 2, std::vector<double>(m + 1));
6     std::vector<int> index(n + m);
7     int r = n, s = m - 1;
8     for (int i = 0; i < n + m; ++i) {
9         index[i] = i;
10    }
11    for (int i = 0; i < n; ++i) {
12        for (int j = 0; j < m - 1; ++j) {
13            value[i][j] = -a[i][j];
14        }
15        value[i][m - 1] = 1;
16        value[i][m] = b[i];
17        if (value[r][m] > value[i][m]) {
18            r = i;
19        }
20    }
21    for (int j = 0; j < m - 1; ++j) {
22        value[n][j] = c[j];
23    }
24    value[n + 1][m - 1] = -1;
25    for (double number; ; ) {
26        if (r < n) {
27            std::swap(index[s], index[r + m]);
28            value[r][s] = 1 / value[r][s];
29            for (int j = 0; j <= m; ++j) {
30                if (j != s) {
31                    value[r][j] *= -value[r][s];
32                }
33            }
34            for (int i = 0; i <= n + 1; ++i) {
35                if (i != r) {
36                    for (int j = 0; j <= m; ++j) {
37                        if (j != s) {
38                            value[i][j] += value[r][j] * value[i][s];
39                        }
40                    }
41                    value[i][s] *= value[r][s];
42                }
43            }
44        }
45        r = s = -1;
46        for (int j = 0; j < m; ++j) {
47            if (s < 0 || index[s] > index[j]) {
48                if (value[n + 1][j] > eps || value[n + 1][j] > -eps && value[n][j] > eps) {
49                    s = j;
50                }
51            }
52        }
53        if (s < 0) {
54            break;
55        }
56        for (int i = 0; i < n; ++i) {
57            if (value[i][s] < -eps) {
58                if (r < 0
59                    || (number = value[r][m] / value[r][s] - value[i][m] / value[i][s]) < -eps
60                    || number < eps && index[r + m] > index[i + m]) {
61                    r = i;
62                }
63            }
64        }
65        if (r < 0) {
66            // Solution is unbounded.
67            return std::vector<double>();
68        }
69    }
70    if (value[n + 1][m] < -eps) {
71        // No solution.
72        return std::vector<double>();
73    }
74    std::vector<double> answer(m - 1);
75    for (int i = m; i < n + m; ++i) {
76        if (index[i] < m - 1) {
77            answer[index[i]] = value[i - m][m];
78        }

```

```
79 | }  
80 | return answer;  
81 | }
```

11 图论

11.1 拓扑排序

```

1 vi top;
2 auto top_sort = [&]() -> bool {
3     vi d(n + 1);
4     std::queue<int> q;
5     for (int i = 1; i <= n; i++) {
6         d[i] = e[i].size();
7         if (!d[i]) q.push(i);
8     }
9     while (!q.empty()) {
10        int u = q.front();
11        q.pop();
12        top.push_back(u);
13        for (auto v : e[u]) {
14            d[v]--;
15            if (!d[v]) q.push(v);
16        }
17    }
18    if (top.size() != n) return false;
19    return true;
20 };

```

11.2 最短路

11.2.1 最短路

Floyd

```

1 auto floyd = [&]() -> vvi {
2     vvi dist(n + 1, vi(n + 1, inf));
3     for (int i = 1; i <= n; i++) {
4         for (int j = 1; j <= n; j++) {
5             Min(dist[i][j], e[i][j]);
6         }
7         dist[i][i] = 0;
8     }
9     for (int k = 1; k <= n; k++) {
10        for (int i = 1; i <= n; i++) {
11            for (int j = 1; j <= n; j++) {
12                Min(dist[i][j], dist[i][k] + dist[k][j]);
13            }
14        }
15    }
16    return dist;
17 };

```

Dijkstra

```

1 auto dijkstra = [&](int s) -> vl {
2     vl dist(n + 1, INF);
3     vi vis(n + 1, 0);
4     dist[s] = 0;
5     std::priority_queue<PLI, std::vector<PLI>, std::greater<PLI>> q;
6     q.emplace(0LL, s);
7     while (!q.empty()) {
8         auto [dis, u] = q.top();
9         q.pop();
10        if (vis[u]) continue;
11        vis[u] = 1;
12        for (const auto& [v, w] : e[u]) {
13            if (dist[v] > dis + w) {
14                dist[v] = dis + w;
15                q.emplace(dist[v], v);
16            }
17        }
18    }
19    return dist;
20 };

```

Johnson

```

1 // Johnson 全源最短路 //
2
3 // 负环 //
4 vl dist1(n + 1);
5 vi vis(n + 1), cnt(n + 1);
6 auto spfa = [&]() -> bool {
7     std::queue<int> q;
8     for (int u = 1; u <= n; u++) {
9         q.push(u);
10        vis[u] = false;
11    }
12    while (!q.empty()) {
13        auto u = q.front();
14        q.pop();
15        vis[u] = false;
16        for (auto [v, w] : e[u]) {
17            if (dist1[v] > dist1[u] + w) {
18                dist1[v] = dist1[u] + w;
19                Max(cnt[v], cnt[u] + 1);
20                if (cnt[v] >= n) return true;
21                if (!vis[v]) {
22                    q.push(v);
23                    vis[v] = true;
24                }
25            }
26        }
27    }
28    return false;
29 };
30
31 // dijkstra //
32 vl dist2(n + 1);
33 auto dijkstra = [&](int s) {
34     for (int u = 1; u <= n; u++) {
35         dist2[u] = 1e9;
36         vis[u] = false;
37     }
38     dist2[s] = 0;
39     std::priority_queue<PLI, std::vector<PLI>, std::greater<PLI>> q;
40     q.emplace(0, s);
41     while (!q.empty()) {
42         auto [d, u] = q.top();
43         q.pop();
44         if (vis[u]) continue;
45         vis[u] = true;
46         for (const auto& [v, w] : e[u]) {
47             if (dist2[v] > d + w) {
48                 dist2[v] = d + w;
49                 q.emplace(dist2[v], v);
50             }
51         }
52     }
53 };
54
55 if (spfa()) {
56     std::cout << -1 << '\n';
57     return;
58 }
59 for (int u = 1; u <= n; u++) {
60     for (auto& [v, w] : e[u]) {
61         w += dist1[u] - dist1[v];
62     }
63 }
64 for (int u = 1; u <= n; u++) {
65     dijkstra(u);
66 }

```

11.2.2 最短路计数

Dijkstra

```

1 auto dijkstra = [&](int s) -> std::pair<vl, vi> {
2     vl dist(n + 1, INF);
3     vi cnt(n + 1), vis(n + 1);
4     dist[s] = 0;
5     cnt[s] = 1;
6     std::priority_queue<PLI, std::vector<PLI>, std::greater<PLI>> q;
7     q.emplace(0LL, s);
8     while (!q.empty()) {
9         auto [dis, u] = q.top();
10        q.pop();

```



```

11     if (vis[u]) continue;
12     vis[u] = 1;
13     for (const auto& [v, w] : e[u]) {
14         if (dist[v] > dis + w) {
15             dist[v] = dis + w;
16             cnt[v] = cnt[u];
17             q.push({dist[v], v});
18         } else if (dist[v] == dis + w) {
19             // cnt[v] += cnt[u];
20             cnt[v] += cnt[u];
21             cnt[v] %= 100003;
22         }
23     }
24 }
25 return {dist, cnt};
26 };

```

Floyd

```

1 auto floyd() = [&] -> std::pair<vvi, vvi> {
2     vvi dist(n + 1, vi(n + 1, inf));
3     vvi cnt(n + 1, vi(n + 1));
4     for (int i = 1; i <= n; i++) {
5         for (int j = 1; j <= n; j++) {
6             Min(dist[i][j], e[i][j]);
7         }
8         dist[i][i] = 0;
9     }
10    for (int k = 1; k <= n; k++) {
11        for (int i = 1; i <= n; i++) {
12            for (int j = 1; j <= n; j++) {
13                if (dist[i][j] == dist[i][k] + dist[k][j]) {
14                    cnt[i][j] += cnt[i][k] * cnt[k][j];
15                } else if (dist[i][j] > dist[i][k] + dist[k][j]) {
16                    cnt[i][j] = cnt[i][k] * cnt[k][j];
17                    dist[i][j] = dist[i][k] + dist[k][j];
18                }
19            }
20        }
21    }
22    return {dist, cnt};
23 };

```

11.2.3 负环

```

1 auto spfa = [&]() -> bool {
2     std::queue<int> q;
3     vi vis(n + 1), cnt(n + 1);
4     for (int i = 1; i <= n; i++) {
5         q.push(i);
6         vis[i] = 1;
7     }
8     while (!q.empty()) {
9         auto u = q.front();
10        q.pop();
11        vis[u] = 0;
12        for (const auto& [v, w] : e[u]) {
13            if (dist[v] > dist[u] + w) {
14                dist[v] = dist[u] + w;
15                cnt[v] = cnt[u] + 1;
16                if (cnt[v] >= n) return true;
17                if (!vis[v]) {
18                    q.push(v);
19                    vis[v] = 1;
20                }
21            }
22        }
23    }
24    return false;
25 };

```

11.2.4 分层最短路

有一个 n 个点 m 条边的无向图, 你可以选择 k 条道路以零代价通行, 求 s 到 t 的最小花费.

