Competitive Programming Reference

First, solve the problem. Then, write the code.

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By

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Contents

Coding Resources

C++

Decimal Precision

```
// rounds up the decimal number
cout << setprecision(N) << n << endl;
// specify N fixed number of decimals
cout << fixed << setprecision(N) << n << endl;
```

Include All Libraries

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

Int To Binary

```
typedef long long int lli;

lli bitsInInt(lli n) {  // clz = count leading zeroes
  return sizeof(n) * 8 - __builtin_clzll(n);
}

vector<bool> intToBitsArray(lli n) {
  n = abs(n);
  if (!n) return {};
  int length = bitsInInt(n), lastPos = length - 1;
  vector<bool> v(length);
  for (lli i = lastPos, j = 0; i > -1LL; i--, j++)
    v[j] = (n >> i) & 1LL;
  return v;
}
```

IO Optimization

```
int main() {
  ios_base::sync_with_stdio(0);
  cin.tie(0);
}
```

Map Value To Int

```
// val = value
typedef string Val;
unordered_map<Val, int> intForVal;
unordered_map<int, Val> valForInt;
int mapId = 0;
int Map(Val val) {
  if (intForVal.count(val)) return intForVal[val];
  valForInt[mapId] = val;
  return intForVal[val] = mapId++;
}

Val IMap(int n) { return valForInt[n]; }

void initMapping() {
  mapId = 0;
  intForVal.clear();
  valForInt.clear();
}
```

Permutations

```
typedef vector<int> T;  // typedef string T;

vector<T> permutations(T v) {
  vector<vector<int>> ans;
  sort(v.begin(), v.end());
  do
    ans.push_back(v);
  while (next_permutation(v.begin(), v.end()));
  return ans;
}
```

Print Vector

```
void printv(vector<int> v) {
  if (v.size() == 0) {
    cout << "[]" << endl;
    return;
  }
  cout << "[" << v[0];
  for (int i = 1; i < v.size(); i++)
    cout << ", " << v[i];
  cout << "]" << endl;
}
```

Priority Queue Of Object

```
struct Object {
  char first;
  int second;
};

int main() {
  auto cmp = [](const Object& a, const Object& b) {
    return a.second > b.second;
  };
  priority_queue<Object, vector<Object>,
                 decltype(cmp)> pq(cmp);
  vector<Object> v = {{'c', 3}, {'a', 1}, {'b', 2}};
  sort(v.begin(), v.end(), cmp);
  return 0;
}
```

Random

```cpp
int random(int min, int max) {
  return min + rand() % (max - min + 1);
}

int main() {
  srand(time(0));
  // code ...
}
```

Read Line

```cpp
// when reading lines, don't mix 'cin' with
// 'getline' just use getline and split
string input() {
  string ans;
  // cin >> ws; // eats all whitespaces.
  getline(cin, ans);
  return ans;
}
```

Sort Pair

```cpp
pair<int, int> p;
// sorts array on the basis of the first element
sort(p.begin(), p.end());
```

Sort Vector Of Object

```cpp
struct Object {
  char first;
  int second;
};

bool cmp(const Object& a, const Object& b) {
  return a.second > b.second;
}

int main() {
  vector<Object> v = {{'c', 3}, {'a', 1}, {'b', 2}};
  sort(v.begin(), v.end(), cmp);
  printv(v);
  return 0;
}
```

Split String

```cpp
vector<string> split(string str, char token) {
  stringstream test(str);
  string seg;
  vector<string> seglist;
  while (getline(test, seg, token))
    seglist.push_back(seg);
  return seglist;
}
```

Typedef

```cpp
typedef TYPE ALIAS;
// example:
typedef int T;
```

Python

Combinations

```python
import itertools
# from arr choose k = > combinations(arr, k)
print(list(itertools.combinations([1, 2, 3], 3)))
```

Fast IO

```python
from sys import stdin, stdout

N = 10
# Reads N chars from stdin(it counts '\n' as char)
stdin.read(N)
# Reads until '\n' or EOF
line = stdin.readline()
# Reads all lines in stdin until EOF
lines = stdin.readlines()
# Writes a string to stdout, it doesn't add '\n'
stdout.write(line)
# Writes a list of strings to stdout
stdout.writelines(lines)
# Reads numbers separated by space in a line
numbers = list(map(int, stdin.readline().split()))
```

Permutations

```python
import itertools
print(list(itertools.permutations([1, 2, 3])))
```

Random

```python
import random
# Initialize the random number generator.
random.seed(None)
# Returns a random integer N such that a <= N <= b.
random.randint(a, b)
# Returns a random integer N such that 0 <= N < b
random.randrange(b)
# Returns a random integer N such that a <= N < b.
random.randrange(a, b)
# Returns and integer with k random bits.
random.getrandbits(k)
# shuffles a list
random.shuffle(li)
```

Sort List

```python
li = ['a', 'c', 'b']
# sorts inplace in descending order
li.sort(reverse=True)
# returns sorted list ascending order
ol = sorted(li)
```

Sort List Of Object

```python
class MyObject :
  def __init__(self, first, second, third):
    self.first = first
    self.second = second
    self.third = third

li = [MyObject('b', 3, 1), MyObject('a', 3, 2),
↪  MyObject('b', 3, 3)]
# returns list sorted by first then by second then by
↪  third in increasing order
ol = sorted(li, key = lambda x: (x.first, x.second,
↪  x.third), reverse=False)
# sorts inplace by first then by second then by third
↪  in increasing order
li.sort(key = lambda x: (x.first, x.second, x.third),
↪  reverse=False)
```

Data Structures

Geometry

K-D Tree

Graphs

UnionFind

```cpp
struct UnionFind {
  int n;
  vector<int> dad, size;

  UnionFind(int N) : n(N), dad(N), size(N, 1) {
    while (N--) dad[N] = N;
  }
  int root(int u) {
    if (dad[u] == u) return u;
    return dad[u] = root(dad[u]);
  }

  bool areConnected(int u, int v) {
    return root(u) == root(v);
  }

  void join(int u, int v) {
    int Ru = root(u), Rv = root(v);
    if (Ru == Rv) return;
    --n, dad[Ru] = Rv;
    size[Rv] += size[Ru];
  }

  int getSize(int u) { return size[root(u)]; }

  int numberOfSets() { return n; }
};
```

