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1 General

```
run.sh
g++ -g -O2 -std=gnu++17 -static prog.cpp
./a.exe
```

test.sh

```
# compile and test all *.in and *.ans
g++ -g -O2 -std=gnu++17 -static prog.cpp
for i in *.in; do
  f=${i%.in}
  ./a.exe < $i > "$f.out"
  diff -b -q "$f.ans" "$f.out"
done
```

Header

```
// use better compiler options
#pragma GCC optimize("Ofast", "unroll-loops")
#pragma GCC target("avx2,fma")
// include everything
#include <bits/stdc++.h>
#include <bits/extc++.h>
#include <sys/resource.h>
// namespaces
using namespace std;
using namespace __gnu_cxx; // rope
using namespace __gnu_pbds; // tree/trie
// common defines
#define fastio
  ios_base::sync_with_stdio(0); cin.tie(0);
  define nostacklim rlimit
    RZ; getrlimit(3, &RZ); RZ.rlim_cur =
    1; setrlimit(3, &RZ);
  define DEBUG(v) cerr<<__LINE__<<": "<<#v<<" =
    "<<v<<'\n';
  define TIMER
    cerr<<1.0*clock()/CLOCKS_PER_SEC<<"s\n";
  define ll long long
  define ull unsigned ll
  define i128 __int128
  define u128 unsigned i128
  define ld long double
  // global variables
mt19937 rng((uint32_t)chrono::steady
  _clock::now().time_since_epoch().count());
```

Fast IO

```
#ifdef _WIN32
#define getchar_unlocked() _getchar_nolock()
#define putchar_unlocked(x) _putchar_nolock(x)
#endif
void read(unsigned int& n) {
  char c; n = 0;
  while ((c=getchar_unlocked())!=' ' && c!='\n')
    n = n * 10 + c - '0';
}
void read(int& n) {
  char c; n = 0; int s = 1;
  if ((c=getchar_unlocked())=='-') s = -1;
  else n = c - '0';
  while ((c=getchar_unlocked())!=' ' && c!='\n')
    n = n * 10 + c - '0';
  n *= s;
}
void read(ld& n) {
  char c; n = 0;
  ld m = 0, o = 1; bool d = false; int s = 1;
  if ((c=getchar_unlocked())=='-') s = -1;
  else if (c == '.') d = true;
  else n = c - '0';
  while ((c=getchar_unlocked())!=' ' && c!='\n') {
    if (c == '.') d = true;
```

```
else if (d) { m=m*10+c-'0'; o*=0.1; }
else n = n * 10 + c - '0';
}
n = s * (n + m * o);
void read(double& n) {
  ld m; read(m); n = m;
}
void read(float& n) {
  ld m; read(m); n = m;
}
void read(string& s) {
  char c; s = "";
  while((c=getchar_unlocked())!=' ' && c!='\n')
    s += c;
}
bool readline(string& s) {
  char c; s = "";
  while(c=getchar_unlocked()) {
    if (c == '\n') return true;
    if (c == EOF) return false;
    s += c;
  }
  return false;
}
void print(unsigned int n) {
  if (n / 10) print(n / 10);
  putchar_unlocked(n % 10 + '0');
}
void print(int n) {
  if (n < 0) { putchar_unlocked('-'); n*=-1; }
  print((unsigned int)n);
}
```

Common Structs

```
// n-dimension vectors
Vec<2, int> v(n, m) = arr[n][m]
// Vec<2, int> v(n, m, -1) default init -1
template<int D, typename T>
struct Vec : public vector<Vec<D-1, T>> {
  template<typename... Args>
  Vec(int n=0, Args... args) : vector<Vec<D-1,
  T>>(n, Vec<D-1, T>(args...)) {}
};
template<typename T>
struct Vec<1, T> : public vector<T> {
  Vec(int n=0, T val=T()) : vector<T>(n, val)
  {}
};
```

2 Algorithms

Min/Max Subarray

```
// max - compare = a < b, reset = a < 0
// min - compare = a > b, reset = a > 0
// returns {sum, {start, end}}
pair<int, pair<int, int>>
  ContiguousSubarray(int* a, int size,
  bool(*compare)(int, int),
  bool(*reset)(int), int defbest = 0) {
  int best = defbest, cur = 0, start = 0, end =
  0, s = 0;
  for (int i = 0; i < size; i++) {
    cur += a[i];
    if ((*compare)(best, cur)) { best = cur;
    start = s; end = i; }
    if ((*reset)(cur)) { cur = 0; s = i + 1; }
  }
  return {best, {start, end}};
}
```

Quickselect

```
#define QSNE -999999
int partition(int arr[], int l, int r)
{
  int x = arr[r], i = l;
  for (int j = l; j <= r - 1; j++)
    if (arr[j] <= x)
      swap(arr[i++], arr[j]);
  swap(arr[i], arr[r]);
  return i;
}
```

```
// find k'th smallest element in unsorted array,
  only if all distinct
int qselect(int arr[], int l, int r, int k)
{
  if (!k > 0 && k <= r - l + 1) return QSNE;
  swap(arr[l + rng() % (r-l+1)], arr[r]);
  int pos = partition(arr, l, r);
  if (pos-l==k-1) return arr[pos];
  if (pos-l>k-1) return qselect(arr, l, pos-1, k);
  return qselect(arr, pos+1, r, k-pos+1-l);
}
// TODO: compare against std::nth_element()
```

Saddleback Search

```
// search for v in 2d array arr[x][y], sorted
  on both axis
pair<int, int> saddleback_search(int** arr, int
  x, int y, int v) {
  int i = x-1, j = 0;
  while (i >= 0 && j < y) {
    if (arr[i][j] == v) return {i, j};
    (arr[i][j] > v)? i--: j++;
  }
  return {-1, -1};
}
```

Ternary Search

```
// < max, > min, or any other unimodal func
#define TERNCOMP(a,b) (a)<(b)
int ternsearch(int a, int b, int (*f)(int)) {
  while (b-a > 4) {
    int m = (a+b)/2;
    if (TERNCOMP((*f)(m), (*f)(m+1))) a = m;
    else b = m+1;
  }
  for (int i = a+1; i <= b; i++)
    if (TERNCOMP((*f)(a), (*f)(i)))
      a = i;
  return a;
}
#define TERNPREC 0.000001
double ternsearch(double a, double b, double
  (*f)(double)) {
  while (b-a > TERNPREC * 4) {
    double m = (a+b)/2;
    if (TERNCOMP((*f)(m), (*f)(m + TERNPREC))) a
    = m;
    else b = m + TERNPREC;
  }
  for (double i = a + TERNPREC; i <= b; i +=
  TERNPREC)
    if (TERNCOMP((*f)(a), (*f)(i)))
      a = i;
  return a;
}
```