```

1 // Problem: 洛谷: P4568 [JLOI2011] 飞行路线

```

```

2
3 int main() {
4     std::ios::sync_with_stdio(false);
5     std::cin.tie(0);
6     std::cout.tie(0);
7
8     int n, m, k, s, t;
9     std::cin >> n >> m >> k;
10    std::cin >> s >> t;
11    std::vector<std::vector<PIL>> e(n * (k + 1) + 1);
12    for (int i = 1; i <= m; i++) {
13        int a, b, c;
14        std::cin >> a >> b >> c;
15        e[a].emplace_back(b, c);
16        e[b].emplace_back(a, c);
17        for (int j = 1; j <= k; j++) {
18            e[a + (j - 1) * n].emplace_back(b + j * n, 0);
19            e[b + (j - 1) * n].emplace_back(a + j * n, 0);
20            e[a + j * n].emplace_back(b + j * n, c);
21            e[b + j * n].emplace_back(a + j * n, c);
22        }
23    }
24
25    auto dijkstra = [&](int s) -> vl {};
26
27    vl dist = dijkstra(s);
28    LL ans = INF;
29    for (int i = t; i <= n * (k + 1); i += n) {
30        Min(ans, dist[i]);
31    }
32
33    std::cout << ans << endl;
34
35    return 0;
36 }

```

11.3 差分约束

对于不等式 $a_i - a_j \leq c$, 建立一条节点 j 指向 i 边权为 c 的有向边. 再连接从 0 指向 i 边权为 0 有向边, 接着跑 0 为起点的单源最短路, 如果有负环则无解, 否则 $a_i = dist_i$ 为一组解.

11.4 最小生成树

11.4.1 最小生成树

Kruskal

```

1 std::vector<std::tuple<int, int, int>> edge;
2
3 // DSU //
4
5 auto kruskal = [&]() -> int {
6     std::sort(all(edge), [&](std::tuple<int, int, int> a, std::tuple<int, int, int> b) {
7         auto [x1, y1, w1] = a;
8         auto [x2, y2, w2] = b;
9         return w1 < w2;
10    });
11    int res = 0, cnt = 0;
12    for (int i = 0; i < m; i++) {
13        auto [a, b, w] = edge[i];
14        a = find(a), b = find(b);
15        if (a != b) {
16            fa[a] = b;
17            res += w;
18            // res = std::max(res, w);
19            cnt++;
20        }
21    }
22    if (cnt < n - 1) return -1;
23    return res;
24 }

```

11.5 强连通分量

11.5.1 强连通分量

Tarjan 算法

```

1 vi dfn(n + 1), low(n + 1), stk(n + 1), belong(n + 1);
2 int timestamp = 0, top = 0, scc_cnt = 0;
3 std::vector<bool> in_stk(n + 1);
4
5 auto tarjan = [&](auto&& self, int u) -> void {
6     dfn[u] = low[u] = ++timestamp;
7     stk[++top] = u;
8     in_stk[u] = true;
9     for (auto v : e[u]) {
10         if (!dfn[v]) {
11             self(self, v);
12             Min(low[u], low[v]);
13         } else if (in_stk[v]) {
14             Min(low[u], dfn[v]);
15         }
16     }
17     if (dfn[u] == low[u]) {
18         scc_cnt++;
19         int v;
20         do {
21             v = stk[top--];
22             in_stk[v] = false;
23             belong[v] = scc_cnt;
24         } while (v != u);
25     }
26 };

```

11.6 双连通分量

11.6.1 点双连通分量

求点双连通分量.

```

1 vvi e(n + 1);
2 vi dfn(n + 1), low(n + 1), is_bcc(n + 1), stk;
3 int timestamp = 0, bcc_cnt = 0, root = 0;
4 vvi bcc(2 * n + 1);
5 std::function<void(int, int)> tarjan = [&](int u, int fa) {
6     dfn[u] = low[u] = ++timestamp;
7     int child = 0;
8     stk.push_back(u);
9     if (u == root and e[u].empty()) {
10         bcc_cnt++;
11         bcc[bcc_cnt].push_back(u);
12         return;
13     }
14     for (auto v : e[u]) {
15         if (!dfn[v]) {
16             tarjan(v, u);
17             low[u] = std::min(low[u], low[v]);
18             if (low[v] >= dfn[u]) {
19                 child++;
20                 if (u != root or child > 1) {
21                     is_bcc[u] = 1;
22                 }
23                 bcc_cnt++;
24                 int z;
25                 do {
26                     z = stk.back();
27                     stk.pop_back();
28                     bcc[bcc_cnt].push_back(z);
29                 } while (z != v);
30                 bcc[bcc_cnt].push_back(u);
31             }
32         } else if (v != fa) {
33             low[u] = std::min(low[u], dfn[v]);
34         }
35     }
36 };
37 for (int i = 1; i <= n; i++) {
38     if (!dfn[i]) {

```

```

39 |         root = i;
40 |         tarjan(i, i);
41 |     }
42 | }

```

求割点.

```

1 | vi dfn(n + 1), low(n + 1), is_bcc(n + 1);
2 | int timestamp = 0, bcc = 0, root = 0;
3 | std::function<void(int, int)> tarjan = [&](int u, int fa) {
4 |     dfn[u] = low[u] = ++timestamp;
5 |     int child = 0;
6 |     for (const auto& v : e[u]) {
7 |         if (!dfn[v]) {
8 |             tarjan(v, u);
9 |             low[u] = std::min(low[u], low[v]);
10 |            if (low[v] >= dfn[u]) {
11 |                child++;
12 |                if ((u != root or child > 1) and !is_bcc[u]) {
13 |                    bcc++;
14 |                    is_bcc[u] = 1;
15 |                }
16 |            }
17 |        } else if (v != fa) {
18 |            low[u] = std::min(low[u], dfn[v]);
19 |        }
20 |    }
21 | };
22 | for (int i = 1; i <= n; i++) {
23 |     if (!dfn[i]) {
24 |         root = i;
25 |         tarjan(i, i);
26 |     }
27 | }

```

11.6.2 边双连通分量

求边双连通分量.

```

1 | std::vector<vpi> e(n + 1);
2 | for (int i = 1; i <= m; i++) {
3 |     int u, v;
4 |     std::cin >> u >> v;
5 |     e[u].emplace_back(v, i);
6 |     e[v].emplace_back(u, i);
7 | }
8 | vi dfn(n + 1), low(n + 1), is_ecc(n + 1), fa(n + 1), stk;
9 | int timestamp = 0, ecc_cnt = 0;
10 | vvi ecc(2 * n + 1);
11 | std::function<void(int, int)> tarjan = [&](int u, int id) {
12 |     low[u] = dfn[u] = ++timestamp;
13 |     stk.push_back(u);
14 |     for (auto [v, idx] : e[u]) {
15 |         if (!dfn[v]) {
16 |             tarjan(v, idx);
17 |             low[u] = std::min(low[u], low[v]);
18 |         } else if (idx != id) {
19 |             low[u] = std::min(low[u], dfn[v]);
20 |         }
21 |     }
22 |     if (dfn[u] == low[u]) {
23 |         ecc_cnt++;
24 |         int v;
25 |         do {
26 |             v = stk.back();
27 |             stk.pop_back();
28 |             ecc[ecc_cnt].push_back(v);
29 |         } while (v != u);
30 |     }
31 | };
32 | for (int i = 1; i <= n; i++) {
33 |     if (!dfn[i]) {
34 |         tarjan(i, 0);
35 |     }
36 | }

```

求桥. (可能有诈)

```

1 | vvi e(n + 1);

```

```

2 vi dfn(n + 1), low(n + 1), is_ecc(n + 1), fa(n + 1);
3 int timestamp = 0, ecc = 0;
4 std::function<void(int, int)> tarjan = [&](int u, int faa) {
5     fa[u] = faa;
6     low[u] = dfn[u] = ++timestamp;
7     for (auto v : e[u]) {
8         if (!dfn[v]) {
9             tarjan(v, u);
10            low[u] = std::min(low[u], low[v]);
11            if (low[v] > dfn[u]) {
12                is_ecc[v] = 1;
13                ecc++;
14            }
15        } else if (dfn[v] < dfn[u] && v != faa) {
16            low[u] = std::min(low[u], dfn[v]);
17        }
18    }
19 };
20 for (int i = 1; i <= n; i++) {
21     if (!dfn[i]) {
22         tarjan(i, i);
23     }
24 }

```

11.7 树上问题 - 树的直径

如果要找到直径上的点, 只能用两次 DFS.

如果边权为负, 只能用树形 DP.

11.7.1 两次 DFS

```

1 vvi e(n + 1);
2 vi d(n + 1);
3 int ans, id;
4 void dfs(int u, int fa){
5     // f[u] = fa; //
6     for(auto v : e[u]){
7         if(v == fa) continue;
8         d[v] = d[u] + 1;
9         if(d[v] > d[id]) id = v;
10        dfs(v, u);
11    }
12 }
13 int main(){
14     dfs(1, 0);
15     d[id] = 0;
16     dfs(id, 0);
17     cout << d[id] << endl;
18     // for(int i = id; i; i = f[i]) cout << i << ' '; //
19     return 0;
20 }

```

11.7.2 树形 DP