Ranges

BIT

```cpp
typedef long long int T;
T neutro = 0;
vector<T> bit;

void initVars(int n) { bit.assign(++n, neutro); }

T F(T a, T b) {
  return a + b;
  // return a * b;
}

// Inverse of F
T I(T a, T b) {
  return a - b;
  // return a / b;
}

// O(N)
void build() {
  for (int i = 1; i < bit.size(); i++) {
    int j = i + (i & -i);
    if (j < bit.size()) bit[j] = F(bit[j], bit[i]);
  }
}

// O(lg(N))
void update(int i, T val) {
  for (i++; i < bit.size(); i += i & -i)
    bit[i] = F(bit[i], val);
}
```

```
// O(lg(N))
T query(int i) {
  T ans = neutro;
  for (i++; i; i -= i & -i) ans = F(ans, bit[i]);
  return ans;
}

// O(lg(N)), [l, r]
T query(int l, int r) {
  return I(query(r), query(--l));
}

void setValAt(T val, int i) { bit[++i] = val; }
```

BIT Range Update

```
typedef long long int T;
T neutro = 0;
vector<T> bit1, bit2;

void initVars(int n) {
  bit1.assign(++n, neutro);
  bit2 = bit1;
}

// O(lg(N))
void update(vector<T> &bit, int i, T val) {
  for (i++; i < bit.size(); i += i & -i)
    bit[i] += val;
}

// O(lg(N)), [l, r]
void update(int l, int r, T val) {
  update(bit1, l, val);
  update(bit1, r + 1, -val);
  update(bit2, r + 1, val * r);
  update(bit2, l, -val * (l - 1));
}

// O(lg(N))
T query(vector<T> &bit, int i) {
  T ans = neutro;
  for (i++; i; i -= i & -i) ans += bit[i];
  return ans;
}

// O(lg(N))
T query(int i) {
  return query(bit1, i) * i + query(bit2, i);
}

// O(lg(N)), [l, r]
T query(int l, int r) {
  return query(r) - query(l - 1);
}
```

Segment Tree

```
// st = segment tree. st[1] = root;
// neutro = operation neutral value
// e.g. for sum is 0, for multiplication
// is 1, for gcd is 0, for min is INF, etc.

template <class T>
struct SegmentTree {
  T neutro = 0;
  int N;
  vector<T> st;

  SegmentTree(int n) : st(2 * n, neutro), N(n) {}

  T F(T a, T b) {
    return a + b;
    // return __gcd(a, b);
    // return a * b;
    // return min(a, b);
  }

  // O(2N)
  void build() {
    for (int i = N - 1; i > 0; i--)
      st[i] = F(st[i << 1], st[i << 1 | 1]);
  }

  // O(lg(2N))
  void update(int i, T val) {
    for (st[i += N] = val; i > 1; i >>= 1)
      st[i >> 1] = F(st[i], st[i ^ 1]);
  }

  // O(3N), [l, r]
  void update(int l, int r, T val) {
    if (l == r)
      update(l, val);
    else {
      for (l += N, r += N; l <= r; l++) st[l] = val;
      build();
    }
  }

  // O(lg(2N)), [l, r]
  T query(int l, int r) {
    T ans = neutro;
    for (l += N, r += N; l <= r; l >>= 1, r >>= 1) {
      if (l & 1) ans = F(ans, st[l++]);
      if (~r & 1) ans = F(ans, st[r--]);
    }
    return ans;
  }

  void setValAt(T val, int i) { st[i + N] = val; }
};
```

Segment Tree Lazy Propagation

```
// st = segment tree, st[1] = root, H = height of d
// u = updates, d = delayed updates
// neutro = operation neutral val
// e.g. for sum is 0, for multiplication
// is 1, for gcd is 0, for min is INF, etc.

template <class T>
struct SegmentTree {
  T neutro = 0;
  int N, H;
  vector<T> st, d;
  vector<bool> u;

  SegmentTree(int n)
      : st(2 * n, neutro), d(n), u(n, 0) {
    H = sizeof(int) * 8 - __builtin_clz(N = n);
  }

  T F(T a, T b) {
    return a + b;
    // return __gcd(a, b);
    // return a * b;
    // return min(a, b);
  }

  void apply(int i, T val, int k) {
    st[i] = val * k;  // sum
    // st[i] = val; // min, max, gcd
    // st[i] = pow(a, k); // multiplication
    if (i < N) d[i] = val, u[i] = 1;
  }

  void calc(int i) {
    if (!u[i]) st[i] = F(st[i << 1], st[i << 1 | 1]);
  }

  // O(2N)
  void build() {
    for (int i = N - 1; i > 0; i--) calc(i);
  }

  // O(lg(N))
  void build(int p) {
    while (p > 1) p >>= 1, calc(p);
  }

  // O(lg(N))
  void push(int p) {
    for (int s = H, k = 1 << (H - 1); s > 0;
         s--, k >>= 1) {
      int i = p >> s;
      if (u[i]) {
        apply(i << 1, d[i], k);
        apply(i << 1 | 1, d[i], k);
        u[i] = 0, d[i] = neutro;
      }
    }
  }

  // O(lg(N)), [l, r]
  void update(int l, int r, T val) {
    push(l += N);
    push(r += N);
    int ll = l, rr = r, k = 1;
    for (; l <= r; l >>= 1, r >>= 1, k <<= 1) {
      if (l & 1) apply(l++, val, k);
      if (~r & 1) apply(r--, val, k);
    }
    build(ll);
    build(rr);
  }

  // O(lg(2N)), [l, r]
  T query(int l, int r) {
    push(l += N);
    push(r += N);
    T ans = neutro;
    for (; l <= r; l >>= 1, r >>= 1) {
      if (l & 1) ans = F(ans, st[l++]);
      if (~r & 1) ans = F(ans, st[r--]);
    }
    return ans;
  }

  void setValAt(T val, int i) { st[i + N] = val; }
};
```