3 Structures

Fenwick Tree

```
// Fenwick tree, array of cumulative sums -
  O(log n) updates, O(log n) gets
struct Fenwick {
  int n; ll* tree;
  void update(int i, int val) {
    ++i;
    while (i <= n) {
      tree[i] += val;
      i += i & (-i);
    }
  }
  Fenwick(int size) {
    n = size;
    tree = new ll[n+1];
    for (int i = 1; i <= n; i++)
      tree[i] = 0;
  }
  Fenwick(int* arr, int size) : Fenwick(size) {
    for (int i = 0; i < n; i++)
      update(i, arr[i]);
  }
  ~Fenwick() { delete[] tree; }
```

```
ll operator[](int i) {
  if (i < 0 || i > n) return 0;
  ll sum = 0;
  ++i;
  while (i>0) {
    sum += tree[i];
    i -= i & (-i);
  }
  return sum;
}
ll getRange(int a, int b) { return
  operator[](b) - operator[](a-1); }
};
```

Hashtable

```
// similar to unordered_map, but faster
struct chash {
  const uint64_t C = (1ll)(2e18 * M_PI) + 71;
  ll operator()(ll x) const { return
  __builtin_bswap64(x*C); }
};
int main() {
  gp_hash_table<ll, int, chash>
  hashable({}, {}, {}, {}, {1<16});
  for (int i = 0; i < 100; i++)
    hashable[i] = 200+i;
  if (hashable.find(10) != hashable.end())
    cout << hashable[10];
}
```

Ordered Set

```
template <typename T>
using oset = tree<T, null_type, less<T>, rb_tree
  _tag, tree_order_statistics_node_update>;
template <typename T, typename D>
using omap = tree<T, D, less<T>, rb_tree
  _tag, tree_order_statistics_node_update>;
int main()
{
  oset<int> o_set;
  o_set.insert(5); o_set.insert(1);
  o_set.insert(3);
  // get second smallest element
  cout << *(o_set.find_by_order(1));
  // number of elements less than k=4
  cout << ' ' << o_set.order_of_key(4) << '\n';
  // equivalent with ordered map
  omap<int, int> o_map;
  o_map[5]=1; o_map[1]=2; o_map[3]=3;
  cout << (*(o_map.find_by_order(1))).first;
  cout << ' ' << o_map.order_of_key(4) << '\n';
}
```

Rope

```
// O(log n) insert, delete, concatenate
int main() {
  // generate rope
  rope<int> v;
  for (int i = 0; i < 100; i++)
    v.push_back(i);
  // move range to front
  rope<int> copy = v.substr(10, 10);
  v.erase(10, 10);
  v.insert(copy.mutable_begin(), copy);
  // print elements of rope
  for (auto it : v)
    cout << it << " ";
}
```

Segment Tree

```
//max(a,b), min(a,b), a+b, a*b, gcd(a,b), a^b
struct SegmentTree {
  typedef int T;
  static constexpr T UNIT = INT_MIN;
  T f(T a, T b) {
    if (a == UNIT) return b;
    if (b == UNIT) return a;
    return max(a, b);
  }
  int n; vector<T> s;
  SegmentTree(int n, T def=UNIT) : s(2*n, def),
  n(n) {}
```

```

SegmentTree(vector<T> arr) :
→ SegmentTree(arr.size()) {
for (int i=0; i<arr.size(); i++)
→ update(i, arr[i]);
}
void update(int pos, T val) {
for (s[pos += n] = val; pos /= 2;)
→ s[pos] = f(s[pos * 2], s[pos*2+1]);
}
T query(int b, int e) { // query [b, e)
T ra = UNIT, rb = UNIT;
for (b+=n, e+=n; b<e; b/=2, e/=2) {
if (b % 2) ra = f(ra, s[b++]);
if (e % 2) rb = f(s[--e], rb);
}
return f(ra, rb);
}
T get(int p) { return query(p, p+1); }
};

```

Trie

```

typedef trie<string, null_type,
→ trie_string_access_traits<,
pat_trie_tag, trie_prefix_search_node_update>
→ trie_type;
int main() {
// generate trie
trie_type trie;
for (int i = 0; i < 20; i++)
→ trie.insert(to_string(i)); // true if new,
→ false if old
// print things with prefix "1"
auto range = trie.prefix_range("1");
for (auto it = range.first; it !=
→ range.second; it++)
→ cout << *it << " ";
}

```

4 Strings

Aho Corasick

```

// range of alphabet for automata to consider
// MAXC = 26, OFFC = 'a' if only lowercase
const int MAXC = 256;
const int OFFC = 0;
struct aho_corasick {
struct state
{
set<pair<int, int>> out;
int fail; vector<int> go;
state() : fail(-1), go(MAXC, -1) {}
};
vector<state> s;
int id = 0;
aho_corasick(string* arr, int size) : s(1) {
for (int i = 0; i < size; i++) {
int cur = 0;
for (int c : arr[i]) {
if (s[cur].go[c-OFFC] == -1) {
s[cur].go[c-OFFC] = s.size();
s.push_back(state());
}
cur = s[cur].go[c-OFFC];
}
s[cur].out.insert({arr[i].size(), id++});
}
for (int c = 0; c < MAXC; c++)
if (s[0].go[c] == -1)
→ s[0].go[c] = 0;
queue<int> sq;
for (int c = 0; c < MAXC; c++) {
if (s[0].go[c] != 0) {
→ s[s[0].go[c]].fail = 0;
sq.push(s[0].go[c]);
}
}
while (sq.size()) {
int e = sq.front(); sq.pop();
for (int c = 0; c < MAXC; c++) {
if (s[e].go[c] != -1) {

```

```

int failure = s[e].fail;
while (s[failure].go[c] == -1)
→ failure = s[failure].fail;
failure = s[failure].go[c];
s[s[e].go[c]].fail = failure;
for (auto length : s[failure].out)
→ s[s[e].go[c]].out.insert(length);
sq.push(s[e].go[c]);
}
}
}
// list of {start pos, pattern id}
vector<pair<int, int>> search(string text)
{
vector<pair<int, int>> toret;
int cur = 0;
for (int i = 0; i < text.size(); i++) {
while (s[cur].go[text[i]-OFFC] == -1)
→ cur = s[cur].fail;
cur = s[cur].go[text[i]-OFFC];
if (s[cur].out.size())
→ for (auto end : s[cur].out)
→ toret.push_back({i - end.first + 1,
→ end.second});
}
return toret;
};

```

Boyer Moore

```

struct defint { int i = -1; };
vector<int> boyermore(string txt, string pat)
{
vector<int> toret; unordered_map<char, defint>
→ badchar;
int m = pat.size(), n = txt.size();
for (int i = 0; i < m; i++) badchar[pat[i]].i
→ = i;
int s = 0;
while (s <= n - m) {
int j = m - 1;
while (j >= 0 && pat[j] == txt[s + j]) j--;
if (j < 0) {
→ toret.push_back(s);
s += (s + m < n) ? m - badchar[txt[s +
→ m]].i : 1;
} else
→ s += max(1, j - badchar[txt[s + j]].i);
}
return toret;
}

