Luna's Magic Reference

Suzune Nisiyama

August 5, 2018

Contents

1 Environment

1.1 Vimrc

```
set ru nu ts=4 sts=4 sw=4 si sm hls is ar bs=2 mouse=a
syntax on
nm <F3> :vsplit %<.in <CR>
nm <F4> :!gedit % <CR>
au BufEnter *.cpp set cin
au BufEnter *.cpp nm <F5> :!time ./%< <CR>|nm <F7> :!gdb ./%< <CR>|nm <F8> :!time ./%< < %<.in <CR>|nm <F9> :!g++ % -o %< -g -std=gnu++14 -O2 -DLOCAL && size %< <CR>
au BufEnter *.java nm <F5> :!time java %< <CR>|nm <F8> :!time java %< < %<.in <CR>|nm <F9> :!javac % <CR>
```

2 Data Structure

2.1 KD tree

```
/* kd_tree : finds the k-th closest point in O(kn^{1-1/k}).
Usage : Stores the data in p[]. Call function init (n, k). Call min_kth (d, k). (or max_kth) (k is 1-based)
Note : Switch to the commented code for Manhattan distance.
Status : SPOJ-FAILURE Accepted.*/
template <int MAXN = 200000, int MAXK = 2>
struct kd_tree {
 int k, size;
 struct point { int data[MAXK], id; } p[MAXN];
 struct kd_node {
  int l, r; point p, dmin, dmax;
  kd_node() {}
  kd_node (const point &rhs) : l (-1), r (-1), p (rhs), dmin (rhs), dmax (rhs) {}
  void merge (const kd_node &rhs, int k) {
   for (register int i = 0; i < k; ++i) {
    dmin.data[i] = std::min (dmin.data[i], rhs.dmin.data[i]);
    dmax.data[i] = std::max (dmax.data[i], rhs.dmax.data[i]); } }
  long long min_dist (const point &rhs, int k) const {
   register long long ret = 0;
   for (register int i = 0; i < k; ++i) {
    if (dmin.data[i] <= rhs.data[i] && rhs.data[i] <= dmax.data[i]) continue;
    ret += std::min (1ll * (dmin.data[i] - rhs.data[i]) * (dmin.data[i] - rhs.data[i]),
     1ll * (dmax.data[i] - rhs.data[i]) * (dmax.data[i] - rhs.data[i]));
//    ret += std::max (0, rhs.data[i] - dmax.data[i]) + std::max (0, dmin.data[i] - rhs.data[i]);
   } return ret; }
  long long max_dist (const point &rhs, int k) {
   long long ret = 0;
   for (int i = 0; i < k; ++i) {
    int tmp = std::max (std::abs (dmin.data[i] - rhs.data[i]), std::abs (dmax.data[i] - rhs.data[i]));
    ret += 1ll * tmp * tmp; }
//    ret += std::max (std::abs (rhs.data[i] - dmax.data[i]) + std::abs (rhs.data[i] - dmin.data[i]));
   }
   return ret; } } tree[MAXN * 4];
 struct result {
  long long dist; point d; result() {}
  result (const long long &dist, const point &d) : dist (dist), d (d) {}
  bool operator > (const result &rhs) const { return dist > rhs.dist || (dist == rhs.dist && d.id > rhs.d.id); }
  bool operator < (const result &rhs) const { return dist < rhs.dist || (dist == rhs.dist && d.id < rhs.d.id); } };
 long long sqrdist (const point &a, const point &b) {
  long long ret = 0;
  for (int i = 0; i < k; ++i) ret += 1ll * (a.data[i] - b.data[i]) * (a.data[i] - b.data[i]);
//  for (int i = 0; i < k; ++i) ret += std::abs (a.data[i] - b.data[i]);
  return ret; }
 int alloc() { tree[size].l = tree[size].r = -1; return size++; }
 void build (const int &depth, int &rt, const int &l, const int &r) {
  if (l > r) return;
  register int middle = (l + r) >> 1;
  std::nth_element (p + l, p + middle, p + r + 1, [=] (const point & a, const point & b) { return a.data[depth] < b.data[depth]; });
  tree[rt = alloc()] = kd_node (p[middle]);
  if (l == r) return;
  build ((depth + 1) % k, tree[rt].l, l, middle - 1);
  build ((depth + 1) % k, tree[rt].r, middle + 1, r);
  if (~tree[rt].l) tree[rt].merge (tree[tree[rt].l], k);
  if (~tree[rt].r) tree[rt].merge (tree[tree[rt].r], k); }
 std::priority_queue<result, std::vector<result>, std::less <result>> heap_l;
 std::priority_queue<result, std::vector<result>, std::greater <result>> heap_r;
 void _min_kth (const int &depth, const int &rt, const int &m, const point &d) {
  result tmp = result (sqrdist (tree[rt].p, d), tree[rt].p);
  if ((int)heap_l.size() < m) heap_l.push (tmp);
  else if (tmp < heap_l.top()) {
   heap_l.pop();
   heap_l.push (tmp); }
  int x = tree[rt].l, y = tree[rt].r;
  if (~x && ~y && sqrdist (d, tree[x].p) > sqrdist (d, tree[y].p)) std::swap (x, y);
  if (~x && ((int)heap_l.size() < m || tree[x].min_dist (d, k) < heap_l.top().dist))
   _min_kth ((depth + 1) % k, x, m, d);
  if (~y && ((int)heap_l.size() < m || tree[y].min_dist (d, k) < heap_l.top().dist))
   _min_kth ((depth + 1) % k, y, m, d); }
 void _max_kth (const int &depth, const int &rt, const int &m, const point &d) {
  result tmp = result (sqrdist (tree[rt].p, d), tree[rt].p);
  if ((int)heap_r.size() < m) heap_r.push (tmp);
  else if (tmp > heap_r.top()) {
   heap_r.pop();
   heap_r.push (tmp); }
  int x = tree[rt].l, y = tree[rt].r;
  if (~x && ~y && sqrdist (d, tree[x].p) < sqrdist (d, tree[y].p)) std::swap (x, y);
  if (~x && ((int)heap_r.size() < m || tree[x].max_dist (d, k) >= heap_r.top().dist))
   _max_kth ((depth + 1) % k, x, m, d);
  if (~y && ((int)heap_r.size() < m || tree[y].max_dist (d, k) >= heap_r.top().dist))
   _max_kth ((depth + 1) % k, y, m, d); }
 void init (int n, int k) { this -> k = k; size = 0; int rt = 0; build (0, rt, 0, n - 1); }
 result min_kth (const point &d, const int &m) { heap_l = decltype (heap_l) (); _min_kth (0, 0, m, d); return heap_l.top (); }
 result max_kth (const point &d, const int &m) { heap_r = decltype (heap_r) (); _max_kth (0, 0, m, d); return heap_r.top (); } };
```

2.2 Splay

```
void push_down (int x) {
 if (~n[x].c[0]) push (n[x].c[0], n[x].t);
 if (~n[x].c[1]) push (n[x].c[1], n[x].t);
 n[x].t = tag (); }
void update (int x) {
 n[x].m = gen (x);
 if (~n[x].c[0]) n[x].m = merge (n[n[x].c[0]].m, n[x].m);
 if (~n[x].c[1]) n[x].m = merge (n[x].m, n[n[x].c[1]].m); }
void rotate (int x, int k) {
 int y = n[x].c[k]; n[x].c[k] = n[y].c[k ^ 1]; n[y].c[k ^ 1] = x;
 if (n[x].f != -1) n[n[x].f].c[n[n[x].f].c[1] == x] = y;
 n[y].f = n[x].f; n[x].f = y; if (~n[x].c[k]) n[n[x].c[k]].f = x;
 update (x); update (y); }
void splay (int x, int s = -1) {
 while (n[x].f != s) {
  int a = -1; if (n[n[x].f].f != s) {
   push_down (n[n[x].f].f);
   a = n[n[n[x].f].f].c[1] == n[x].f; }
  push_down (n[x].f); push_down (x);
  int b = n[n[x].f].c[1] == x;
  if (a == b) rotate (n[n[x].f].f, b);
  else rotate (n[x].f, a);
  if (n[x].f != s) rotate (n[x].f, n[n[x].f].c[1] == x); }
 if (s == -1) root = x; }
```

2.3 Link-cut tree

```
void access (int x) {
 int u = x, v = -1;
 while (u != -1) {
  splay (u); push_down (u);
  if (~n[u].c[1]) n[n[u].c[1]].f = -1, n[n[u].c[1]].p = u;
  n[u].c[1] = v;
  if (~v) n[v].f = u, n[v].p = -1;
  update (u); u = n[v = u].p; }
 splay (x); }
```

3 Formula

3.1 Zeller's congruence

```
/* Zeller's congruence : converts between a calendar date and its Gregorian calendar day. (y >= 1) (0 = Monday, 1 = Tuesday, ..., 6 = Sunday) */
int get_id (int y, int m, int d) {
 if (m < 3) { --y; m += 12; }
 return 365 * y + y / 4 - y / 100 + y / 400 + (153 * (m - 3) + 2) / 5 + d - 307; }
std::tuple <int, int, int> date (int id) {
 int x = id + 1789995, n, i, j, y, m, d;
 n = 4 * x / 146097; x -= (146097 * n + 3) / 4;
 i = (4000 * (x + 1)) / 1461001; x -= 1461 * i / 4 - 31;
 j = 80 * x / 2447; d = x - 2447 * j / 80;
 x = j / 11;
 m = j + 2 - 12 * x; y = 100 * (n - 49) + i + x;
 return std::make_tuple (y, m, d); }
```

3.2 Lattice points below segment

```
/* Euclidean-like algorithm : computes the sum of sum_{i=0}^{n-1} floor((a+bi)/m).*/
long long solve(long long n, long long a, long long b, long long m){
 if (b == 0) return n * (a / m);
```

```
 if (a >= m) return n * (a / m) + solve (n, a % m, b, m);
 if (b >= m) return (n - 1) * n / 2 * (b / m) + solve (n, a, b % m, m);
 return solve ((a + b * n) / m, (a + b * n) % m, m, b); }
```

3.3 Adaptive Simpson's method

```
/* Adaptive Simpson's method : integrates f in [l, r]. */
struct simpson {
 double area (double (*f) (double), double l, double r) {
  double m = l + (r - l) / 2;
  return (f (l) + 4 * f (m) + f (r)) * (r - l) / 6; }
 double solve (double (*f) (double), double l, double r, double eps, double a) {
  double m = l + (r - l) / 2;
  double left = area (f, l, m), right = area (f, m, r);
  if (fabs (left + right - a) <= 15 * eps) return left + right + (left + right - a) / 15.0;
  return solve (f, l, m, eps / 2, left) + solve (f, m, r, eps / 2, right); }
 double solve (double (*f) (double), double l, double r, double eps) {
  return solve (f, l, r, eps, area (f, l, r)); } };
```

3.4 Simplex

```
/* Simplex : n varibles, m constraints, maximize sum c_j x_j with constraint sum a_ij x_j <= b_i.
The solution is in an[]. */
template <int MAXN = 100, int MAXM = 100>
struct simplex {
 int n, m; double a[MAXM][MAXN], b[MAXM], c[MAXN];
 bool infeasible, unbounded;
 double v, an[MAXN + MAXM]; int q[MAXN + MAXM];
 void pivot (int l, int e) {
  std::swap (q[e], q[l + n]);
  double t = a[l][e]; a[l][e] = 1; b[l] /= t;
  for (int i = 0; i < n; ++i) a[l][i] /= t;
  for (int i = 0; i < m; ++i) if (i != l && std::abs (a[i][e]) > EPS) {
   t = a[i][e]; a[i][e] = 0; b[i] -= t * b[l];
   for (int j = 0; j < n; ++j) a[i][j] -= t * a[l][j]; }
  if (std::abs (c[e]) > EPS) {
   t = c[e]; c[e] = 0; v += t * b[l];
   for (int j = 0; j < n; ++j) c[j] -= t * a[l][j]; } }
 bool pre () {
  for (int l, e; ; ) {
   l = e = -1;
   for (int i = 0; i < m; ++i) if (b[i] < -EPS && (!~l || rand () & 1)) l = i;
   if (!~l) return false;
   for (int i = 0; i < n; ++i) if (a[l][i] < -EPS && (!~e || rand () & 1)) e = i;
   if (!~e) return infeasible = true;
   pivot (l, e); } }
 double solve () {
  double p; std::fill (q, q + n + m, -1);
  for (int i = 0; i < n; ++i) q[i] = i;
  v = 0; infeasible = unbounded = false;
  if (pre ()) return 0;
  for (int l, e; ; pivot (l, e)) {
   l = e = -1; for (int i = 0; i < n; ++i) if (c[i] > EPS) { e = i; break; }
   if (!~e) break; p = INF;
   for (int i = 0; i < m; ++i) if (a[i][e] > EPS && p > b[i] / a[i][e])
    p = b[i] / a[i][e], l = i;
   if (!~l) return unbounded = true, 0; }
  for (int i = n; i < n + m; ++i) if (~q[i]) an[q[i]] = b[i - n];
  return v; } };
/* maximize c^T x, subject to Ax <= b, x >= 0 <=>
 minimize b^T y, subject to A^T x >= c, y >= 0 */
```

3.5 Extended Eratosthenes sieve

```
/* Extended Eratosthenes sieve : prefix sum of multiplicative functions. */
template <int SN = 110000, int D = 2>
struct ees {
 int co[SN], prime[SN], psize, sn;
 long long powa[D + 1][SN], powb[D + 1][SN];
 long long funca[SN], funcb[SN];
 long long pow (long long x, int n) {
  long long res = 1;
  for (int i = 0; i < n; ++i) res *= x;
  return res; }
// computes sum of powers.
 long long pre_pow (long long x, int n) {
  if (n == 0) return x;
  if (n == 1) return (1 + x) * x / 2;
  if (n == 2) return (1 + 2 * x) * (1 + x) * x / 6;
  return 0; }
// returns f(p) when p is prime.
 long long pfunc (long long p) { return -1; }
// returns f(k * p) when a prime p divides k.
 long long cfunc (long long k, long long p) { return 0; }
// computes funca[i] (funcb[i]) with powa[d][i] (powb[d][i]).
 void assemble () {
  for (int i = 1; i <= sn; ++i) {
   funca[i] = -powa[0][i];
   funcb[i] = -powb[0][i]; } }
 void init (long long n) {
  sn = std::max ((int) (ceil (sqrt (n)) + 1), 2);
  psize = 0; for (int i = 2; i <= sn; ++i) {
   if (!co[i]) prime[psize++] = i;
   for (int j = 0; 1LL * i * prime[j] <= sn; ++j) {
    co[i * prime[j]] = 1;
    if (i % prime[j] == 0) break; } }
  for (int d = 0; d <= D; ++d) {
   long long *pa = powa[d], *pb = powb[d];
   for (int i = 1; i <= sn; ++i) pa[i] = pre_pow (i, d) - 1;
   for (int i = 1; i <= sn; ++i) pb[i] = pre_pow (n / i, d) - 1;
   for (int i = 0; i < psize; ++i) { int &pi = prime[i];
    for (int j = 1; j <= sn; ++j) if (n / j >= 1LL * pi * pi) {
     long long ch = n / j / pi;
     pb[j] -= ((ch <= sn ? pa[ch] : pb[j * pi]) - pa[pi - 1]) * pow (pi, d);
    } else break;
    for (int j = sn; j >= 1; --j) if (j >= 1LL * pi * pi)
     pa[j] -= (pa[j / pi] - pa[pi - 1]) * pow (pi, d);
    else break; } }
  assemble (); }
 void dfs (int x, int f, long long mul, long long val, long long n, long long &res) {
  for (; x < psize && mul * prime[x] * prime[x] <= n; ++x) {
   long long nmul = mul * prime[x], nval = val * pfunc (prime[x]);
   for (; nmul <= n; nmul *= prime[x], nval = cfunc (val, prime[x]))
    dfs (x + 1, prime[x], nmul, nval, n, res); }
  if (n / mul > f) res += val * ((n / mul <= sn ? funca[n / mul] : funcb[mul]) - funca[f]);
  if (f > 1 && mul % (f * f) == 0) res += val; }
 long long solve (long long n) {
  if (n == 0) return 0;
  long long res = 1;
  init (n); dfs (0, 1, 1, 1, n, res);
  return res; } };
```

3.6 Neural network

```
/* Neural network : ft features, n layers, m neurons per layer. */
template <int ft = 3, int n = 2, int m = 3, int MAXDATA = 100000>
struct network {
 double wp[n][m][ft/* or m, if larger */], bp[n][m], w[m], b, val[n][m], del[n][m], avg[ft + 1], sig[ft + 1];
 network () {
  std::mt19937_64 mt (time (0));
  std::uniform_real_distribution <double> urdn (0, 2 * sqrt (m));
  for (int i = 0; i < n; ++i) for (int j = 0; j < m; ++j) for (int k = 0; k < (i ? m : ft); ++k)
   wp[i][j][k] = urdn (mt);
  for (int i = 0; i < n; ++i) for (int j = 0; j < m; ++j) bp[i][j] = urdn (mt);
  for (int i = 0; i < m; ++i) w[i] = urdn (mt); b = urdn (mt);
  for (int i = 0; i < ft + 1; ++i) avg[i] = sig[i] = 0; }
 double compute (double *x) {
  for (int j = 0; j < m; ++j) {
   val[0][j] = bp[0][j]; for (int k = 0; k < ft; ++k) val[0][j] += wp[0][j][k] * x[k];
   val[0][j] = 1 / (1 + exp (-val[0][j]));
  }
  for (int i = 1; i < n; ++i) for (int j = 0; j < m; ++j) {
   val[i][j] = bp[i][j]; for (int k = 0; k < m; ++k) val[i][j] += wp[i][j][k] * val[i - 1][k];
   val[i][j] = 1 / (1 + exp (-val[i][j]));
  }
  double res = b; for (int i = 0; i < m; ++i) res += val[n - 1][i] * w[i];
//  return 1 / (1 + exp (-res));
  return res; }
 void desc (double *x, double t, double eta) {
  double o = compute (x), delo = (o - t); // * o * (1 - o)
  for (int j = 0; j < m; ++j) del[n - 1][j] = w[j] * delo * val[n - 1][j] * (1 - val[n - 1][j]);
  for (int i = n - 2; i >= 0; --i) for (int j = 0; j < m; ++j) {
   del[i][j] = 0; for (int k = 0; k < m; ++k)
    del[i][j] += wp[i + 1][k][j] * del[i + 1][k] * val[i][j] * (1 - val[i][j]);
  }
  for (int j = 0; j < m; ++j) bp[0][j] -= eta * del[0][j];
  for (int j = 0; j < m; ++j) for (int k = 0; k < ft; ++k) wp[0][j][k] -= eta * del[0][j] * x[k];
  for (int i = 1; i < n; ++i) for (int j = 0; j < m; ++j) bp[i][j] -= eta * del[i][j];
  for (int i = 1; i < n; ++i) for (int j = 0; j < m; ++j) for (int k = 0; k < m; ++k)
   wp[i][j][k] -= eta * del[i][j] * val[i - 1][k];
  b -= eta * delo;
//  for (int i = 0; i < m; ++i) w[i] -= eta * delo * o * (1 - o) * val[i];
  for (int i = 0; i < m; ++i) w[i] -= eta * delo * val[n - 1][i]; }
 void train (double data[MAXDATA][ft + 1], int dn, int epoch, double eta) {
  for (int i = 0; i < ft + 1; ++i) for (int j = 0; j < dn; ++j) avg[i] += data[j][i];
  for (int i = 0; i < ft + 1; ++i) avg[i] /= dn;
```

```
  for (int i = 0; i < ft + 1; ++i) for (int j = 0; j < dn; ++j)
   sig[i] += (data[j][i] - avg[i]) * (data[j][i] - avg[i]);
  for (int i = 0; i < ft + 1; ++i) sig[i] = sqrt (sig[i] / dn);
  for (int i = 0; i < ft + 1; ++i) for (int j = 0; j < dn; ++j)
   data[j][i] = (data[j][i] - avg[i]) / sig[i];
  for (int cnt = 0; cnt < epoch; ++cnt) for (int test = 0; test < dn; ++test)
   desc (data[test], data[test][ft], eta); }
 double predict (double *x) {
  for (int i = 0; i < ft; ++i) x[i] = (x[i] - avg[i]) / sig[i];
  return compute (x) * sig[ft] + avg[ft]; }
 std::string to_string () {
  std::ostringstream os; os << std::fixed << std::setprecision (16);
  for (int i = 0; i < n; ++i) for (int j = 0; j < m; ++j) for (int k = 0; k < (i ? m : ft); ++k)
   os << wp[i][j][k] << " ";
  for (int i = 0; i < n; ++i) for (int j = 0; j < m; ++j) os << bp[i][j] << " ";
  for (int i = 0; i < m; ++i) os << w[i] << " "; os << b << " ";
  for (int i = 0; i < ft + 1; ++i) os << avg[i] << " ";
  for (int i = 0; i < ft + 1; ++i) os << sig[i] << " ";
  return os.str (); }
 void read (const std::string &str) {
  std::istringstream is (str);
  for (int i = 0; i < n; ++i) for (int j = 0; j < m; ++j) for (int k = 0; k < (i ? m : ft); ++k)
   is >> wp[i][j][k];
  for (int i = 0; i < n; ++i) for (int j = 0; j < m; ++j) is >> bp[i][j];
  for (int i = 0; i < m; ++i) is >> w[i]; is >> b;
  for (int i = 0; i < ft + 1; ++i) is >> avg[i];
  for (int i = 0; i < ft + 1; ++i) is >> sig[i]; } };
```