```

1 vvi e(n + 1);
2 vi d1(n + 1), d2(n + 1);
3 int ans;
4 void dfs(int u, int fa){
5     d1[u] = d2[u] = 0;
6     for(int v : e[u]){
7         if(v == fa) continue;
8         dfs(v, u);
9         int t = d1[v] + 1; // t = d1[v] + w; //
10        if(t > d1[u]){
11            d2[u] = d1[u];
12            d1[u] = t;
13        }
14        else if(t > d2[u]){
15            d2[u] = t;
16        }
17    }
18    Max(ans, d1[u] + d2[u]);
19 }

```

```

20 | int main(){
21 |     dfs(1, 0);
22 |     cout << ans << endl;
23 |     return 0;
24 | }

```

11.8 树上问题 - 树的重心

只考虑点带权值

```

1 | int sum; // 点权和 //
2 | vi size(n + 1), weight(n + 1), w(n + 1), depth(n + 1);
3 | std::array<int, 2> centroid = {0, 0};
4 | auto get_centroid = [&](auto&& self, int u, int fa) -> void {
5 |     size[u] = w[u];
6 |     weight[u] = 0;
7 |     for (auto v : e[u]) {
8 |         if (v == fa) continue;
9 |         self(self, v, u);
10 |         size[u] += size[v];
11 |         Max(weight[u], size[v]);
12 |     }
13 |     Max(weight[u], sum - size[u]);
14 |     if (weight[u] <= sum / 2) {
15 |         centroid[centroid[0] != 0] = u;
16 |     }
17 | };

```

11.9 树上问题 - DSU on tree

给出一棵 n 个节点以 1 为根的树, 每个节点染上一种颜色, 询问以 u 为节点的子树中有多少种颜色.

```

1 | // Problem: 洛谷: U41492 树上数颜色
2 |
3 | int main() {
4 |     std::ios::sync_with_stdio(false);
5 |     std::cin.tie(0);
6 |     std::cout.tie(0);
7 |
8 |     int n, m, dfn = 0, cnttot = 0;
9 |     std::cin >> n;
10 |     vvi e(n + 1);
11 |     vi siz(n + 1), col(n + 1), son(n + 1), dfnl(n + 1), dfnr(n + 1), rank(n + 1);
12 |     vi ans(n + 1), cnt(n + 1);
13 |
14 |     for (int i = 1; i < n; i++) {
15 |         int u, v;
16 |         std::cin >> u >> v;
17 |         e[u].push_back(v);
18 |         e[v].push_back(u);
19 |     }
20 |     for (int i = 1; i <= n; i++) {
21 |         std::cin >> col[i];
22 |     }
23 |     auto add = [&](int u) -> void {
24 |         if (cnt[col[u]] == 0) cnttot++;
25 |         cnt[col[u]]++;
26 |     };
27 |     auto del = [&](int u) -> void {
28 |         cnt[col[u]]--;
29 |         if (cnt[col[u]] == 0) cnttot--;
30 |     };
31 |     auto dfs1 = [&](auto&& self, int u, int fa) -> void {
32 |         dfnl[u] = ++dfn;
33 |         rank[dfn] = u;
34 |         siz[u] = 1;
35 |         for (auto v : e[u]) {
36 |             if (v == fa) continue;
37 |             self(self, v, u);
38 |             siz[u] += siz[v];
39 |             if (!son[u] or siz[son[u]] < siz[v]) son[u] = v;
40 |         }
41 |         dfnr[u] = dfn;
42 |     };
43 |     auto dfs2 = [&](auto&& self, int u, int fa, bool op) -> void {
44 |         for (auto v : e[u]) {
45 |             if (v == fa or v == son[u]) continue;

```

```

46         self(self, v, u, false);
47     }
48     if (son[u]) self(self, son[u], u, true);
49     for (auto v : e[u]) {
50         if (v == fa || v == son[u]) continue;
51         rep(i, dfnl[v], dfnr[v]) { add(rank[i]); }
52     }
53     add(u);
54     ans[u] = cnttot;
55     if (op == false) {
56         rep(i, dfnl[u], dfnr[u]) { del(rank[i]); }
57     }
58 };
59 dfs1(dfs1, 1, 0);
60 dfs2(dfs2, 1, 0, false);
61 std::cin >> m;
62 for (int i = 1; i <= m; i++) {
63     int u;
64     std::cin >> u;
65     std::cout << ans[u] << endl;
66 }
67 return 0;
68 }

```

11.10 树上问题 - LCA

11.10.1 倍增算法

```

1 // Problem: 洛谷: P3379 【模板】最近公共祖先 (LCA)
2
3 // LCA //
4 vvi e(n + 1), fa(n + 1, vi(50));
5 vi dep(n + 1);
6
7 auto dfs = [&](auto&& self, int u) -> void {
8     for (auto v : e[u]) {
9         if (v == fa[u][0]) continue;
10        dep[v] = dep[u] + 1;
11        fa[v][0] = u;
12        self(self, v);
13    }
14 };
15
16 auto init = [&]() -> void {
17     dep[root] = 1;
18     dfs(dfs, root);
19     for (int j = 1; j <= 30; j++) {
20         for (int i = 1; i <= n; i++) {
21             fa[i][j] = fa[fa[i][j - 1]][j - 1];
22         }
23     }
24 };
25 init();
26
27 auto LCA = [&](int a, int b) -> int {
28     if (dep[a] > dep[b]) std::swap(a, b);
29     int d = dep[b] - dep[a];
30     for (int i = 0; (1 << i) <= d; i++) {
31         if (d & (1 << i)) b = fa[b][i];
32     }
33     if (a == b) return a;
34     for (int i = 30; i >= 0 and a != b; i--) {
35         if (fa[a][i] == fa[b][i]) continue;
36         a = fa[a][i];
37         b = fa[b][i];
38     }
39     return fa[a][0];
40 };
41
42 auto dist = [&](int a, int b) -> int { return dep[a] + dep[b] - dep[LCA(a, b)] * 2; };

```

11.11 树上问题 - 树链剖分

11.11.1 轻重链剖分

对一棵有根树进行如下 4 种操作:

- 1 $x\ y\ z$: 将节点 x 到节点 y 的最短路径上所有节点的值加上 z .
- 2 $x\ y$: 查询节点 x 到节点 y 的最短路径上所有节点的值的和.
- 3 $x\ z$: 将以节点 x 为根的子树上所有节点的值加上 z .
- 4 x : 查询以节点 x 为根的子树上所有节点的值的和.

```

1 // Problem: 洛谷: P3384 【模板】重链剖分/树链剖分
2
3 // HLD //
4 int cnt = 0;
5 vi son(n + 1), fa(n + 1), siz(n + 1), depth(n + 1);
6 vi dfn(n + 1), rank(n + 1), top(n + 1), botton(n + 1);
7
8 auto dfs1 = [&](auto&& self, int u) -> void {
9     son[u] = -1, siz[u] = 1;
10    for (auto v : e[u]) {
11        if (depth[v] != 0) continue;
12        depth[v] = depth[u] + 1;
13        fa[v] = u;
14        self(self, v);
15        siz[u] += siz[v];
16        if (son[u] == -1 or siz[v] > siz[son[u]]) son[u] = v;
17    }
18 };
19
20 auto dfs2 = [&](auto&& self, int u, int t) -> void {
21     top[u] = t;
22     dfn[u] = ++cnt;
23     rank[cnt] = u;
24     botton[u] = dfn[u];
25     if (son[u] == -1) return;
26     self(self, son[u], t);
27     Max(botton[u], botton[son[u]]);
28     for (auto v : e[u]) {
29         if (v != son[u] and v != fa[u]) {
30             self(self, v, v);
31             Max(botton[u], botton[v]);
32         }
33     }
34 };
35
36 depth[root] = 1;
37 dfs1(dfs1, root);
38 dfs2(dfs2, root, root);
39
40 /*
41
42 // 求 LCA //
43 auto LCA = [&](int a, int b) -> int {
44     while (top[a] != top[b]) {
45         if (depth[top[a]] < depth[top[b]]) std::swap(a, b);
46         a = fa[top[a]];
47     }
48     return (depth[a] > depth[b] ? b : a);
49 };
50
51 // 维护 u 到 v 的路径 //
52 while (top[u] != top[v]) {
53     if (depth[top[u]] < depth[top[v]]) std::swap(u, v);
54     opt(dfn[top[u]], dfn[u]);
55     u = fa[top[u]];
56 }
57 if (dfn[u] > dfn[v]) std::swap(u, v);
58 opt(dfn[u], dfn[v]);
59
60 // 维护 u 为根的子树 //
61 opt(dfn[u], botton[u]);
62
63 */
64
65 // segment tree //
66
67 /*

```



```

68 | build() 函数中
69 | if(l == r) tree[u] = {l, l, w[rank[l]], 0};
70 | /*
71 | build(1, 1, n);
72 |
73 | for (int i = 1; i <= m; i++) {
74 |     int op, u, v;
75 |     LL k;
76 |     std::cin >> op;
77 |     if (op == 1) {
78 |         std::cin >> u >> v >> k;
79 |         while (top[u] != top[v]) {
80 |             if (depth[top[u]] < depth[top[v]]) std::swap(u, v);
81 |             modify(1, dfn[top[u]], dfn[u], k);
82 |             u = fa[top[u]];
83 |         }
84 |         if (dfn[u] > dfn[v]) std::swap(u, v);
85 |         modify(1, dfn[u], dfn[v], k);
86 |     } else if (op == 2) {
87 |         std::cin >> u >> v;
88 |         LL ans = 0;
89 |         while (top[u] != top[v]) {
90 |             if (depth[top[u]] < depth[top[v]]) std::swap(u, v);
91 |             ans = (ans + query(1, dfn[top[u]], dfn[u])) % p;
92 |             u = fa[top[u]];
93 |         }
94 |         if (dfn[u] > dfn[v]) std::swap(u, v);
95 |         ans = (ans + query(1, dfn[u], dfn[v])) % p;
96 |         std::cout << ans << endl;
97 |     } else if (op == 3) {
98 |         std::cin >> u >> k;
99 |         modify(1, dfn[u], botton[u], k);
100 |     } else {
101 |         std::cin >> u;
102 |         std::cout << query(1, dfn[u], botton[u]) % p << endl;
103 |     }
104 | }

```

11.12 树上问题 - 树分治

11.12.1 点分治

第一个题

一棵 $n \leq 10^4$ 个点的树, 边权 $w \leq 10^4$. $m \leq 100$ 次询问树上是否存在长度为 $k \leq 10^7$ 的路径.