```

English Conversion

```

const string ones[] = {"", "one", "two",
→ "three", "four", "five", "six", "seven",
→ "eight", "nine"};
const string teens[] = {"ten", "eleven",
→ "twelve", "thirteen", "fourteen",
→ "fifteen", "sixteen", "seventeen",
→ "eighteen", "nineteen"};
const string tens[] = {"twenty", "thirty",
→ "forty", "fifty", "sixty", "seventy",
→ "eighty", "ninety"};
const string mags[] = {"thousand", "million",
→ "billion", "trillion", "quadrillion",
→ "quintillion", "sextillion",
→ "septillion"};
string convert(int num, int carry) {
if (num < 0) return "negative " +
→ convert(-num, 0);
if (num < 10) return ones[num];
if (num < 20) return teens[num % 10];
if (num < 100) return tens[(num / 10) - 2] +
→ (num%10==0?"":" ") + ones[num % 10];
if (num < 1000) return ones[num / 100] +
→ (num%100==0?"":" ") + "hundred" +
→ (num%100==0?"":" ") + convert(num % 100,
→ 0);
}

```

```

return convert(num / 1000, carry + 1) + " " +
→ mags[carry] + " " + convert(num % 1000,
→ 0);
}
string convert(int num) {
return (num == 0) ? "zero" : convert(num, 0);
}

```

Knuth Morris Pratt

```

vector<int> kmp(string txt, string pat) {
vector<int> toret;
int m = txt.length(), n = pat.length();
int next[n + 1];
for (int i = 0; i < n + 1; i++)
→ next[i] = 0;
for (int i = 1; i < n; i++) {
int j = next[i + 1];
while (j > 0 && pat[j] != pat[i])
→ j = next[j];
if (j > 0 || pat[j] == pat[i])
→ next[i + 1] = j + 1;
}
for (int i = 0, j = 0; i < m; i++) {
if (txt[i] == pat[j]) {
if (++j == n)
→ toret.push_back(i - j + 1);
} else if (j > 0) {
j = next[j];
}
}
return toret;
}

```

Longest Common Prefix (array)

```

// longest common prefix of strings in array
string lcp(string* arr, int n, bool sorted =
→ false) {
if (n == 0) return "";
if (!sorted) sort(arr, arr + n);
string r = ""; int v = 0;
while (v < arr[0].length() && arr[0][v] ==
→ arr[n-1][v])
→ r += arr[0][v++];
return r;
}

```

Longest Common Subsequence

```

string lcs(string a, string b) {
int m = a.length(), n = b.length();
int L[m+1][n+1];
for (int i = 0; i <= m; i++) {
for (int j = 0; j <= n; j++) {
if (i == 0 || j == 0) L[i][j] = 0;
else if (a[i-1] == b[j-1]) L[i][j] =
→ L[i-1][j-1] + 1;
else L[i][j] = max(L[i-1][j], L[i][j-1]);
}
}
// return L[m][n]; // length of lcs
string out = "";
int i = m - 1, j = n - 1;
while (i >= 0 && j >= 0) {
if (a[i] == b[j]) {
out = a[i--] + out;
j--;
} else if (L[i][j+1] > L[i+1][j]) i--;
else j--;
}
return out;
}

```

Longest Common Substring

```

// l is array of palindrome length at that
→ index
int manacher(string s, int* l) {
int n = s.length() * 2;
for (int i = 0, j = 0, k; i < n; i += k, j =
→ max(j-k, 0)) {

```

```

while (i >= j && i + j + 1 < n && s[(i-j)/2]
→ == s[(i+j+1)/2]) j++;
l[i] = j;
for (k = 1; i >= k && j >= k && l[i-k] !=
→ j-k; k++)
→ l[i+k] = min(l[i-k], j-k);
return *max_element(l, l + n);
}

```

Cyclic Rotation (Lyndon)

```

// simple strings = smaller than its nontrivial
→ suffixes
// lyndon factorization = simple strings
→ factorized
// "abaaba" -> "ab", "aab", "a"
vector<string> duval(string s) {
int n = s.length();
vector<string> lyndon;
for (int i = 0; i < n; i++) {
int j = i+1, k = i;
for (; j < n && s[k] <= s[j]; j++)
if (s[k] < s[j]) k = i;
else k++;
for (; i <= k; i += j - k)
→ lyndon.push_back(s.substr(i, j-k));
}
return lyndon;
}
// lexicographically smallest rotation
int minRotation(string s) {
int n = s.length(); s += s;
auto d = duval(s); int i = 0, a = 0;
while (a + d[i].length() < n) a +=
→ d[i++].length();
while (i && d[i] == d[i-1]) a -=
→ d[i--].length();
return a;
}

```

Subsequence Count

```

// "banana", "ban" >> 3 (ban, ba..n, b..an)
ull subsequences(string body, string subs) {
int m = subs.length(), n = body.length();
if (m > n) return 0;
ull** arr = new ull*[m+1];
for (int i = 0; i <= m; i++) arr[i] = new
→ ull[n+1];
for (int i = 1; i <= m; i++) arr[i][0] = 0;
for (int i = 0; i <= n; i++) arr[0][i] = 1;
for (int i = 1; i <= m; i++)
for (int j = 1; j <= n; j++)
→ arr[i][j] = arr[i][j-1] + ((body[j-1] ==
→ subs[i-1])? arr[i-1][j-1] : 0);
return arr[m][n];
}

```

Suffix Array + LCP

```

struct SuffixArray {
vector<int> sa, lcp;
SuffixArray(string& s, int lim=256) {
int n = s.length() + 1, k = 0, a, b;
vector<int> x(begin(s), end(s)+1), y(n),
→ ws(max(n, lim)), rank(n);
sa = lcp = y;
iota(begin(sa), end(sa), 0);
for (int j = 0, p = 0; p < n; j = max(1, j *
→ 2), lim = p) {
p = j; iota(begin(y), end(y), n - j);
for (int i = 0; i < (n); i++)
if (sa[i] >= j)
→ y[p++] = sa[i] - j;
fill(begin(ws), end(ws), 0);
for (int i = 0; i < (n); i++) ws[x[i]]++;
for (int i = 1; i < (lim); i++) ws[i] +=
→ ws[i - 1];
}
}

```

```

for (int i = n; i--;) sa[--ws[x[y[i]]]] =
    y[i];
swap(x, y); p = 1; x[sa[0]] = 0;
for (int i = 1; i < (n); i++) {
    a = sa[i - 1]; b = sa[i];
    x[b] = (y[a] == y[b] && y[a + j] == y[b +
    j]) ? p - 1 : p++;
}
for (int i = 1; i < (n); i++) rank[sa[i]] =
    i;
for (int i = 0, j; i < n - 1; lcp[rank[i++]]
    = k)
    for (k && k--, j = sa[rank[i] - 1];
        s[i + k] == s[j + k]; k++);
}
}

```

String Utilities

```

void lowercase(string& s) {
    transform(s.begin(), s.end(), s.begin(),
        ::tolower);
}
void uppercase(string& s) {
    transform(s.begin(), s.end(), s.begin(),
        ::toupper);
}
void trim(string &s) {
    s.erase(s.begin(), find_if_not(s.begin(), s)
        .end(), [](int c){return
        isspace(c);});
    s.erase(find_if_not(s.rbegin(), s.rend(), [](int
        c){return isspace(c);}).base(), s.end());
}
vector<string> split(string& s, char token) {
    vector<string> v; stringstream ss(s);
    for (string e; getline(ss, e, token);)
        v.push_back(e);
    return v;
}