Sparse Table

```
// st = sparse table, Arith = Arithmetic
typedef int T;
int neutro = 0;
vector<vector<T>> st;

T F(T a, T b) {
  // return min(a, b);
  return __gcd(a, b);
  // return a + b; // Arith
  // return a * b; // Arith
}

// O(Nlg(N))
void build(vector<T> &arr) {
  st.assign(log2(arr.size()), vector<T>(arr.size()));
  st[0] = arr;
  for (int i = 1; (1 << i) <= arr.size(); i++)
    for (int j = 0; j + (1 << i) <= arr.size(); j++)
      st[i][j] = F(st[i - 1][j],
                   st[i - 1][j + (1 << (i - 1))]);
}

// O(1), [l, r]
T query(int l, int r) {
  int i = log2(r - l + 1);
  return F(st[i][l], st[i][r + 1 - (1 << i)]);
}
```

```
// O(lg(N)), [l, r]
T queryArith(int l, int r) {
  T ans = neutro;
  while (true) {
    int k = log2(r - l + 1);
    ans = F(ans, st[k][l]);
    l += 1 << k;
    if (l > r) break;
  }
  return ans;
}
```

Strings

Trie

```
// wpt = number of words passing through
// w = number of words ending in the node
// c = character

struct Trie {

  struct Node {
    // for lexicographical order use 'map'
    // map<char, Node *> ch;
    unordered_map<char, Node *> ch;
    int w = 0, wpt = 0;
  };

  Node *root = new Node();

  // O(STR.SIZE)
  void insert(string str) {
    Node *curr = root;
    for (auto &c : str) {
      if (!curr->ch.count(c))
        curr->ch[c] = new Node();
      curr->wpt++, curr = curr->ch[c];
    }
    curr->wpt++, curr->w++;
  }

  // O(STR.SIZE)
  Node *find(string &str) {
    Node *curr = root;
    for (auto &c : str) {
      if (!curr->ch.count(c)) return nullptr;
      curr = curr->ch[c];
    }
    return curr;
  }

  // O(STR.SIZE) number of words with given prefix
  int prefixCount(string prefix) {
    Node *node = find(prefix);
    return node ? node->wpt : 0;
  }

  // O(STR.SIZE) number of words matching str
  int strCount(string str) {
    Node *node = find(str);
    return node ? node->w : 0;
  }

  // O(N)
  void getWords(Node *curr, vector<string> &words,
                string &word) {
    if (!curr) return;
    if (curr->w) words.push_back(word);
    for (auto &c : curr->ch) {
      getWords(c.second, words, word += c.first);
      word.pop_back();
    }
  }

  // O(N)
  vector<string> getWords() {
    vector<string> words;
    string word = "";
    getWords(root, words, word);
    return words;
  }

  // O(N)
  vector<string> getWordsByPrefix(string prefix) {
    vector<string> words;
    getWords(find(prefix), words, prefix);
  }

  // O(STR.SIZE)
  bool remove(Node *curr, string &str, int &i) {
    if (i == str.size()) {
      curr->wpt--;
      return curr->w ? !(curr->w = 0) : 0;
    }
    int c = str[i];
    if (!curr->ch.count(c)) return false;
    if (remove(curr->ch[c], str, ++i)) {
      if (!curr->ch[c]->wpt)
        curr->wpt--, curr->ch.erase(c);
      return true;
    }
    return false;
  }

  // O(STR.SIZE)
  int remove(string str) {
    int i = 0;
    return remove(root, str, i);
  }
};
```

Trees And Heaps

Red Black Tree

```
template <class K, class V>
struct RedBlackTree {

  struct Node {
    K key;
    V val;
    Node *l, *r;  // left, right
    bool isRed;
    Node(K k, V v, bool isRed)
        : key(k), val(v), isRed(isRed) {}
  };

  Node *root = nullptr;

  int compare(K a, K b) {
    if (a < b) return -1;
    if (a > b) return 1;
    return 0;
  }

  // O(lg(N))
  V at(K key) {
    Node *x = root;
    while (x) {
      int cmp = compare(key, x->key);
      if (!cmp) return x->val;
      if (cmp < 0) x = x->l;
      if (cmp > 0) x = x->r;
    }
    throw runtime_error("Key doesn't exist");
  }

  Node *rotateLeft(Node *h) {
    Node *x = h->r;
    h->r = x->l;
    x->l = h;
    x->isRed = h->isRed;
    h->isRed = 1;
    return x;
  }

  Node *rotateRight(Node *h) {
    Node *x = h->l;
    h->l = x->r;
    x->r = h;
    x->isRed = h->isRed;
    h->isRed = 1;
    return x;
  }

  void flipColors(Node *h) {
    h->isRed = 1;
    h->l->isRed = 0;
    h->r->isRed = 0;
  }

  // O(lg(N))
  Node *insert(Node *h, K key, V val) {
    if (!h) return new Node(key, val, 1);
    int cmp = compare(key, h->key);
    if (!cmp) h->val = val;
    if (cmp < 0) h->l = insert(h->l, key, val);
    if (cmp > 0) h->r = insert(h->r, key, val);
    if (h->r && h->r->isRed && !(h->l && h->l->isRed))
      h = rotateLeft(h);
    if (h->l && h->l->isRed && h->l->l &&
        h->l->l->isRed)
      h = rotateRight(h);
    if (h->l && h->l->isRed && h->r && h->r->isRed)
      flipColors(h);
    return h;
  }

  // O(lg(N))
  void insert(K key, V val) {
    root = insert(root, key, val);
  }
};
```