```

1 | // 洛谷 P3806 【模板】点分治1
2 |
3 | int main() {
4 |     std::ios::sync_with_stdio(false);
5 |     std::cin.tie(0);
6 |     std::cout.tie(0);
7 |
8 |     int n, m, k;
9 |     std::cin >> n >> m;
10 |
11 |     std::vector<vpi> e(n + 1);
12 |     std::map<int, PII> mp;
13 |
14 |     for (int i = 1; i < n; i++) {
15 |         int u, v, w;
16 |         std::cin >> u >> v >> w;
17 |         e[u].emplace_back(v, w);
18 |         e[v].emplace_back(u, w);
19 |     }
20 |     for (int i = 1; i <= m; i++) {
21 |         std::cin >> k;
22 |         mp[i] = {k, 0};
23 |     }
24 |
25 |     // centroid decomposition //
26 |     int top1 = 0, top2 = 0, root;
27 |     vi len1(n + 1), len2(n + 1), vis(n + 1);
28 |     static std::array<int, 20000010> cnt;
29 |
30 |     std::function<int(int, int)> get_size = [&](int u, int fa) -> int {
31 |         if (vis[u]) return 0;
32 |         int ans = 1;
33 |         for (auto [v, w] : e[u]) {
34 |             if (v == fa) continue;

```

```

35     ans += get_size(v, u);
36 }
37 return ans;
38 };
39
40 std::function<int(int, int, int, int&)> get_root = [&](int u, int fa, int tot,
41                                                     int& root) -> int {
42     if (vis[u]) return 0;
43     int sum = 1, maxx = 0;
44     for (auto [v, w] : e[u]) {
45         if (v == fa) continue;
46         int tmp = get_root(v, u, tot, root);
47         Max(maxx, tmp);
48         sum += tmp;
49     }
50     Max(maxx, tot - sum);
51     if (2 * maxx <= tot) root = u;
52     return sum;
53 };
54
55 std::function<void(int, int, int)> get_dist = [&](int u, int fa, int dist) -> void {
56     if (dist <= 10000000) len1[++top1] = dist;
57     for (auto [v, w] : e[u]) {
58         if (v == fa or vis[v]) continue;
59         get_dist(v, u, dist + w);
60     }
61 };
62
63 auto solve = [&](int u, int dist) -> void {
64     top2 = 0;
65     for (auto [v, w] : e[u]) {
66         if (vis[v]) continue;
67         top1 = 0;
68         get_dist(v, u, w);
69         for (int i = 1; i <= top1; i++) {
70             for (int tt = 1; tt <= m; tt++) {
71                 int k = mp[tt].ff;
72                 if (k >= len1[i]) mp[tt].ss |= cnt[k - len1[i]];
73             }
74         }
75         for (int i = 1; i <= top1; i++) {
76             len2[++top2] = len1[i];
77             cnt[len1[i]] = 1;
78         }
79     }
80     for (int i = 1; i <= top2; i++) cnt[len2[i]] = 0;
81 };
82
83 std::function<void(int)> divide = [&](int u) -> void {
84     vis[u] = cnt[0] = 1;
85     solve(u, 0);
86     for (auto [v, w] : e[u]) {
87         if (vis[v]) continue;
88         get_root(v, u, get_size(v, u), root);
89         divide(root);
90     }
91 };
92
93 get_root(1, 0, get_size(1, 0), root);
94 divide(root);
95
96 for (int i = 1; i <= m; i++) {
97     if (mp[i].ss == 0) {
98         std::cout << "NAY" << endl;
99     } else {
100         std::cout << "AYE" << endl;
101     }
102 }
103
104 return 0;
105 }

```

第二个题

一棵 $n \leq 4 \times 10^4$ 个点的树, 边权 $w \leq 10^3$. 询问树上长度不超过 $k \leq 2 \times 10^4$ 的路径的数量.

```

1 // 洛谷 P4178 Tree
2
3 int main() {
4     std::ios::sync_with_stdio(false);
5     std::cin.tie(0);
6     std::cout.tie(0);
7
8     int n, k;
9     std::cin >> n;

```

```

10  std::vector<vpi> e(n + 1);
11  for (int i = 1; i < n; i++) {
12      int u, v, w;
13      std::cin >> u >> v >> w;
14      e[u].emplace_back(v, w);
15      e[v].emplace_back(u, w);
16  }
17  std::cin >> k;
18
19  // centroid decomposition //
20  int root;
21  vi len, vis(n + 1);
22
23  std::function<int(int, int)> get_size = [&](int u, int fa) -> int {
24      if (vis[u]) return 0;
25      int ans = 1;
26      for (auto [v, w] : e[u]) {
27          if (v == fa) continue;
28          ans += get_size(v, u);
29      }
30      return ans;
31  };
32
33  std::function<int(int, int, int, int)> get_root = [&](int u, int fa, int tot,
34      int& root) -> int {
35      if (vis[u]) return 0;
36      int sum = 1, maxx = 0;
37      for (auto [v, w] : e[u]) {
38          if (v == fa) continue;
39          int tmp = get_root(v, u, tot, root);
40          maxx = std::max(maxx, tmp);
41          sum += tmp;
42      }
43      maxx = std::max(maxx, tot - sum);
44      if (2 * maxx <= tot) root = u;
45      return sum;
46  };
47
48  std::function<void(int, int, int)> get_dist = [&](int u, int fa, int dist) -> void {
49      len.push_back(dist);
50      for (auto [v, w] : e[u]) {
51          if (v == fa || vis[v]) continue;
52          get_dist(v, u, dist + w);
53      }
54  };
55
56  auto solve = [&](int u, int dist) -> int {
57      len.clear();
58      get_dist(u, 0, dist);
59      std::sort(all(len));
60      int ans = 0;
61      for (int l = 0, r = len.size() - 1; l < r;) {
62          if (len[l] + len[r] <= k) {
63              ans += r - l++;
64          } else {
65              r--;
66          }
67      }
68      return ans;
69  };
70
71  std::function<int(int)> divide = [&](int u) -> int {
72      vis[u] = true;
73      int ans = solve(u, 0);
74      for (auto [v, w] : e[u]) {
75          if (vis[v]) continue;
76          ans -= solve(v, w);
77          get_root(v, u, get_size(v, u), root);
78          ans += divide(root);
79      }
80      return ans;
81  };
82
83  get_root(1, 0, get_size(1, 0), root);
84  std::cout << divide(root) << endl;
85
86  return 0;
87 }

```

11.13 基环树

11.13.1 找环

```

1 // Pseudotree //
2
3 vi roots, vis(n + 1), tmp;
4 int found = 0;
5 std::function<void(int, int)> find_ring = [&](int u, int fa) -> void {
6     if (found) return;
7     tmp.push_back(u);
8     vis[u] = true;
9     for (auto v : e[u]) {
10         if (v == fa) continue;
11         if (!vis[v]) {
12             find_ring(v, u);
13         } else {
14             int flag = 0;
15             for (auto x : tmp) {
16                 if (x == v) flag = 1;
17                 if (flag) roots.push_back(x);
18             }
19             found = 1;
20             return;
21         }
22     }
23     tmp.pop_back();
24 };
25 find_ring(1, 0);

```

11.14 树上问题 - AHU 算法

```

1 std::map<vi, int> mapple;
2 std::function<int(vvi&, int, int)> tree_hash = [&](vvi& e, int u, int fa) -> int {
3     vi code;
4     if (u == 0) code.push_back(-1);
5     for (auto v : e[u]) {
6         if (v == fa) continue;
7         code.push_back(tree_hash(e, v, u));
8     }
9     std::sort(all(code));
10    int id = mapple.size();
11    auto it = mapple.find(code);
12    if (it == mapple.end()) {
13        mapple[code] = id;
14    } else {
15        id = it->ss;
16    }
17    return id;
18 };

```

11.15 虚树

```

1 // virtual tree //
2
3 auto build_vtree = [&](vi ver) -> void {
4     std::sort(all(ver), [&](int x, int y) { return dfn[x] < dfn[y]; });
5     vi stk = {1};
6     for (auto v : ver) {
7         int u = stk.back();
8         int lca = LCA(v, u);
9         if (lca != u) {
10             while (dfn[lca] < dfn[stk.end()[-2]]) {
11                 g[stk.end()[-2]].push_back(stk.back());
12                 stk.pop_back();
13             }
14             u = stk.back();
15             if (dfn[lca] != dfn[stk.end()[-2]]) {
16                 g[lca].push_back(u);
17                 stk.pop_back();
18                 stk.push_back(lca);
19             } else {
20                 g[lca].push_back(u);
21                 stk.pop_back();

```

```

22     }
23     }
24     stk.push_back(v);
25 }
26 while (stk.size() > 1) {
27     int u = stk.end()[-2];
28     int v = stk.back();
29     g[u].push_back(v);
30     stk.pop_back();
31 }
32 };

```

11.16 2 - SAT

给出 n 个集合, 每个集合有 2 个元素, 已知若干个数对 (a, b) , 表示 a 与 b 矛盾. 要从每个集合各选择一个元素, 判断能否一共选 n 个两两不矛盾的元素.

设集合 $\{a1, a2\}, \{b1, b2\}$, 如果 $a1$ 与 $b2$ 矛盾, 为了自治, 建立由 $a1 \rightarrow b1, a2 \rightarrow b2$ 这两条有向边. 表示选了 $a1$ 则必须选 $b1$, 选了 $b2$ 则必须选 $a2$ 才能够自治.

然后跑一遍 Tarjan 判断是否有一个集合中的两个元素在同一个 SCC 中, 若有则无解, 否则有解. 构造方案只需要把几个不矛盾的 SCC 拼起来.