```

5 Greedy

Interval Cover

```

// L,R = interval [L,R], in = {{l,r}, index}
// does not handle case where L==R
vector<int> intervalCover(double L, double R,
    vector<pair<double,double>,int>> in) {
    vector<pair<double,int>> pos = {L,-1};
    vector<int> a;
    sort(begin(in), end(in));
    while (pos.first < R) {
        double cur = pos.first;
        while (i < (int)in.size() &&
            in[i].first <= cur)
            pos = max(pos, {in[i].first.second, in[i].second});
        i++;
        if (pos.first == cur) return {};
        a.push_back(pos.second);
    }
    return a;
}

```

6 Math

Catalan Numbers

```

ull* catalan = new ull[1000000];
void genCatalan(int n, int mod) {
    catalan[0] = catalan[1] = 1;
    for (int i = 2; i <= n; i++) {
        catalan[i] = 0;
        for (int j = i - 1; j >= 0; j--) {
            catalan[i] += (catalan[j] * catalan[i-j-1])
                % mod;
            if (catalan[i] >= mod)
                catalan[i] -= mod;
        }
    }
}
// TODO: consider binomial coefficient method

```

Combinatorics (nCr, nPr)

```

// can optimize by precomputing factorials, and
// fact[n]/fact[n-r]
ull nPr(ull n, ull r) {
    ull v = 1;
    for (ull i = n-r+1; i <= n; i++)
        v *= i;
    return v;
}
ull nPr(ull n, ull r, ull m) {
    ull v = 1;
    for (ull i = n-r+1; i <= n; i++)
        v = (v * i) % m;
    return v;
}
ull nCr(ull n, ull r) {
    long double v = 1;
    for (ull i = 1; i <= r; i++)
        v = v * (n-r+i) / i;
    return (ull)(v + 0.001);
}
// requires modulo math
// can optimize by precomputing mfacs and
// minv-mfac
ull nCr(ull n, ull r, ull m) {
    return mfacs(n, m) * minv(mfacs(r, m), m) % m *
        minv(mfacs(n-r, m), m) % m;
}

```

Chinese Remainder Theorem

```

bool ecrt(ll* r, ll* m, int n, ll& re, ll& mo)
    = {
    ll x, y, d; mo = m[0]; re = r[0];
    for (int i = 1; i < n; i++) {
        d = egcd(mo, m[i], x, y);
        if ((r[i] - re) % d != 0) return false;
        x = (r[i] - re) / d * x % (m[i] / d);
        re += x * mo;
        mo = mo / d * m[i];
        re %= mo;
    }
    re = (re + mo) % mo;
    return true;
}

```

Count Digit Occurences

```

/*count(n,d) counts the number of occurences of
    a digit d in the range [0,n]*/
ll digit_count(ll n, ll d) {
    ll result = 0;
    while (n != 0) {
        result += ((n/10) == d ? 1 : 0);
        n /= 10;
    }
    return result;
}
ll count(ll n, ll d) {
    if (n < 10) return (d > 0 && n >= d);
    if ((n % 10) != 9) return digit_count(n, d) +
        count(n-1, d);
    return 10*count(n/10, d) + (n/10) + (d > 0);
}

```

Discrete Logarithm

```

unordered_map<int, int> dlogc;
int discretelog(int a, int b, int m) {
    dlogc.clear();
    ll n = sqrt(m)+1, an = 1;
    for (int i = 0; i < n; i++)
        an = (an * a) % m;
    ll c = an;
    for (int i = 1; i <= n; i++) {
        if (!dlogc.count(c)) dlogc[c] = i;
        c = (c * an) % m;
    }
    c = b;
    for (int i = 0; i <= n; i++) {
        if (dlogc.count(c)) return (dlogc[c] * n - i
            + m - 1) % (m-1);
        c = (c * a) % m;
    }
    return -1;
}

```

Euler Phi / Totient

```

int phi(int n) {
    int r = n;
    for (int i = 2; i * i <= n; i++) {
        if (n % i == 0) r -= r / i;
        while (n % i == 0) n /= i;
    }
    if (n > 1) r -= r / n;
    return r;
}
#define n 100000
ll phi[n+1];
void computeTotient() {
    for (int i=1; i<=n; i++) phi[i] = i;
    for (int p=2; p<=n; p++) {
        if (phi[p] == p) {
            phi[p] = p-1;
            for (int i = 2*p; i<=n; i += p) phi[i] =
                (phi[i]/p) * (p-1);
        }
    }
}

```

Factorials

```

// digits in factorial
#define kamenetsky(n) (floor((n * log10(n /
    M_E)) + (log10(2 * M_PI * n) / 2.0)) + 1)
// approximation of factorial
#define stirling(n) ((n == 1) ? 1 : sqrt(2 *
    M_PI * n) * pow(n / M_E, n))
// natural log of factorial
#define lfactorial(n) (lgamma(n+1))

```

Prime Factorization

```

// do not call directly
ll pollard_rho(ll n, ll s) {
    ll x, y;
    x = y = rand() % (n - 1) + 1;
    int head = 1, tail = 2;
    while (true) {
        x = mult(x, x, n);
        x = (x + s) % n;
        if (x == y) return n;
        ll d = __gcd(max(x - y, y - x), n);
        if (1 < d && d < n) return d;
        if (++head == tail) y = x, tail <= 1;
    }
}
// call for prime factors
void factorize(ll n, vector<ll> &divisor) {
    if (n == 1) return;
    if (isPrime(n)) divisor.push_back(n);
    else {
        ll d = n;
        while (d >= n) d = pollard_rho(n, rand() % (n
            - 1) + 1);
        factorize(n / d, divisor);
        factorize(d, divisor);
    }
}

```

Farey Fractions

```

// generate 0 <= a/b <= 1 ordered, b <= n
// farey(4) = 0/1 1/4 1/3 1/2 2/3 3/4 1/1
// length is sum of phi(i) for i = 1 to n
vector<pair<int, int>> farey(int n) {
    int h = 0, k = 1, x = 1, y = 0, r;
    vector<pair<int, int>> v;
    do {
        v.push_back({h, k});
        r = (n-y)/k;
        y += r*k; x += r*h;
        swap(x,h); swap(y,k);
        x = -x; y = -y;
    } while (k > 1);
    v.push_back({1, 1});
    return v;
}