Treap

Geometry

Convex Hull

Max Interval Overlap

```
typedef long long int T;
typedef pair<T, T> Interval;
vector<Interval> maxIntervals;
```

```cpp
// O(N * lg(N))
int maxOverlap(vector<Interval> &arr) {
  maxIntervals.clear();
  map<T, int> m;
  int maxI = 0, curr = 0, isFirst = 1;
  T l = -1LL, r = -1LL;
  for (auto &i : arr) m[i.first]++, m[i.second + 1]--;
  for (auto &p : m) {
    curr += p.second;
    if (curr > maxI) maxI = curr, l = p.first;
    if (curr == maxI) r = p.first;
  }
  curr = 0;
  for (auto &p : m) {
    curr += p.second;
    if (curr == maxI && isFirst)
      l = p.first, isFirst = 0;
    if (curr < maxI && !isFirst)
      maxIntervals.push_back({l, p.first - 1}),
          isFirst = 1;
  }
  return maxI;
}

// O(MaxPoint) maxPoint < vector::max_size
int maxOverlap(vector<Interval> &arr) {
  maxIntervals.clear();
  T maxPoint = 0;
  for (auto &i : arr)
    if (i.second > maxPoint) maxPoint = i.second;
  vector<int> x(maxPoint + 2);
  for (auto &i : arr) x[i.first]++, x[i.second + 1]--;
  int maxI = 0, curr = 0, isFirst = 1;
  T l = -1LL, r = -1LL;
  for (int i = 0; i < x.size(); i++) {
    curr += x[i];
    if (curr > maxI) maxI = curr;
  }
  curr = 0;
  for (int i = 0; i < x.size(); i++) {
    curr += x[i];
    if (curr == maxI && isFirst) l = i, isFirst = 0;
    if (curr < maxI && !isFirst)
      maxIntervals.push_back({l, i - 1}), isFirst = 1;
  }
  return maxI;
}
```

Graphs

Articulation Points And Bridges

```cpp
// APB = articulation points and bridges
// ap = Articulation Point
// br = bridges, p = parent
// disc = discovery time
// low = lowTime, ch = children

typedef pair<int, int> Edge;
int Time;
vector<vector<int>> ady;
vector<int> disc, low, ap;
vector<Edge> br;

void initVars(int N) { ady.assign(N, vector<int>()); }

void addEdge(int u, int v) {
  ady[u].push_back(v);
  ady[v].push_back(u);
}

int dfsAPB(int u, int p) {
  int ch = 0;
  low[u] = disc[u] = ++Time;
  for (int &v : ady[u]) {
    if (v == p) continue;
    if (!disc[v]) {
      ch++, dfsAPB(v, u);
      if (disc[u] <= low[v]) ap[u]++;
      if (disc[u] < low[v]) br.push_back({u, v});
      low[u] = min(low[u], low[v]);
    } else
      low[u] = min(low[u], disc[v]);
  }
  return ch;
}

// O(N)
void APB() {
  br.clear();
  ap = low = disc = vector<int>(ady.size());
  Time = 0;
  for (int u = 0; u < ady.size(); u++)
    if (!disc[u]) ap[u] = dfsAPB(u, u) > 1;
}
```

Connected Components

```cpp
// comp = component
int compId;
vector<vector<int>> ady;
vector<int> getComp;
```

```cpp
void initVars(int N) {
  ady.assign(N, vector<int>());
  getComp.assign(N, -1);
  compId = 0;
}
void addEdge(int u, int v) {
  ady[u].push_back(v);
  ady[v].push_back(u);
}
void dfsCC(int u, vector<int> &comp) {
  if (getComp[u] > -1) return;
  getComp[u] = compId;
  comp.push_back(u);
  for (auto &v : ady[u]) dfsCC(v, comp);
}
// O(N)
vector<vector<int>> connectedComponents() {
  vector<vector<int>> comps;
  for (int u = 0; u < ady.size(); u++) {
    vector<int> comp;
    dfsCC(u, comp);
    if (!comp.empty())
      comps.push_back(comp), compId++;
  }
  return comps;
}
```

Flood Fill

```cpp
int n, m, oldColor = 0, color = 1;
vector<vector<int>> mat;
vector<vector<int>> movs = {
    {1, 0}, {0, 1}, {-1, 0}, {0, -1}};
void floodFill(int i, int j) {
  if (i >= mat.size() || i < 0 ||
      j >= mat[i].size() || j < 0 ||
      mat[i][j] != oldColor)
    return;
  mat[i][j] = color;
  for (auto move : movs)
    floodFill(i + move[1], j + move[0]);
}
void floodFill() {
  for (int i = 0; i < n; i++)
    for (int j = 0; j < m; j++)
      if (mat[i][j] == oldColor) floodFill(i, j);
}
```

Heavy Light Decomposition

```cpp
// p = parent;
#include "../Data Structures/Ranges/Segment Tree.cpp"
typedef int T;
vector<vector<int>> ady;
vector<int> p, heavy, depth, root, stPos, vals;
SegmentTree<T> st(0);
void initVars(int n) {
  ady.assign(n, vector<int>());
  heavy.assign(n, -1);
  vals.assign(n, 0);
  p = root = stPos = depth = heavy;
  st = SegmentTree<T>(n);
}
void addEdge(int u, int v, T val) {
  ady[u].push_back(v);
  p[v] = u, vals[v] = val;
}
T F(T a, T b) { return a + b; }
// O(N)
int dfs(int u) {
  int size = 1, maxSubtree = 0;
  for (int &v : ady[u]) {
    depth[v] = depth[u] + 1;
    int subtree = dfs(v);
    if (subtree > maxSubtree)
      heavy[u] = v, maxSubtree = subtree;
    size += subtree;
  }
  return size;
}
// O(N)
void initHeavyLight() {
  for (int i = 0; i < ady.size(); i++)
    if (p[i] < 0) dfs(i);
  for (int i = 0, pos = 0; i < ady.size(); i++)
    if (p[i] < 0 || heavy[p[i]] != i)
      for (int j = i; ~j; j = heavy[j]) {
        st.setValAt(vals[j], stPos[j] = pos++);
        root[j] = i;
      }
  st.build();
}
// O(lg^2 (N))
template <class Op>
void processPath(int u, int v, Op op) {
  for (; root[u] != root[v]; v = p[root[v]]) {
    if (depth[root[u]] > depth[root[v]]) swap(u, v);
    op(stPos[root[v]], stPos[v]);
  }
  if (depth[u] > depth[v]) swap(u, v);
  // for values on edges
  if (u != v) op(stPos[u] + 1, stPos[v]);
  // for values on nodes
  // op(stPos[u], stPos[v]);
}
// O(lg^2 (N))
void update(int u, int v, T val) {
  processPath(u, v, [&val](int l, int r) {
    st.update(l, r, val);
  });
}
```

```
// O(lg^2 (N))
T query(int u, int v) {
  T ans = T();
  processPath(u, v, [&ans](int l, int r) {
    ans = F(ans, st.query(l, r));
  });
  return ans;
}
```