```

1 // Problem: 洛谷: P5782 [POI2001] 和平委员会
2
3 int main() {
4     std::ios::sync_with_stdio(false);
5     std::cin.tie(0);
6     std::cout.tie(0);
7
8     int n, m;
9     std::cin >> n >> m;
10    n *= 2;
11    vvi e(n + 1);
12    for (int i = 1; i <= m; i++) {
13        int u, v;
14        std::cin >> u >> v;
15        e[u].push_back(v & 1 ? v + 1 : v - 1);
16        e[v].push_back(u & 1 ? u + 1 : u - 1);
17    }
18
19    // tarjan //
20
21    vi ans;
22    for (int i = 1; i <= n; i += 2) {
23        if (belong[i] == belong[i + 1]) {
24            std::cout << "NIE" << endl;
25            return 0;
26        } else {
27            ans.push_back(belong[i] > belong[i + 1] ? i + 1 : i);
28        }
29    }
30    for (auto x : ans) {
31        std::cout << x << endl;
32    }
33
34    return 0;
35 }

```

11.17 欧拉图

Hierholzer 算法

11.17.1 有向图

```

1 struct node{
2     int to;
3     bool exist;
4 };
5 vector<node> edge[N];

```

```

6  vector<int> ans;
7  int n, m, flag1, flag2;
8  int d[N], last[N];
9  bool cmp(node a, node b){
10     return a.to < b.to;
11 }
12 void hierholzer(int u){
13     for(int i = 0; i < edge[u].size(); i = max(i, last[u]) + 1){
14         // 比i++能加速 //
15         if(edge[u][i].exist){
16             edge[u][i].exist = 0;
17             last[u] = i;
18             hierholzer(edge[u][i].to);
19         }
20     }
21     ans.push_back(u);
22 }
23 bool check(){
24     for(int i = 1; i <= n; i++){
25         if(d[i] > 1 || d[i] < -1) return 0;
26         if(d[i] == 1) flag1++;
27         else if(d[i] == -1) flag2++;
28     }
29     if(flag1 > 1 || flag2 > 1) return 0;
30     return 1;
31 }
32 int main(){
33     /* 边: a -> b
34     scanf("%d%d", &a, &b);
35     edge[a].push_back((node){b, 1});
36     d[a]++;
37     d[b]--;
38     */
39     for(int i = 1; i <= n; i++){
40         sort(edge[i].begin(), edge[i].end(), cmp);
41     }
42     // 要求字典序最下, 对边排序 //
43     if(!check()){
44         cout << "No" << endl;
45         return 0;
46     }
47     int id = 1;
48     for(int i = 1; i <= n; i++){
49         if(d[i] == 1){
50             id = i;
51             break;
52         }
53     }
54     hierholzer(id);
55     for(int i = ans.size() - 1; i >= 0; i--){
56         printf("%d ", ans[i]);
57     }
58     return 0;
59 }

```

11.17.2 无向图

```

1  struct node{
2      int to, revref;
3      bool exist;
4  };
5  vector<node> edge[N];
6  vector<int> ans;
7  int n, m, flag;
8  int d[N], reftop[N], last[N];
9  bool cmp(node a, node b){
10     return a.to < b.to;
11 }
12 void hierholzer(int u){
13     for (int i = 0; i < edge[u].size(); i = max(i, last[u]) + 1){
14         // 比i++能加速 //
15         if(edge[u][i].exist){
16             auto t = edge[u][i];
17             t.exist = 0;
18             edge[t.to][t.revref].exist = 0;
19             last[u] = i;
20             hierholzer(t.to);
21         }
22     }
23     ans.push_back(u);
24 }
25 bool check(){

```

```

26     for(int i = 1; i <= n; i++){
27         if(d[i] % 2 == 1) flag++;
28     }
29     if(flag == 0 || flag == 2) return 1;
30     return 0;
31 }
32 int main(){
33     /* 边: a -> b
34     scanf("%d%d", &a, &b);
35     edge[a].push_back((node){b, 0, 1});
36     edge[b].push_back((node){a, 0, 1});
37     d[a]++;
38     d[b]++;
39     */
40     for(int i = 1; i <= n; i++){
41         sort(edge[i].begin(), edge[i].end(), cmp);
42     }
43     for(int i = 1; i <= n; i++){
44         for(int j = 0; j < edge[i].size(); j++){
45             edge[i][j].revref = reftop[edge[i][j].to]++;
46         }
47     }
48     if(!check()){
49         cout << "No" << endl;
50         return 0;
51     }
52     int id = 0;
53     for(int i = 1; i <= n; i++){
54         if(!d[id] && d[i]) id = i;
55         else if(!d[id] & 1) && (d[i] & 1)) id = i;
56     }
57     hierholzer(id);
58     for(int i = ans.size() - 1; i >= 0; i--){
59         cout << ans[i] << endl;
60     }
61     return 0;
62 }

```

11.18 最小环

11.18.1 Dijkstra

枚举所有边，每一次求删除一条边之后对这条边的起点跑一次 Dijkstra.

总复杂度 $O(m(n + m) \log n)$

11.18.2 floyd

```

1  auto min_circle = [&]() -> int {
2      vvi dist(n + 1, vi(n + 1, inf));
3      for (int i = 1; i <= n; i++) {
4          for (int j = 1; j <= n; j++) {
5              Min(dist[i][j], g[i][j]);
6          }
7          dist[i][i] = 0;
8      }
9      for (int k = 1; k <= n; k++) {
10         for (int i = 1; i < k; i++) {
11             for (int j = 1; j < i; j++) {
12                 Min(ans, dist[i][j] + g[i][k] + g[k][j]);
13             }
14         }
15         for (int i = 1; i <= n; i++) {
16             for (int j = 1; j <= n; j++) {
17                 Min(dist[i][j], dist[i][k] + dist[k][j]);
18             }
19         }
20     }
21     return ans;
22 };

```

总复杂度 $O(n^3)$

11.19 网络流 - 最大流

11.19.1 Dinic

时间复杂度为 $O(n^2m)$, 单位流量是 $O(m \cdot \min\{m^{\frac{1}{2}}, n^{\frac{2}{3}}\})$.

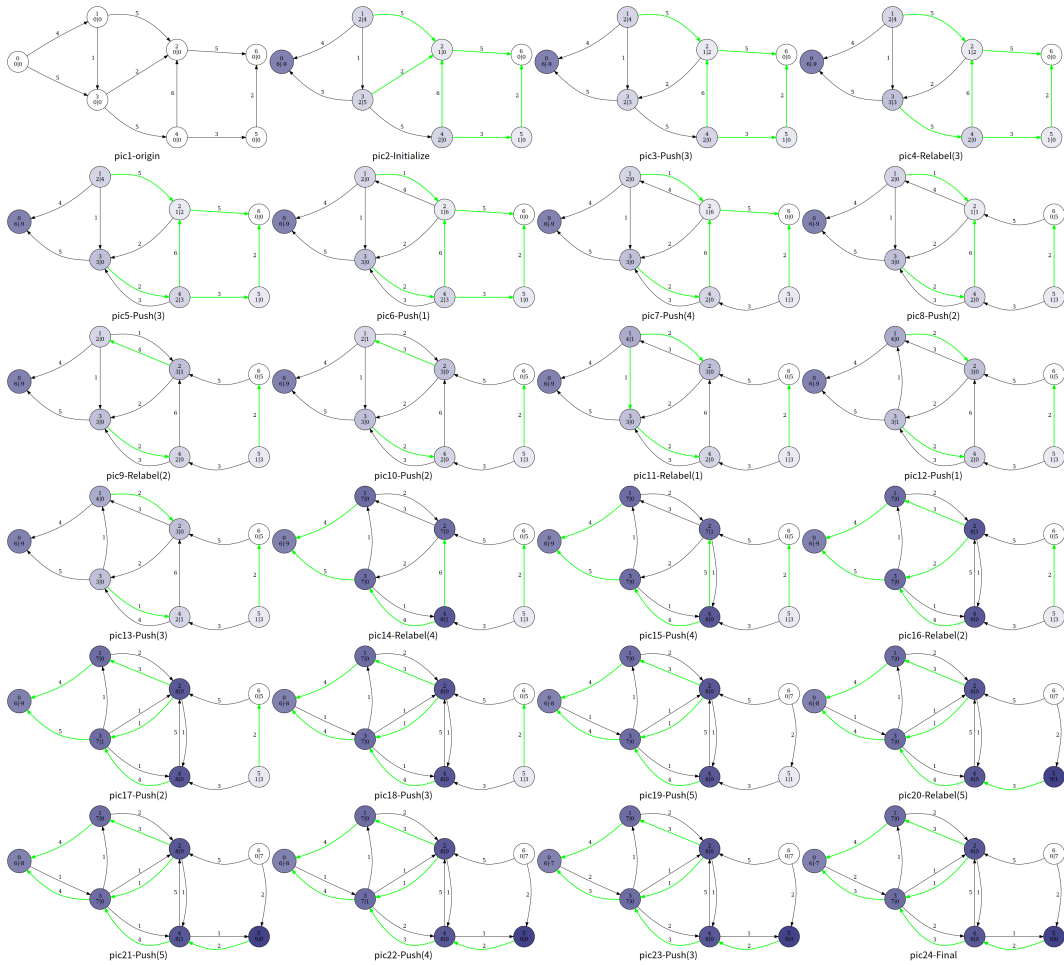
```