4 Number theory

4.1 Fast power module

```
/* Fast power module : $x^n$ */
int fpm (int x, int n, int mod) {
 int ans = 1, mul = x; while (n) {
  if (n & 1) ans = int (1ll * ans * mul % mod);
  mul = int (1ll * mul * mul % mod); n >>= 1; }
 return ans; }
long long mul_mod (long long x, long long y, long long mod) {
 long long t = (x * y - (long long) ((long double) x / mod * y + 1E-3) * mod) % mod;
 return t < 0 ? t + mod : t; }
long long llfpm (long long x, long long n, long long mod) {
 long long ans = 1, mul = x; while (n) {
  if (n & 1) ans = mul_mod (ans, mul, mod);
  mul = mul_mod (mul, mul, mod); n >>= 1; }
 return ans; }
```

4.2 Euclidean algorithm

```
/* Euclidean algorithm : solves for ax + by = gcd (a, b). */
void euclid (const long long &a, const long long &b, long long &x, long long &y) {
 if (b == 0) x = 1, y = 0;
 else euclid (b, a % b, y, x), y -= a / b * x; }

long long inverse (long long x, long long m) {
 long long a, b; euclid (x, m, a, b); return (a % m + m) % m; }
```

4.3 Discrete Fourier transform

```
/* Discrete Fourier transform : the nafarious you-know-what thing.
Usage : call init for the suggested array size, and solve for the transform. (use f!=0 for the inverse) */
template <int MAXN = 1000000>
struct dft {
  typedef std::complex <double> complex;
  complex e[2][MAXN];
  int init (int n) {
   int len = 1;
   for (; len <= 2 * n; len <<= 1);
   for (int i = 0; i < len; ++i) {
    e[0][i] = complex (cos (2 * PI * i / len), sin (2 * PI * i / len));
    e[1][i] = complex (cos (2 * PI * i / len), -sin (2 * PI * i / len)); }
   return len; }
  void solve (complex *a, int n, int f) {
   for (int i = 0, j = 0; i < n; ++i) {
    if (i > j) std::swap (a[i], a[j]);
    for (int t = n >> 1; (j ^= t) < t; t >>= 1); }
   for (int i = 2; i <= n; i <<= 1)
    for (int j = 0; j < n; j += i)
     for (int k = 0; k < (i >> 1); ++k) {
      complex A = a[j + k];
      complex B = e[f][n / i * k] * a[j + k + (i >> 1)];
      a[j + k] = A + B;
      a[j + k + (i >> 1)] = A - B; }
   if (f == 1) {
    for (int i = 0; i < n; ++i) a[i] = complex (a[i].real () / n, a[i].imag ()); } } };
```

4.4 Fast Walsh-Hadamard transform

```
/* Fast Walsh-Hadamard transform : binary operation transform. */
void fwt (int *a, int n, int w) {
 for (int i = 1; i < n; i <<= 1)
  for(int j = 0; j < n; j += i << 1) {
   for(int k = 0; k < i; ++k) {
    int x = a[j + k], y = a[i + j + k];
    if (w) {
    /* xor : a[j + k] = (x + y) / 2, a[i + j + k] = (x - y) / 2, and : a[j + k] = x - y, or : a[i + j + k] = y - x; */
    }else{
    /* xor : a[j + k] = x + y, a[i + j + k] = x - y, and : a[j + k] = x + y, or : a[i + j + k] = x + y; */
    } } } }
```

4.5 Number theoretic transform

```
/* Number theoretic transform : NTT for any module.
Usage : Perform NTT on 3 modules and call crt () to merge the result. */
template <int MAXN = 1000000>
struct ntt {
 int MOD[3] = {1045430273, 1051721729, 1053818881}, PRT[3] = {3, 6, 7};
 void solve (int *a, int n, int f = 0, int mod = 998244353, int prt = 3) {
  for (int i = 0, j = 0; i < n; ++i) {
   if (i > j) std::swap (a[i], a[j]);
   for (int t = n >> 1; (j ^= t) < t; t >>= 1); }
  for (int i = 2; i <= n; i <<= 1) {
   static int exp[MAXN]; exp[0] = 1;
   exp[1] = fpm (prt, (mod - 1) / i, mod);
   if (f == 1) exp[1] = fpm (exp[1], mod - 2, mod);
   for (int k = 2; k < (i >> 1); ++k) {
    exp[k] = int (1ll * exp[k - 1] * exp[1] % mod); }
   for (int j = 0; j < n; j += i) {
    for (int k = 0; k < (i >> 1); ++k) {
     int &pA = a[j + k], &pB = a[j + k + (i >> 1)];
     int A = pA, B = int (1ll * pB * exp[k] % mod);
     pA = (A + B) % mod;
     pB = (A - B + mod) % mod; } } }
  if (f == 1) {
   int rev = fpm (n, mod - 2, mod);
   for (int i = 0; i < n; ++i) a[i] = int (1ll * a[i] * rev % mod); } }
 int crt (int *a, int mod) {
  static int inv[3][3];
  for (int i = 0; i < 3; ++i) for (int j = 0; j < 3; ++j)
   inv[i][j] = (int) inverse (MOD[i], MOD[j]);
  static int x[3];
  for (int i = 0; i < 3; ++i) { x[i] = a[i];
   for (int j = 0; j < i; ++j) {
    int t = (x[i] - x[j] + MOD[i]) % MOD[i];
    if (t < 0) t += MOD[i];
    x[i] = int (1LL * t * inv[j][i] % MOD[i]); } }
  int sum = 1, ret = x[0] % mod;
  for (int i = 1; i < 3; ++i) {
   sum = int (1LL * sum * MOD[i - 1] % mod);
   ret += int (1LL * x[i] * sum % mod);
   if (ret >= mod) ret -= mod; }
  return ret; } };
```

4.6 Polynomial operation

```
template <int MAXN = 1000000>
struct polynomial {
 ntt <MAXN> tr;
 /* inverse : finds a polynomial $b$ so that $a(x)b(x) \equiv 1 \mod x^n \mod mod$.
Note : $n$ must be a power of $2$. 2x max length. */
 void inverse (int *a, int *b, int n, int mod, int prt) {
  static int c[MAXN]; b[0] = ::inverse (a[0], mod); b[1] = 0;
  for (int m = 2, i; m <= n; m <<= 1) {
   std::copy (a, a + m, c);
   std::fill (b + m, b + m + m, 0); std::fill (c + m, c + m + m, 0);
   tr.solve (c, m + m, 0, mod, prt); tr.solve (b, m + m, 0, mod, prt);
   for (int i = 0; i < m + m; ++i) b[i] = 1LL * b[i] * (2 - 1LL * b[i] * c[i] % mod + mod) % mod;
   tr.solve (b, m + m, 1, mod, prt); std::fill (b + m, b + m + m, 0); } }
 /* sqrt : finds a polynomial $b$ so that $b^2(x) \equiv a(x) \mod x^n \mod mod$.
Note : $n \geq 2$ must be a power of $2$. 2x max length. */
 void sqrt (int *a, int *b, int n, int mod, int prt) {
  static int d[MAXN], ib[MAXN]; b[0] = 1; b[1] = 0;
  int i2 = ::inverse (2, mod), m, i;
  for (int m = 2; m <= n; m <<= 1) {
   std::copy (a, a + m, d);
   std::fill (d + m, d + m + m, 0); std::fill (b + m, b + m + m, 0);
   tr.solve (d, m + m, 0, mod, prt); inverse (b, ib, m, mod, prt);
   tr.solve (ib, m + m, 0, mod, prt); tr.solve (b, m + m, 0, mod, prt);
   for (int i = 0; i < m + m; ++i) b[i] = (1LL * b[i] * i2 + 1LL * i2 * d[i] % mod * ib[i]) % mod;
   tr.solve (b, m + m, 1, mod, prt); std::fill (b + m, b + m + m, 0); } }
 /* divide : given polynomial $a(x)$ and $b(x)$ with degree $n$ and $m$ respectively, finds $a(x) = d(x)b(x) + r(x)$ with $deg(d) \leq n - m$ and $deg(r) < m$. 4x max length required. */
```

```
void divide (int *a, int n, int *b, int m, int *d, int *r, int mod, int prt) {
 static int u[MAXN], v[MAXN]; while (!b[m - 1]) --m;
 int p = 1, t = n - m + 1; while (p < t << 1) p <<= 1;
 std::fill (u, u + p, 0); std::reverse_copy (b, b + m, u); inverse (u, v, p, mod, prt);
 std::fill (v + t, v + p, 0); tr.solve (v, p, 0, mod, prt); std::reverse_copy (a, a + n, u);
 std::fill (u + t, u + p, 0); tr.solve (u, p, 0, mod, prt);
 for (int i = 0; i < p; ++i) u[i] = 1LL * u[i] * v[i] % mod;
 tr.solve (u, p, 1, mod, prt); std::reverse (u, u + t); std::copy (u, u + t, d);
 for (p = 1; p < n; p <<= 1); std::fill (u + t, u + p, 0);
 tr.solve (u, p, 0, mod, prt); std::copy (b, b + m, v);
 std::fill (v + m, v + p, 0); tr.solve (v, p, 0, mod, prt);
 for (int i = 0; i < p; ++i) u[i] = 1LL * u[i] * v[i] % mod;
 tr.solve (u, p, 1, mod, prt);
 for (int i = 0; i < m; ++i) r[i] = (a[i] - u[i] + mod) % mod;
 std::fill (r + m, r + p, 0); } };
```

4.7 Chinese remainder theorem

```
/* Chinese remainder theroem : finds positive integers x = out.first + k * out.second that satisfies x % in[i].second = in[i].first. */
struct crt {
 long long fix (const long long &a, const long long &b) { return (a % b + b) % b; }
 bool solve (const std::vector <std::pair <long long, long long>> &in, std::pair <long long, long long> &out) {
  out = std::make_pair (1LL, 1LL);
  for (int i = 0; i < (int) in.size (); ++i) {
   long long n, u;
   euclid (out.second, in[i].second, n, u);
   long long divisor = std::__gcd (out.second, in[i].second);
   if ((in[i].first - out.first) % divisor) return false;
   n *= (in[i].first - out.first) / divisor;
   n = fix (n, in[i].second);
   out.first += out.second * n;
   out.second *= in[i].second / divisor;
   out.first = fix (out.first, out.second); }
  return true; } };
```

4.8 Linear Recurrence

```
/* Linear recurrence : finds the n-th element of a linear recurrence.
Usage : vector <int> - first n terms, vector <int> - transition function, calc (k) : the kth term mod MOD.
Example : In : {2, 1}, {2, 1} : $a_1 = 2, a_2 = 1, a_n = 2a_{n-1} + a_{n-2}$, Out : calc (3) = 5, calc (10007) = 959155122 (MOD 1E9+7) */
struct linear_rec {
 const int LOG = 30, MOD = 1E9 + 7; int n;
 std::vector <int> first, trans;
 std::vector <std::vector <int>> bin;
 std::vector <int> add (std::vector <int> &a, std::vector <int> &b) {
  std::vector <int> result(n * 2 + 1, 0);
  for (int i = 0; i <= n; ++i) for (int j = 0; j <= n; ++j)
   if ((result[i + j] += 1LL * a[i] * b[j] % MOD) >= MOD) result[i + j] -= MOD;
  for (int i = 2 * n; i > n; --i) {
   for (int j = 0; j < n; ++j)
    if ((result[i - 1 - j] += 1LL * result[i] * trans[j] % MOD) >= MOD) result[i - 1 - j] -= MOD;
   result[i] = 0; }
  result.erase(result.begin() + n + 1, result.end());
  return result; }
 linear_rec (const std::vector <int> &first, const std::vector <int> &trans) : first(first), trans(trans) {
   n = first.size(); std::vector <int> a(n + 1, 0); a[1] = 1; bin.push_back(a);
   for (int i = 1; i < LOG; ++i) bin.push_back(add(bin[i - 1], bin[i - 1])); }
 int solve (int k) {
  std::vector <int> a(n + 1, 0); a[0] = 1;
  for (int i = 0; i < LOG; ++i) if (k >> i & 1) a = add(a, bin[i]);
  int ret = 0;
  for (int i = 0; i < n; ++i) if ((ret += (long long) a[i + 1] * first[i] % MOD) >= MOD) ret -= MOD;
  return ret; } };
```

4.9 Berlekamp Massey algorithm

```
/* Berlekamp Massey algorithm : Complexity: O(n^2) Requirement: const MOD, inverse(int)
Input: the first elements of the sequence
Output: the recursive equation of the given sequence
Example In: {1, 1, 2, 3}
Example Out: {1, 1000000006, 1000000006} (MOD = 1e9+7) */
struct berlekamp-massey {
 struct Poly { std::vector <int> a; Poly() { a.clear(); }
  Poly (std::vector <int> &a) : a (a) {}
  int length () const { return a.size(); }
  Poly move (int d) { std::vector <int> na (d, 0);
   na.insert (na.end (), a.begin (), a.end ());
   return Poly (na); }
  int calc(std::vector <int> &d, int pos) { int ret = 0;
   for (int i = 0; i < (int) a.size (); ++i) {
    if ((ret += 1LL * d[pos - i] * a[i] % MOD) >= MOD) {
      ret -= MOD; } }
   return ret; }
  Poly operator - (const Poly &b) {
   std::vector <int> na (std::max (this -> length (), b.length ()));
   for (int i = 0; i < (int) na.size (); ++i) {
    int aa = i < this -> length () ? this -> a[i] : 0,
    bb = i < b.length () ? b.a[i] : 0;
    na[i] = (aa + MOD - bb) % MOD; }
   return Poly (na); } };
 Poly operator * (const int &c, const Poly &p) {
  std::vector <int> na (p.length ());
  for (int i = 0; i < (int) na.size (); ++i) {
   na[i] = 1LL * c * p.a[i] % MOD; }
  return na; }
 std::vector <int> solve(vector<int> a) {
  int n = a.size (); Poly s, b;
  s.a.push_back (1), b.a.push_back (1);
  for (int i = 0, j = -1, ld = 1; i < n; ++i) {
   int d = s.calc(a, i); if (d) {
    if ((s.length () - 1) * 2 <= i) {
     Poly ob = b; b = s;
     s = s - 1LL * d * inverse (ld) % MOD * ob.move (i - j);
     j = i; ld = d;
    } else {
     s = s - 1LL * d * inverse (ld) % MOD * b.move (i - j); } } }
  return s.a; } };
```

4.10 Baby step giant step algorithm

```
/* Baby step giant step algorithm : Solves $a^x = b \mod c$ in $O(\sqrt{c})$. */
struct bsgs {
 int solve (int a, int b, int c) {
  std::unordered_map <int, int> bs;
  int m = (int) sqrt ((double) c) + 1, res = 1;
  for (int i = 0; i < m; ++i) {
   if (bs.find (res) == bs.end ()) bs[res] = i;
   res = int (1LL * res * a % c); }
  int mul = 1, inv = (int) inverse (a, c);
  for (int i = 0; i < m; ++i) mul = int (1LL * mul * inv % c);
  res = b % c;
  for (int i = 0; i < m; ++i) {
   if (bs.find (res) != bs.end ()) return i * m + bs[res];
   res = int (1LL * res * mul % c); }
  return -1; } };
```

4.11 Pell equation

```
/* Pell equation : finds the smallest integer root of $x^2 - ny^2 = 1$ when $n$ is not a square number, with the solution set $x_{k+1} = x_0x_k + ny_0y_k, y_{k+1} = x_0y_k + y_0x_k$. */
template <int MAXN = 100000>
struct pell {
 std::pair <long long, long long> solve (long long n) {
  static long long p[MAXN], q[MAXN], g[MAXN], h[MAXN], a[MAXN];
  p[1] = q[0] = h[1] = 1; p[0] = q[1] = g[1] = 0;
  a[2] = (long long) (floor (sqrtl (n) + 1e-7L));
  for (int i = 2; ; ++i) {
   g[i] = -g[i - 1] + a[i] * h[i - 1];
   h[i] = (n - g[i] * g[i]) / h[i - 1];
   a[i + 1] = (g[i] + a[2]) / h[i];
   p[i] = a[i] * p[i - 1] + p[i - 2];
   q[i] = a[i] * q[i - 1] + q[i - 2];
   if (p[i] * p[i] - n * q[i] * q[i] == 1)
    return { p[i], q[i] }; } } };
```

4.12 Quadric residue

```
/* Quadric residue : finds solution for $x^2 = n \mod p (0 \le a < p)$ with prime $p$ in $O(\log p)$ complexity. */
struct quadric {
 void multiply(long long &c, long long &d, long long a, long long b, long long w, long long p) {
  int cc = (a * c + b * d % p * w) % p;
  int dd = (a * d + b * c) % p; c = cc, d = dd; }
 bool solve(int n, int p, int &x) {
  if (n == 0) return x = 0, true; if (p == 2) return x = 1, true;
  if (power (n, p / 2, p) == p - 1) return false;
  long long c = 1, d = 0, b = 1, a, w;
  do { a = rand() % p; w = (a * a - n + p) % p;
   if (w == 0) return x = a, true;
  } while (power (w, p / 2, p) != p - 1);
  for (int times = (p + 1) / 2; times; times >>= 1) {
   if (times & 1) multiply (c, d, a, b, w, p);
   multiply (a, b, a, b, w, p); }
  return x = c, true; } };
```

4.13 Miller Rabin primality test

```
/* Miller Rabin : tests whether a certain integer is prime. */
struct miller_rabin {
 int BASE[12] = {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37};
 bool check (const long long &p, const long long &b) {
  long long n = p - 1;
  for (; ~n & 1; n >>= 1);
  long long res = llfpm (b, n, p);
  for (; n != p - 1 && res != 1 && res != p - 1; n <<= 1)
   res = mul_mod (res, res, p);
  return res == p - 1 || (n & 1) == 1; }
 bool solve (const long long &n) {
  if (n < 2) return false;
  if (n < 4) return true;
  if (~n & 1) return false;
  for (int i = 0; i < 12 && BASE[i] < n; ++i) if (!check (n, BASE[i])) return false;
  return true; } };
```

4.14 Pollard's Rho algorithm

```
/* Pollard's Rho : factorizes an integer. */
struct pollard_rho {
 miller_rabin is_prime;
 const long long thr = 13E9;
 long long facize (const long long &n, const long long &seed) {
  long long x = rand () % (n - 1) + 1, y = x;
  for (int head = 1, tail = 2; ; ) {
   x = mul_mod (x, x, n);
   x = (x + seed) % n;
   if (x == y) return n;
   long long ans = std::__gcd (std::abs (x - y), n);
   if (ans > 1 && ans < n) return ans;
   if (++head == tail) { y = x; tail <<= 1; } } }
 void search (const long long &n, std::vector <long long> &div) {
  if (n > 1) {
   if (is_prime.solve (n)) div.push_back (n);
   else {
    long long fac = n;
    for (; fac >= n; fac = facize (n, rand () % (n - 1) + 1));
    search (n / fac, div); search (fac, div); } } }
 std::vector <long long> solve (const long long &n) {
  std::vector <long long> ans;
  if (n > thr) search (n, ans);
  else {
   long long rem = n;
   for (long long i = 2; i * i <= rem; ++i)
    while (!(rem % i)) { ans.push_back (i); rem /= i; }
   if (rem > 1) ans.push_back (rem); }
  return ans; } };
```

5 Geometry

```
#define cd const double &
const double EPS = 1E-8, PI = acos (-1);
int sgn (cd x) { return x < -EPS ? -1 : x > EPS; }
int cmp (cd x, cd y) { return sgn (x - y); }
double sqr (cd x) { return x * x; }
double msqrt (cd x) { return sgn (x) <= 0 ? 0 : sqrt (x); }
```