Is Bipartite

```
vector<vector<int>> ady;

void initVars(int N) { ady.assign(N, vector<int>()); }

void addEdge(int u, int v) {
  ady[u].push_back(v);
  ady[v].push_back(u);
}

// O(N)
bool isBipartite() {
  vector<int> color(ady.size(), -1);
  for (int s = 0; s < ady.size(); s++) {
    if (color[s] > -1) continue;
    color[s] = 0;
    queue<int> q;
    q.push(s);
    while (!q.empty()) {
      int u = q.front();
      q.pop();
      for (int &v : ady[u]) {
        if (color[v] < 0)
          q.push(v), color[v] = !color[u];
        if (color[v] == color[u]) return false;
      }
    }
  }
  return true;
}
```

LCA

```
// st = sparse table
typedef pair<int, int> T;
int neutro = 0;
vector<vector<T>> st;
vector<int> first;
vector<T> tour;
vector<vector<int>> ady;

void initVars(int N) { ady.assign(N, vector<int>()); }

void addEdge(int u, int v) {
  ady[u].push_back(v);
  ady[v].push_back(u);
}

T F(T a, T b) { return a.first < b.first ? a : b; }

void build() {
  st.assign(log2(tour.size()),
            vector<T>(tour.size()));
  st[0] = tour;
  for (int i = 1; (1 << i) <= tour.size(); i++)
    for (int j = 0; j + (1 << i) <= tour.size(); j++)
      st[i][j] = F(st[i - 1][j],
                   st[i - 1][j + (1 << (i - 1))]);
}

void eulerTour(int u, int p, int h) {
  first[u] = tour.size();
  tour.push_back({h, u});
  for (int v : ady[u])
    if (v != p) {
      eulerTour(v, u, h + 1);
      tour.push_back({h, u});
    }
}

// O(N * lg(N))
void preprocess() {
  tour.clear();
  first.assign(ady.size(), -1);
  eulerTour(0, 0, 0);
  build();
}

// O(1)
int lca(int u, int v) {
  int l = min(first[u], first[v]);
  int r = max(first[u], first[v]);
  int i = log2(r - l + 1);
  return F(st[i][l], st[i][r + 1 - (1 << i)]).second;
}
```

MST Kruskal

```
// N = number of nodes, Wedge = Weighted Edge
#include "../Data Structures/Graphs/UnionFind.cpp"
typedef int T;
typedef pair<int, int> Edge;
typedef pair<T, Edge> Wedge;
vector<Wedge> Wedges;
vector<Wedge> mst;
UnionFind uf(0);

void initVars(int N) {
  mst.clear();
  Wedges.clear();
  uf = UnionFind(N);
}

void addEdge(int u, int v, T w) {
  Wedges.push_back({w, {u, v}});
}
```

```
T kruskal() {
  T cost = 0;
  sort(Wedges.begin(), Wedges.end());
  // reverse(Wedges.begin(), Wedges.end());
  for (Wedge &wedge : Wedges) {
    int u = wedge.second.first,
        v = wedge.second.second;
    if (!uf.areConnected(u, v))
      uf.join(u, v), mst.push_back(wedge),
          cost += wedge.first;
  }
  return cost;
}
```

MST Prim

```
// st = spanning tree, p = parent
// vis = visited, dist = distance
typedef int T;
typedef pair<int, int> Edge;
typedef pair<T, Edge> Wedge;
typedef pair<T, int> DistNode;
int INF = 1 << 30;
vector<vector<int>> ady;
unordered_map<int, unordered_map<int, T>> weight;
vector<int> p, vis;
vector<T> dist;
vector<vector<Wedge>> msts;

void initVars(int N) {
  ady.assign(N, vector<int>());
  p.assign(N, 0);
  vis.assign(N, 0);
  dist.assign(N, INF);
  weight.clear();
  msts.clear();
}

void addEdge(int u, int v, T w) {
  ady[u].push_back(v);
  weight[u][v] = w;
  ady[v].push_back(u);
  weight[v][u] = w;
}
```

```
// O(E * log(V))
T prim(int s) {
  vector<Wedge> mst;
  vector<set<Edge>::iterator> pos(ady.size());
  vector<T> dist(ady.size(), INF);
  set<Edge> q;
  T cost = dist[s] = 0;
  q.insert({0, s});
  while (q.size()) {
    int u = q.begin()->second;
    q.erase(q.begin());
    vis[u] = 1, cost += dist[u];
    mst.push_back({dist[u], {p[u], u}});
    for (int &v : ady[u]) {
      T w = weight[u][v];
      if (!vis[v] && w < dist[v]) {
        if (dist[v] != INF) q.erase(pos[v]);
        pos[v] = q.insert({dist[v] = w, v}).first;
      }
    }
  }
  msts.push_back(
      vector<Wedge>(mst.begin() + 1, mst.end()));
  return cost;
}
// ~ O(E * log(V))
T primLazy(int s) {
  vector<Wedge> mst;
  vector<set<Edge>::iterator> pos(ady.size());
  vector<T> dist(ady.size(), INF);
  priority_queue<DistNode> q;
  T cost = dist[s] = 0;
  q.push({0, s});
  while (q.size()) {
    pair<int, int> aux = q.top();
    int u = aux.second;
    q.pop();
    if (dist[u] < -aux.first) continue;
    vis[u] = 1, cost += dist[u];
    mst.push_back({dist[u], {p[u], u}});
    for (int &v : ady[u]) {
      T w = weight[u][v];
      if (!vis[v] && w < dist[v])
        q.push({-(dist[v] = w), v});
    }
  }
  msts.push_back(
      vector<Wedge>(mst.begin() + 1, mst.end()));
  return cost;
}
// O(V + E * log(V))
T prim() {
  T cost = 0;
  map<int, T> q;
  for (int i = 0; i < ady.size(); i++)
    if (!vis[i]) cost += prim(i);
  return cost;
}
```