1 struct edge {
2     int from, to;
3     LL cap, flow;
4
5     edge(int u, int v, LL c, LL f) : from(u), to(v), cap(c), flow(f) {}
6 };
7
8 struct Dinic {
9     int n, m = 0, s, t;
10    std::vector<edge> e;
11    vi g[N];
12    int d[N], cur[N], vis[N];
13
14    void init(int n) {
15        for (int i = 0; i < n; i++) g[i].clear();
16        e.clear();
17        m = 0;
18    }
19
20    void add(int from, int to, LL cap) {
21        e.push_back(edge(from, to, cap, 0));
22        e.push_back(edge(to, from, 0, 0));
23        g[from].push_back(m++);
24        g[to].push_back(m++);
25    }
26
27    bool bfs() {
28        for (int i = 1; i <= n; i++) {
29            vis[i] = 0;
30        }
31        std::queue<int> q;
32        q.push(s), d[s] = 0, vis[s] = 1;
33        while (!q.empty()) {
34            int u = q.front();
35            q.pop();
36            for (int i = 0; i < g[u].size(); i++) {
37                edge& ee = e[g[u][i]];
38                if (!vis[ee.to] and ee.cap > ee.flow) {
39                    vis[ee.to] = 1;
40                    d[ee.to] = d[u] + 1;
41                    q.push(ee.to);
42                }
43            }
44        }
45        return vis[t];
46    }
47
48    LL dfs(int u, LL now) {
49        if (u == t || now == 0) return now;
50        LL flow = 0, f;
51        for (int& i = cur[u]; i < g[u].size(); i++) {
52            edge& ee = e[g[u][i]];
53            edge& er = e[g[u][i] ^ 1];
54            if (d[u] + 1 == d[ee.to] and (f = dfs(ee.to, std::min(now, ee.cap - ee.flow))) > 0) {
55                ee.flow += f, er.flow -= f;
56                flow += f, now -= f;
57                if (now == 0) break;
58            }
59        }
60        return flow;
61    }
62
63    LL dinic() {
64        LL ans = 0;
65        while (bfs()) {
66            for (int i = 1; i <= n; i++) cur[i] = 0;
67            ans += dfs(s, INF);
68        }
69        return ans;
70    }
71 } maxf;

```


11.19.2 HLPP

时间复杂度上界为 $O(n^2\sqrt{m})$. 使用记得先跑 `init()`.



```

1 struct HLPP {
2     int n, m = 0, s, t;
3     std::vector<edge> e; // 边 //
4     std::vector<node> nd; // 点 //
5     std::vector<int> g[N]; // 点的连边编号 //
6     std::priority_queue<node> q;
7     std::queue<int> qq;
8     bool vis[N];
9     int cnt[N];
10
11 void init() {
12     e.clear();
13     nd.clear();
14     for (int i = 0; i <= n + 1; i++) {
15         nd.push_back(node(inf, i, 0));
16         g[i].clear();
17         vis[i] = false;
18     }
19 }
20
21 void add(int u, int v, LL w) {
22     e.push_back(edge(u, v, w));
23     e.push_back(edge(v, u, 0));
24     g[u].push_back(m++);
25     g[v].push_back(m++);
26 }
27
28 void bfs() {
29     nd[t].hight = 0;
30     qq.push(t);
31     while (!qq.empty()) {
32         int u = qq.front();
33         qq.pop();
34         vis[u] = false;
35         for (auto j : g[u]) {
36             int v = e[j].to;
37             if (e[j].cap == 0 && nd[v].hight > nd[u].hight + 1) {

```

```

38         nd[v].hight = nd[u].hight + 1;
39         if (vis[v] == false) {
40             qq.push(v);
41             vis[v] = true;
42         }
43     }
44 }
45 }
46 return;
47 }
48
49 void _push(int u) {
50     for (auto j : g[u]) {
51         edge &ee = e[j], &er = e[j ^ 1];
52         int v = ee.to;
53         node &nu = nd[u], &nv = nd[v];
54         if (ee.cap && nv.hight + 1 == nu.hight) {
55             // 推流 //
56             LL flow = std::min(ee.cap, nu.flow);
57             ee.cap -= flow, er.cap += flow;
58             nu.flow -= flow, nv.flow += flow;
59             if (vis[v] == false && v != t && v != s) {
60                 q.push(nv);
61                 vis[v] = true;
62             }
63             if (nu.flow == 0) break;
64         }
65     }
66 }
67
68 void relabel(int u) {
69     nd[u].hight = inf;
70     for (auto j : g[u]) {
71         int v = e[j].to;
72         if (e[j].cap && nd[v].hight + 1 < nd[u].hight) {
73             nd[u].hight = nd[v].hight + 1;
74         }
75     }
76 }
77
78 LL hlpp() {
79     bfs();
80     if (nd[s].hight == inf) return 0;
81     nd[s].hight = n;
82     for (int i = 1; i <= n; i++) {
83         if (nd[i].hight < inf) cnt[nd[i].hight]++;
84     }
85     for (auto j : g[s]) {
86         int v = e[j].to;
87         int flow = e[j].cap;
88         if (flow) {
89             e[j].cap -= flow, e[j ^ 1].cap += flow;
90             nd[s].flow -= flow, nd[v].flow += flow;
91             if (vis[v] == false && v != s && v != t) {
92                 q.push(nd[v]);
93                 vis[v] = true;
94             }
95         }
96     }
97     while (!q.empty()) {
98         int u = q.top().id;
99         q.pop();
100         vis[u] = false;
101         _push(u);
102         if (nd[u].flow) {
103             cnt[nd[u].hight]--;
104             if (cnt[nd[u].hight] == 0) {
105                 for (int i = 1; i <= n; i++) {
106                     if (i != s && i != t && nd[i].hight > nd[u].hight && nd[i].hight < n + 1) {
107                         nd[i].hight = n + 1;
108                     }
109                 }
110             }
111             // 上面为 gap 优化 //
112             relabel(u);
113             cnt[nd[u].hight]++;
114             q.push(nd[u]);
115             vis[u] = true;
116         }
117     }
118     return nd[t].flow;
119 }
120 } maxf;

```

11.20 网络流 - 费用流

11.20.1 Dinic + SPFA

处理无负环的网络.

```

1 struct edge {
2     int from, to;
3     LL cap, cost;
4
5     edge(int u, int v, LL c, LL w) : from(u), to(v), cap(c), cost(w) {}
6 };
7
8 struct MCMF {
9     int n, m = 0, s, t;
10    std::vector<edge> e;
11    vi g[N];
12    int cur[N], vis[N];
13    LL dist[N], minc;
14
15    void init(int n) {
16        for (int i = 0; i < n; i++) g[i].clear();
17        e.clear();
18        minc = m = 0;
19    }
20
21    void add(int from, int to, LL cap, LL cost) {
22        e.push_back(edge(from, to, cap, cost));
23        e.push_back(edge(to, from, 0, -cost));
24        g[from].push_back(m++);
25        g[to].push_back(m++);
26    }
27
28    bool spfa() {
29        rep(i, 1, n) { dist[i] = INF, cur[i] = 0; }
30        std::queue<int> q;
31        q.push(s), dist[s] = 0, vis[s] = 1;
32        while (!q.empty()) {
33            int u = q.front();
34            q.pop();
35            vis[u] = 0;
36            for (int j = cur[u]; j < g[u].size(); j++) {
37                edge& ee = e[g[u][j]];
38                int v = ee.to;
39                if (ee.cap && dist[v] > dist[u] + ee.cost) {
40                    dist[v] = dist[u] + ee.cost;
41                    if (!vis[v]) {
42                        q.push(v);
43                        vis[v] = 1;
44                    }
45                }
46            }
47        }
48        return dist[t] != INF;
49    }
50
51    LL dfs(int u, LL now) {
52        if (u == t) return now;
53        vis[u] = 1;
54        LL ans = 0;
55        for (int& i = cur[u]; i < g[u].size() && ans < now; i++) {
56            edge &ee = e[g[u][i]], &er = e[g[u][i] ^ 1];
57            int v = ee.to;
58            if (!vis[v] && ee.cap && dist[v] == dist[u] + ee.cost) {
59                LL f = dfs(v, std::min(ee.cap, now - ans));
60                if (f) {
61                    minc += f * ee.cost, ans += f;
62                    ee.cap -= f;
63                    er.cap += f;
64                }
65            }
66        }
67        vis[u] = 0;
68        return ans;
69    }
70
71    PLL mcmf() {
72        LL maxf = 0;
73        while (spfa()) {
74            LL tmp;
75            while ((tmp = dfs(s, INF))) maxf += tmp;
76        }
77        return std::makepair(maxf, minc);
78    }

```

```
79 } minc_maxf;
```

11.20.2 Primal-Dual 原始对偶算法

处理无负环的网络.