```

Fast Fourier Transform

```

#define cd complex<double>
const double PI = acos(-1);
void fft(vector<cd>& a, bool invert) {
    int n = a.size();
    for (int i = 1, j = 0; i < n; i++) {
        int bit = n >> 1;
        for (; j & bit; bit >>= 1) j ^= bit;
        if (i < j) swap(a[i], a[j]);
    }
    for (int len = 2; len <= n; len <= 1) {
        double ang = 2 * PI / len * (invert ? -1 :
            1);
        cd wlen(cos(ang), sin(ang));
        for (int i = 0; i < n; i += len) {
            cd w(1);
            for (int j = 0; j < len / 2; j++) {
                cd u = a[i+j], v = a[i+j+len/2] * w;
                a[i+j] = u + v;
                a[i+j+len/2] = u - v;
                w *= wlen;
            }
        }
        if (invert)
            for (auto& x : a)
                x /= n;
    }
}
vector<int> fftmult(vector<int> const& a,
    vector<int> const& b) {
    vector<cd> fa(a.begin(), a.end()),
        fb(b.begin(), b.end());
    int n = 1 << (32 - __builtin_clz(a.size() +
        b.size() - 1));
    fa.resize(n); fb.resize(n);
    fft(fa, false); fft(fb, false);
    for (int i = 0; i < n; i++) fa[i] *= fb[i];
    fft(fa, true);
    vector<int> toret(n);
    for (int i = 0; i < n; i++) toret[i] =
        round(fa[i].real());
    return toret;
}

```

Greatest Common Denominator

```

ll egcd(ll a, ll b, ll& x, ll& y) {
    if (b == 0) { x = 1; y = 0; return a; }
    ll gcd = egcd(b, a % b, x, y);
    x -= a / b * y;
    swap(x, y);
    return gcd;
}

```

Josephus Problem

```

// 0-indexed, arbitrary k
int josephus(int n, int k) {
    if (n == 1) return 0;
    if (k == 1) return n-1;
    if (k > n) return (josephus(n-1,k)+k)%n;
    int res = josephus(n-n/k,k)-n/k;
    return res + ((res<0)?n:res/(k-1));
}
// fast case if k=2, traditional josephus
int josephus(int n) {
    return 2*(n-(1<<(32-__builtin_clz(n)-1)));
}

```

Least Common Multiple

```

#define lcm(a,b) ((a*b)/__gcd(a,b))

```


Modulo Operations

```
#define MOD 1000000007
#define madd(a,b,m) (a+b-((a+b-m)>=0)?m:0))
#define mult(a,b,m) ((ull)a*b%m)
#define msb(a,b,m) (a-b+((a<b)?m:0))
ll mpow(ll b, ll e, ll m) {
    ll x = 1;
    while (e > 0) {
        if (e % 2) x = (x * b) % m;
        b = (b * b) % m;
        e /= 2;
    }
    return x % m;
}
ull mfac(ull n, ull m) {
    ull f = 1;
    for (int i = n; i > 1; i--)
        f = (f * i) % m;
    return f;
}
// if m is not guaranteed to be prime
ll minv(ll b, ll m) {
    ll x = 0, y = 0;
    if (egcd(b, m, x, y) != 1) return -1;
    return (x % m + m) % m;
}
ll mdv_compmod(int a, int b, int m) {
    if (__gcd(b, m) != 1) return -1;
    return mult(a, minv(b, m), m);
}
// if m is prime (like 10^9+7)
ll mdv_primemod(int a, int b, int m) {
    return mult(a, mpow(b, m-2, m), m);
}
```

Matrix

```
template<typename T>
struct Mat : public Vec<2, T> {
    int w, h;
    Mat(int x, int y) : Vec<2, T>(x, y), w(x),
        h(y) {}
    static Mat<T> identity(int n) { Mat<T> m(n,n);
        for (int i=0;i<n;i++) m[i][i] = 1; return
        m; }
    Mat<T> & operator+=(const Mat<T>& m) {
        for (int i = 0; i < w; i++)
            for (int j = 0; j < h; j++)
                (*this)[i][j] += m[i][j];
        return *this;
    }
    Mat<T> & operator-=(const Mat<T>& m) {
        for (int i = 0; i < w; i++)
            for (int j = 0; j < h; j++)
                (*this)[i][j] -= m[i][j];
        return *this;
    }
    Mat<T> operator*(const Mat<T>& m) {
        Mat<T> z(w,m.h);
        for (int i = 0; i < w; i++)
            for (int j = 0; j < h; j++)
                for (int k = 0; k < m.h; k++)
                    z[i][k] += (*this)[i][j] * m[j][k];
        return z;
    }
    Mat<T> operator+(const Mat<T>& m) { Mat<T>
        a=*this; return a+m; }
    Mat<T> operator-(const Mat<T>& m) { Mat<T>
        a=*this; return a-m; }
    Mat<T> & operator*=(const Mat<T>& m) { return
        *this = (*this)*m; }
    Mat<T> power(int n) {
        Mat<T> a = Mat<T>::identity(w), m=*this;
        for (;n;n/=2,m*=m) if (n&1) a *= m;
        return a;
    }
};
```

Permutation

```
// c = array size, n = nth perm, return index
vector<int> gen_permutation(int c, int n) {
```

```
vector<int> idx(c), per(c), fac(c); int i;
for (i = 0; i < c; i++) idx[i] = i;
for (i = 1; i <= c; i++) fac[i-1] = n/i, n/=i;
for (i = c - 1; i >= 0; i--)
    per[c-i-1] = idx[fac[i]],
    idx.erase(idx.begin() + fac[i]);
return per;
}
```

Miller-Rabin Primality Test

```
// Miller-Rabin primality test - O(10 log^3 n)
bool isPrime(ull n) {
    if (n < 2) return false;
    if (n == 2) return true;
    if (n % 2 == 0) return false;
    ull s = n - 1;
    while (s % 2 == 0) s /= 2;
    for (int i = 0; i < 10; i++) {
        ull temp = s;
        ull a = rand() % (n - 1) + 1;
        ull mod = mpow(a, temp, n);
        while (temp != n-1 && mod != 1 && mod != n-1) {
            mod = mult(mod, mod, n);
            temp *= 2;
        }
        if (mod != n-1 && temp % 2 == 0) return false;
    }
    return true;
}
```

Sieve of Eratosthenes

```
bitset<1000000001> sieve;
// generate sieve - O(n log n)
void genSieve(int n) {
    sieve[0] = sieve[1] = 1;
    for (ull i = 3; i * i < n; i += 2)
        if (!sieve[i])
            for (ull j = i * 3; j <= n; j += i * 2)
                sieve[j] = 1;
}
// query sieve after it's generated - O(1)
bool querySieve(int n) {
    return n == 2 || (n % 2 != 0 && !sieve[n]);
}
```

Simpson's / Approximate Integrals

```
// integrate f from a to b, k iterations
// error <= (b-a)/18.0 * M * ((b-a)/2k)^4
// where M = max(abs(f''''(a))) for x in [a,b]
// "f" is a function "double func(double x)"
double Simpsons(double a, double b, int k,
    double (*f)(double)) {
    double dx = (b-a)/(2.0*k), t = 0;
    for (int i = 0; i < k; i++)
        t += ((i==0)?1:2)*(*f)(a+2*i*dx) + 4 *
            (*f)(a+(2*i+1)*dx);
    return (t + (*f)(b)) * (b-a) / 6.0 / k;
}
```