Strongly Connected Components

```cpp
// tv = top value from stack
// sccs = strongly connected components
// scc = strongly connected component
// disc = discovery time, low = low time
// s = stack, top = top index of the stack

int Time, top;
vector<vector<int>> ady, sccs;
vector<int> disc, low, s;

void initVars(int N) { ady.assign(N, vector<int>()); }

void addEdge(int u, int v) { ady[u].push_back(v); }

void dfsSCCS(int u) {
  if (disc[u]) return;
  low[u] = disc[u] = ++Time;
  s[++top] = u;
  for (int &v : ady[u])
    dfsSCCS(v), low[u] = min(low[u], low[v]);
  if (disc[u] == low[u]) {
    vector<int> scc;
    while (true) {
      int tv = s[top--];
      scc.push_back(tv);
      low[tv] = ady.size();
      if (tv == u) break;
    }
    sccs.push_back(scc);
  }
}

// O(N)
void SCCS() {
  s = low = disc = vector<int>(ady.size());
  Time = 0, top = -1, sccs.clear();
  for (int u = 0; u < ady.size(); u++) dfsSCCS(u);
}
```

Topological Sort

```cpp
// vis = visited
vector<vector<int>> ady;
vector<int> vis, toposorted;

void initVars(int N) {
  ady.assign(N, vector<int>());
  vis.assign(N, 0);
  toposorted.clear();
}

void addEdge(int u, int v) { ady[u].push_back(v); }

// returns false if there is a cycle
// O(N)
bool toposort(int u) {
  vis[u] = 1;
  for (auto &v : ady[u])
    if (v != u && vis[v] != 2 &&
        (vis[v] || !toposort(v)))
      return false;
  vis[u] = 2;
  toposorted.push_back(u);
  return true;
}

// O(N)
bool toposort() {
  for (int u = 0; u < ady.size(); u++)
    if (!vis[u] && !toposort(u)) return false;
  return true;
}
```

Cycles

Get All Simple Cycles

Get Some Cycles

```cpp
// at least detects one cycle per component
vector<vector<int>> ady, cycles;
vector<int> vis, cycle;
bool flag = false, isDirected = false;
int root = -1;

void initVars(int N) {
  ady.assign(N, vector<int>());
  vis.assign(N, 0);
  cycles.clear();
  root = -1, flag = false;
}

void addEdge(int u, int v) {
  ady[u].push_back(v);
  if (!isDirected) ady[v].push_back(u);
}
```

```cpp
// O(N)
bool hasCycle(int u, int prev) {
  vis[u] = 1;
  for (auto &v : ady[u]) {
    if (v == u || vis[v] == 2 ||
        (!isDirected && v == prev))
      continue;
    if (flag) {
      if (!vis[v]) hasCycle(v, u);
      continue;
    }
    if (vis[v] || hasCycle(v, u)) {
      if (root == -1) root = v, flag = true;
      cycle.push_back(u);
      if (root == u)
        flag = false, root = -1,
        cycles.push_back(cycle), cycle.clear();
    }
  }
  vis[u] = 2;
  return flag;
}

// O(N)
bool hasCycle() {
  for (int u = 0; u < ady.size(); u++)
    if (!vis[u]) cycle.clear(), hasCycle(u, -1);
  return cycles.size() > 0;
}
```

Has Cycle

```cpp
vector<vector<int>> ady;
vector<int> vis;
bool isDirected = false;

void initVars(int N) {
  ady.assign(N, vector<int>());
  vis.assign(N, 0);
}

void addEdge(int u, int v) {
  ady[u].push_back(v);
  if (!isDirected) ady[v].push_back(u);
}

bool hasCycle(int u, int prev) {
  vis[u] = 1;
  for (auto &v : ady[u])
    if (v != u && vis[v] != 2 &&
        (isDirected || v != prev) &&
        (vis[v] || hasCycle(v, u)))
      return true;
  vis[u] = 2;
  return false;
}
```

```cpp
// O(N)
bool hasCycle() {
  for (int u = 0; u < ady.size(); u++)
    if (!vis[u] && hasCycle(u, -1)) return true;
}
```

Flow

Max Flow Dinic

```cpp
// cap[a][b] = Capacity from a to b
// flow[a][b] = flow occupied from a to b
// level[a] = level in graph of node a

typedef int T;
vector<int> level;
vector<vector<int>> ady;
unordered_map<int, unordered_map<int, T>> cap, flow;

void initVars(int N) {
  ady.assign(N, vector<int>());
  cap.clear();
  flow.clear();
}

void addEdge(int u, int v, T capacity) {
  cap[u][v] = capacity;
  ady[u].push_back(v);
}

bool levelGraph(int s, int t) {
  level = vector<int>(ady.size());
  level[s] = 1;
  queue<int> q;
  q.push(s);
  while (!q.empty()) {
    int u = q.front();
    q.pop();
    for (int &v : ady[u]) {
      if (!level[v] && flow[u][v] < cap[u][v]) {
        q.push(v);
        level[v] = level[u] + 1;
      }
    }
  }
  return level[t];
}
```

```
T blockingFlow(int u, int t, T currPathMaxFlow) {
  if (u == t) return currPathMaxFlow;
  for (int v : ady[u]) {
    T capleft = cap[u][v] - flow[u][v];
    if ((level[v] == (level[u] + 1)) &&
        (capleft > 0)) {
      T pathMaxFlow = blockingFlow(
          v, t, min(currPathMaxFlow, capleft));
      if (pathMaxFlow > 0) {
        flow[u][v] += pathMaxFlow;
        flow[v][u] -= pathMaxFlow;
        return pathMaxFlow;
      }
    }
  }
  return 0;
}

// O(E * V^2)
T dinicMaxFlow(int s, int t) {
  if (s == t) return -1;
  T maxFlow = 0;
  while (levelGraph(s, t))
    while (T flow = blockingFlow(s, t, 1 << 30))
      maxFlow += flow;
  return maxFlow;
}
```

Maximum Bipartite Matching

```
// mbm = maximum bipartite matching
#include "Max Flow Dinic.cpp"

void addEdgeMBM(int u, int v) {
  addEdge(u += 2, v += 2, 1);
  addEdge(0, u, 1);
  addEdge(v, 1, 1);
}

// O(E * V^2)
T mbm() { return dinicMaxFlow(0, 1); }
```