```
1 struct edge {
2     int from, to;
3     LL cap, cost;
4
5     edge(int u, int v, LL c, LL w) : from(u), to(v), cap(c), cost(w) {}
6 };
7
8 struct node {
9     int v, e;
10
11     node(int _v = 0, int _e = 0) : v(_v), e(_e) {}
12 };
13
14 const int maxn = 5000 + 10;
15
16 struct MCMF {
17     int n, m = 0, s, t;
18     std::vector<edge> e;
19     vi g[maxn];
20     int dis[maxn], vis[maxn], h[maxn];
21     node p[maxn * 2];
22
23     void add(int from, int to, LL cap, LL cost) {
24         e.push_back(edge(from, to, cap, cost));
25         e.push_back(edge(to, from, 0, -cost));
26         g[from].push_back(m++);
27         g[to].push_back(m++);
28     }
29
30     bool dijkstra() {
31         std::priority_queue<PII, std::vector<PII>, std::greater<PII>> q;
32         for (int i = 1; i <= n; i++) {
33             dis[i] = inf;
34             vis[i] = 0;
35         }
36         dis[s] = 0;
37         q.push({0, s});
38         while (!q.empty()) {
39             int u = q.top().ss;
40             q.pop();
41             if (vis[u]) continue;
42             vis[u] = 1;
43             for (auto i : g[u]) {
44                 edge ee = e[i];
45                 int v = ee.to, nc = ee.cost + h[u] - h[v];
46                 if (ee.cap and dis[v] > dis[u] + nc) {
47                     dis[v] = dis[u] + nc;
48                     p[v] = node(u, i);
49                     if (!vis[v]) q.push({dis[v], v});
50                 }
51             }
52         }
53         return dis[t] != inf;
54     }
55
56     void spfa() {
57         std::queue<int> q;
58         for (int i = 1; i <= n; i++) h[i] = inf;
59         h[s] = 0, vis[s] = 1;
60         q.push(s);
61         while (!q.empty()) {
62             int u = q.front();
63             q.pop();
64             vis[u] = 0;
65             for (auto i : g[u]) {
66                 edge ee = e[i];
67                 int v = ee.to;
68                 if (ee.cap and h[v] > h[u] + ee.cost) {
69                     h[v] = h[u] + ee.cost;
70                     if (!vis[v]) {
71                         vis[v] = 1;
72                         q.push(v);
73                     }
74                 }
75             }
76         }
77     }
78 }
```

```

77     }
78
79     PLL mcmf() {
80         LL maxf = 0, minc = 0;
81         spfa();
82         while (dijkstra()) {
83             LL minf = INF;
84             for (int i = 1; i <= n; i++) h[i] += dis[i];
85             for (int i = t; i != s; i = p[i].v) minf = std::min(minf, e[p[i].e].cap);
86             for (int i = t; i != s; i = p[i].v) {
87                 e[p[i].e].cap -= minf;
88                 e[p[i].e ^ 1].cap += minf;
89             }
90             maxf += minf;
91             minc += minf * h[t];
92         }
93         return std::makepair(maxf, minc);
94     }
95 } minc_maxf;

```

11.21 网络流 - 最小割

最小割解决的问题是将图中的点集 V 划分成 S 与 T , 使得 S 与 T 之间的连边的容量总和最小.

11.21.1 最大流最小割定理

网络中 s 到 t 的最大流流量的值等于所要求的最小割的值. 所以求最小割只需要跑 Dinic 即可.

11.21.2 获取 S 中的点

在 Dinic 的 bfs 函数中, 每次将所有点的 d 数组值改为无穷大, 最后跑完最大流之后 d 数组不为无穷大的就是和源点一起在 S 集合中的点.

11.21.3 例子

最小割的本质是对图中点集进行 2-划分, 网络流只是求解答的手段.

1. 在图中花费最小的代价断开一些边使得源点 s 无法流到汇点 t
直接跑最大流就得到了答案.
2. 在图中删除最少的点使得源点 s 无法流到汇点 t
对每个点进行拆点, 在 i 与 i' 之间建立容量为 1 的有向边.

11.22 图匹配 - 二分图最大匹配

11.22.1 Kuhn-Munkres 算法

时间复杂度: $O(n^3)$.

```

1  auto KM = [&](int n1, int n2, vvi e) -> std::pair<vi, vi> {
2      vi vis(n2 + 1);
3      vi l(n1 + 1, -1), r(n2 + 1, -1);
4      std::function<bool(int)> dfs = [&](int u) -> bool {
5          for (auto v : e[u]) {
6              if (!vis[v]) {
7                  vis[v] = 1;
8                  if (r[v] == -1 or dfs(r[v])) {
9                      r[v] = u;
10                     return true;
11                 }
12             }

```

```

13     }
14     return false;
15 };
16 for (int i = 1; i <= n1; i++) {
17     std::fill(all(vis), 0);
18     dfs(i);
19 }
20 for (int i = 1; i <= n2; i++) {
21     if (r[i] == -1) continue;
22     l[r[i]] = i;
23 }
24 return {l, r};
25 };
26 auto [mchl, mchr] = KM(n1, n2, e);
27 std::cout << mchl.size() - std::count(all(mchl), -1) << endl;

```

11.22.2 Hopcroft-Karp 算法

据说时间复杂度是 $O(m\sqrt{n})$ 的, 但是快的飞起.

```

1 vpi e(m);
2 auto hopcroft_karp = [&](int n, int m, vpi& e) -> std::pair<vi, vi> {
3     vi g(e.size()), l(n + 1, -1), r(m + 1, -1), d(n + 2);
4     for (auto [u, v] : e) d[u]++;
5     std::partial_sum(all(d), d.begin());
6     for (auto [u, v] : e) g[--d[u]] = v;
7     for (vi a, p, q(n + 1);) {
8         a.assign(n + 1, -1);
9         p.assign(n + 1, -1);
10        int t = 1;
11        for (int i = 1; i <= n; i++) {
12            if (l[i] == -1) {
13                q[t++] = a[i] = p[i] = i;
14            }
15        }
16        bool match = false;
17        for (int i = 1; i < t; i++) {
18            int u = q[i];
19            if (l[a[u]] != -1) continue;
20            for (int j = d[u]; j < d[u + 1]; j++) {
21                int v = g[j];
22                if (r[v] == -1) {
23                    while (v != -1) {
24                        r[v] = u;
25                        std::swap(l[u], v);
26                        u = p[u];
27                    }
28                    match = true;
29                    break;
30                }
31                if (p[r[v]] == -1) {
32                    q[t++] = v = r[v];
33                    p[v] = u;
34                    a[v] = a[u];
35                }
36            }
37        }
38        if (!match) break;
39    }
40    return {l, r};
41 };
42 auto [mchl, mchr] = hopcroft_karp(n1, n2, e);
43 std::cout << mchl.size() - std::count(all(mchl), -1) << endl;

```

11.23 图匹配 - 二分图最大权匹配

11.23.1 Kuhn-Munkres

注意是否为完美匹配, 非完美选 0, 完美选 $-INF$.

```

1 auto KM = [&](int n, vvl e) -> std::tuple<LL, vi, vi> {
2     vl la(n + 1), lb(n + 1), pp(n + 1), vx(n + 1);
3     vi l(n + 1, -1), r(n + 1, -1);
4     vi va(n + 1), vb(n + 1);
5     LL delta;
6     auto bfs = [&](int x) -> void {

```

```

7      int a, y = 0, y1 = 0;
8      std::fill(all(pp), 0);
9      std::fill(all(vx), INF);
10     r[y] = x;
11     do {
12         a = r[y], delta = INF, vb[y] = 1;
13         for (int b = 1; b <= n; b++) {
14             if (!vb[b]) {
15                 if (vx[b] > la[a] + lb[b] - e[a][b]) {
16                     vx[b] = la[a] + lb[b] - e[a][b];
17                     pp[b] = y;
18                 }
19                 if (vx[b] < delta) {
20                     delta = vx[b];
21                     y1 = b;
22                 }
23             }
24         }
25         for (int b = 0; b <= n; b++) {
26             if (vb[b]) {
27                 la[r[b]] -= delta;
28                 lb[b] += delta;
29             } else
30                 vx[b] -= delta;
31         }
32         y = y1;
33     } while (r[y] != -1);
34     while (y) {
35         r[y] = r[pp[y]];
36         y = pp[y];
37     }
38 };
39 for (int i = 1; i <= n; i++) {
40     std::fill(all(vb), 0);
41     bfs(i);
42 }
43 LL ans = 0;
44 for (int i = 1; i <= n; i++) {
45     if (r[i] == -1) continue;
46     l[r[i]] = i;
47     ans += e[r[i]][i];
48 }
49 return {ans, l, r};
50 };
51
52 auto [ans, mchl, mchr] = KM(n, e);

```

12 计算几何

12.1 二维基础

12.1.1 向量计算