5.1 Point

```
#define cp const point &
struct point {
 double x, y;
 explicit point (cd x = 0, cd y = 0) : x (x), y (y) {}
 int dim () const { return sgn (y) == 0 ? sgn (x) > 0 : sgn (y) > 0; }
 point unit () const { double l = msqrt (x * x + y * y); return point (x / l, y / l); }
 //counter-clockwise
 point rot90 () const { return point (-y, x); }
 //clockwise
 point _rot90 () const { return point (y, -x); }
 point rot (cd t) const {
  double c = cos (t), s = sin (t);
  return point (x * c - y * s, x * s + y * c); } };
bool operator == (cp a, cp b) { return cmp (a.x, b.x) == 0 && cmp (a.y, b.y) == 0; }
bool operator != (cp a, cp b) { return cmp (a.x, b.x) != 0 || cmp (a.y, b.y) != 0; }
bool operator < (cp a, cp b) { return cmp (a.x, b.x) == 0 ? cmp (a.y, b.y) < 0 : cmp (a.x, b.x) < 0; }
point operator - (cp a) { return point (-a.x, -a.y); }
point operator + (cp a, cp b) { return point (a.x + b.x, a.y + b.y); }
point operator - (cp a, cp b) { return point (a.x - b.x, a.y - b.y); }
point operator * (cp a, cd b) { return point (a.x * b, a.y * b); }
point operator / (cp a, cd b) { return point (a.x / b, a.y / b); }
double dot (cp a, cp b) { return a.x * b.x + a.y * b.y; }
double det (cp a, cp b) { return a.x * b.y - a.y * b.x; }
double dis2 (cp a, cp b = point ()) { return sqr (a.x - b.x) + sqr (a.y - b.y); }
double dis (cp a, cp b = point ()) { return msqrt (dis2 (a, b)); }
```

5.2 Line

```
#define cl const line &
struct line {
 point s, t;
 explicit line (cp s = point (), cp t = point ()) : s (s), t (t) {} };
bool point_on_segment (cp a, cl b) { return sgn (det (a - b.s, b.t - b.s)) == 0 && sgn (dot (b.s - a, b.t - a)) <= 0; }
bool two_side (cp a, cp b, cl c) { return sgn (det (a - c.s, c.t - c.s)) * sgn (det (b - c.s, c.t - c.s)) < 0; }
bool intersect_judgment (cl a, cl b) {
 if (point_on_segment (b.s, a) || point_on_segment (b.t, a)) return true;
 if (point_on_segment (a.s, b) || point_on_segment (a.t, b)) return true;
 return two_side (a.s, a.t, b) && two_side (b.s, b.t, a); }
point line_intersect (cl a, cl b) {
 double s1 = det (a.t - a.s, b.s - a.s), s2 = det (a.t - a.s, b.t - a.s);
 return (b.s * s2 - b.t * s1) / (s2 - s1); }
double point_to_line (cp a, cl b) { return std::abs (det (b.t - b.s, a - b.s)) / dis (b.s, b.t); }
point project_to_line (cp a, cl b) { return b.s + (b.t - b.s) * (dot (a - b.s, b.t - b.s) / dis2 (b.t, b.s)); }
double point_to_segment (cp a, cl b) {
 if (sgn (dot (b.s - a, b.t - b.s) * dot (b.t - a, b.t - b.s)) <= 0) return std::abs (det (b.t - b.s, a - b.s)) / dis (b.s, b.t);
 return std::min (dis (a, b.s), dis (a, b.t)); }
bool in_polygon (cp p, const std::vector <point> & po) {
 int n = (int) po.size (), counter = 0;
 for (int i = 0; i < n; ++i) {
  point a = po[i], b = po[(i + 1) % n];
  //Modify the next line if necessary.
  if (point_on_segment (p, line (a, b))) return true;
  int x = sgn (det (p - a, b - a)), y = sgn (a.y - p.y), z = sgn (b.y - p.y);
  if (x > 0 && y <= 0 && z > 0) counter++;
  if (x < 0 && z <= 0 && y > 0) counter--; }
 return counter != 0; }
double polygon_area (const std::vector <point> &a) {
 double ans = 0.0;
 for (int i = 0; i < (int) a.size (); ++i) ans += det (a[i], a[(i + 1) % a.size ()]) / 2.0;
 return ans; }
```

5.3 Circle

```
#define cc const circle &
struct circle {
 point c; double r;
 explicit circle (point c = point (), double r = 0) : c (c), r (r) {} };
bool operator == (cc a, cc b) { return a.c == b.c && cmp (a.r, b.r) == 0; }
bool operator != (cc a, cc b) { return !(a == b); }
bool in_circle (cp a, cc b) { return cmp (dis (a, b.c), b.r) <= 0; }
circle make_circle (cp a, cp b) { return circle ((a + b) / 2, dis (a, b) / 2); }
circle make_circle (cp a, cp b, cp c) { point p = circumcenter (a, b, c); return circle (p, dis (p, a)); }
//In the order of the line vector.
std::vector <point> line_circle_intersect (cl a, cc b) {
 if (cmp (point_to_line (b.c, a), b.r) > 0) return std::vector <point> ();
 double x = msqrt (sqr (b.r) - sqr (point_to_line (b.c, a)));
 point s = project_to_line (b.c, a), u = (a.t - a.s).unit ();
 if (sgn (x) == 0) return std::vector <point> ({s});
 return std::vector <point> ({s - u * x, s + u * x}); }
double circle_intersect_area (cc a, cc b) {
 double d = dis (a.c, b.c);
 if (sgn (d - (a.r + b.r)) >= 0) return 0;
 if (sgn (d - abs(a.r - b.r)) <= 0) {
  double r = std::min (a.r, b.r); return r * r * PI; }
 double x = (d * d + a.r * a.r - b.r * b.r) / (2 * d), t1 = acos (min (1., max (-1., x / a.r))), t2 = acos (min (1., max (-1., (d - x) / b.r)));
 return a.r * a.r * t1 + b.r * b.r * t2 - d * a.r * sin (t1); }
//Counter-clockwise with respect of vector O_aO_b.
std::vector <point> circle_intersect (cc a, cc b) {
 if (a.c == b.c || cmp (dis (a.c, b.c), a.r + b.r) > 0 || cmp (dis (a.c, b.c), std::abs (a.r - b.r)) < 0) return std::vector <point> ();
 point r = (b.c - a.c).unit (); double d = dis (a.c, b.c);
 double x = ((sqr (a.r) - sqr (b.r)) / d + d) / 2, h = msqrt (sqr (a.r) - sqr (x));
 if (sgn (h) == 0) return std::vector <point> ({a.c + r * x});
 return std::vector <point> ({a.c + r * x - r.rot90 () * h, a.c + r * x + r.rot90 () * h}); }
//Counter-clockwise with respect of point a.
std::vector <point> tangent (cp a, cc b) { circle p = make_circle (a, b.c); return circle_intersect (p, b); }
//Counter-clockwise with respect of point O_a.
std::vector <line> extangent (cc a, cc b) {
 std::vector <line> ret;
 if (cmp (dis (a.c, b.c), std::abs (a.r - b.r)) <= 0) return ret;
```

```
 if (sgn (a.r - b.r) == 0) {
  point dir = b.c - a.c; dir = (dir * a.r / dis (dir)).rot90 ();
  ret.push_back (line (a.c - dir, b.c - dir));
  ret.push_back (line (a.c + dir, b.c + dir));
 } else {
  point p = (b.c * a.r - a.c * b.r) / (a.r - b.r);
  std::vector <point> pp = tangent (p, a), qq = tangent (p, b);
  if (pp.size () == 2 && qq.size () == 2) {
   if (cmp (a.r, b.r) < 0) std::swap (pp[0], pp[1]), std::swap (qq[0], qq[1]);
   ret.push_back (line (pp[0], qq[0]));
   ret.push_back (line (pp[1], qq[1])); } }
 return ret; }
//Counter-clockwise with respect of point O_a.
std::vector <line> intangent (cc c1, cc c2) {
 std::vector <line> ret;
 point p = (b.c * a.r + a.c * b.r) / (a.r + b.r);
 std::vector <point> pp = tangent (p, a), qq = tangent (p, b);
 if (pp.size () == 2 && qq.size () == 2) {
  ret.push_back (line (pp[0], qq[0]));
  ret.push_back (line (pp[1], qq[1])); }
 return ret; }
```

5.4 Centers of a triangle

```
point incenter (cp a, cp b, cp c) {
 double p = dis (a, b) + dis (b, c) + dis (c, a);
 return (a * dis (b, c) + b * dis (c, a) + c * dis (a, b)) / p; }
point circumcenter (cp a, cp b, cp c) {
 point p = b - a, q = c - a, s (dot (p, p) / 2, dot (q, q) / 2);
 return a + point (det (s, point (p.y, q.y)), det (point (p.x, q.x), s)) / det (p, q); }
point orthocenter (cp a, cp b, cp c) { return a + b + c - circumcenter (a, b, c) * 2; }
```

5.5 Fermat point

```
/* Fermat point : finds a point P that minimizes |PA| + |PB| + |PC|. */
point fermat_point (cp a, cp b, cp c) {
 if (a == b) return a; if (b == c) return b; if (c == a) return c;
 double ab = dis (a, b), bc = dis (b, c), ca = dis (c, a);
 double cosa = dot (b - a, c - a) / ab / ca;
 double cosb = dot (a - b, c - b) / ab / bc;
 double cosc = dot (b - c, a - c) / ca / bc;
 double sq3 = PI / 3.0; point mid;
 if (sgn (cosa + 0.5) < 0) mid = a;
 else if (sgn (cosb + 0.5) < 0) mid = b;
 else if (sgn (cosc + 0.5) < 0) mid = c;
 else if (sgn (det (b - a, c - a)) < 0) mid = line_intersect (line (a, b + (c - b).rot (sq3)), line (b, c + (a - c).rot (sq3)));
 else mid = line_intersect (line (a, c + (b - c).rot (sq3)), line (c, b + (a - b).rot (sq3)));
 return mid; }
```

5.6 Convex hull

```
//Counter-clockwise, with minimum number of points.
bool turn_left (cp a, cp b, cp c) { return sgn (det (b - a, c - a)) >= 0; }
std::vector <point> convex_hull (std::vector <point> a) {
 int cnt = 0; std::sort (a.begin (), a.end ());
 static std::vector <point> ret; ret.resize (a.size () << 1);
 for (int i = 0; i < (int) a.size (); ++i) {
  while (cnt > 1 && turn_left (ret[cnt - 2], a[i], ret[cnt - 1])) --cnt;
  ret[cnt++] = a[i]; }
 int fixed = cnt;
 for (int i = (int) a.size () - 1; i >= 0; --i) {
  while (cnt > fixed && turn_left (ret[cnt - 2], a[i], ret[cnt - 1])) --cnt;
  ret[cnt++] = a[i]; }
 return std::vector <point> (ret.begin (), ret.begin () + cnt - 1); }
```

5.7 Half plane intersection

```
/* Online half plane intersection : complexity O(n) each operation. */
std::vector <point> cut (const std::vector<point> &c, line p) {
 std::vector <point> ret;
 if (c.empty ()) return ret;
 for (int i = 0; i < (int) c.size (); ++i) {
  int j = (i + 1) % (int) c.size ();
  if (turn_left (p.s, p.t, c[i])) ret.push_back (c[i]);
  if (two_side (c[i], c[j], p)) ret.push_back (line_intersect (p, line (c[i], c[j]))); }
 return ret; }
/* Offline half plane intersection : complexity O(n log n). */
bool turn_left (cl l, cp p) { return turn_left (l.s, l.t, p); }
int cmp (cp a, cp b) { return a.dim () != b.dim () ? (a.dim () < b.dim () ? -1 : 1) : -sgn (det (a, b)); }
std::vector <point> half_plane_intersect (std::vector <line> h) {
 typedef std::pair <point, line> polar;
 std::vector <polar> g; g.resize (h.size ());
 for (int i = 0; i < (int) h.size (); ++i) g[i] = std::make_pair (h[i].t - h[i].s, h[i]);
 sort (g.begin (), g.end (), [&] (const polar &a, const polar &b) {
  if (cmp (a.first, b.first) == 0) return sgn (det (a.second.t - a.second.s, b.second.t - a.second.s)) < 0;
  else return cmp (a.first, b.first) < 0; });
 h.resize (std::unique (g.begin (), g.end (), [] (const polar &a, const polar &b) { return cmp (a.first, b.first) == 0 }) - g.begin ());
 for (int i = 0; i < (int) h.size (); ++i) h[i] = g[i].second;
 int fore = 0, rear = -1; std::vector <line> ret (h.size (), line ());
 for (int i = 0; i < (int) h.size (); ++i) {
  while (fore < rear && !turn_left (h[i], line_intersect (ret[rear - 1], ret[rear]))) --rear;
  while (fore < rear && !turn_left (h[i], line_intersect (ret[fore], ret[fore + 1]))) ++fore;
  ret[++rear] = h[i]; }
 while (rear - fore > 1 && !turn_left (ret[fore], line_intersect (ret[rear - 1], ret[rear]))) --rear;
 while (rear - fore > 1 && !turn_left (ret[rear], line_intersect (ret[fore], ret[fore + 1]))) ++fore;
 if (rear - fore < 2) return std::vector <point> ();
 std::vector <point> ans; ans.resize (rear + 1);
 for (int i = 0; i < rear + 1; ++i) ans[i] = line_intersect (ret[i], ret[(i + 1) % (rear + 1)]);
 return ans; }
```

5.8 Nearest pair of points

```
/* Nearest pair of points : [l, r), need to sort p first. */
double solve (std::vector <point> &p, int l, int r) {
 if (l + 1 >= r) return INF;
 int m = (l + r) / 2; double mx = p[m].x; std::vector <point> v;
 double ret = std::min (solve(p, l, m), solve(p, m, r));
 for (int i = l; i < r; ++i)
  if (sqr (p[i].x - mx) < ret) v.push_back (p[i]);
 sort (v.begin (), v.end (), [&] (cp a, cp b) { return a.y < b.y; } );
 for (int i = 0; i < v.size (); ++i)
  for (int j = i + 1; j < v.size (); ++j) {
   if (sqr (v[i].y - v[j].y) > ret) break;
   ret = min (ret, dis2 (v[i] - v[j])); }
 return ret; }
```

5.9 Minimum circle

```
circle minimum_circle (std::vector <point> p) {
 circle ret; std::random_shuffle (p.begin (), p.end ());
 for (int i = 0; i < (int) p.size (); ++i) if (!in_circle (p[i], ret)) {
  ret = circle (p[i], 0); for (int j = 0; j < i; ++j)
   if (!in_circle (p[j], ret)) {
    ret = make_circle (p[j], p[i]); for (int k = 0; k < j; ++k)
     if (!in_circle (p[k], ret)) ret = make_circle (p[i], p[j], p[k]); } }
 return ret; }
```

5.10 Intersection of a polygon and a circle

```
struct polygon_circle_intersect {
 double sector_area (cp a, cp b, const double &r) {
  double c = (2.0 * r * r - dis2 (a, b)) / (2.0 * r * r);
  return r * r * acos (c) / 2.0; }
 double area (cp a, cp b, const double &r) {
  double dA = dot (a, a), dB = dot (b, b), dC = point_to_segment (point (), line (a, b));
  if (sgn (dA - r * r) <= 0 && sgn (dB - r * r) <= 0) return det (a, b) / 2.0;
  point tA = a.unit () * r, tB = b.unit () * r;
  if (sgn (dC - r) > 0) return sector_area (tA, tB, r);
  std::vector <point> ret = line_circle_intersect (line (a, b), circle (point (), r));
  if (sgn (dA - r * r) > 0 && sgn (dB - r * r) > 0)
   return sector_area (tA, ret[0], r) + det (ret[0], ret[1]) / 2.0 + sector_area (ret[1], tB, r);
  if (sgn (dA - r * r) > 0) return det (ret[0], b) / 2.0 + sector_area (tA, ret[0], r);
  else return det (a, ret[1]) / 2.0 + sector_area (ret[1], tB, r); }
 double solve (const std::vector <point> &p, cc c) {
  double ret = 0.0;
  for (int i = 0; i < (int) p.size (); ++i) {
   int s = sgn (det (p[i] - c.c, p[(i + 1) % p.size ()] - c.c));
   if (s > 0) ret += area (p[i] - c.c, p[(i + 1) % p.size ()] - c.c, c.r);
   else ret -= area (p[(i + 1) % p.size ()] - c.c, p[i] - c.c, c.r); }
  return std::abs (ret); } };
```

5.11 Union of circles

```
template <int MAXN = 500> struct union_circle {
 int C; circle c[MAXN]; double area[MAXN];
 struct event {
  point p; double ang; int delta;
  event (cp p = point (), double ang = 0, int delta = 0) : p(p), ang(ang), delta(delta) {}
  bool operator < (const event &a) { return ang < a.ang; }
 };
 void addevent(cc a, cc b, std::vector <event> &evt, int &cnt) {
  double d2 = dis2 (a.c, b.c), d_ratio = ((a.r - b.r) * (a.r + b.r) / d2 + 1) / 2,
   p_ratio = msqrt (std::max (0., -(d2 - sqr(a.r - b.r)) * (d2 - sqr(a.r + b.r)) / (d2 * d2 * 4)));
  point d = b.c - a.c, p = d.rot(PI / 2), q0 = a.c + d * d_ratio + p * p_ratio, q1 = a.c + d * d_ratio - p * p_ratio;
  double ang0 = atan2 ((q0 - a.c).y, (q0 - a.c).x), ang1 = atan2 ((q1 - a.c).x, (q1 - a.c).y);
  evt.emplace_back(q1, ang1, 1); evt.emplace_back(q0, ang0, -1); cnt += ang1 > ang0; }
 bool same(cc a, cc b) { return sgn (dis (a.c, b.c)) == 0 && sgn (a.r - b.r) == 0; }
 bool overlap(cc a, cc b) { return sgn (a.r - b.r - dis (a.c, b.c)) >= 0; }
 bool intersect(cc a, cc b) { return sgn (dis (a.c, b.c) - a.r - b.r) < 0; }
 void solve() {
  std::fill (area, area + C + 2, 0);
  for (int i = 0; i < C; ++i) {
   int cnt = 1; std::vector <event> evt;
   for (int j = 0; j < i; ++j) if (same (c[i], c[j])) ++cnt;
   for (int j = 0; j < C; ++j) if (j != i && !same (c[i], c[j]) && overlap (c[j], c[i])) ++cnt;
   for (int j = 0; j < C; ++j) if (j != i && !overlap (c[j], c[i]) && !overlap (c[i], c[j]) && intersect (c[i], c[j]))
    addevent (c[i], c[j], evt, cnt);
   if (evt.empty ()) area[cnt] += PI * c[i].r * c[i].r;
   else {
    std::sort (evt.begin (), evt.end ());
    evt.push_back (evt.front ());
    for (int j = 0; j + 1 < (int) evt.size (); ++j) {
     cnt += evt[j].delta; area[cnt] += det(evt[j].p, evt[j + 1].p) / 2;
     double ang = evt[j + 1].ang - evt[j].ang; if (ang < 0) ang += PI * 2;
     area[cnt] += ang * c[i].r * c[i].r / 2 - sin(ang) * c[i].r * c[i].r / 2; } } } } };
```

5.12 3D point

```
#define cp3 const point3 &
struct point3 {
 double x, y, z;
 explicit point3 (cd x = 0, cd y = 0, cd z = 0) : x (x), y (y), z (z) {} };
point3 operator + (cp3 a, cp3 b) { return point3 (a.x + b.x, a.y + b.y, a.z + b.z); }
point3 operator - (cp3 a, cp3 b) { return point3 (a.x - b.x, a.y - b.y, a.z - b.z); }
point3 operator * (cp3 a, cd b) { return point3 (a.x * b, a.y * b, a.z * b); }
point3 operator / (cp3 a, cd b) { return point3 (a.x / b, a.y / b, a.z / b); }
double dot (cp3 a, cp3 b) { return a.x * b.x + a.y * b.y + a.z * b.z; }
point3 det (cp3 a, cp3 b) { return point3 (a.y * b.z - a.z * b.y, -a.x * b.z + a.z * b.x, a.x * b.y - a.y * b.x); }
double dis2 (cp3 a, cp3 b = point3 ()) { return sqr (a.x - b.x) + sqr (a.y - b.y) + sqr (a.z - b.z); }
double dis (cp3 a, cp3 b = point3 ()) { return msqrt (dis2 (a, b)); }
//right-handed, if x+ -> y+ is right-handed
point3 rotate(cp3 p, cp3 axis, double w) {
 double x = axis.x, y = axis.y, z = axis.z;
 double s = x * x + y * y + z * z, ss = msqrt(s), cosw = cos(w), sinw = sin(w);
 double a[4][4]; memset(a, 0, sizeof (a));
 a[3][3] = 1;
 a[0][0] = ((y * y + z * z) * cosw + x * x) / s;
 a[0][1] = x * y * (1 - cosw) / s + z * sinw / ss;
 a[0][2] = x * z * (1 - cosw) / s - y * sinw / ss;
 a[1][0] = x * y * (1 - cosw) / s - z * sinw / ss;
 a[1][1] = ((x * x + z * z) * cosw + y * y) / s;
 a[1][2] = y * z * (1 - cosw) / s + x * sinw / ss;
 a[2][0] = x * z * (1 - cosw) / s + y * sinw / ss;
 a[2][1] = y * z * (1 - cosw) / s - x * sinw / ss;
 a[2][2] = ((x * x + y * y) * cos(w) + z * z) / s;
 double ans[4] = {0, 0, 0, 0}, c[4] = {p.x, p.y, p.z, 1};
 for (int i = 0; i < 4; ++i) for (int j = 0; j < 4; ++j)
  ans[i] += a[j][i] * c[j];
 return point3 (ans[0], ans[1], ans[2]);
}
```