ShortestPaths

Bellman Ford

```
// N = number of nodes
// returns {} if there is a negative weight cycle
typedef int T;
int MAXN = 20001, N, INF = 1 << 30, isDirected = true;
vector<vector<int>> ady;
unordered_map<int, unordered_map<int, T>> weight;

void initVars(int N) {
  ady.assign(N, vector<int>());
  weight.clear();
}

void addEdge(int u, int v, T w) {
  ady[u].push_back(v);
  weight[u][v] = w;
  if (isDirected) return;
  ady[v].push_back(u);
  weight[v][u] = w;
}

// O(V * E)
vector<T> bellmanFord(int s) {
  vector<T> dist(ady.size(), INF);
  dist[s] = 0;
  for (int i = 1; i <= ady.size(); i++)
    for (int u = 0; u < ady.size(); u++)
      for (auto &v : ady[u]) {
        T w = weight[u][v], d = dist[u] + w;
        if (dist[u] != INF && d < dist[v]) {
          if (i == ady.size()) return {};
          dist[v] = d;
        }
      }
  return dist;
}
```

Dijkstra

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

typedef int T;
typedef pair<T, int> DistNode;
int INF = 1 << 30, isDirected = false;
vector<vector<int>> ady;
unordered_map<int, unordered_map<int, T>> weight;

void initVars(int N) {
  ady.assign(N, vector<int>());
  weight.clear();
}

void addEdge(int u, int v, T w) {
  ady[u].push_back(v);
  weight[u][v] = w;
  if (isDirected) return;
  ady[v].push_back(u);
  weight[v][u] = w;
}
```

```cpp
// O(E * lg(V))
vector<T> dijkstra(int s) {
  vector<set<DistNode>::iterator> pos(ady.size());
  vector<T> dist(ady.size(), INF);
  set<DistNode> q;
  q.insert({0, s}), dist[s] = 0;
  while (q.size()) {
    int u = q.begin()->second;
    q.erase(q.begin());
    for (int &v : ady[u]) {
      T w = weight[u][v], d = dist[u] + w;
      if (d < dist[v]) {
        if (dist[v] != INF) q.erase(pos[v]);
        pos[v] = q.insert({dist[v] = d, v}).first;
      }
    }
  }
  return dist;
}

// ~ O(E * lg(V))
vector<T> dijkstraLazy(int s) {
  vector<T> dist(ady.size(), INF);
  priority_queue<DistNode> q;
  q.push({0, s}), dist[s] = 0;
  while (q.size()) {
    DistNode top = q.top();
    q.pop();
    int u = top.second;
    if (dist[u] < -top.first) continue;
    for (int &v : ady[u]) {
      T w = weight[u][v], d = dist[u] + w;
      if (d < dist[v]) q.push({-(dist[v] = d), v});
    }
  }
  return dist;
}
```

Shortest Path in Directed Acyclic Graph

```cpp
// vis = visited
typedef int T;
vector<vector<int>> ady;
vector<int> vis, toposorted;
int INF = 1 << 30;
unordered_map<int, unordered_map<int, T>> weight;

void initVars(int N) {
  ady.assign(N, vector<int>());
  vis.assign(N, 0);
  toposorted.clear();
  weight.clear();
}

void addEdge(int u, int v, int w) {
  ady[u].push_back(v);
  weight[u][v] = w;
}

// returns false if there is a cycle
// O(N)
bool toposort(int u) {
  vis[u] = 1;
  for (auto &v : ady[u])
    if (v != u && vis[v] != 2 &&
        (vis[v] || !toposort(v)))
      return false;
  vis[u] = 2;
  toposorted.push_back(u);
  return true;
}

// O(N)
vector<T> sssp(int s) {
  vector<T> dist(ady.size(), INF);
  dist[s] = 0;
  toposort(s);
  while (toposorted.size()) {
    int u = toposorted.back();
    toposorted.pop_back();
    for (auto &v : ady[u]) {
      T w = weight[u][v], d = dist[u] + w;
      if (d < dist[v]) dist[v] = d;
    }
  }
  return dist;
}
```

Maths

Number Theory

Divisibility Criterion

```python
def divisorCriteria(n, lim):
    results = []
    tenElevated = 1
    for i in range(lim):
        # remainder = pow(10, i, n)
        remainder = tenElevated % n
        negremainder = remainder - n
        if(remainder <= abs(negremainder)):
            results.append(remainder)
        else:
            results.append(negremainder)
        tenElevated *= 10
    return results
```

```python
def testDivisibility(dividend, divisor,
↪  divisor_criteria):
    dividend = str(dividend)
    addition = 0
    dividendSize = len(dividend)
    i = dividendSize - 1
    j = 0
    while j < dividendSize:
        addition += int(dividend[i]) *
        ↪  divisor_criteria[j]
        i -= 1
        j += 1
    return addition % divisor == 0

if __name__ == '__main__':
    dividend, divisor = map(int, input().split())
    divisor_criteria = divisorCriteria(divisor,
    ↪  len(str(dividend)))
    print(divisor_criteria)
    print(testDivisibility(dividend, divisor,
    ↪  divisor_criteria))
```

Extended Euclidean

```cpp
// gcd(a, b) = ax + by
vector<long long int> extendedGCD(long long int a,
                                  long long int b) {
  if (a > 0LL && b == 0LL) return {a, 1LL, 0LL};
  long long int x = 1LL, y = 0LL, prevx = 0LL,
                prevy = 1LL, q, remainder;
  while (true) {
    q = a / b;
    remainder = a - b * q;
    if (remainder == 0LL) break;
    a = b;
    b = remainder;
    x = x - prevx * q;
    swap(x, prevx);
    y = y - prevy * q;
    swap(y, prevy);
  }
  // gcd = b, x = prevx, y = prevy
  return {b, prevx, prevy};
}
```

GCD

```cpp
// recursive
int gcd(int a, int b) {
  return !b ? a : gcd(b, a % b);
}
```

```cpp
// iterative
int gcd(int a, int b) {
  while (b) {
    a %= b;
    swap(a, b);
  }
  return a;
}
```

LCM

```cpp
int lcm(int a, int b) {
  int c = gcd(a, b);
  return c ? a / c * b : 0;
}
```

Prime Check Miller Rabin