Common Equations Solvers

```
// ax^2 + bx + c = 0, find x
vector<double> solveEq(double a, double b,
    double c) {
    vector<double> r;
    double z = b * b - 4 * a * c;
    if (z == 0)
        r.push_back(-b/(2*a));
    else if (z > 0) {
        r.push_back((sqrt(z)-b)/(2*a));
        r.push_back((sqrt(z)+b)/(2*a));
    }
    return r;
}
// ax^3 + bx^2 + cx + d = 0, find x
vector<double> solveEq(double a, double b,
    double c, double d) {
    vector<double> res;
    long double a1 = b/a, a2 = c/a, a3 = d/a;
    long double q = (a1*a1 - 3*a2)/9.0, sq =
        -2*sqrt(q);
    long double r = (2*a1*a1*a1 - 9*a1*a2 +
        27*a3)/54.0;
```

```
long double z = r*r-q*q, theta;
if (z <= 0) {
    theta = acos(r/sqrt(q*q));
    res.push_back(sq*cos(theta/3.0) - a1/3.0);
    res.push_back(sq*cos((theta+2.0*PI)/3.0) -
        a1/3.0);
    res.push_back(sq*cos((theta+4.0*PI)/3.0) -
        a1/3.0);
}
else {
    res.push_back(pow(sqrt(z)+fabs(r), 1/3.0));
    res[0] = (res[0] + q / res[0]) * ((r<0)?1:-1)
        - a1 / 3.0;
    return res;
}
// linear diophantine equation ax + by = c,
// find x and y
// infinite solutions of form x+k*b/g, y-k*a/g
bool solveEq(ll a, ll b, ll c, ll &x, ll &y, ll
    &g) {
    g = egcd(abs(a), abs(b), x, y);
    if (c % g) return false;
    x *= c / g * ((a < 0) ? -1 : 1);
    y *= c / g * ((b < 0) ? -1 : 1);
    return true;
}
// m = # equations, n = # variables, a[m][n+1]
// = coefficient matrix
// a[i][0]x + a[i][1]y + ... + a[i][n]z =
// a[i][n+1]
const double eps = 1e-7;
bool zero(double a) { return (a < eps) && (a >
    -eps); }
vector<double> solveEq(double **a, int m, int
    n) {
    int cur = 0;
    for (int i = 0; i < n; i++) {
        for (int j = cur; j < m; j++) {
            if (!zero(a[j][i])) {
                if (j != cur) swap(a[j], a[cur]);
                for (int sat = 0; sat < m; sat++) {
                    if (sat == cur) continue;
                    double num = a[sat][i] / a[cur][i];
                    for (int sot = 0; sot <= n; sot++)
                        a[sat][sot] -= a[cur][sot] * num;
                }
                cur++;
                break;
            }
        }
        for (int j = cur; j < m; j++)
            if (!zero(a[j][n])) return vector<double>();
        vector<double> ans(n,0);
        for (int i = 0, sat = 0; i < n; i++)
            if (sat < m && !zero(a[sat][i]))
                ans[i] = a[sat][n] / a[sat++][i];
        return ans;
    }
}
```

Graycode Conversions

```
ull graycode2ull(ull n) {
    ull i = 0;
    for (; n; n = n >> 1) i ^= n;
    return i;
}
ull ull2graycode(ull n) {
    return n ^ (n >> 1);
}
```

Unix/Epoch Time

```
// 0-indexed month/time, 1-indexed day
// minimum 1970, 0, 1, 0, 0, 0
ull toEpoch(int year, int month, int day, int
    hour, int minute, int second) {
    struct tm t; time_t epoch;
    t.tm_year = year - 1900; t.tm_mon = month;
    t.tm_mday = day; t.tm_hour = hour;
    t.tm_min = minute; t.tm_sec = second;
```

```
t.tm_isdst = 0; // 1 = daylight savings
epoch = mktime(&t);
return (ull)epoch;
}
vector<int> toDate(ull epoch) {
    time_t e=epoch; struct tm t=*localtime(&e);
    return {t.tm_year+1900,t.tm_mon,t.tm_mday,t
        .tm_hour,t.tm_min,t.tm_sec};
}
int getWeekday(ull epoch) {
    time_t e=epoch; struct tm t=*localtime(&e);
    return t.tm_wday; // 0-6, 0 = sunday
}
int getDayOfYear(ull epoch) {
    time_t e=epoch; struct tm t=*localtime(&e);
    return t.tm_yday; // 0-365
}
const int months[] =
    {31,28,31,30,31,30,31,31,30,31,30,31};
bool validDate(int year, int month, int day) {
    bool leap = !(year%(year%25?4:16));
    if (month >= 12) return false;
    return day <= months[month] + (leap &&
        month == 1);
}
```

7 Graphs

```
struct edge {
    int u,v,w;
    edge(int u,int v,int w) : u(u),v(v),w(w) {}
    edge() : u(0), v(0), w(0) {}
};
bool operator < (const edge &e1, const edge
    &e2) { return e1.w < e2.w; }
bool operator > (const edge &e1, const edge
    &e2) { return e1.w > e2.w; }
struct subset { int p, rank; };

// Eulerian Path
#define edge_list vector<edge>
#define adj_sets vector<set<int>>
struct EulerPathGraph {
    adj_sets graph; // actually indexes incident
    edges
    edge_list edges; int n; vector<int> indeg;
    EulerPathGraph(int n): n(n) {
        indeg = *(new vector<int>(n,0));
        graph = *(new adj_sets(n, set<int>()));
    }
    void add_edge(int u, int v) {
        graph[u].insert(edges.size());
        indeg[v]++;
        edges.push_back(edge(u,v,0));
    }
    bool eulerian_path(vector<int> &circuit) {
        if(edges.size()==0) return false;
        stack<int> st;
        int a[] = {-1, -1};
        for(int v=0;v<n;v++) {
            if(indeg[v]!=graph[v].size()) {
                bool b = indeg[v] > graph[v].size();
                if (abs(((int)indeg[v])-((int)graph[v]
                    .size())) > 1) return
                    false;
                if (a[b] != -1) return false;
                a[b] = v;
            }
        }
        int s = (a[0]!=-1 && a[1]!=-1 ? a[0] :
            (a[0]==-1 && a[1]==-1 ? edges[0].u : -1));
        if(s==-1) return false;
        while(!st.empty() || !graph[s].empty()) {
            if (graph[s].empty()) {
                circuit.push_back(s); s = st.top();
                st.pop();
            }
            else {
                int w = edges[*graph[s].begin()].v;
```

```

... graph[s].erase(graph[s].begin());
... st.push(s); s = w;
... }
... }
circuit.push_back(s);
return circuit.size()-1==edges.size();
}
};

```

Floyd Warshall

```

const ll inf = 1LL << 62;
#define FOR(i,n) for (int i = 0; i < n; i++)
void floydWarshall(Vec<2, ll>& m) {
    int n = m.size();
    FOR(i,n) m[i][i] = min(m[i][i], 0LL);
    FOR(k,n) FOR(i,n) FOR(j,n) if (m[i][k] != inf
    && m[k][j] != inf) {
        auto newDist = max(m[i][k] + m[k][j], -inf);
        m[i][j] = min(m[i][j], newDist);
    }
    FOR(k,n) if (m[k][k] < 0) FOR(i,n) FOR(j,n)
    if (m[i][k] != inf && m[k][j] != inf)
    m[i][j] = -inf;
}