5.13 3D line

```
#define cl3 const line3 &
struct line3 {
 point3 s, t;
 explicit line3 (cp3 s = point3 (), cp3 t = point3 ()) : s (s), t (t) {} };
point3 line_plane_intersection (cl3 a, cl3 b) { return a.s + (a.t - a.s) * dot (b.s - a.s, b.t - b.s) / dot (a.t - a.s, b.t - b.s); }
line3 plane_intersection (cl3 a, cl3 b) {
 point3 p = det (a.t - a.s, b.t - b.s), q = det (a.t - a.s, p), s = line_plane_intersection (line3 (a.s, a.s + q), b);
 return line3 (s, s + p); }
point3 project_to_plane (cp3 a, cl3 b) { return a + (b.t - b.s) * dot (b.t - b.s, b.s - a) / dis2 (b.t - b.s); }
```

5.14 3D convex hull

```
/* 3D convex hull : initializes n and p / outputs face */
template <int MAXN = 500>
struct convex_hull3 {
 double mix (cp3 a, cp3 b, cp3 c) { return dot (det (a, b), c); }
 double volume (cp3 a, cp3 b, cp3 c, cp3 d) { return mix (b - a, c - a, d - a); }
 struct tri {
  int a, b, c;
  tri() {}
  tri(int _a, int _b, int _c): a(_a), b(_b), c(_c) {}
  double area() const { return dis (det (p[b] - p[a], p[c] - p[a])) / 2; }
  point3 normal() const { return det (p[b] - p[a], p[c] - p[a]).unit (); }
  double dis (cp3 p0) const { return dot (normal (), p0 - p[a]); } };
 int n; std::vector <point3> p;
 std::vector <tri> face, tmp;
 int mark[MAXN][MAXN], time;
 void add (int v) {
  ++time; tmp.clear ();
  for (int i = 0; i < (int) face.size (); ++i) {
   int a = face[i].a, b = face[i].b, c = face[i].c;
   if (sgn (volume (p[v], p[a], p[b], p[c])) > 0)
    mark[a][b] = mark[b][a] = mark[a][c] = mark[c][a] = mark[b][c] = mark[c][b] = time;
   else tmp.push_back (face[i]); }
  face.clear (); face = tmp;
  for (int i = 0; i < (int) tmp.size (); ++i) {
   int a = face[i].a, b = face[i].b, c = face[i].c;
   if (mark[a][b] == time) face.emplace_back (v, b, a);
   if (mark[b][c] == time) face.emplace_back (v, c, b);
   if (mark[c][a] == time) face.emplace_back (v, a, c); } }
 void reorder () {
  for (int i = 2; i < n; ++i) {
   point3 tmp = det (p[i] - p[0], p[i] - p[1]);
   if (sgn (dis (tmp))) {
    std::swap (p[i], p[2]);
    for (int j = 3; j < n; ++ j)
     if (sgn (volume (p[0], p[1], p[2], p[j]))) {
      std::swap (p[j], p[3]); return; } } } }
 void build_convex () {
  reorder (); face.clear ();
  face.emplace_back (0, 1, 2);
  face.emplace_back (0, 2, 1);
  for (int i = 3; i < n; ++i) add(i); } };
```

6 Graph

```
template <int MAXN = 100000, int MAXM = 100000>
struct edge_list {
 int size, begin[MAXN], dest[MAXM], next[MAXM];
 void clear (int n) { size = 0; std::fill (begin, begin + n, -1); }
 edge_list (int n = MAXN) { clear (n); }
 void add_edge (int u, int v) { dest[size] = v; next[size] = begin[u]; begin[u] = size++; } };
template <int MAXN = 100000, int MAXM = 100000>
struct cost_edge_list {
 int size, begin[MAXN], dest[MAXM], next[MAXM], cost[MAXM];
 void clear (int n) { size = 0; std::fill (begin, begin + n, -1); }
 cost_edge_list (int n = MAXN) { clear (n); }
 void add_edge (int u, int v, int c) { dest[size] = v; next[size] = begin[u]; cost[size] = c; begin[u] = size++; } };
```

6.1 Hopcoft-Karp algorithm

```
/* Hopcoft-Karp algorithm : unweighted maximum matching for bipartition graphs with complexity O(m√n). */
template <int MAXN = 100000, int MAXM = 100000>
struct hopcoft_karp {
 int mx[MAXN], my[MAXM], lv[MAXN];
 bool dfs (edge_list <MAXN, MAXM> &e, int x) {
  for (int i = e.begin[x]; ~i; i = e.next[i]) {
   int y = e.dest[i], w = my[y];
   if (!~w || (lv[x] + 1 == lv[w] && dfs (e, w))) {
    mx[x] = y; my[y] = x; return true; } }
  lv[x] = -1; return false; }
 int solve (edge_list <MAXN, MAXM> &e, int n, int m) {
  std::fill (mx, mx + n, -1); std::fill (my, my + m, -1);
  for (int ans = 0; ; ) {
   std::vector <int> q;
   for (int i = 0; i < n; ++i)
    if (mx[i] == -1) {
     lv[i] = 0; q.push_back (i);
    } else lv[i] = -1;
   for (int head = 0; head < (int) q.size(); ++head) {
    int x = q[head];
    for (int i = e.begin[x]; ~i; i = e.next[i]) {
     int y = e.dest[i], w = my[y];
```

```
   if (~w && lv[w] < 0) { lv[w] = lv[x] + 1; q.push_back (w); } } }
  int d = 0; for (int i = 0; i < n; ++i) if (!~mx[i] && dfs (e, i)) ++d;
  if (d == 0) return ans; else ans += d; } } };
```

6.2 Kuhn-Munkres algorithm

```
/* Kuhn Munkres algorithm : weighted maximum matching on bipartition graphs.
Note : the graph is 1-based. */
template <int MAXN = 500>
struct kuhn_munkres {
 int n, w[MAXN][MAXN], lx[MAXN], ly[MAXN], m[MAXN], way[MAXN], sl[MAXN];
 bool u[MAXN];
 void hungary(int x) {
  m[0] = x;  int j0 = 0;
  std::fill (sl, sl + n + 1, INF); std::fill (u, u + n + 1, false);
  do {
   u[j0] = true; int i0 = m[j0], d = INF, j1 = 0;
   for (int j = 1; j <= n; ++j)
    if (u[j] == false) {
     int cur = -w[i0][j] - lx[i0] - ly[j];
     if (cur < sl[j]) { sl[j] = cur; way[j] = j0; }
     if (sl[j] < d) { d = sl[j]; j1 = j; } }
   for (int j = 0; j <= n; ++j) {
    if (u[j]) { lx[m[j]] += d; ly[j] -= d; }
    else sl[j] -= d; }
   j0 = j1; } while (m[j0] != 0);
  do {
   int j1 = way[j0]; m[j0] = m[j1]; j0 = j1;
  } while (j0); }
 int solve() {
  for (int i = 1; i <= n; ++i) m[i] = lx[i] = ly[i] = way[i] = 0;
  for (int i = 1; i <= n; ++i) hungary (i);
  int sum = 0; for (int i = 1; i <= n; ++i) sum += w[m[i]][i];
  return sum; } };
```

6.3 Blossom algorithm

```
/* Blossom algorithm : maximum match for general graph. */
template <int MAXN = 500, int MAXM = 250000>
struct blossom {
 int match[MAXN], d[MAXN], fa[MAXN], c1[MAXN], c2[MAXN], v[MAXN], q[MAXN];
 int *qhead, *qtail;
 struct {
  int fa[MAXN];
  void init (int n) { for(int i = 1; i <= n; i++) fa[i] = i; }
  int find (int x) { if (fa[x] != x) fa[x] = find (fa[x]); return fa[x]; }
  void merge (int x, int y) { x = find (x); y = find (y); fa[x] = y; } } ufs;
 void solve (int x, int y) {
  if (x == y) return;
  if (d[y] == 0) {
   solve (x, fa[fa[y]]); match[fa[y]] = fa[fa[y]];
   match[fa[fa[y]]] = fa[y];
  } else if (d[y] == 1) {
   solve (match[y], c1[y]); solve (x, c2[y]);
   match[c1[y]] = c2[y]; match[c2[y]] = c1[y]; } }
 int lca (int x, int y, int root) {
  x = ufs.find (x); y = ufs.find (y);
  while (x != y && v[x] != 1 && v[y] != 0) {
   v[x] = 0; v[y] = 1;
   if (x != root) x = ufs.find (fa[x]);
   if (y != root) y = ufs.find (fa[y]); }
  if (v[y] == 0) std::swap (x, y);
  for (int i = x; i != y; i = ufs.find (fa[i])) v[i] = -1;
  v[y] = -1; return x; }
 void contract (int x, int y, int b) {
  for (int i = ufs.find (x); i != b; i = ufs.find (fa[i])) {
   ufs.merge (i, b);
   if (d[i] == 1) { c1[i] = x; c2[i] = y; *qtail++ = i; } } }
 bool bfs (int root, int n, const edge_list <MAXN, MAXM> &e) {
  ufs.init (n); std::fill (d, d + MAXN, -1); std::fill (v, v + MAXN, -1);
  qhead = qtail = q; d[root] = 0; *qtail++ = root;
  while (qhead < qtail) {
   for (int loc = *qhead++, i = e.begin[loc]; ~i; i = e.next[i]) {
     int dest = e.dest[i];
     if (match[dest] == -2 || ufs.find (loc) == ufs.find (dest)) continue;
     if (d[dest] == -1)
      if (match[dest] == -1) {
       solve (root, loc); match[loc] = dest;
       match[dest] = loc; return 1;
      } else {
       fa[dest] = loc; fa[match[dest]] = dest;
       d[dest] = 1; d[match[dest]] = 0;
       *qtail++ = match[dest];
      } else if (d[ufs.find (dest)] == 0) {
       int b = lca (loc, dest, root);
       contract (loc, dest, b); contract (dest, loc, b); } } }
  return 0; }
 int solve (int n, const edge_list <MAXN, MAXM> &e) {
  std::fill (fa, fa + n, 0); std::fill (c1, c1 + n, 0);
  std::fill (c2, c2 + n, 0); std::fill (match, match + n, -1);
  int re = 0; for (int i = 0; i < n; i++)
   if (match[i] == -1) if (bfs (i, n, e)) ++re; else match[i] = -2;
  return re; } };
```

6.4 Weighted blossom algorithm

```
/* Weighted blossom algorithm (vfleaking ver.) : maximum matching for general weighted graphs with complexity O(n^3).
Usage : Set n to the size of the vertices. Run init (). Set g[][].w to the weight of the edge. Run solve ().
The first result is the answer, the second one is the number of matching pairs. Obtain the matching with match[].
Note : 1-based. */
struct weighted_blossom {
 static const int INF = INT_MAX, MAXN = 400;
 struct edge{ int u, v, w; edge (int u = 0, int v = 0, int w = 0): u(u), v(v), w(w) {} };
 int n, n_x;
 edge g[MAXN * 2 + 1][MAXN * 2 + 1];
 int lab[MAXN * 2 + 1], match[MAXN * 2 + 1], slack[MAXN * 2 + 1], st[MAXN * 2 + 1], pa[MAXN * 2 + 1];
 int flower_from[MAXN * 2 + 1][MAXN + 1], S[MAXN * 2 + 1], vis[MAXN * 2 + 1];
 std::vector <int> flower[MAXN * 2 + 1]; std::queue <int> q;
 int e_delta (const edge &e) { return lab[e.u] + lab[e.v] - g[e.u][e.v].w * 2; }
 void update_slack (int u, int x) { if (!slack[x] || e_delta (g[u][x]) < e_delta (g[slack[x]][x])) slack[x] = u; }
 void set_slack (int x) { slack[x] = 0; for (int u = 1; u <= n; ++u) if(g[u][x].w > 0 && st[u] != x && S[st[u]] == 0)
  update_slack(u, x); }
 void q_push (int x) {
  if (x <= n) q.push (x);
  else for (size_t i = 0; i < flower[x].size (); i++) q_push (flower[x][i]); }
 void set_st (int x, int b) {
  st[x] = b; if (x > n) for (size_t i = 0; i < flower[x].size (); ++i) set_st (flower[x][i], b); }
 int get_pr (int b, int xr){
  int pr = std::find (flower[b].begin (), flower[b].end (), xr) - flower[b].begin ();
  if (pr % 2 == 1) { std::reverse (flower[b].begin () + 1, flower[b].end ()); return (int) flower[b].size () - pr;
  } else return pr; }
 void set_match (int u, int v){
  match[u] = g[u][v].v; if (u > n) {
   edge e = g[u][v]; int xr = flower_from[u][e.u], pr = get_pr (u, xr);
   for (int i = 0; i < pr; ++i) set_match (flower[u][i], flower[u][i ^ 1]);
   set_match (xr, v); std::rotate (flower[u].begin (), flower[u].begin () + pr, flower[u].end ()); } }
 void augment (int u, int v) {
  for (; ; ) {
   int xnv = st[match[u]]; set_match (u, v);
   if (!xnv) return; set_match (xnv, st[pa[xnv]]);
   u = st[pa[xnv]], v = xnv; } }
 int get_lca (int u, int v){
  static int t = 0;
  for (++t; u || v; std::swap (u, v)) {
   if (u == 0) continue; if (vis[u] == t) return u;
   vis[u] = t; u = st[match[u]]; if (u) u = st[pa[u]]; }
  return 0; }
 void add_blossom (int u, int lca, int v) {
  int b = n + 1; while (b <= n_x && st[b]) ++b;
  if (b > n_x) ++n_x;
  lab[b] = 0, S[b] = 0;
  match[b] = match[lca]; flower[b].clear ();
  flower[b].push_back (lca);
  for (int x = u, y; x != lca; x = st[pa[y]]) {
   flower[b].push_back (x), flower[b].push_back (y = st[match[x]]), q_push (y); }
  std::reverse (flower[b].begin () + 1, flower[b].end ());
  for (int x = v, y; x != lca; x = st[pa[y]]) {
   flower[b].push_back (x), flower[b].push_back (y = st[match[x]]), q_push(y); }
  set_st (b, b);
  for (int x = 1; x <= n_x; ++x) g[b][x].w = g[x][b].w = 0;
  for (int x = 1; x <= n; ++x) flower_from[b][x] = 0;
  for (size_t i = 0; i < flower[b].size (); ++i){
   int xs = flower[b][i];
   for (int x = 1; x <= n_x; ++x) if (g[b][x].w == 0 || e_delta(g[xs][x]) < e_delta(g[b][x]))
    g[b][x] = g[xs][x], g[x][b] = g[x][xs];
   for (int x = 1;x <= n; ++x) if(flower_from[xs][x]) flower_from[b][x] = xs; }
  set_slack (b); }
 void expand_blossom (int b) {
  for (size_t i = 0; i < flower[b].size (); ++i) set_st (flower[b][i], flower[b][i]);
  int xr = flower_from[b][g[b][pa[b]].u], pr = get_pr(b, xr);
  for (int i = 0; i < pr; i += 2) {
   int xs = flower[b][i], xns = flower[b][i + 1];
   pa[xs] = g[xns][xs].u; S[xs] = 1, S[xns] = 0;
   slack[xs] = 0, set_slack(xns); q_push(xns); }
  S[xr] = 1, pa[xr] = pa[b];
  for (size_t i = pr + 1; i < flower[b].size (); ++i) {
   int xs = flower[b][i]; S[xs] = -1, set_slack(xs); }
```

```
  st[b] = 0; }
 bool on_found_edge (const edge &e) {
  int u = st[e.u], v = st[e.v];
  if (S[v] == -1) {
   pa[v] = e.u, S[v] = 1; int nu = st[match[v]];
   slack[v] = slack[nu] = 0; S[nu] = 0, q_push(nu);
  } else if(S[v] == 0) {
   int lca = get_lca(u, v);
   if (!lca) return augment(u, v), augment(v, u), true;
   else add_blossom(u, lca, v); }
  return false; }
 bool matching () {
  memset (S + 1, -1, sizeof (int) * n_x);
  memset (slack + 1, 0, sizeof (int) * n_x);
  q = std::queue <int> ();
  for (int x = 1; x <= n_x; ++x) if (st[x] == x && !match[x]) pa[x] = 0, S[x] = 0, q_push (x);
  if (q.empty ()) return false;
  for (; ; ) {
   while (q.size ()) {
    int u = q.front (); q.pop ();
    if (S[st[u]] == 1) continue;
    for (int v = 1; v <= n; ++v) if (g[u][v].w > 0 && st[u] != st[v]) {
     if(e_delta (g[u][v]) == 0){
      if (on_found_edge (g[u][v])) return true;
     } else update_slack (u, st[v]); } }
   int d = INF;
   for (int b = n + 1; b <= n_x; ++b) if(st[b] == b && S[b] == 1) d = std::min (d, lab[b] / 2);
   for (int x = 1; x <= n_x; ++x) if(st[x] == x && slack[x]) {
    if (S[x] == -1) d = std::min (d, e_delta (g[slack[x]][x]));
    else if (S[x] == 0) d = std::min (d, e_delta (g[slack[x]][x]) / 2); }
   for (int u = 1; u <= n; ++u) {
    if (S[st[u]] == 0){
     if(lab[u] <= d) return 0;
     lab[u] -= d;
    } else if (S[st[u]] == 1) lab[u] += d; }
   for (int b = n + 1; b <= n_x; ++b)
    if (st[b] == b) {
     if (S[st[b]] == 0) lab[b] += d * 2;
     else if (S[st[b]] == 1) lab[b] -= d * 2; }
   q = std::queue <int> ();
   for (int x = 1; x <= n_x; ++x)
    if (st[x] == x && slack[x] && st[slack[x]] != x && e_delta(g[slack[x]][x]) == 0)
     if(on_found_edge (g[slack[x]][x]))return true;
   for (int b = n + 1; b <= n_x; ++b) if (st[b] == b && S[b] == 1 && lab[b] == 0) expand_blossom(b); }
  return false; }
 std::pair <long long, int> solve () {
  memset (match + 1, 0, sizeof (int) * n); n_x = n;
  int n_matches = 0; long long tot_weight = 0;
  for (int u = 0; u <= n; ++u) st[u] = u, flower[u].clear();
  int w_max = 0;
  for (int u = 1; u <= n; ++u) for (int v = 1; v <= n; ++v) {
   flower_from[u][v] = (u == v ? u : 0); w_max = std::max (w_max, g[u][v].w); }
  for (int u = 1; u <= n; ++u) lab[u] = w_max;
  while (matching ()) ++n_matches;
  for (int u = 1; u <= n; ++u) if (match[u] && match[u] < u) tot_weight += g[u][match[u]].w;
  return std::make_pair (tot_weight, n_matches); }
 void init () { for (int u = 1; u <= n; ++u) for (int v = 1; v <= n; ++v) g[u][v] = edge (u, v, 0); }
};
```