```python
from random import randrange


def is_prime(p):
    k = 100
    if p == 2 or p == 3:
        return True
    if (p & 1) == 0 or p == 1:
        return False
    phi = p - 1
    d = phi
    r = 0
    while (d & 1) == 0:
        d = int(d >> 1)
        r += 1
    for i in range(k):
        a = randrange(2, p - 2)
        exp = pow(a, d, p)
        if exp == 1 or exp == p - 1:
            continue
        flag = False
        for j in range(r - 1):
            exp = pow(exp, 2, p)
            if exp == 1:
                return False
            if exp == p - 1:
                flag = True
                break
        if flag:
            continue
        else:
            return False
    return True
```

Prime Sieve

```
vector<int> primeSieve(int n) {
  vector<int> sieve(n + 1);
  for (int i = 4; i <= n; i += 2) sieve[i] = 2;
  for (int i = 3; i * i <= n; i += 2)
    if (!sieve[i])
      for (int j = i * i; j <= n; j += 2 * i)
        if (!sieve[j]) sieve[j] = i;
  return sieve;
}
```

Strings

KMP

```
// p = pattern, t = text
// f = error function, cf = create error function
// pos = positions where pattern is found in text

int MAXN = 1000000;
vector<int> f(MAXN + 1);

vector<int> kmp(string &p, string &t, int cf) {
  vector<int> pos;
  if (cf) f[0] = -1;
  for (int i = cf, j = 0; j < t.size();) {
    while (i > -1 && p[i] != t[j]) i = f[i];
    i++, j++;
    if (cf) f[j] = i;
    if (!cf && i == p.size())
      pos.push_back(j - i), i = f[i];
  }
  return pos;
}

vector<int> search(string &p, string &t) {
  kmp(p, p, -1);        // create error function
  return kmp(p, t, 0);  // search in text
}
```

Rabin Karp

```
class RollingHash {
 public:
  vector<unsigned long long int> pow;
  vector<unsigned long long int> hash;
  unsigned long long int B;

  RollingHash(const string &text) : B(257) {
    int N = text.size();
    pow.resize(N + 1);
    hash.resize(N + 1);
    pow[0] = 1;
    hash[0] = 0;
    for (int i = 1; i <= N; ++i) {
      // in c++ an unsigned long long int is
      // automatically modulated by 2^64
      pow[i] = pow[i - 1] * B;
      hash[i] = hash[i - 1] * B + text[i - 1];
    }
  }
  unsigned long long int getWordHash() {
    return hash[hash.size() - 1];
  }
  unsigned long long int getSubstrHash(int begin,
                                       int end) {
    return hash[end] -
           hash[begin - 1] * pow[end - begin + 1];
  }

  int size() { return hash.size(); }
};
vector<int> rabinKarp(RollingHash &rhStr,
                      string &pattern) {
  vector<int> positions;
  RollingHash rhPattern(pattern);
  unsigned long long int patternHash =
      rhPattern.getWordHash();
  int windowSize = pattern.size(), end = windowSize;
  for (int i = 1; end < rhStr.size(); i++) {
    if (patternHash == rhStr.getSubstrHash(i, end))
      positions.push_back(i);
    end = i + windowSize;
  }
  return positions;
}
```

Techniques

Binary Search

Multiple Queries

Mo

```
// q = query
// qs = queries
```

```cpp
struct Query {
  int l, r;
};

int blksize;
vector<Query> qs;
vector<int> arr;

void initVars(int N, int M) {
  arr = vector<int>(N);
  qs = vector<Query>(M);
}

bool cmp(Query &a, Query &b) {
  if (a.l == b.l) return a.r < b.r;
  return a.l / blksize < b.l / blksize;
}

void getResults() {
  blksize = (int)sqrt(arr.size());
  sort(qs.begin(), qs.end(), cmp);
  int prevL = 0, prevR = -1;
  int sum = 0;
  for (auto &q : qs) {
    int L = q.l, R = q.r;
    while (prevL < L) {
      sum -= arr[prevL];  // problem specific
      prevL++;
    }
    while (prevL > L) {
      prevL--;
      sum += arr[prevL];  // problem specific
    }
    while (prevR < R) {
      prevR++;
      sum += arr[prevR];  // problem specific
    }
    while (prevR > R) {
      sum -= arr[prevR];  // problem specific
      prevR--;
    }

    cout << "sum[" << L << ", " << R << "] = " << sum
         << endl;
  }
}

int main() {
  initVars(9, 2);
  arr = {1, 1, 2, 1, 3, 4, 5, 2, 8};
  qs = {{0, 8}, {3, 5}};
  getResults();
}
```

SQRT Decomposition

```cpp
// sum of elements in range
int neutro = 0;
vector<int> arr;
vector<int> blks;

void initVars(int n) {
  arr.assign(n, neutro);
  blks.assign(sqrt(n), neutro);
}

void preprocess() {
  for (int i = 0, j = 0; i < arr.size(); i++) {
    if (i == blks.size() * j) j++;
    blks[j - 1] += arr[i];  // problem specific
  }
}

// problem specific
void update(int i, int val) {
  blks[i / blks.size()] += val - arr[i];
  arr[i] = val;
}

int query(int l, int r) {
  int sum = 0;
  int lblk = l / blks.size();
  if (l != blks.size() * lblk++)
    while (l < r && l != lblk * blks.size()) {
      sum += arr[l];  // problem specific
      l++;
    }

  while (l + blks.size() <= r) {
    sum += blks[l / blks.size()];  // problem specific
    l += blks.size();
  }
  while (l <= r) {
    sum += arr[l];  // problem specific
    l++;
  }
  return sum;
}

int main() {
  initVars(10);
  arr = {1, 5, 2, 4, 6, 1, 3, 5, 7, 10};
  preprocess();
  for (int i = 0; i < blks.size() + 1; i++)
    cout << blks[i] << " ";
  // output: 8 11 15 10
  cout << endl;
  cout << query(3, 8) << " ";
  cout << query(1, 6) << " ";
  update(8, 0);
  cout << query(8, 8) << endl;
  // output: 26 21 0
  return 0;
}
```