```

Minimum Spanning Tree

```

// returns vector of edges in the mst
// graph[i] = vector of edges incident to
// vertex i
// places total weight of the mst in &total
// if returned vector has size != n-1, there is
// no MST
vector<edge> mst(vector<vector<edge>> graph,
    ll &total) {
    total = 0;
    priority_queue<edge, vector<edge>,
    greater<edge>> pq;
    vector<edge> MST;
    bitset<20001> marked; // change size as needed
    marked[0] = 1;
    for (edge ep : graph[0]) pq.push(ep);
    while (MST.size() != graph.size()-1 &&
    pq.size() != 0) {
        edge e = pq.top(); pq.pop();
        int u = e.u, v = e.v, w = e.w;
        if (marked[u] && marked[v]) continue;
        else if (marked[u]) swap(u, v);
        for (edge ep : graph[u]) pq.push(ep);
        marked[u] = 1;
        MST.push_back(e);
        total += e.w;
    }
    return MST;
}

```

Union Find

```

int uf_find(subset* s, int i) {
    if (s[i].p != i) s[i].p = uf_find(s, s[i].p);
    return s[i].p;
}
void uf_union(subset* s, int x, int y) {
    int xp = uf_find(s, x), yp = uf_find(s, y);
    if (s[xp].rank > s[yp].rank) s[yp].p = xp;
    else if (s[xp].rank < s[yp].rank) s[xp].p =
    yp;
    else { s[yp].p = xp; s[xp].rank++; }
}

```

8 2D Geometry

```

#define point complex<double>
#define EPS 0.0000001
#define sq(a) ((a)*(a))
#define cb(a) ((a)*(a)*(a))
double dot(point a, point b) { return
    real(conj(a)*b); }
double cross(point a, point b) { return
    imag(conj(a)*b); }
struct line { point a, b; };

```

```

struct circle { point c; double r; };
struct segment { point a, point b; };
struct triangle { point a, b, c; };
struct rectangle { point tl, br; };
struct convex_polygon {
    vector<point> points;
    convex_polygon(vector<point> points) :
    points(points) {}
    convex_polygon(triangle a) {
        points.push_back(a.a); points.push_back(a.b);
        points.push_back(a.c);
    };
    convex_polygon(rectangle a) {
        points.push_back(a.tl);
        points.push_back({real(a.tl),
        imag(a.br)});
        points.push_back(a.br);
        points.push_back({real(a.br),
        imag(a.tl)});
    };
};
struct polygon {
    vector<point> points;
    polygon(vector<point> points) : points(points) {}
    polygon(triangle a) {
        points.push_back(a.a); points.push_back(a.b);
        points.push_back(a.c);
    };
    polygon(rectangle a) {
        points.push_back(a.tl);
        points.push_back({real(a.tl),
        imag(a.br)});
        points.push_back(a.br);
        points.push_back({real(a.br),
        imag(a.tl)});
    };
    polygon(convex_polygon a) {
        for (point v : a.points)
        points.push_back(v);
    };
};
// triangle methods
double area_heron(double a, double b, double c) {
    if (a < b) swap(a, b);
    if (a < c) swap(a, c);
    if (b < c) swap(b, c);
    if (a > b + c) return -1;
    return sqrt((a+b+c)*(c-a+b)*(c+a-b)*(a+b-c)
    /16.0);
}
// segment methods
double lengthsq(segment a) { return
    sq(real(a.a) - real(a.b)) + sq(imag(a.a) -
    imag(a.b)); }
double length(segment a) { return
    sqrt(lengthsq(a)); }
// circle methods
double circumference(circle a) { return 2 * a.r
    * M_PI; }
double area(circle a) { return sq(a.r) * M_PI;
    };
// rectangle methods
double width(rectangle a) { return
    abs(real(a.br) - real(a.tl)); }
double height(rectangle a) { return
    abs(imag(a.br) - real(a.tl)); }
double diagonal(rectangle a) { return
    sqrt(sq(width(a)) + sq(height(a))); }
double area(rectangle a) { return width(a) *
    height(a); }
double perimeter(rectangle a) { return 2 *
    (width(a) + height(a)); }

```

```

// check if `a` fit's inside `b`
// swap equalities to exclude tight fits
bool doesFitInside(rectangle a, rectangle b) {
    int x = width(a), w = width(b), y = height(a),
    h = height(b);
    if (x > y) swap(x, y);
    if (w > h) swap(w, h);
    if (w < x) return false;
    if (y <= h) return true;
    double a=sq(y)-sq(x), b=x*h-y*w, c=x*w-y*h;
    return sq(a) <= sq(b) + sq(c);
}
// polygon methods
// negative area = CCW, positive = CW
double area(polygon a) {
    double area = 0.0; int n = a.points.size();
    for (int i = 0, j = 1; i < n; i++, j = (j +
    1) % n)
        area +=
        (real(a.points[j]-a.points[i]))*(imag(a
        .points[j]+a.points[i]));
    return area / 2.0;
}
// get both unsigned area and centroid
pair<double, point> area_centroid(polygon a) {
    int n = a.points.size();
    double area = 0;
    point c(0, 0);
    for (int i = n - 1, j = 0; j < n; i = j++) {
        double v = cross(a.points[i], a.points[j]) /
        2;
        area += v;
        c += (a.points[i] + a.points[j]) * (v / 3);
    }
    c /= area;
    return {area, c};
}
Intersection
// -1 coincide, 0 parallel, 1 intersection
int intersection(line a, line b, point& p) {
    if (abs(cross(a.b - a.a, b.b - b.a)) > EPS) {
        p = cross(b.a - a.a, b.b - a.b) / cross(a.b -
        a.a, b.b - b.a) * (b - a) + a;
        return 1;
    }
    if (abs(cross(a.b - a.a, a.b - b.a)) > EPS)
    return 0;
    return -1;
}
// area of intersection
double intersection(circle a, circle b) {
    double d = abs(a.c - b.c);
    if (d <= b.r - a.r) return area(a);
    if (d <= a.r - b.r) return area(b);
    if (d >= a.r + b.r) return 0;
    double alpha = acos((sq(a.r) + sq(d) -
    sq(b.r)) / (2 * a.r * d));
    double beta = acos((sq(b.r) + sq(d) - sq(a.r))
    / (2 * b.r * d));
    return sq(a.r) * (alpha - 0.5 * sin(2 *
    alpha)) + sq(b.r) * (beta - 0.5 * sin(2 *
    beta));
}
// -1 outside, 0 inside, 1 tangent, 2
int intersection(circle a, circle b,
    vector<point>& inter) {
    double d2 = norm(b.c - a.c), rS = a.r + b.r,
    rD = a.r - b.r;
    if (d2 > sq(rS)) return -1;
    if (d2 < sq(rD)) return 0;
    double ca = 0.5 * (1 + rS * rD / d2);
    point z = point(ca, sqrt(sq(a.r) / d2 -
    sq(ca)));
    inter.push_back(a.c + (b.c - a.c) * z);
    if (abs(imag(z)) > EPS) inter.push_back(a.c +
    (b.c - a.c) * conj(z));
    return inter.size();
}