6.5 Maximum flow

```
/* Sparse graph maximum flow : isap.*/
template <int MAXN = 1000, int MAXM = 100000>
struct isap {
 struct flow_edge_list {
  int size, begin[MAXN], dest[MAXM], next[MAXM], flow[MAXM];
  void clear (int n) { size = 0; std::fill (begin, begin + n, -1); }
  flow_edge_list (int n = MAXN) { clear (n); }
  void add_edge (int u, int v, int f) {
   dest[size] = v; next[size] = begin[u]; flow[size] = f; begin[u] = size++;
   dest[size] = u; next[size] = begin[v]; flow[size] = 0; begin[v] = size++; } };
 int pre[MAXN], d[MAXN], gap[MAXN], cur[MAXN], que[MAXN], vis[MAXN];
 int solve (flow_edge_list &e, int n, int s, int t) {
  for (int i = 0; i < n; ++i) { pre[i] = d[i] = gap[i] = vis[i] = 0; cur[i] = e.begin[i]; }
  int l = 0, r = 0; que[0] = t; gap[0] = 1; vis[t] = true;
  while (l <= r) { int u = que[l++];
   for (int i = e.begin[u]; ~i; i = e.next[i])
    if (e.flow[i] == 0 && !vis[e.dest[i]]) {
     que[++r] = e.dest[i];
     vis[e.dest[i]] = true;
     d[e.dest[i]] = d[u] + 1;
     ++gap[d[e.dest[i]]]; } }
  for (int i = 0; i < n; ++i) if (!vis[i]) d[i] = n, ++gap[n];
  int u = pre[s] = s, v, maxflow = 0;
  while (d[s] < n) {
   v = n; for (int i = cur[u]; ~i; i = e.next[i])
    if (e.flow[i] && d[u] == d[e.dest[i]] + 1) {
     v = e.dest[i]; cur[u] = i; break; }
    if (v < n) {
     pre[v] = u; u = v;
     if (v == t) {
      int dflow = INF, p = t; u = s;
      while (p != s) { p = pre[p]; dflow = std::min (dflow, e.flow[cur[p]]); }
      maxflow += dflow; p = t;
      while (p != s) { p = pre[p]; e.flow[cur[p]] -= dflow; e.flow[cur[p] ^ 1] += dflow; } }
    } else {
     int mindist = n + 1;
     for (int i = e.begin[u]; ~i; i = e.next[i])
      if (e.flow[i] && mindist > d[e.dest[i]]) {
       mindist = d[e.dest[i]]; cur[u] = i; }
     if (!--gap[d[u]]) return maxflow;
     gap[d[u] = mindist + 1]++; u = pre[u]; } }
  return maxflow; } };
/* Dense graph maximum flow : dinic. */
template <int MAXN = 1000, int MAXM = 100000>
struct dinic {
 struct flow_edge_list {
  int size, begin[MAXN], dest[MAXM], next[MAXM], flow[MAXM];
  void clear (int n) { size = 0; std::fill (begin, begin + n, -1); }
  flow_edge_list (int n = MAXN) { clear (n); }
  void add_edge (int u, int v, int f) {
   dest[size] = v; next[size] = begin[u]; flow[size] = f; begin[u] = size++;
   dest[size] = u; next[size] = begin[v]; flow[size] = 0; begin[v] = size++; } };
 int n, s, t, d[MAXN], w[MAXN], q[MAXN];
 int bfs (flow_edge_list &e) {
  std::fill (d, d + n, -1);
  int l, r; q[l = r = 0] = s, d[s] = 0;
  for (; l <= r; l ++)
   for (int k = e.begin[q[l]]; ~k; k = e.next[k])
    if (!~d[e.dest[k]] && e.flow[k] > 0) d[e.dest[k]] = d[q[l]] + 1, q[++r] = e.dest[k];
  return ~d[t] ? 1 : 0; }
 int dfs (flow_edge_list &e, int u, int ext) {
  if (u == t) return ext; int k = w[u], ret = 0;
  for (; ~k; k = e.next[k], w[u] = k) {
   if (ext == 0) break;
   if (d[e.dest[k]] == d[u] + 1 && e.flow[k] > 0) {
    int flow = dfs (e, e.dest[k], std::min (e.flow[k], ext));
    if (flow > 0) {
     e.flow[k] -= flow, e.flow[k ^ 1] += flow;
     ret += flow, ext -= flow; } } }
  if (!~k) d[u] = -1; return ret; }
 int solve (flow_edge_list &e, int n_, int s_, int t_) {
  int ans = 0; n = n_; s = s_; dinic::t = t_;
  while (bfs (e)) {
   for (int i = 0; i < n; ++i) w[i] = e.begin[i];
   ans += dfs (e, s, INF); }
  return ans; } };
```

6.6 Minimum cost flow

```
/* Sparse graph minimum cost flow : EK. */
template <int MAXN = 1000, int MAXM = 100000>
struct minimum_cost_flow {
 struct cost_flow_edge_list {
  int size, begin[MAXN], dest[MAXM], next[MAXM], cost[MAXM], flow[MAXM];
  void clear (int n) { size = 0; std::fill (begin, begin + n, -1); }
  cost_flow_edge_list (int n = MAXN) { clear (n); }
  void add_edge (int u, int v, int c, int f) {
   dest[size] = v; next[size] = begin[u]; cost[size] = c; flow[size] = f; begin[u] = size++;
   dest[size] = u; next[size] = begin[v]; cost[size] = -c; flow[size] = 0; begin[v] = size++; } };
 int n, s, t, prev[MAXN], dist[MAXN], occur[MAXN];
 bool augment (cost_flow_edge_list &e) {
  std::vector <int> queue;
  std::fill (dist, dist + n, INF); std::fill (occur, occur + n, 0);
  dist[s] = 0; occur[s] = true; queue.push_back (s);
  for (int head = 0; head < (int)queue.size(); ++head) {
   int x = queue[head];
   for (int i = e.begin[x]; ~i; i = e.next[i]) {
    int y = e.dest[i];
    if (e.flow[i] && dist[y] > dist[x] + e.cost[i]) {
     dist[y] = dist[x] + e.cost[i]; prev[y] = i;
     if (!occur[y]) {
      occur[y] = true; queue.push_back (y); } } }
   occur[x] = false; }
  return dist[t] < INF; }
 std::pair <int, int> solve (cost_flow_edge_list &e, int n_, int s_, int t_) {
  n = n_; s = s_; t = t_; std::pair <int, int> ans = std::make_pair (0, 0);
  while (augment (e)) {
   int num = INF;
   for (int i = t; i != s; i = e.dest[prev[i] ^ 1]) {
    num = std::min (num, e.flow[prev[i]]); }
   ans.first += num;
   for (int i = t; i != s; i = e.dest[prev[i] ^ 1]) {
    e.flow[prev[i]] -= num; e.flow[prev[i] ^ 1] += num;
    ans.second += num * e.cost[prev[i]]; } }
  return ans; } };
/* Dense graph minimum cost flow : zkw. */
template <int MAXN = 1000, int MAXM = 100000>
struct zkw_flow {
 struct cost_flow_edge_list {
  int size, begin[MAXN], dest[MAXM], next[MAXM], cost[MAXM], flow[MAXM];
  void clear (int n) { size = 0; std::fill (begin, begin + n, -1); }
  cost_flow_edge_list (int n = MAXN) { clear (n); }
  void add_edge (int u, int v, int c, int f) {
```

```
  dest[size] = v; next[size] = begin[u]; cost[size] = c; flow[size] = f; begin[u] = size++;
  dest[size] = u; next[size] = begin[v]; cost[size] = -c; flow[size] = 0; begin[v] = size++; } };
 int n, s, t, tf, tc, dis[MAXN], slack[MAXN], visit[MAXN];
 int modlable() {
  int delta = INF;
  for (int i = 0; i < n; i++) {
   if (!visit[i] && slack[i] < delta) delta = slack[i];
   slack[i] = INF; }
  if (delta == INF) return 1;
  for (int i = 0; i < n; i++) if (visit[i]) dis[i] += delta;
  return 0; }
 int dfs (cost_flow_edge_list &e, int x, int flow) {
  if (x == t) { tf += flow; tc += flow * (dis[s] - dis[t]); return flow; }
  visit[x] = 1; int left = flow;
  for (int i = e.begin[x]; ~i; i = e.next[i])
   if (e.flow[i] > 0 && !visit[e.dest[i]]) {
    int y = e.dest[i];
    if (dis[y] + e.cost[i] == dis[x]) {
     int delta = dfs (e, y, std::min (left, e.flow[i]));
     e.flow[i] -= delta; e.flow[i ^ 1] += delta; left -= delta;
     if (!left) { visit[x] = false; return flow; }
    } else
     slack[y] = std::min (slack[y], dis[y] + e.cost[i] - dis[x]); }
  return flow - left; }
 std::pair <int, int> solve (cost_flow_edge_list &e, int n_, int s_, int t_) {
  n = n_; s = s_; t = t_; tf = tc = 0;
  std::fill (dis + 1, dis + t + 1, 0);
  do { do {
   std::fill (visit + 1, visit + t + 1, 0);
  } while (dfs (e, s, INF)); } while (!modlable ());
  return std::make_pair (tf, tc);
 } };
```

6.7 Stoer Wagner algorithm

```
/* Stoer Wagner algorithm : Finds the minimum cut of an undirected graph. (1-based) */
template <int MAXN = 500>
struct stoer_wagner {
 int n, edge[MAXN][MAXN];
 int dist[MAXN];
 bool vis[MAXN], bin[MAXN];
 stoer_wagner () {
  memset (edge, 0, sizeof (edge));
  memset (bin, false, sizeof (bin)); }
 int contract (int &s, int &t) {
  memset (dist, 0, sizeof (dist));
  memset (vis, false, sizeof (vis));
  int i, j, k, mincut, maxc;
  for (i = 1; i <= n; i++) {
   k = -1; maxc = -1;
   for (j = 1; j <= n; j++)
    if (!bin[j] && !vis[j] && dist[j] > maxc) {
     k = j; maxc = dist[j]; }
   if (k == -1) return mincut;
   s = t; t = k; mincut = maxc; vis[k] = true;
   for (j = 1; j <= n; j++) if (!bin[j] && !vis[j])
    dist[j] += edge[k][j]; }
  return mincut; }
 int solve () {
  int mincut, i, j, s, t, ans;
  for (mincut = INF, i = 1; i < n; i++) {
   ans = contract (s, t); bin[t] = true;
   if (mincut > ans) mincut = ans;
   if (mincut == 0) return 0;
   for (j = 1; j <= n; j++) if (!bin[j])
    edge[s][j] = (edge[j][s] += edge[j][t]); }
  return mincut; } };
```

6.8 DN maximum clique

```
/* DN maximum clique : n <= 150 */
typedef bool BB[N]; struct Maxclique {
const BB *e; int pk, level; const float Tlimit;
struct Vertex { int i, d; Vertex (int i) : i(i), d(0) {} };
typedef std::vector <Vertex> Vertices; Vertices V;
typedef std::vector <int> ColorClass; ColorClass QMAX, Q;
std::vector <ColorClass> C;
static bool desc_degree (const Vertex &vi,const Vertex &vj) { return vi.d > vj.d; }
void init_colors (Vertices &v) {
 const int max_degree = v[0].d;
 for (int i = 0; i < (int) v.size(); ++i) v[i].d = std::min (i, max_degree) + 1; }
void set_degrees (Vertices &v) {
 for (int i = 0, j; i < (int) v.size (); ++i)
  for (v[i].d = j = 0; j < (int) v.size (); ++j)
   v[i].d += e[v[i].i][v[j].i]; }
struct StepCount { int i1, i2; StepCount(): i1 (0), i2 (0) {} };
std::vector <StepCount> S;
bool cut1 (const int pi, const ColorClass &A) {
 for (int i = 0; i < (int) A.size (); ++i)
  if (e[pi][A[i]]) return true; return false; }
void cut2 (const Vertices &A, Vertices & B) {
 for (int i = 0; i < (int) A.size () - 1; ++i)
  if (e[A.back().i][A[i].i]) B.push_back(A[i].i); }
void color_sort (Vertices & R) {
 int j = 0, maxno = 1, min_k = std::max ((int) QMAX.size () - (int) Q.size() + 1, 1);
 C[1].clear (); C[2].clear ();
 for (int i = 0; i < (int) R.size (); ++i) {
  int pi = R[i].i, k = 1; while (cut1(pi, C[k])) ++k;
  if (k > maxno) maxno = k, C[maxno + 1].clear();
  C[k].push_back (pi); if (k < min_k) R[j++].i = pi; }
 if (j > 0) R[j - 1].d = 0;
 for (int k = min_k; k <= maxno; ++k)
  for (int i = 0; i < (int) C[k].size (); ++i)
   R[j].i = C[k][i], R[j++].d = k; }
void expand_dyn (Vertices &R) {
 S[level].i1 = S[level].i1 + S[level - 1].i1 - S[level].i2;
 S[level].i2 = S[level - 1].i1;
 while ((int) R.size ()) {
  if ((int) Q.size () + R.back ().d > (int) QMAX.size ()) {
   Q.push_back (R.back ().i); Vertices Rp; cut2 (R, Rp);
   if ((int) Rp.size ()) {
    if((float) S[level].i1 / ++pk < Tlimit) degree_sort (Rp);
    color_sort (Rp); ++S[level].i1, ++level;
    expand_dyn (Rp); --level;
   } else if ((int) Q.size () > (int) QMAX.size ()) QMAX = Q;
   Q.pop_back (); } else return; R.pop_back (); } }
void mcqdyn (int *maxclique, int &sz) {
 set_degrees (V); std::sort (V.begin (), V.end (), desc_degree); init_colors (V);
 for (int i = 0; i < (int) V.size () + 1; ++i) S[i].i1 = S[i].i2 = 0;
 expand_dyn (V); sz = (int) QMAX.size ();
 for (int i = 0; i < (int) QMAX.size (); i++) maxclique[i] = QMAX[i]; }
void degree_sort (Vertices & R) {
 set_degrees(R); std::sort(R.begin(), R.end(), desc_degree); }
Maxclique (const BB *conn, const int sz, const float tt = .025) : pk (0), level (1), Tlimit (tt) {
 for(int i = 0; i < sz; i++) V.push_back (Vertex (i));
 e = conn, C.resize (sz + 1), S.resize (sz + 1); } };

BB e[N]; int ans, sol[N]; for (...) e[x][y] = e[y][x] = true;
Maxclique mc (e, n); mc.mcqdyn (sol, ans); //0-based.
for (int i = 0; i < ans; ++i) std::cout << sol[i] << std::endl;
```

6.9 Dominator tree

```
/* Dominator tree : finds the immediate dominator (idom[]) of each node, idom[x] will be x if x does not have a dominator, and will be -1 if x is not reachable from s. */
template <int MAXN = 100000, int MAXM = 100000>
struct dominator_tree {
 int dfn[MAXN], sdom[MAXN], idom[MAXN], id[MAXN], f[MAXN], fa[MAXN], smin[MAXN], stamp;
 void predfs (int x, const edge_list <MAXN, MAXM> & succ) {
  id[dfn[x] = stamp++] = x;
  for (int i = succ.begin[x]; ~i; i = succ.next[i]) {
   int y = succ.dest[i];
   if (dfn[y] < 0) { f[y] = x; predfs (y, succ); } } }
 int getfa (int x) {
  if (fa[x] == x) return x;
  int ret = getfa (fa[x]);
  if (dfn[sdom[smin[fa[x]]]] < dfn[sdom[smin[x]]])
   smin[x] = smin[fa[x]];
  return fa[x] = ret; }
 void solve (int s, int n, const edge_list <MAXN, MAXM> &succ) {
  std::fill (dfn, dfn + n, -1); std::fill (idom, idom + n, -1);
  static edge_list <MAXN, MAXM> pred, tmp; pred.clear (n);
  for (int i = 0; i < n; ++i) for (int j = succ.begin[i]; ~j; j = succ.next[j])
   pred.add_edge (succ.dest[j], i);
  stamp = 0; tmp.clear (n); predfs (s, succ);
  for (int i = 0; i < stamp; ++i) fa[id[i]] = smin[id[i]] = id[i];
  for (int o = stamp - 1; o >= 0; --o) {
   int x = id[o];
   if (o) {
    sdom[x] = f[x];
    for (int i = pred.begin[x]; ~i; i = pred.next[i]) {
     int p = pred.dest[i];
     if (dfn[p] < 0) continue;
     if (dfn[p] > dfn[x]) { getfa (p); p = sdom[smin[p]]; }
     if (dfn[sdom[x]] > dfn[p]) sdom[x] = p; }
    tmp.add_edge (sdom[x], x); }
   while (~tmp.begin[x]) {
    int y = tmp.dest[tmp.begin[x]];
    tmp.begin[x] = tmp.next[tmp.begin[x]]; getfa (y);
    if (x != sdom[smin[y]]) idom[y] = smin[y];
    else idom[y] = x; }
   for (int v : succ[x]) if (f[v] == x) fa[v] = x; }
  idom[s] = s; for (int i = 1; i < stamp; ++i) {
   int x = id[i]; if (idom[x] != sdom[x]) idom[x] = idom[idom[x]]; } } };
```

6.10 Tarjan

```
/* Tarjan : strongly-connected components. */
template <int MAXN = 1000000>
struct tarjan {
 int comp[MAXN], size;
 int dfn[MAXN], ind, low[MAXN], ins[MAXN], stk[MAXN], stks;
```

```
 void dfs (const edge_list <MAXN, MAXM> &e, int i) {
  dfn[i] = low[i] = ind++;
  ins[i] = 1; stk[stks++] = i;
  for (int x = e.begin[i]; ~x; x = e.next[x]) {
   int j = e.dest[x]; if (!~dfn[j]) {
    dfs (j);
    if (low[i] > low[j]) low[i] = low[j];
    if (low[j] >= dfn[i]); //vertex-biconnected
    if (low[j] > dfn[i]); //edge-biconnected
   } else if (ins[j] && low[i] > dfn[j])
    low[i] = dfn[j]; }
  if (dfn[i] == low[i]) {   //strongly-connected
   for (int j = -1; j != i;
    j = stk[--stks], ins[j] = 0, comp[j] = size);
   ++size; } }
 void solve (const edge_list <MAXN, MAXM> &e, int n) {
  size = ind = stks = 0;
  std::fill (dfn, dfn + n, -1);
  for (int i = 0; i < n; ++i) if (!~dfn[i])
   dfs (e, i); } };
```

7 String

7.1 Manacher

```
/* Manacher : Odd parlindromes only. */
for (int i = 1, j = 0; i != (n << 1) - 1; ++i) {
 int p = i >> 1, q = i - p, r = ((j + 1) >> 1) + l[j] - 1;
 l[i] = r < q ? 0 : std::min (r - q + 1, l[(j << 1) - i]);
 while (p - l[i] != -1 && q + l[i] != n
  && s[p - l[i]] == s[q + l[i]]) l[i]++;
 if (q + l[i] - 1 > r) j = i;
 a += l[i]; }
```

7.2 Suffix Array

```
/* Suffix Array : sa[i] - the beginning position of the ith smallest suffix, rk[i] - the rank of the suffix beginning at position i. height[i] - the longest common prefix of sa[i] and sa[i - 1]. */
template <int MAXN = 1000000, int MAXC = 26>
struct suffix_array {
 int rk[MAXN], height[MAXN], sa[MAXN];
 int cmp (int *x, int a, int b, int d) {
  return x[a] == x[b] && x[a + d] == x[b + d]; }
 void doubling (int *a, int n) {
  static int sRank[MAXN], tmpA[MAXN], tmpB[MAXN];
  int m = MAXC, *x = tmpA, *y = tmpB;
  for (int i = 0; i < m; ++i) sRank[i] = 0;
  for (int i = 0; i < n; ++i) ++sRank[x[i] = a[i]];
  for (int i = 1; i < m; ++i) sRank[i] += sRank[i - 1];
  for (int i = n - 1; i >= 0; --i) sa[--sRank[x[i]]] = i;
  for (int d = 1, p = 0; p < n; m = p, d <<= 1) {
   p = 0; for (int i = n - d; i < n; ++i) y[p++] = i;
   for (int i = 0; i < n; ++i) if (sa[i] >= d) y[p++] = sa[i] - d;
   for (int i = 0; i < m; ++i) sRank[i] = 0;
   for (int i = 0; i < n; ++i) ++sRank[x[i]];
   for (int i = 1; i < m; ++i) sRank[i] += sRank[i - 1];
   for (int i = n - 1; i >= 0; --i) sa[--sRank[x[y[i]]]] = y[i];
   std::swap (x, y); x[sa[0]] = 0; p = 1; y[n] = -1;
   for (int i = 1; i < n; ++i)
    x[sa[i]] = cmp (y, sa[i], sa[i - 1], d) ? p - 1 : p++; } }
 void solve (int *a, int n) {
  a[n] = -1; doubling (a, n);
  for (int i = 0; i < n; ++i) rk[sa[i]] = i;
  int cur = 0;
  for (int i = 0; i < n; ++i)
   if (rk[i]) {
    if (cur) cur--;
    for (; a[i + cur] == a[sa[rk[i] - 1] + cur]; ++cur);
    height[rk[i]] = cur; } } };
```

7.3 Suffix Automaton

```
/* Suffix automaton : head - the first state. tail - the last state. Terminating states can be reached via visiting the ancestors of tail. state::len - the longest length of the string in the state. state::right - 1 - the first location in the string where the state can be reached. state::parent - the parent link. state::dest - the automaton link. */
template <int MAXN = 1000000, int MAXC = 26>
struct suffix_automaton {
 struct state {
  int len, right; state *parent, *dest[MAXC];
  state (int len = 0, int right = 0) : len (len), right (right), parent (NULL) {
   memset (dest, 0, sizeof (dest)); }
 } node_pool[MAXN * 2], *tot_node, *null = new state();
 state *head, *tail;
 void extend (int token) {
  state *p = tail;
  state *np = tail -> dest[token] ? null : new (tot_node++) state (tail -> len + 1, tail -> len + 1);
  while (p && !p -> dest[token]) p -> dest[token] = np, p = p -> parent;
  if (!p) np -> parent = head;
  else {
   state *q = p -> dest[token];
   if (p -> len + 1 == q -> len) {
    np -> parent = q;
   } else {
    state *nq = new (tot_node++) state (*q);
    nq -> len = p -> len + 1;
    np -> parent = q -> parent = nq;
    while (p && p -> dest[token] == q) {
     p -> dest[token] = nq, p = p -> parent;
    } } }
  tail = np == null ? np -> parent : np; }
 void init () {
  tot_node = node_pool;
  head = tail = new (tot_node++) state (); }
 suffix_automaton () { init (); } };
```