```

1  tandu struct pnt {
2      T x, y;
3
4      pnt(T _x = 0, T _y = 0) { x = _x, y = _y; }
5
6      pnt operator+(const pnt& a) const { return pnt(x + a.x, y + a.y); }
7
8      pnt operator-(const pnt& a) const { return pnt(x - a.x, y - a.y); }
9
10     /*
11     bool operator<(const pnt& a) const {
12         if (std::is_same<T, double>::value) {
13             if (fabs(x - a.x) < eps) return y < a.y;
14         } else {
15             if (x == a.x) return y < a.y;
16         }
17         return x < a.x;
18     }
19     */
20
21     // 注意数乘会不会爆 int //
22     pnt operator*(const T k) const { return pnt(k * x, k * y); }
23
24     U operator*(const pnt& a) const { return (U) x * a.x + (U) y * a.y; }
25
26     U operator^(const pnt& a) const { return (U) x * a.y - (U) y * a.x; }
27
28     U dist(const pnt a) { return ((U) a.x - x) * ((U) a.x - x) + ((U) a.y - y) * ((U) a.y - y); }
29
30     U len() { return dist(pnt(0, 0)); }
31
32     // a, b, c 成逆时针 //
33     friend U area(pnt a, pnt b, pnt c) { return (b - a) ^ (c - a); }
34
35     // 两向量夹角, 返回 cos 值 //
36     double get_angle(pnt a) {
37         return (double) (pnt(x, y) * a) / sqrt((double) pnt(x, y).len() * (double) a.len());
38     }
39 };
40 typedef pnt<LL, LL> point;

```

12.1.2 线段

```

1  struct line {
2      point a, b;
3
4      line(point _a = {}, point _b = {}) { a = _a, b = _b; }
5
6      // 交点类型为 double //
7      friend point iPoint(line p, line q) {
8          point v1 = p.b - p.a;
9          point v2 = q.b - q.a;
10         point u = q.a - p.a;
11         return q.a + (q.b - q.a) * ((u ^ v1) * 1. / (v1 ^ v2));
12     }
13
14     // 极角排序 //
15     bool operator<(const line& p) const {
16         double t1 = std::atan2((b - a).y, (b - a).x);
17         double t2 = std::atan2((p.b - p.a).y, (p.b - p.a).x);
18         if (fabs(t1 - t2) > eps) {
19             return t1 < t2;
20         }
21         return ((p.a - a) ^ (p.b - a)) > eps;
22     }
23 };

```


12.2 凸包

12.2.1 二维凸包

```

1 // convex hull //
2 auto andrew = [&]() -> std::vector<point> {
3     std::sort(all(v));
4     std::vector<point> stk;
5     for (int i = 0; i < n; i++) {
6         point x = v[i];
7         while (stk.size() > 1 and ((stk.end()[-1] - stk.end()[-2]) ^ (x - stk.end()[-2])) <= 0) {
8             stk.pop_back();
9         }
10        stk.push_back(x);
11    }
12    int tmp = stk.size();
13    for (int i = n - 2; i >= 0; i--) {
14        point x = v[i];
15        while (stk.size() > tmp and ((stk.end()[-1] - stk.end()[-2]) ^ (x - stk.end()[-2])) <= 0) {
16            stk.pop_back();
17        }
18        stk.push_back(x);
19    }
20    return stk;
21 };
22 auto convex = andrew();

```

12.3 半平面交

```

1 // half plain intersection //
2 auto halfPlain = [&](std::vector<line>& ln) -> std::vector<point> {
3     std::sort(all(ln));
4     ln.erase(
5         unique(
6             all(ln),
7             [](line& p, line& q) {
8                 double t1 = std::atan2((p.b - p.a).y, (p.b - p.a).x);
9                 double t2 = std::atan2((q.b - q.a).y, (q.b - q.a).x);
10                return fabs((t1 - t2)) < eps;
11            },
12            ln.end());
13    auto check = [&](line p, line q, line r) -> bool {
14        point a = iPoint(p, q);
15        return ((r.b - r.a) ^ (a - r.a)) < -eps;
16    };
17    line q[ln.size() + 2];
18    int hh = 1, tt = 0;
19    q[++tt] = ln[0];
20    q[++tt] = ln[1];
21    for (int i = 2; i < (int) ln.size(); i++) {
22        while (hh < tt and check(q[tt - 1], q[tt], ln[i])) tt--;
23        while (hh < tt and check(q[hh + 1], q[hh], ln[i])) hh++;
24        q[++tt] = ln[i];
25    }
26    while (hh < tt and check(q[tt - 1], q[tt], q[hh])) tt--;
27    while (hh < tt and check(q[hh + 1], q[hh], q[tt])) hh++;
28    q[tt + 1] = q[hh];
29    std::vector<point> ans;
30    for (int i = hh; i <= tt; i++) {
31        ans.push_back(iPoint(q[i], q[i + 1]));
32    }
33    return ans;
34 };
35 auto p = halfPlain(ln);

```

13 离线算法

13.1 莫队

13.1.1 普通莫队

```

1  int block = n / sqrt(2 * m / 3);
2  std::sort(all(q), [&](node a, node b) {
3      return a.l / block == b.l / block ? (a.r == b.r ? 0 : ((a.l / block) & 1) ^ (a.r < b.r))
4          : a.l < b.l;
5  });
6
7  auto move = [&](int x, int op) -> void {
8      if (op == 1) {
9          ...
10     } else {
11         ...
12     }
13 };
14
15 for (int k = 1, l = 1, r = 0; k <= m; k++) {
16     node Q = q[k];
17     while (l > Q.l) {
18         move(--l, 1);
19     }
20     while (r < Q.r) {
21         move(++r, 1);
22     }
23     while (l < Q.l) {
24         move(l++, -1);
25     }
26     while (r > Q.r) {
27         move(r--, -1);
28     }
29 }

```

13.1.2 带修改莫队

13.1.3 树上莫队

13.2 离散化

```

1  std::sort(all(a));
2  a.erase(unique(all(a)), a.end());
3  auto get_id = [&](const int& x) -> int { return lower_bound(all(a), x) - a.begin() + 1; };

```

13.3 CDQ 分治

n 个三维数对 (a_i, b_i, c_i) , 设 $f(i)$ 表示 $a_j \leq a_i$ 且 $b_j \leq b_i$ 且 $c_j \leq c_i$ 且 $i \neq j$ 的个数.

输出 $f(i)$ ($0 \leq i \leq n-1$) 的值.

```

1  // 洛谷 P3810 【模板】三维偏序(陌上花开)
2
3  struct data {
4      int a, b, c, cnt, ans;
5
6      data(int _a = 0, int _b = 0, int _c = 0, int _cnt = 0, int _ans = 0) {
7          a = _a, b = _b, c = _c, cnt = _cnt, ans = _ans;
8      }
9
10     bool operator!=(data x) {
11         if (a != x.a) return true;
12         if (b != x.b) return true;
13         if (c != x.c) return true;
14         return false;
15     }
16 };

```

```

17
18 int main() {
19     std::ios::sync_with_stdio(false);
20     std::cin.tie(0);
21     std::cout.tie(0);
22
23     int n, k;
24     std::cin >> n >> k;
25     static data v1[N], v2[N];
26     for (int i = 1; i <= n; i++) {
27         std::cin >> v1[i].a >> v1[i].b >> v1[i].c;
28     }
29
30     std::sort(v1 + 1, v1 + n + 1, [&](data x, data y) {
31         if (x.a != y.a) return x.a < y.a;
32         if (x.b != y.b) return x.b < y.b;
33         return x.c < y.c;
34     });
35
36     int t = 0, top = 0;
37     for (int i = 1; i <= n; i++) {
38         t++;
39         if (v1[i] != v1[i + 1]) {
40             v2[++top] = v1[i];
41             v2[top].cnt = t;
42             t = 0;
43         }
44     }
45
46     // BIT //
47
48     // CDQ //
49     std::function<void(int, int)> CDQ = [&](int l, int r) -> void {
50         if (l == r) return;
51         int mid = (l + r) >> 1;
52         CDQ(l, mid), CDQ(mid + 1, r);
53         std::sort(v2 + 1, v2 + mid + 1, [&](data x, data y) {
54             if (x.b != y.b) return x.b < y.b;
55             return x.c < y.c;
56         });
57         std::sort(v2 + mid + 1, v2 + r + 1, [&](data x, data y) {
58             if (x.b != y.b) return x.b < y.b;
59             return x.c < y.c;
60         });
61         int i = l, j = mid + 1;
62         while (j <= r) {
63             while (i <= mid && v2[i].b <= v2[j].b) {
64                 add(v2[i].c, v2[i].cnt);
65                 i++;
66             }
67             v2[j].ans += query(v2[j].c);
68             j++;
69         }
70         for (int ii = l; ii < i; ii++) {
71             add(v2[ii].c, -v2[ii].cnt);
72         }
73         return;
74     };
75
76     CDQ(1, top);
77     vi ans(n + 1);
78     for (int i = 1; i <= top; i++) {
79         ans[v2[i].ans + v2[i].cnt] += v2[i].cnt;
80     }
81     for (int i = 1; i <= n; i++) {
82         std::cout << ans[i] << endl;
83     }
84
85     return 0;
86 }

```