```

```

// points of intersection
vector<point> intersection(line a, circle c) {
    vector<point> inter;
    c.c -= a.a;
    a.b -= a.a;
    point m = a.b * real(c.c / a.b);
    double d2 = norm(m - c.c);
    if (d2 > sq(c.r)) return 0;
    double l = sqrt((sq(c.r) - d2) / norm(a.b));
    inter.push_back(a.a + m + l * a.b);
    if (abs(l) > EPS) inter.push_back(a.a + m - l
    * a.b);
    return inter;
}
// area of intersection
double intersection(rectangle a, rectangle b) {
    double x1 = max(real(a.tl), real(b.tl)), y1 =
    max(imag(a.tl), imag(b.tl));
    double x2 = min(real(a.br), real(b.br)), y2 =
    min(imag(a.br), imag(b.br));
    return (x2 <= x1 || y2 <= y1) ? 0 :
    (x2-x1)*(y2-y1);
}
Convex Hull
bool cmp(point a, point b) {
    if (abs(real(a) - real(b)) > EPS) return
    real(a) < real(b);
    if (abs(imag(a) - imag(b)) > EPS) return
    imag(a) < imag(b);
    return false;
}
convex_polygon convexhull(polygon a) {
    sort(a.points.begin(), a.points.end(), cmp);
    vector<point> lower, upper;
    for (int i = 0; i < a.points.size(); i++) {
        while (lower.size() >= 2 &&
        cross(lower.back() - lower[lower.size() -
        2], a.points[i] - lower.back()) < EPS)
        lower.pop_back();
        while (upper.size() >= 2 &&
        cross(upper.back() - upper[upper.size() -
        2], a.points[i] - upper.back()) > -EPS)
        upper.pop_back();
        lower.push_back(a.points[i]);
        upper.push_back(a.points[i]);
    }
    lower.insert(lower.end(), upper.rbegin() + 1,
    upper.rend());
    return convex_polygon(lower);
}

```

9 3D Geometry

```

struct point3d {
    double x, y, z;
    point3d operator+(point3d a) const { return
    {x+a.x, y+a.y, z+a.z}; }
    point3d operator-(double a) const { return
    {x*a, y*a, z*a}; }
    point3d operator-() const { return {-x, -y,
    -z}; }
    point3d operator-(point3d a) const { return
    *this - a; }
    point3d operator/(double a) const { return
    *this * (1/a); }
    double norm() { return x*x + y*y + z*z; }
    double abs() { return sqrt(norm()); }
    point3d normalize() { return *this /
    this->abs(); }
};
double dot(point3d a, point3d b) { return
    a.x*b.x + a.y*b.y + a.z*b.z; }
point3d cross(point3d a, point3d b) { return
    {a.y*b.z - a.z*b.y, a.z*b.x - a.x*b.z,
    a.x*b.y - a.y*b.x}; }

```

```
struct line3d { point3d a, b; };
struct plane { double a, b, c, d; } // a*x +
↳ b*y + c*z + d = 0
struct sphere { point3d c; double r; };
#define sq(a) ((a)*(a))
#define cb(a) ((a)*(a)*(a))
double surface(circle a) { return 4 * sq(a.r) *
↳ M_PI; }
double volume(circle a) { return 4.0/3.0 *
↳ cb(a.r) * M_PI; }
```

10 Optimization

```
Snoob
// SameNumberOfOneBits, next permutation
int snoob(int a) {
    int b = a & -a, c = a + b;
    return c | ((a ^ c) >> 2) / b;
}
// example usage
int main() {
    char l1[] = {'1', '2', '3', '4', '5'};
    char l2[] = {'a', 'b', 'c', 'd'};
    int d1 = 5, d2 = 4;
    // prints 12345abcd, 1234a5bcd, ...
    int min = (1<<d1)-1, max = min << d2;
    for (int i = min; i <= max; i = snoob(i)) {
        int p1 = 0, p2 = 0, v = i;
        while (p1 < d1 || p2 < d2) {
            cout << ((v & 1) ? l1[p1++] : l2[p2++]);
            v /= 2;
        }
        cout << '\n';
    }
}
```

```
Powers
bool isPowerOf2(ll a) {
    return a > 0 && !(a & a-1);
}
bool isPowerOf3(ll a) {
    return a>0&&!(12157665459056928801ull%a);
}
bool isPower(ll a, ll b) {
    double x = log(a) / log(b);
    return abs(x-round(x)) < 0.00000000001;
}
```

11 Additional

```
Judge Speed
// kattis: 0.50s
// codeforces: 0.421s
// atcoder: 0.455s
#include <bits/stdc++.h>
using namespace std;
int v = 1e9/2, p = 1;
int main() {
    for (int i = 1; i <= v; i++) p *= i;
    cout << p;
}
```

Judge Pre-Contest Checks

- __int128 and __float128 support?
- does extra or missing whitespace cause WA?
- documentation up to date?
- printer usage available and functional?

```
// each case tests a different fail condition
// try them before contests to see error codes
struct g { int arr[1000000]; g(){};
vector<g> a;
// 0=WA 1=TLE 2=MLE 3=OLE 4=SIGABRT 5=SIGFPE
↳ 6=SIGSEGV 7=recursive MLE
int judge(int n) {
    if (n == 0) exit(0);
    if (n == 1) while(1);
    if (n == 2) while(1) a.push_back(g());
    if (n == 3) while(1) putchar_unlocked('a');
```

```
if (n == 4) assert(0);
if (n == 5) 0 / 0;
if (n == 6) *(int*)(0) = 0;
return n + judge(n + 1);
}
```

GCC Builtin Docs

```
// 128-bit integer
__int128 a;
unsigned __int128 b;
// 128-bit float
// minor improvements over long double
float128 c;
// log2 floor
__lg(n);
// number of 1 bits
// can add ll like popcountll for long longs
__builtin_popcount(n);
// number of trailing zeroes
__builtin_ctz(n);
// number of leading zeroes
__builtin_clz(n);
// 1-indexed least significant 1 bit
__builtin_ffs(n);
// parity of number
__builtin_parity(n);
```

Limits

int	±2147483647	±2 ³¹ − 1	10 ⁹
uint	4294967295	2 ³² − 1	10 ⁹
ll	±9223372036854775807	±2 ⁶³ − 1	10 ¹⁸
ull	18446744073709551615	2 ⁶⁴ − 1	10 ¹⁹
i128	±170141183460469231...	±2 ¹²⁷ − 1	10 ³⁸
u128	340282366920938463...	2 ¹²⁸ − 1	10 ³⁸

Complexity classes input size (per second):

$O(n^n)$ or $O(n!)$	$n \leq 10$
$O(2^n)$	$n \leq 30$
$O(n^3)$	$n \leq 1000$
$O(n^2)$	$n \leq 30000$
$O(n\sqrt{n})$	$n \leq 10^6$
$O(n \log n)$	$n \leq 10^7$
$O(n)$	$n < 10^9$