7.4 Palindromic tree

```
/* Palindromic tree : extend () - returns whether the tree has generated a new node. odd, even - the root of two trees. last - the node representing the last char. node::len - the palindromic string length of the node. */
template <int MAXN = 1000000, int MAXC = 26>
struct palindromic_tree {
 struct node {
  node *child[MAXC], *fail; int len;
  node (int len) : fail (NULL), len (len) {
   memset (child, NULL, sizeof (child)); }
 } node_pool[MAXN * 2], *tot_node;
 int size, text[MAXN];
 node *odd, *even, *last;
 node *match (node *now) {
  for (; text[size - now -> len - 1] != text[size]; now = now -> fail);
  return now; }
 bool extend (int token) {
  text[++size] = token; node *now = match (last);
  if (now -> child[token])
   return last = now -> child[token], false;
  last = now -> child[token] = new (tot_node++) node (now -> len + 2);
  if (now == odd) last -> fail = even;
  else {
   now = match (now -> fail);
   last -> fail = now -> child[token]; }
  return true; }
 void init() {
  text[size = 0] = -1; tot_node = node_pool;
  last = even = new (tot_node++) node (0); odd = new (tot_node++) node (-1);
  even -> fail = odd; }
 palindromic_tree () { init (); } };
```

7.5 Regular expression

```
std::string str = ("The␣the␣there");
std::regex pattern ("(th|Th)[\\w]*", std::regex_constants::optimize | std::regex_constants::ECMAScript);
std::smatch match; //std::cmatch for char *

std::regex_match (str, match, pattern);

auto mbegin = std::sregex_iterator (str.begin (), str.end (), pattern);
auto mend = std::sregex_iterator ();
std::cout << "Found␣" << std::distance (mbegin, mend) << "␣words:\n";
for (std::sregex_iterator i = mbegin; i != mend; ++i) {
 match = *i;
/* The word is match[0], backreferences are match[i] up to match.size ().
 match.prefix () and match.suffix () give the prefix and the suffix.
 match.length () gives length and match.position () gives position of the match. */ }
std::regex_replace (str, pattern, "sh$1");
//$n is the backreference, $& is the entire match, $` is the prefix, $' is the suffix, $$ is the $ sign.
```

8 Tips

8.1 Java

```
/* Java reference : References on Java IO, structures, etc. */
import java.io.*;
import java.lang.*;
import java.math.*;
import java.util.*;
/* Common usage:
Scanner in = new Scanner (System.in);
Scanner in = new Scanner (new BufferedInputStream (System.in));
in.nextInt () / in.nextBigInteger () / in.nextBigDecimal () / in.nextDouble ()
in.nextLine () / in.hasNext ()
System.out.print (...);
System.out.println (...);
System.out.printf (...);
BigInteger : BigInteger.valueOf (int) / abs / negate () / max / min / add / subtract / multiply / divide / remainder (BigInteger) / gcd (BigInteger) / modInverse (BigInteger mod) / modPow (BigInteger ex, BigInteger mod) / pow (int ex) / not () / and / or / xor (BigInteger) / shiftLeft / shiftRight (int) / compareTo (BigInteger) / intValue () / longValue () / toString (int radix) / isProbablePrime (int certainty) / nextProbablePrime ()
```

```
BigDecimal : consists of a BigInteger value and a scale. The scale is the number of digits to the right of the decimal point.
divide (BigDecimal) : exact divide.
divide (BigDecimal, int scale, RoundingMode roundingMode) : divide with roundingMode, which may be: CEILING / DOWN / FLOOR / HALF_DOWN / HALF_EVEN / HALF_UP / UNNECESSARY / UP.
BigDecimal setScale (int newScale, RoundingMode roundingMode) : returns a BigDecimal with newScale.
doubleValue () / toPlainString () : converts to other types.
Arrays : Arrays.sort (T [] a); Arrays.sort (T [] a, int fromIndex, int toIndex); Arrays.sort (T [] a, int fromIndex, int toIndex, Comperator <? super T> comperator);
LinkedList <E> : addFirst / addLast (E) / getFirst / getLast / removeFirst / removeLast () / clear () / add (int, E) / remove (int) / size () / contains / removeFirstOccurrence / removeLastOccurrence (E)
ListIterator <E> listIterator (int index) : returns an iterator :
 E next / previous () : accesses and iterates.
 hasNext / hasPrevious () : checks availablity.
 nextIndex / previousIndex () : returns the index of a subsequent call.
 add / set (E) / remove () : changes element.
PriorityQueue <E> (int initcap, Comparator <? super E> comparator) : add (E) / clear () / iterator () / peek () / poll () / size ()
TreeMap <K, V> (Comparator <? super K> comparator) : Map.Entry <K, V> ceilingEntry / floorEntry / higherEntry / lowerEntry (K): getKey / getValue () / setValue (V) : entries.
 clear () / put (K, V) / get (K) / remove (K) / size ()
StringBuilder : StringBuilder (string) / append (int, string, ...) / insert (int offset, ...) charAt (int) / setCharAt (int, char) / delete (int, int) / reverse () / length () / toString ()
String : String.format (String, ...) / toLowerCase / toUpperCase () */
/* Examples on Comparator :
public class Main {
 public static class Point {
  public int x; public int y;
  public Point () {
   x = 0;
   y = 0; }
  public Point (int xx, int yy) {
   x = xx;
   y = yy; } };
 public static class Cmp implements Comparator <Point> {
  public int compare (Point a, Point b) {
   if (a.x < b.x) return -1;
   if (a.x == b.x) {
    if (a.y < b.y) return -1;
    if (a.y == b.y) return 0; }
   return 1; } };
 public static void main (String [] args) {
  Cmp c = new Cmp ();
  TreeMap <Point, Point> t = new TreeMap <Point, Point> (c);
  return; } };
*/
/* or :
 public static class Point implements Comparable <Point> {
  public int x; public int y;
  public Point () {
   x = 0;
   y = 0; }
  public Point (int xx, int yy) {
   x = xx;
   y = yy; }
  public int compareTo (Point p) {
   if (x < p.x) return -1;
   if (x == p.x) {
    if (y < p.y) return -1;
    if (y == p.y) return 0; }
   return 1; }
  public boolean equalTo (Point p) {
   return (x == p.x && y == p.y); }
  public int hashCode () {
   return x + y; } };
*/
//Faster IO :
public class Main {
 static class InputReader {
  public BufferedReader reader;
  public StringTokenizer tokenizer;
  public InputReader (InputStream stream) {
   reader = new BufferedReader (new InputStreamReader (stream), 32768);
   tokenizer = null; }
  public String next() {
   while (tokenizer == null || !tokenizer.hasMoreTokens()) {
    try {
     String line = reader.readLine();
     tokenizer = new StringTokenizer (line);
    } catch (IOException e) {
     throw new RuntimeException (e); } }
   return tokenizer.nextToken(); }
  public BigInteger nextBigInteger() {
   return new BigInteger (next (), 10); /* radix */ }
  public int nextInt() {
   return Integer.parseInt (next()); }
  public double nextDouble() {
   return Double.parseDouble (next()); } }
 public static void main (String[] args) {
  InputReader in = new InputReader (System.in);
 } }
```

8.2 Random numbers

```
std::mt19937_64 mt (time (0));
std::uniform_int_distribution <int> uid (1, 100);
std::uniform_real_distribution <double> urd (1, 100);
std::cout << uid (mt) << "␣" << urd (mt) << "\n";
```

8.3 Formatting

```
//Faster cin/cout.
std::ios::sync_with_stdio (0);
std::cin.tie (0); std::cout.tie (0);
//getline : gets a line.
std::string str;
std::getline (std::cin, str, '#');
char ch[100];
std::cin.getline (ch, 100, '#');
//fgets : gets a line with '\n' at the end.
fgets (ch, 100, stdin);
//peek : gets the next character.
int c = std::cin.peek ();
//ignore : ignores characters.
std::cin.ignore (100, '#');
std::cin.ignore (100, EOF);
//read : reads all characters.
std::cin.seekg (0, std::cin.end);
int length = std::cin.tellg ();
std::cin.seekg (0, std::cin.beg);
char *buf = new char[length];
std::cin.read (buf, length);
//width : specifies output minimal width.
std::cout.width (10); // std::cout << std::setw (10);
std::cout.fill ('#'); // std::cout << std::setfill ('#');
std::cout << std::left << x << "\n";
std::cout << std::internal << x << "\n";
std::cout << std::right << x << "\n";
//precision : specifies float precision.
std::cout.precision (10); // std::cout << std::setprecision (10);
std::cout << std::fixed; // std::cout << std::scientific;
```

8.4 Read hack

```
#define __ __attribute__ ((optimize ("-O3")))
#define _ __ __inline __attribute__ ((__gnu_inline__, __always_inline__, __artificial__))
_ int next_int () {
 const int SIZE = 110000; static char buf[SIZE + 1]; static int p = SIZE;
 register int ans = 0, f = 1, sgn = 1;
 while ((p < SIZE || (p = 0, buf[fread (buf, 1, SIZE, stdin)] = 0, buf[0])) && (isdigit (buf[p]) && (ans = ans * 10 + buf[p] - '0', f = 0, 1) || f && (buf[p] == '-' && (sgn = 0), 1))) ++p;
 return sgn ? ans : -ans; }
```

8.5 Stack hack

```
//C++
#pragma comment (linker, "/STACK:36777216")
//G++
int __size__ = 256 << 20;
char *__p__ = (char*) malloc(__size__) + __size__;
__asm__ ("movl␣%0,␣%%esp\n" :: "r"(__p__));
```

8.6 Time hack

```
clock_t t = clock ();
std::cout << 1. * t / CLOCKS_PER_SEC << "\n";
```

8.7 Builtin functions

1. `__builtin_clz`: Returns the number of leading 0-bits in x, starting at the most significant bit position. If x is 0, the result is undefined.
2. `__builtin_ctz`: Returns the number of trailing 0-bits in x, starting at the least significant bit position. If x is 0, the result is undefined.
3. `__builtin_clrsb`: Returns the number of leading redundant sign bits in x, i.e. the number of bits following the most significant bit that are identical to it. There are no special cases for 0 or other values.
4. `__builtin_popcount`: Returns the number of 1-bits in x.
5. `__builtin_parity`: Returns the parity of x, i.e. the number of 1-bits in x modulo 2.
6. `__builtin_bswap16`, `__builtin_bswap32`, `__builtin_bswap64`: Returns x with the order of the bytes (8 bits as a group) reversed.
7. `bitset::_Find_first()`, `bitset::_Find_next(idx)`: bitset built-in functions.

8.8 Prufer sequence

In combinatorial mathematics, the Prufer sequence of a labeled tree is a unique sequence associated with the tree. The sequence for a tree on n vertices has length $n-2$.

One can generate a labeled tree's Prufer sequence by iteratively removing vertices from the tree until only two vertices remain. Specifically, consider a labeled tree T with vertices $1, 2, \ldots, n$. At step i, remove the leaf with the smallest label and set the ith element of the Prufer sequence to be the label of this leaf's neighbour.

One can generate a labeled tree from a sequence in three steps. The tree will have $n+2$ nodes, numbered from 1 to $n+2$. For each node set its degree to the number of times it appears in the sequence plus 1. Next, for each number in the sequence $a[i]$, find the first (lowest-numbered) node, j, with degree equal to 1, add the edge $(j, a[i])$ to the tree, and decrement the degrees of j and $a[i]$. At the end of this loop two nodes with degree 1 will remain (call them u, v). Lastly, add the edge (u, v) to the tree.

The Prufer sequence of a labeled tree on n vertices is a unique sequence of length $n-2$ on the labels 1 to n - this much is clear. Somewhat less obvious is the fact that for a given sequence S of length $n-2$ on the labels 1 to n, there is a unique labeled tree whose Prufer sequence is S.

8.9 Spanning tree counting

Kirchhoff's Theorem: the number of spanning trees in a graph G is equal to *any* cofactor of the Laplacian matrix of G, which is equal to the difference between the graph's degree matrix (a diagonal matrix with vertex degrees on the diagonals) and its adjacency matrix (a (0,1)-matrix with 1's at places corresponding to entries where the vertices are adjacent and 0's otherwise).

The number of edges with a certain weight in a minimum spanning tree is fixed given a graph. Moreover, the number of its arrangements can be obtained by finding a minimum spanning tree, compressing connected components of other edges in that tree into a point, and then applying Kirrchoff's theorem with only edges of the certain weight in the graph. Therefore, the number of minimum spanning trees in a graph can be solved by multiplying all numbers of arrangements of edges of different weights together.

8.10 Matching

8.10.1 Tutte-Berge formula

The theorem states that the size of a maximum matching of a graph $G = (V, E)$ equals

$$\frac{1}{2}\min_{U\subseteq V}\left(|U| - \mathrm{odd}(G-U) + |V|\right),$$

where $\mathrm{odd}(H)$ counts how many of the connected components of the graph H have an odd number of vertices.

8.10.2 Tutte theorem

A graph, $G = (V, E)$, has a perfect matching if and only if for every subset U of V, the subgraph induced by $V-U$ has at most $|U|$ connected components with an odd number of vertices.

8.10.3 Hall's marriage theorem

A family S of finite sets has a transversal if and only if S satisfies the marriage condition.

8.11 Lucas's theorem

For non-negative integers m and n and a prime p, the following congruence relation holds:

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

where

$$m = m_k p^k + m_{k-1}p^{k-1} + \cdots + m_1 p + m_0,$$

and

$$n = n_k p^k + n_{k-1}p^{k-1} + \cdots + n_1 p + n_0$$

are the base p expansions of m and n respectively. This uses the convention that $\binom{m}{n} = 0$ if $m < n$.

8.12 Mobius inversion

8.12.1 Mobius inversion formula

$$[x = 1] = \sum_{d|x}\mu(d)$$

8.12.2 Gcd inversion

$$\begin{aligned}\sum_{a=1}^{n}\sum_{b=1}^{n} gcd^2(a,b) &= \sum_{d=1}^{n} d^2 \sum_{i=1}^{\lfloor \frac{n}{d}\rfloor}\sum_{j=1}^{\lfloor \frac{n}{d}\rfloor}[gcd(i,j)=1] \\ &= \sum_{d=1}^{n} d^2 \sum_{i=1}^{\lfloor \frac{n}{d}\rfloor}\sum_{j=1}^{\lfloor \frac{n}{d}\rfloor}\sum_{t|gcd(i,j)}\mu(t) \\ &= \sum_{d=1}^{n} d^2 \sum_{t=1}^{\lfloor \frac{n}{d}\rfloor}\mu(t)\sum_{i=1}^{\lfloor \frac{n}{d}\rfloor}[t|i]\sum_{j=1}^{\lfloor \frac{n}{d}\rfloor}[t|j] \\ &= \sum_{d=1}^{n} d^2 \sum_{t=1}^{\lfloor \frac{n}{d}\rfloor}\mu(t)\lfloor\frac{n}{dt}\rfloor^2\end{aligned}$$

The formula can be computed in $O(nlogn)$ complexity.
Moreover, let $l = dt$, then

$$\sum_{d=1}^{n} d^2 \sum_{t=1}^{\lfloor \frac{n}{d}\rfloor}\mu(t)\lfloor\frac{n}{dt}\rfloor^2 = \sum_{l=1}^{n}\lfloor\frac{n}{l}\rfloor^2\sum_{d|l}d^2\mu(\frac{l}{d})$$

Let $f(l) = \sum_{d|l} d^2\mu(\frac{l}{d})$. It can be proven that $f(l)$ is multiplicative. Besides, $f(p^k) = p^{2k} - p^{2k-2}$.

Therefore, with linear sieve the formula can be computed in $O(n)$ complexity.

8.13 2-SAT

In terms of the implication graph, two literals belong to the same strongly connected component whenever there exist chains of implications from one literal to the other and vice versa. Therefore, the two literals must have the same value in any satisfying assignment to the given 2-satisfiability instance. In particular, if a variable and its negation both belong to the same strongly connected component, the instance cannot be satisfied, because it is impossible to assign both of these literals the same value. As Aspvall et al. showed, this is a necessary and sufficient condition: a 2-CNF formula is satisfiable if and only if there is no variable that belongs to the same strongly connected component as its negation.

This immediately leads to a linear time algorithm for testing satisfiability of 2-CNF formulae: simply perform a strong connectivity analysis on the implication graph and check that each variable and its negation belong to different components. However, as Aspvall et al. also showed, it also leads to a linear time algorithm for finding a satisfying assignment, when one exists. Their algorithm performs the following steps:

Construct the implication graph of the instance, and find its strongly connected components using any of the known linear-time algorithms for strong connectivity analysis.

Check whether any strongly connected component contains both a variable and its negation. If so, report that the instance is not satisfiable and halt.

Construct the condensation of the implication graph, a smaller graph that has one vertex for each strongly connected component, and an edge from component i to component j whenever the implication graph contains an edge uv such that u belongs to component i and v belongs to component j. The condensation is automatically a directed acyclic graph and, like the implication graph from which it was formed, it is skew-symmetric.

Topologically order the vertices of the condensation. In practice this may be efficiently achieved as a side effect of the previous step, as components are generated by Kosaraju's algorithm in topological order and by Tarjan's algorithm in reverse topological order.

For each component in the reverse topological order, if its variables do not already have truth assignments, set all the literals in the component to be true. This also causes all of the literals in the complementary component to be set to false.

8.14 Dynamic programming

8.14.1 Divide & conquer optimization

For recurrence

$$f(i) = \min_{k<i}\{b(k) + c[k][i]\}$$

$k(i) \le k(i+1)$ holds true if $c[a][c] + c[b][d] < c[a][d] + c[b][c]$.

8.14.2 Knuth optimization

For recurrence

$$f(i,j) = \min_{i<k<j}\{f(i,k) + f(k,j)\} + c[i][j]$$

$k(i, j-1) \le k(i,j) \le k(i+1,j)$ holds true if $c[a][c] + c[b][d] < c[a][d] + c[b][c]$.

8.15 Interesting numbers

8.15.1 Binomial Coefficients

$$\binom{n}{k} = (-1)^k\binom{k-n-1}{k},\quad \sum_{k\le n}\binom{r+k}{k} = \binom{r+n+1}{n}$$

$$\sum_{k=0}^{n}\binom{k}{m} = \binom{n+1}{m+1}$$

$$\sqrt{1+z} = 1 + \sum_{k=1}^{\infty}\frac{(-1)^{k-1}}{k\times 2^{2k-1}}\binom{2k-2}{k-1}z^k$$

$$\sum_{k=0}^{r}\binom{r-k}{m}\binom{s+k}{n} = \binom{r+s+1}{m+n+1}$$

$$C_{n,m} = \binom{n+m}{m} - \binom{n+m}{m-1}, n \ge m$$

$$\binom{n}{k} \equiv [n\&k = k] \pmod 2$$

$$\binom{n_1+\cdots+n_p}{m} = \sum_{k_1+\cdots+k_p=m}\binom{n_1}{k_1}\cdots\binom{n_p}{k_p}$$

8.15.2 Fibonacci Numbers

$$F(z) = \frac{z}{1-z-z^2}$$

$$f_n = \frac{\phi^n - \hat{\phi}^n}{\sqrt{5}}, \phi = \frac{1+\sqrt{5}}{2}, \hat{\phi} = \frac{1-\sqrt{5}}{2}$$

$$\sum_{k=1}^{n} f_k = f_{n+2} - 1,\quad \sum_{k=1}^{n} f_k^2 = f_n f_{n+1}$$

$$\sum_{k=0}^{n} f_k f_{n-k} = \frac{1}{5}(n-1)f_n + \frac{2}{5}nf_{n-1}$$

$$\frac{f_{2n}}{f_n} = f_{n-1} + f_{n+1}$$

$$f_1 + 2f_2 + 3f_3 + \cdots + nf_n = nf_{n+2} - f_{n+3} + 2]$$

$$\gcd(f_m, f_n) = f_{\gcd(m,n)}$$

$$f_n^2 + (-1)^n = f_{n+1}f_{n-1}$$
$$f_{n+k} = f_n f_{k+1} + f_{n-1} f_k$$
$$f_{2n+1} = f_n^2 + f_{n+1}^2$$
$$(-1)^k f_{n-k} = f_n f_{k-1} - f_{n-1} f_k$$
$$\text{Modulo } f_n, f_{mn+r} \equiv \begin{cases} f_r, & m \bmod 4 = 0; \\ (-1)^{r+1} f_{n-r}, & m \bmod 4 = 1; \\ (-1)^n f_r, & m \bmod 4 = 2; \\ (-1)^{r+1+n} f_{n-r}, & m \bmod 4 = 3. \end{cases}$$

Period modulo a prime p is a factor of $2p + 2$ or $p - 1$.
Only exception: $G(5) = 20$.
Period modulo the power of a prime p^k: $G(p^k) = G(p)p^{k-1}$.
Period modulo $n = p_1^{k_1}...p_m^{k_m}$: $G(n) = lcm(G(p_1^{k_1}), ..., G(p_m^{k_m}))$.

8.15.3 Lucas Numbers

$$L_0 = 2, L_1 = 1, L_n = L_{n-1} + L_{n-2} = (\frac{1+\sqrt{5}}{2})^n + \frac{1-\sqrt{5}}{2})^n$$
$$L(x) = \frac{2-x}{1-x-x^2}$$

8.15.4 Catlan Numbers

$$c_1 = 1, c_n = \sum_{i=0}^{n-1} c_i c_{n-1-i} = c_{n-1}\frac{4n-2}{n+1} = \frac{\binom{2n}{n}}{n+1}$$
$$= \binom{2n}{n} - \binom{2n}{n-1}, c(x) = \frac{1-\sqrt{1-4x}}{2x}$$

8.15.5 Stirling Cycle Numbers

Divide n elements into k non-empty cycles.

$$s(n,0) = 0, s(n,n) = 1, s(n+1,k) = s(n,k-1) - ns(n,k)$$
$$s(n,k) = (-1)^{n-k}\begin{bmatrix} n \\ k \end{bmatrix}$$
$$\begin{bmatrix} n+1 \\ k \end{bmatrix} = n\begin{bmatrix} n \\ k \end{bmatrix} + \begin{bmatrix} n \\ k-1 \end{bmatrix}, \begin{bmatrix} n+1 \\ 2 \end{bmatrix} = n!H_n$$
$$x^{\underline{n}} = x(x-1)...(x-n+1) = \sum_{k=0}^{n}\begin{bmatrix} n \\ k \end{bmatrix}(-1)^{n-k}x^k$$
$$x^{\overline{n}} = x(x+1)...(x+n-1) = \sum_{k=0}^{n}\begin{bmatrix} n \\ k \end{bmatrix}x^k$$

8.15.6 Stirling Subset Numbers

Divide n elements into k non-empty subsets.

$$\begin{Bmatrix} n+1 \\ k \end{Bmatrix} = k\begin{Bmatrix} n \\ k \end{Bmatrix} + \begin{Bmatrix} n \\ k-1 \end{Bmatrix}$$
$$x^n = \sum_{k=0}^{n}\begin{Bmatrix} n \\ k \end{Bmatrix}x^{\underline{k}} = \sum_{k=0}^{n}\begin{Bmatrix} n \\ k \end{Bmatrix}(-1)^{n-k}x^{\overline{k}}$$
$$m!\begin{Bmatrix} n \\ m \end{Bmatrix} = \sum_{k=0}^{m}\binom{m}{k}k^n(-1)^{m-k}$$
$$\sum_{k=1}^{n} k^p = \sum_{k=0}^{p}\begin{Bmatrix} p \\ k \end{Bmatrix}(n+1)^{\underline{k}}$$

For a fixed k, generating functions :

$$\sum_{n=0}^{\infty}\begin{Bmatrix} n \\ k \end{Bmatrix}x^{n-k} = \prod_{r=1}^{k}\frac{1}{1-rx}$$

8.15.7 Motzkin Numbers

Draw non-intersecting chords between n points on a circle.
Pick n numbers $k_1, k_2, ..., k_n \in \{-1, 0, 1\}$ so that $\sum_i^a k_i (1 \le a \le n)$ is non-negative and the sum of all numbers is 0.

$$M_{n+1} = M_n + \sum_{i}^{n-1} M_i M_{n-1-i} = \frac{(2n+3)M_n + 3nM_{n-1}}{n+3}$$
$$M_n = \sum_{i=0}^{\lfloor \frac{n}{2} \rfloor}\binom{n}{2k}Catlan(k)$$
$$M(X) = \frac{1-x-\sqrt{1-2x-3x^2}}{2x^2}$$

8.15.8 Eulerian Numbers

Permutations of the numbers 1 to n in which exactly k elements are greater than the previous element.

$$\left\langle {n \atop k} \right\rangle = (k+1)\left\langle {n-1 \atop k} \right\rangle + (n-k)\left\langle {n-1 \atop k-1} \right\rangle$$
$$x^n = \sum_k \left\langle {n \atop k} \right\rangle \binom{x+k}{n}$$
$$\left\langle {n \atop m} \right\rangle = \sum_{k=0}^{m}\binom{n+1}{k}(m+1-k)^n(-1)^k$$

8.15.9 Harmonic Numbers

Sum of the reciprocals of the first n natural numbers.

$$\sum_{k=1}^{n} H_k = (n+1)H_n - n$$
$$\sum_{k=1}^{n} kH_k = \frac{n(n+1)}{2}H_n - \frac{n(n-1)}{4}$$
$$\sum_{k=1}^{n}\binom{k}{m}H_k = \binom{n+1}{m+1}(H_{n+1} - \frac{1}{m+1})$$

8.15.10 Pentagonal Number Theorem

$$\prod_{n=1}^{\infty}(1-x^n) = \sum_{n=-\infty}^{\infty}(-1)^k x^{k(3k-1)/2}$$
$$p(n) = p(n-1) + p(n-2) - p(n-5) - p(n-7) + \cdots$$
$$f(n,k) = p(n) - p(n-k) - p(n-2k) + p(n-5k) + p(n-7k) - \cdots$$

8.15.11 Bell Numbers

Divide a set that has exactly n elements.

$$B_n = \sum_{k=1}^{n}\begin{Bmatrix} n \\ k \end{Bmatrix}, \quad B_{n+1} = \sum_{k=0}^{n}\binom{n}{k}B_k$$
$$B_{p^m+n} \equiv mB_n + B_{n+1} \pmod{p}$$
$$B(x) = \sum_{n=0}^{\infty}\frac{B_n}{n!}x^n = e^{e^x - 1}$$

8.15.12 Bernoulli Numbers

$$B_n = 1 - \sum_{k=0}^{n-1}\binom{n}{k}\frac{B_k}{n-k+1}$$
$$G(x) = \sum_{k=0}^{\infty}\frac{B_k}{k!}x^k = \frac{1}{\sum_{k=0}^{\infty}\frac{x^k}{(k+1)!}}$$
$$\sum_{k=1}^{n} k^m = \frac{1}{m+1}\sum_{k=0}^{m}\binom{m+1}{k}B_k n^{m-k+1}$$

8.15.13 Sum of Powers

$$\sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6}, \quad \sum_{i=1}^{n} i^3 = (\frac{n(n+1)}{2})^2$$
$$\sum_{i=1}^{n} i^4 = \frac{n(n+1)(2n+1)(3n^2+3n-1)}{30}$$
$$\sum_{i=1}^{n} i^5 = \frac{n^2(n+1)^2(2n^2+2n-1)}{12}$$

8.15.14 Sum of Squares

Denote $r_k(n)$ the ways to form n with k squares. If :

$$n = 2^{a_0}p_1^{2a_1}\cdots p_r^{2a_r}q_1 b_1 \cdots q_s b_s$$

where $p_i \equiv 3 \mod 4$, $q_i \equiv 1 \mod 4$, then

$$r_2(n) = \begin{cases} 0 & \text{if any } a_i \text{ is a half-integer} \\ 4\prod_{1}^{r}(b_i+1) & \text{if all } a_i \text{ are integers} \end{cases}$$

$r_3(n) > 0$ when and only when n is not $4^a(8b+7)$.

8.15.15 Derangement

$$D_1 = 0, D_2 = 1, D_n = n!(\frac{1}{0!} - \frac{1}{1!} + \frac{1}{2!} - \frac{1}{3!} + ... + \frac{(-1)^n}{n!})$$
$$D_n = (n-1)(D_{n-1} + D_{n-2})$$

8.15.16 Tetrahedron Volume

If U, V, W, u, v, w are lengths of edges of the tetrahedron (first three form a triangle; u opposite to U and so on)

$$V = \frac{\sqrt{4u^2v^2w^2 - \sum_{cyc} u^2(v^2+w^2-U^2)^2 + \prod_{cyc}(v^2+w^2-U^2)}}{12}$$

8.16 Game theory

8.16.1 Ferguson game

There are two boxes with m stones and n stones. Each player can empty any one box and move any positive number of stones from another box to this box each step. The player who cannot do so loses.
Solution: The first player loses if and only if both m and n are odd.

8.16.2 Anti-Nim game

Nim game where the player who takes the last stone loses.
Solution: The first player wins when:

1. Each pile contains only one stone, and there are even number of piles, or:

2. There exists at least one pile with more than one stone, and the nim-value of the game is not zero.

8.16.3 Fibonacci game

Two players take turns to collect stones from one pile with n stones. The first player may take any positive number of stones during the first move, but not all of them. After that, each player may take any positive number of stones, but less than twice the number of stones taken during the last turn. The player who takes the last stone wins.

Solution: The first player wins if and only if n is not a fibonacci number.

8.16.4 Wythoff's game

The game is played with two piles of counters. Players take turns removing counters from one or both piles; when removing counters from both piles, the numbers of counters removed from each pile must be equal. The game ends when one person removes the last counter or counters, thus winning.

Solution: The second player wins if and only if $\lfloor \frac{\sqrt{5}+1}{2}|A-B|\rfloor = \min(A,B)$

8.16.5 Joseph cycle

n players are numbered with $0, 1, 2, ..., n-1$. $f_{1,m} = 0, f_{n,m} = (f_{n-1,m} + m) \mod n$.

9 Appendix

9.1 Calculus table

$(\frac{u}{v})' = \frac{u'v-uv'}{v^2}$
$(a^x)' = (\ln a)a^x$
$(\tan x)' = \sec^2 x$
$(\cot x)' = \csc^2 x$
$(\sec x)' = \tan x \sec x$
$(\csc x)' = -\cot x \csc x$
$(\arcsin x)' = \frac{1}{\sqrt{1-x^2}}$
$(\arccos x)' = -\frac{1}{\sqrt{1-x^2}}$
$(\arctan x)' = \frac{1}{1+x^2}$
$(\operatorname{arccot} x)' = -\frac{1}{1+x^2}$
$(\operatorname{arccsc} x)' = -\frac{1}{x\sqrt{1-x^2}}$
$(\operatorname{arcsec} x)' = \frac{1}{x\sqrt{1-x^2}}$
$(\tanh x)' = \operatorname{sech}^2 x$
$(\coth x)' = -\operatorname{csch}^2 x$
$(\operatorname{sech} x)' = -\operatorname{sech} x \tanh x$
$(\operatorname{csch} x)' = -\operatorname{csch} x \coth x$
$(\operatorname{arcsinh} x)' = \frac{1}{\sqrt{1+x^2}}$
$(\operatorname{arccosh} x)' = \frac{1}{\sqrt{x^2-1}}$
$(\operatorname{arctanh} x)' = \frac{1}{1-x^2}$
$(\operatorname{arccoth} x)' = \frac{1}{x^2-1}$
$(\operatorname{arccsch} x)' = -\frac{1}{|x|\sqrt{1+x^2}}$
$(\operatorname{arcsech} x)' = -\frac{1}{x\sqrt{1-x^2}}$

9.1.1 $ax + b$ $(a \neq 0)$

1. $\int \frac{x}{ax+b}\mathrm{d}x = \frac{1}{a^2}(ax + b - b\ln|ax + b|) + C$
2. $\int \frac{x^2}{ax+b}\mathrm{d}x = \frac{1}{a^3}\left(\frac{1}{2}(ax + b)^2 - 2b(ax + b) + b^2\ln|ax + b|\right) + C$
3. $\int \frac{\mathrm{d}x}{x(ax+b)} = -\frac{1}{b}\ln\left|\frac{ax+b}{x}\right| + C$
4. $\int \frac{\mathrm{d}x}{x^2(ax+b)} = -\frac{1}{bx} + \frac{a}{b^2}\ln\left|\frac{ax+b}{x}\right| + C$
5. $\int \frac{x}{(ax+b)^2}\mathrm{d}x = \frac{1}{a^2}\left(\ln|ax + b| + \frac{b}{ax+b}\right) + C$
6. $\int \frac{x^2}{(ax+b)^2}\mathrm{d}x = \frac{1}{a^3}\left(ax + b - 2b\ln|ax + b| - \frac{b^2}{ax+b}\right) + C$
7. $\int \frac{\mathrm{d}x}{x(ax+b)^2} = \frac{1}{b(ax+b)} - \frac{1}{b^2}\ln\left|\frac{ax+b}{x}\right| + C$

9.1.2 $\sqrt{ax + b}$

1. $\int \sqrt{ax + b}\mathrm{d}x = \frac{2}{3a}\sqrt{(ax + b)^3} + C$
2. $\int x\sqrt{ax + b}\mathrm{d}x = \frac{2}{15a^2}(3ax - 2b)\sqrt{(ax + b)^3} + C$
3. $\int x^2\sqrt{ax + b}\mathrm{d}x = \frac{2}{105a^3}(15a^2x^2 - 12abx + 8b^2)\sqrt{(ax + b)^3} + C$
4. $\int \frac{x}{\sqrt{ax+b}}\mathrm{d}x = \frac{2}{3a^2}(ax - 2b)\sqrt{ax + b} + C$
5. $\int \frac{x^2}{\sqrt{ax+b}}\mathrm{d}x = \frac{2}{15a^3}(3a^2x^2 - 4abx + 8b^2)\sqrt{ax + b} + C$
6. $\int \frac{\mathrm{d}x}{x\sqrt{ax+b}} = \begin{cases} \frac{1}{\sqrt{b}}\ln\left|\frac{\sqrt{ax+b}-\sqrt{b}}{\sqrt{ax+b}+\sqrt{b}}\right| + C & (b > 0) \\ \frac{2}{\sqrt{-b}}\arctan\sqrt{\frac{ax+b}{-b}} + C & (b < 0) \end{cases}$
7. $\int \frac{\mathrm{d}x}{x^2\sqrt{ax+b}} = -\frac{\sqrt{ax+b}}{bx} - \frac{a}{2b}\int \frac{\mathrm{d}x}{x\sqrt{ax+b}}$
8. $\int \frac{\sqrt{ax+b}}{x}\mathrm{d}x = 2\sqrt{ax + b} + b\int \frac{\mathrm{d}x}{x\sqrt{ax+b}}$
9. $\int \frac{\sqrt{ax+b}}{x^2}\mathrm{d}x = -\frac{\sqrt{ax+b}}{x} + \frac{a}{2}\int \frac{\mathrm{d}x}{x\sqrt{ax+b}}$

9.1.3 $x^2 \pm a^2$

1. $\int \frac{\mathrm{d}x}{x^2+a^2} = \frac{1}{a}\arctan\frac{x}{a} + C$
2. $\int \frac{\mathrm{d}x}{(x^2+a^2)^n} = \frac{x}{2(n-1)a^2(x^2+a^2)^{n-1}} + \frac{2n-3}{2(n-1)a^2}\int \frac{\mathrm{d}x}{(x^2+a^2)^{n-1}}$
3. $\int \frac{\mathrm{d}x}{x^2-a^2} = \frac{1}{2a}\ln\left|\frac{x-a}{x+a}\right| + C$

9.1.4 $ax^2 + b$ $(a > 0)$

1. $\int \frac{\mathrm{d}x}{ax^2+b} = \begin{cases} \frac{1}{\sqrt{ab}}\arctan\sqrt{\frac{a}{b}}x + C & (b > 0) \\ \frac{1}{2\sqrt{-ab}}\ln\left|\frac{\sqrt{a}x-\sqrt{-b}}{\sqrt{a}x+\sqrt{-b}}\right| + C & (b < 0) \end{cases}$
2. $\int \frac{x}{ax^2+b}\mathrm{d}x = \frac{1}{2a}\ln\left|ax^2 + b\right| + C$
3. $\int \frac{x^2}{ax^2+b}\mathrm{d}x = \frac{x}{a} - \frac{b}{a}\int \frac{\mathrm{d}x}{ax^2+b}$
4. $\int \frac{\mathrm{d}x}{x(ax^2+b)} = \frac{1}{2b}\ln\frac{x^2}{|ax^2+b|} + C$
5. $\int \frac{\mathrm{d}x}{x^2(ax^2+b)} = -\frac{1}{bx} - \frac{a}{b}\int \frac{\mathrm{d}x}{ax^2+b}$
6. $\int \frac{\mathrm{d}x}{x^3(ax^2+b)} = \frac{a}{2b^2}\ln\frac{|ax^2+b|}{x^2} - \frac{1}{2bx^2} + C$
7. $\int \frac{\mathrm{d}x}{(ax^2+b)^2} = \frac{x}{2b(ax^2+b)} + \frac{1}{2b}\int \frac{\mathrm{d}x}{ax^2+b}$

9.1.5 $ax^2 + bx + c$ $(a > 0)$

1. $\frac{\mathrm{d}x}{ax^2+bx+c} = \begin{cases} \frac{2}{\sqrt{4ac-b^2}}\arctan\frac{2ax+b}{\sqrt{4ac-b^2}} + C & (b^2 < 4ac) \\ \frac{1}{\sqrt{b^2-4ac}}\ln\left|\frac{2ax+b-\sqrt{b^2-4ac}}{2ax+b+\sqrt{b^2-4ac}}\right| + C & (b^2 > 4ac) \end{cases}$
2. $\int \frac{x}{ax^2+bx+c}\mathrm{d}x = \frac{1}{2a}\ln|ax^2 + bx + c| - \frac{b}{2a}\int \frac{\mathrm{d}x}{ax^2+bx+c}$

9.1.6 $\sqrt{x^2 + a^2}$ $(a > 0)$

1. $\int \frac{\mathrm{d}x}{\sqrt{x^2+a^2}} = \operatorname{arsh}\frac{x}{a} + C_1 = \ln(x + \sqrt{x^2 + a^2}) + C$
2. $\int \frac{\mathrm{d}x}{\sqrt{(x^2+a^2)^3}} = \frac{x}{a^2\sqrt{x^2+a^2}} + C$
3. $\int \frac{x}{\sqrt{x^2+a^2}}\mathrm{d}x = \sqrt{x^2 + a^2} + C$
4. $\int \frac{x}{\sqrt{(x^2+a^2)^3}}\mathrm{d}x = -\frac{1}{\sqrt{x^2+a^2}} + C$
5. $\int \frac{x^2}{\sqrt{x^2+a^2}}\mathrm{d}x = \frac{x}{2}\sqrt{x^2 + a^2} - \frac{a^2}{2}\ln(x + \sqrt{x^2 + a^2}) + C$
6. $\int \frac{x^2}{\sqrt{(x^2+a^2)^3}}\mathrm{d}x = -\frac{x}{\sqrt{x^2+a^2}} + \ln(x + \sqrt{x^2 + a^2}) + C$
7. $\int \frac{\mathrm{d}x}{x\sqrt{x^2+a^2}} = \frac{1}{a}\ln\frac{\sqrt{x^2+a^2}-a}{|x|} + C$
8. $\int \frac{\mathrm{d}x}{x^2\sqrt{x^2+a^2}} = -\frac{\sqrt{x^2+a^2}}{a^2x} + C$
9. $\int \sqrt{x^2 + a^2}\mathrm{d}x = \frac{x}{2}\sqrt{x^2 + a^2} + \frac{a^2}{2}\ln(x + \sqrt{x^2 + a^2}) + C$
10. $\int \sqrt{(x^2 + a^2)^3}\mathrm{d}x = \frac{x}{8}(2x^2 + 5a^2)\sqrt{x^2 + a^2} + \frac{3}{8}a^4\ln(x + \sqrt{x^2 + a^2}) + C$
11. $\int x\sqrt{x^2 + a^2}\mathrm{d}x = \frac{1}{3}\sqrt{(x^2 + a^2)^3} + C$
12. $\int x^2\sqrt{x^2 + a^2}\mathrm{d}x = \frac{x}{8}(2x^2 + a^2)\sqrt{x^2 + a^2} - \frac{a^4}{8}\ln(x + \sqrt{x^2 + a^2}) + C$
13. $\int \frac{\sqrt{x^2+a^2}}{x}\mathrm{d}x = \sqrt{x^2 + a^2} + a\ln\frac{\sqrt{x^2+a^2}-a}{|x|} + C$
14. $\int \frac{\sqrt{x^2+a^2}}{x^2}\mathrm{d}x = -\frac{\sqrt{x^2+a^2}}{x} + \ln(x + \sqrt{x^2 + a^2}) + C$

9.1.7 $\sqrt{x^2 - a^2}$ $(a > 0)$

1. $\int \frac{\mathrm{d}x}{\sqrt{x^2-a^2}} = \frac{x}{|x|}\operatorname{arch}\frac{|x|}{a} + C_1 = \ln\left|x + \sqrt{x^2 - a^2}\right| + C$
2. $\int \frac{\mathrm{d}x}{\sqrt{(x^2-a^2)^3}} = -\frac{x}{a^2\sqrt{x^2-a^2}} + C$
3. $\int \frac{x}{\sqrt{x^2-a^2}}\mathrm{d}x = \sqrt{x^2 - a^2} + C$
4. $\int \frac{x}{\sqrt{(x^2-a^2)^3}}\mathrm{d}x = -\frac{1}{\sqrt{x^2-a^2}} + C$
5. $\int \frac{x^2}{\sqrt{x^2-a^2}}\mathrm{d}x = \frac{x}{2}\sqrt{x^2 - a^2} + \frac{a^2}{2}\ln|x + \sqrt{x^2 - a^2}| + C$
6. $\int \frac{x^2}{\sqrt{(x^2-a^2)^3}}\mathrm{d}x = -\frac{x}{\sqrt{x^2-a^2}} + \ln|x + \sqrt{x^2 - a^2}| + C$
7. $\int \frac{\mathrm{d}x}{x\sqrt{x^2-a^2}} = \frac{1}{a}\arccos\frac{a}{|x|} + C$
8. $\int \frac{\mathrm{d}x}{x^2\sqrt{x^2-a^2}} = \frac{\sqrt{x^2-a^2}}{a^2x} + C$
9. $\int \sqrt{x^2 - a^2}\mathrm{d}x = \frac{x}{2}\sqrt{x^2 - a^2} - \frac{a^2}{2}\ln|x + \sqrt{x^2 - a^2}| + C$
10. $\int \sqrt{(x^2 - a^2)^3}\mathrm{d}x = \frac{x}{8}(2x^2 - 5a^2)\sqrt{x^2 - a^2} + \frac{3}{8}a^4\ln|x + \sqrt{x^2 - a^2}| + C$
11. $\int x\sqrt{x^2 - a^2}\mathrm{d}x = \frac{1}{3}\sqrt{(x^2 - a^2)^3} + C$
12. $\int x^2\sqrt{x^2 - a^2}\mathrm{d}x = \frac{x}{8}(2x^2 - a^2)\sqrt{x^2 - a^2} - \frac{a^4}{8}\ln|x + \sqrt{x^2 - a^2}| + C$
13. $\int \frac{\sqrt{x^2-a^2}}{x}\mathrm{d}x = \sqrt{x^2 - a^2} - a\arccos\frac{a}{|x|} + C$
14. $\int \frac{\sqrt{x^2-a^2}}{x^2}\mathrm{d}x = -\frac{\sqrt{x^2-a^2}}{x} + \ln|x + \sqrt{x^2 - a^2}| + C$

9.1.8 $\sqrt{a^2 - x^2}$ $(a > 0)$

1. $\int \frac{\mathrm{d}x}{\sqrt{a^2-x^2}} = \arcsin\frac{x}{a} + C$
2. $\frac{\mathrm{d}x}{\sqrt{(a^2-x^2)^3}} = \frac{x}{a^2\sqrt{a^2-x^2}} + C$
3. $\int \frac{x}{\sqrt{a^2-x^2}}\mathrm{d}x = -\sqrt{a^2 - x^2} + C$
4. $\int \frac{x}{\sqrt{(a^2-x^2)^3}}\mathrm{d}x = \frac{1}{\sqrt{a^2-x^2}} + C$
5. $\int \frac{x^2}{\sqrt{a^2-x^2}}\mathrm{d}x = -\frac{x}{2}\sqrt{a^2 - x^2} + \frac{a^2}{2}\arcsin\frac{x}{a} + C$
6. $\int \frac{x^2}{\sqrt{(a^2-x^2)^3}}\mathrm{d}x = \frac{x}{\sqrt{a^2-x^2}} - \arcsin\frac{x}{a} + C$
7. $\int \frac{\mathrm{d}x}{x\sqrt{a^2-x^2}} = \frac{1}{a}\ln\frac{a-\sqrt{a^2-x^2}}{|x|} + C$
8. $\int \frac{\mathrm{d}x}{x^2\sqrt{a^2-x^2}} = -\frac{\sqrt{a^2-x^2}}{a^2x} + C$
9. $\int \sqrt{a^2 - x^2}\mathrm{d}x = \frac{x}{2}\sqrt{a^2 - x^2} + \frac{a^2}{2}\arcsin\frac{x}{a} + C$
10. $\int \sqrt{(a^2 - x^2)^3}\mathrm{d}x = \frac{x}{8}(5a^2 - 2x^2)\sqrt{a^2 - x^2} + \frac{3}{8}a^4\arcsin\frac{x}{a} + C$
11. $\int x\sqrt{a^2 - x^2}\mathrm{d}x = -\frac{1}{3}\sqrt{(a^2 - x^2)^3} + C$
12. $\int x^2\sqrt{a^2 - x^2}\mathrm{d}x = \frac{x}{8}(2x^2 - a^2)\sqrt{a^2 - x^2} + \frac{a^4}{8}\arcsin\frac{x}{a} + C$
13. $\int \frac{\sqrt{a^2-x^2}}{x}\mathrm{d}x = \sqrt{a^2 - x^2} + a\ln\frac{a-\sqrt{a^2-x^2}}{|x|} + C$
14. $\int \frac{\sqrt{a^2-x^2}}{x^2}\mathrm{d}x = -\frac{\sqrt{a^2-x^2}}{x} - \arcsin\frac{x}{a} + C$

9.1.9 $\sqrt{\pm ax^2 + bx + c}$ $(a > 0)$

1. $\int \frac{\mathrm{d}x}{\sqrt{ax^2+bx+c}} = \frac{1}{\sqrt{a}}\ln|2ax + b + 2\sqrt{a}\sqrt{ax^2 + bx + c}| + C$
2. $\int \sqrt{ax^2 + bx + c}\mathrm{d}x = \frac{2ax+b}{4a}\sqrt{ax^2 + bx + c} + \frac{4ac-b^2}{8\sqrt{a^3}}\ln|2ax + b + 2\sqrt{a}\sqrt{ax^2 + bx + c}| + C$
3. $\int \frac{x}{\sqrt{ax^2+bx+c}}\mathrm{d}x = \frac{1}{a}\sqrt{ax^2 + bx + c} - \frac{b}{2\sqrt{a^3}}\ln|2ax+b+2\sqrt{a}\sqrt{ax^2 + bx + c}| + C$
4. $\int \frac{\mathrm{d}x}{\sqrt{c+bx-ax^2}} = -\frac{1}{\sqrt{a}}\arcsin\frac{2ax-b}{\sqrt{b^2+4ac}} + C$
5. $\int \sqrt{c + bx - ax^2}\mathrm{d}x = \frac{2ax-b}{4a}\sqrt{c + bx - ax^2} + \frac{b^2+4ac}{8\sqrt{a^3}}\arcsin\frac{2ax-b}{\sqrt{b^2+4ac}} + C$

6. $\int \frac{x}{\sqrt{c+bx-ax^2}}\mathrm{d}x = -\frac{1}{a}\sqrt{c+bx-ax^2} + \frac{b}{2\sqrt{a^3}} \arcsin \frac{2ax-b}{\sqrt{b^2+4ac}} + C$

9.1.10 $\sqrt{\pm\frac{x-a}{x-b}}$ & $\sqrt{(x-a)(x-b)}$

1. $\int \sqrt{\frac{x-a}{x-b}}\mathrm{d}x = (x-b)\sqrt{\frac{x-a}{x-b}} + (b-a)\ln(\sqrt{|x-a|} + \sqrt{|x-b|}) + C$
2. $\int \sqrt{\frac{x-a}{b-x}}\mathrm{d}x = (x-b)\sqrt{\frac{x-a}{b-x}} + (b-a)\arcsin\sqrt{\frac{x-a}{b-x}} + C$
3. $\int \frac{\mathrm{d}x}{\sqrt{(x-a)(b-x)}} = 2\arcsin\sqrt{\frac{x-a}{b-x}} + C \ (a < b)$
4. $\int \sqrt{(x-a)(b-x)}\mathrm{d}x = \frac{2x-a-b}{4}\sqrt{(x-a)(b-x)} + \frac{(b-a)^2}{4}\arcsin\sqrt{\frac{x-a}{b-x}} + C$ $(a < b)$

9.1.11 Triangular function

1. $\int \tan x\mathrm{d}x = -\ln|\cos x| + C$
2. $\int \cot x\mathrm{d}x = \ln|\sin x| + C$
3. $\int \sec x\mathrm{d}x = \ln\left|\tan\left(\frac{\pi}{4} + \frac{x}{2}\right)\right| + C = \ln|\sec x + \tan x| + C$
4. $\int \csc x\mathrm{d}x = \ln\left|\tan\frac{x}{2}\right| + C = \ln|\csc x - \cot x| + C$
5. $\int \sec^2 x\mathrm{d}x = \tan x + C$
6. $\int \csc^2 x\mathrm{d}x = -\cot x + C$
7. $\int \sec x \tan x\mathrm{d}x = \sec x + C$
8. $\int \csc x \cot x\mathrm{d}x = -\csc x + C$
9. $\int \sin^2 x\mathrm{d}x = \frac{x}{2} - \frac{1}{4}\sin 2x + C$
10. $\int \cos^2 x\mathrm{d}x = \frac{x}{2} + \frac{1}{4}\sin 2x + C$
11. $\int \sin^n x\mathrm{d}x = -\frac{1}{n}\sin^{n-1} x\cos x + \frac{n-1}{n}\int \sin^{n-2} x\mathrm{d}x$
12. $\int \cos^n x\mathrm{d}x = \frac{1}{n}\cos^{n-1} x\sin x + \frac{n-1}{n}\int \cos^{n-2} x\mathrm{d}x$
13. $\frac{\mathrm{d}x}{\sin^n x} = -\frac{1}{n-1}\frac{\cos x}{\sin^{n-1} x} + \frac{n-2}{n-1}\int \frac{\mathrm{d}x}{\sin^{n-2} x}$
14. $\frac{\mathrm{d}x}{\cos^n x} = \frac{1}{n-1}\frac{\sin x}{\cos^{n-1} x} + \frac{n-2}{n-1}\int \frac{\mathrm{d}x}{\cos^{n-2} x}$
15. $$\begin{aligned}&\int \cos^m x \sin^n x\mathrm{d}x \\ &= \frac{1}{m+n}\cos^{m-1} x\sin^{n+1} x + \frac{m-1}{m+n}\int \cos^{m-2} x\sin^n x\mathrm{d}x \\ &= -\frac{1}{m+n}\cos^{m+1} x\sin^{n-1} x + \frac{n-1}{m+1}\int \cos^m x\sin^{n-2} x\mathrm{d}x\end{aligned}$$
16. $\int \sin ax\cos bx\mathrm{d}x = -\frac{1}{2(a+b)}\cos(a+b)x - \frac{1}{2(a-b)}\cos(a-b)x + C$
17. $\int \sin ax\sin bx\mathrm{d}x = -\frac{1}{2(a+b)}\sin(a+b)x + \frac{1}{2(a-b)}\sin(a-b)x + C$
18. $\int \cos ax\cos bx\mathrm{d}x = \frac{1}{2(a+b)}\sin(a+b)x + \frac{1}{2(a-b)}\sin(a-b)x + C$
19. $\int \frac{\mathrm{d}x}{a+b\sin x} = \begin{cases}\frac{2}{\sqrt{a^2-b^2}}\arctan\frac{a\tan\frac{x}{2}+b}{\sqrt{a^2-b^2}} + C & (a^2 > b^2) \\ \frac{1}{\sqrt{b^2-a^2}}\ln\left|\frac{a\tan\frac{x}{2}+b-\sqrt{b^2-a^2}}{a\tan\frac{x}{2}+b+\sqrt{b^2-a^2}}\right| + C & (a^2 < b^2)\end{cases}$
20. $\int \frac{\mathrm{d}x}{a+b\cos x} = \begin{cases}\frac{2}{a+b}\sqrt{\frac{a+b}{a-b}}\arctan\left(\sqrt{\frac{a-b}{a+b}}\tan\frac{x}{2}\right) + C & (a^2 > b^2) \\ \frac{1}{a+b}\sqrt{\frac{a+b}{a-b}}\ln\left|\frac{\tan\frac{x}{2}+\sqrt{\frac{a+b}{b-a}}}{\tan\frac{x}{2}-\sqrt{\frac{a+b}{b-a}}}\right| + C & (a^2 < b^2)\end{cases}$
21. $\int \frac{\mathrm{d}x}{a^2\cos^2 x+b^2\sin^2 x} = \frac{1}{ab}\arctan\left(\frac{b}{a}\tan x\right) + C$
22. $\int \frac{\mathrm{d}x}{a^2\cos^2 x-b^2\sin^2 x} = \frac{1}{2ab}\ln\left|\frac{b\tan x+a}{b\tan x-a}\right| + C$
23. $\int x\sin ax\mathrm{d}x = \frac{1}{a^2}\sin ax - \frac{1}{a}x\cos ax + C$
24. $\int x^2\sin ax\mathrm{d}x = -\frac{1}{a}x^2\cos ax + \frac{2}{a^2}x\sin ax + \frac{2}{a^3}\cos ax + C$
25. $\int x\cos ax\mathrm{d}x = \frac{1}{a^2}\cos ax + \frac{1}{a}x\sin ax + C$
26. $\int x^2\cos ax\mathrm{d}x = \frac{1}{a}x^2\sin ax + \frac{2}{a^2}x\cos ax - \frac{2}{a^3}\sin ax + C$

9.1.12 Inverse triangular function $(a > 0)$

1. $\int \arcsin\frac{x}{a}\mathrm{d}x = x\arcsin\frac{x}{a} + \sqrt{a^2-x^2} + C$
2. $\int x\arcsin\frac{x}{a}\mathrm{d}x = (\frac{x^2}{2} - \frac{a^2}{4})\arcsin\frac{x}{a} + \frac{x}{4}\sqrt{x^2-x^2} + C$
3. $\int x^2\arcsin\frac{x}{a}\mathrm{d}x = \frac{x^3}{3}\arcsin\frac{x}{a} + \frac{1}{9}(x^2+2a^2)\sqrt{a^2-x^2} + C$
4. $\int \arccos\frac{x}{a}\mathrm{d}x = x\ arccos\frac{x}{a} - \sqrt{a^2-x^2} + C$
5. $\int x\arccos\frac{x}{a}\mathrm{d}x = (\frac{x^2}{2} - \frac{a^2}{4})\arccos\frac{x}{a} - \frac{x}{4}\sqrt{a^2-x^2} + C$
6. $\int x^2\arccos\frac{x}{a}\mathrm{d}x = \frac{x^3}{3}\arccos\frac{x}{a} - \frac{1}{9}(x^2+2a^2)\sqrt{a^2-x^2} + C$
7. $\int \arctan\frac{x}{a}\mathrm{d}x = x\arctan\frac{x}{a} - \frac{a}{2}\ln(a^2+x^2) + C$
8. $\int x\arctan\frac{x}{a}\mathrm{d}x = \frac{1}{2}(a^2+x^2)\arctan\frac{x}{a} - \frac{a}{2}x + C$
9. $\int x^2\arctan\frac{x}{a}\mathrm{d}x = \frac{x^3}{3}\arctan\frac{x}{a} - \frac{a}{6}x^2 + \frac{a^3}{6}\ln(a^2+x^2) + C$

9.1.13 Exponential function

1. $\int a^x\mathrm{d}x = \frac{1}{\ln a}a^x + C$
2. $\int \mathrm{e}^{ax}\mathrm{d}x = \frac{1}{a}a^{ax} + C$
3. $\int x\mathrm{e}^{ax}\mathrm{d}x = \frac{1}{a^2}(ax-1)a^{ax} + C$
4. $\int x^n\mathrm{e}^{ax}\mathrm{d}x = \frac{1}{a}x^n\mathrm{e}^{ax} - \frac{n}{a}\int x^{n-1}\mathrm{e}^{ax}\mathrm{d}x$
5. $\int xa^x\mathrm{d}x = \frac{x}{\ln a}a^x - \frac{1}{(\ln a)^2}a^x + C$
6. $\int x^n a^x\mathrm{d}x = \frac{1}{\ln a}x^n a^x - \frac{n}{\ln a}\int x^{n-1}a^x\mathrm{d}x$
7. $\int \mathrm{e}^{ax}\sin bx\mathrm{d}x = \frac{1}{a^2+b^2}\mathrm{e}^{ax}(a\sin bx - b\cos bx) + C$
8. $\int \mathrm{e}^{ax}\cos bx\mathrm{d}x = \frac{1}{a^2+b^2}\mathrm{e}^{ax}(b\sin bx + a\cos bx) + C$
9. $\int \mathrm{e}^{ax}\sin^n bx\mathrm{d}x = \frac{1}{a^2+b^2n^2}\mathrm{e}^{ax}\sin^{n-1} bx(a\sin bx - nb\cos bx) + \frac{n(n-1)b^2}{a^2+b^2n^2}\int \mathrm{e}^{ax}\sin^{n-2} bx\mathrm{d}x$
10. $\int \mathrm{e}^{ax}\cos^n bx\mathrm{d}x = \frac{1}{a^2+b^2n^2}\mathrm{e}^{ax}\cos^{n-1} bx(a\cos bx + nb\sin bx) + \frac{n(n-1)b^2}{a^2+b^2n^2}\int \mathrm{e}^{ax}\cos^{n-2} bx\mathrm{d}x$

9.1.14 Logarithmic function

1. $\int \ln x\mathrm{d}x = x\ln x - x + C$
2. $\int \frac{\mathrm{d}x}{x\ln x} = \ln|\ln x| + C$
3. $\int x^n\ln x\mathrm{d}x = \frac{1}{n+1}x^{n+1}(\ln x - \frac{1}{n+1}) + C$
4. $\int (\ln x)^n\mathrm{d}x = x(\ln x)^n - n\int (\ln x)^{n-1}\mathrm{d}x$
5. $\int x^m(\ln x)^n\mathrm{d}x = \frac{1}{m+1}x^{m+1}(\ln x)^n - \frac{n}{m+1}\int x^m(\ln x)^{n-1}\mathrm{d}x$

9.2 Regular expression

9.2.1 Special pattern characters

Characters	Description
`.`	Not newline
`\t`	Tab (HT)
`\n`	Newline (LF)
`\v`	Vertical tab (VT)
`\f`	Form feed (FF)
`\r`	Carriage return (CR)
`\cletter`	Control code
`\xhh`	ASCII character
`\uhhhh`	Unicode character
`\0`	Null
`\int`	Backreference
`\d`	Digit
`\D`	Not digit
`\s`	Whitespace
`\S`	Not whitespace
`\w`	Word (letters, numbers and the underscore)
`\W`	Not word
`\character`	Character
`[class]`	Character class
`[^class]`	Negated character class

9.2.2 Quantifiers

Characters	Times
`*`	0 or more
`+`	1 or more
`?`	0 or 1
`{int}`	`int`
`{int,}`	`int` or more
`{min,max}`	Between `min` and `max`

By default, all these quantifiers are greedy (i.e., they take as many characters that meet the condition as possible). This behavior can be overridden to ungreedy (i.e., take as few characters that meet the condition as possible) by adding a question mark (`?`) after the quantifier.

9.2.3 Groups

Characters	Description
`(subpattern)`	Group with backreference
`(?:subpattern)`	Group without backreference

9.2.4 Assertions

Characters	Description
`^`	Beginning of line
`$`	End of line
`\b`	Word boundary
`\B`	Not a word boundary
`(?=subpattern)`	Positive lookahead
`(?!subpattern)`	Negative lookahead

9.2.5 Alternative

A regular expression can contain multiple alternative patterns simply by separating them with the separator operator (`|`): The regular expression will match if any of the alternatives match, and as soon as one does.

9.2.6 Character classes

Class	Description
`[:alnum:]`	Alpha-numerical character
`[:alpha:]`	Alphabetic character
`[:blank:]`	Blank character
`[:cntrl:]`	Control character
`[:digit:]`	Decimal digit character
`[:graph:]`	Character with graphical representation
`[:lower:]`	Lowercase letter
`[:print:]`	Printable character
`[:punct:]`	Punctuation mark character
`[:space:]`	Whitespace character
`[:upper:]`	Uppercase letter
`[:xdigit:]`	Hexadecimal digit character
`[:d:]`	Decimal digit character
`[:w:]`	Word character
`[:s:]`	Whitespace character

Please note that the brackets in the class names are additional to those opening and closing the class definition. For example:

`[[:alpha:]]` is a character class that matches any alphabetic character.

`[abc[:digit:]]` is a character class that matches a, b, c, or a digit.

`[^[:space:]]` is a character class that matches any character except a whitespace.

9.3 Operator precedence

Precedence	Operator	Associativity
1	`::`	Left-to-right

2	`a++ a--`
	`type() type{}`
	`a()`
	`a[]`
	`. ->`	

3	`++a --a`
	`+a -a`
	`! ~`
	`(type)`
	`*a`
	`&a`
	`sizeof`
	`new new[]`
	`delete delete[]`
		Right-to-left

4	`.* ->*`	Left-to-right
5	`a*b a/b a%b`	
6	`a+b a-b`	
7	`<< >>`	
8	`< <=` `> >=`	
9	`== !=`	
10	`a&b`	
11	`a^b`	
12	`a|b`	
13	`&&`	
14	`||`	

15	`a?b:c`
	`throw`
	`=`
	`+= -= *= /= %=`
	`<<= >>=`
	`&= ^= |=`
		Right-to-left

16	`,`	Left-to-right